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An Assessment of the Vulnerability of Australian Forests to the Impacts of Climate Change

Part 5: Synthesis

Sarah Boulter

A Preliminary Assessment of the Vulnerability of Australian Forests to the Impacts of Climate Change

WP5 Final Report

Synthesis

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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision-makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

Cover image
Terry Reis

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Executive Summary

This report is a synthesis of the Forest Vulnerability Assessment project undertaken by a consortium of research groups. The project was an initiative of the Natural Resource Management Ministerial Council (NRMMC) and undertaken under the auspices of the National Climate Change Adaptation Research Facility (NCCARF), Griffith University. The project was established in 2009 to:

- review current knowledge of the likely biophysical and socio-economic consequences of climate change on Australia's forests,
- understand the vulnerabilities of Australia's forests,
- identify current adaptation actions, and
- identify information gaps to improve adaptative capacity.

The assessment was carried out using a basic vulnerability assessment framework which considers *sensitivity*, *exposure* and *adaptive capacity* to determine the vulnerability of Australia's forests to climate change. Each of these factors was considered in turn using the general scientific literature. In addition interviews with stakeholders were used to identify key issues and current actions by forest managers and policy-makers. Four reports were developed and published as result of each of those projects (Cockfield et al., 2010, Medlyn et al., 2010, Wilson and Turton, 2010, Woods et al., 2010). This synthesis report was developed based on those reports. The work was undertaken primarily in 2010 but this final report was not accepted for release until November 2012.

A regional scale assessment was also carried out using an agro-ecological classification of Australia to understand forest vulnerability to climate change within each region **(*Section 8*)**.

Terms of Reference The following definition of forests was adopted for the assessment:

> *A FOREST is an area, incorporating all living and non-living components, that is dominated by trees having usually a single stem and a mature or potentially mature stand height exceeding two metres and with existing or potential crown cover of overstorey strata about equal to or greater than 20%. This includes Australia's diverse native forests and plantations, regardless of age. It is also sufficiently broad to encompass areas of trees that are sometimes described as woodlands.* Australia's State of the Forests Report (Montreal Process Implementation Group for Australia, 2008)

Forest management types were categorised into four types: conservation forests, native production forests, plantations and environmental plantings **(*see Section 1.2.1*)**.

A series of climate scenarios using a high emissions scenario were generated against which the assessment could be carried out **(*see Section 1.4*)**.

Exposure The exposure of forests to changes in climate will depend on global trends in greenhouse gas emissions and local variability in climate response. Precise predictions of changes in climate cannot be made because of uncertainty surrounding the change in greenhouse gas emissions, the rate of climate change associated with certain levels of emissions and regional differences in climate change. Nonetheless we can make several broad conclusions with a high level of confidence about the future climate under which forests must be managed and the following climate scenarios (***see Section 2.1***) were the basis of our vulnerability assessment:

- There is high confidence that temperatures will increase over most of Australia, with an increase in mean maximum temperatures of between 3.5 - 4.5ºC in February by 2070.
- Rainfall patterns are more difficult to predict but there is some confidence they will vary across Australia. The scenarios used in this assessment predict a wetter-wet season and drier-dry season in Australia's north. In the southern half of Australia the scenarios predicted decreased winter rain.

- There is a high level of confidence that the weather will become more highly variable, with increased storm frequency and severity, fewer frost days, an increase in the number of extremely hot days and longer, drier drought conditions.

Sensitivity There is likely to be significant variation in how individual organisms, species, communities and ecosystems will be affected by climate change. Species will be directly affected by changes in climate at an individual level, with flow-on effects to ecosystem structure, composition and function. Changes in climate will also create indirect effects such as exposure to fire, introduced species and diseases that will impact on forests. When multiple impacts and flow-on effects are considered, the contemplated potential responses are complex. The following direct and indirect effects of climate change on individual trees were considered and evidence of the impacts reported in the scientific literature summarised.

- **Increased atmospheric CO_2** – While there is evidence that Australia's forests have the physical capacity to increase productivity or growth in response to increasing atmospheric CO_2, the availability of water and nutrients will change this response. In nutrient poor sites there may be no increase in carbon uptake and growth. There is sound evidence that water use efficiency can improve under increased CO_2 availability. What is unclear is whether this will translate into improved drought tolerance among forest trees **(*see Section 3.2.1*)**.

- **Rising temperatures** – The effect of rising temperature on individual species will depend on (i) whether the organism is currently living at a temperature above or below its optimal temperature, and (ii) its capacity to acclimatize. For example, a plant living at a temperature cooler than its optimal temperature, is likely to see increased growth and survival under warmer temperatures. Rising temperatures are also associated with reduced frosts. Again this has both positive and negative implications with species that are currently precluded from frost susceptible areas potentially more successful in these areas as the number of frost days diminishes. However, there is some evidence that less frost days could reduce acclimation to these conditions increasing the negative impact of frosts when they do occur **(*see Section 3.2.2*)**.

- **Rainfall** – While predicted changes in rainfall for specific regions remains quite uncertain the assessment considered existing evidence of potential sensitivities. The impact of drought will depend (i) on the duration and severity of the drought conditions, (ii) the drought tolerance of individual species, and (iii) avoidance strategies of individual species (e.g. use of groundwater). Where rainfall increases, forests may increase water uptake to a point above which runoff will increase **(*see Section 3.2.4*)**.

- **Fire** – As with the direct effects of temperature and rainfall, the response of an individual species to fire will depend on its sensitivity to fire. In addition, the impact of fire on forest communities will depend on the season, frequency and severity of fires **(*see Section 4.5.1*)**. Changes in fire regimes have the potential to change community composition and structure.

For individual species, changes in environmental conditions may alter phenological or life cycle events. The evidence from Australia is limited and mixed, but any changes may interrupt interactions with other species such as pollination, frugivory and parasitism. Potential outcomes may be either positive or negative for individual species **(*see Section 3.3*)**.

Impacts on individual organisms and species will have flow-on effects to species interactions and ecosystems. The key changes to ecosystems are:

- **Changes in species distributions** – Range shifts are most likely to be polewards or to higher elevations. For some species this may represent an expansion of range, for others a reduction. A species range is not just determined by climate and is affected by interactions with other species and the behaviour of individual species. However at this stage, evidence of climate tolerance of individual species is the primary parameter by which future species distributions are predicted **(*see Section 4.2*).**

- **Changes in community compositions** – The composition and diversity of forest communities is highly likely to change as a result of shifting distributions of species, local extinctions and the introduction of new species. Introduced species include existing diseases, weeds and pests with expanded ranges, but also species new to an area. Some weed and pest species are predicted to become a reduced threat in some areas under climate change **(*see Section 4.3*).**
- **Changes in forest structure** – Again shifting distributions, local extinctions and the introduction of new species is likely to result in changes to forest structure. Current evidence of changed forest structure has been associated with increasing CO_2, temperature changes, rainfall patterns, grazing and fire, but it is difficult to point to a single causal link **(*see Section 4.4*).**
- **Disruption of biotic processes** – There is potential for both spatial mismatches (e.g. distribution shifts, local extinctions) and temporal mismatches (e.g. changes in life cycle timing). This has the potential to have both negative and positive impacts on the survival of different organisms **(*see Section 4.4*).**

Adaptive capacity Australia's natural systems have a limited innate capacity to adapt to climate change, beyond which adaptation will be constrained by: rates of evolutionary change versus rates of climate change; contractions of suitable habitat; limited capacity to migrate (e.g. fragmentation of suitable habitat prevents dispersal); and extreme events that diminish a forest's capacity to recover. In human systems there is considerable capacity to adapt. The adaptive capacity of Australia's forests is strengthened by several well developed systems such as: a well developed economy; extensive scientific knowledge; practice of sustainable forest management and technical capabilities; disaster mitigation strategies and plans; and well developed biosecurity procedures. In addition there is a history of management and existing policies in place specific to forests. The focus in this report is on the adaptation measures available to humans.

- In a socio-economic context adaptation refers to responses to actual or expected climatic changes in physical, economic or social conditions, by humans, individually, in a group or as an organised authority which moderates harm or exploits beneficial opportunities.
- A review of the historical and current approach to forest management identified the 'evolution' of the sustainable development approach both internationally and in Australia. Australia's key policy on forests, the National Forest Policy Statement is built on this principle. The Regional Forest Agreements are the key instruments through which this policy is intended to be implemented ***(see Section 7.2)***.
- Identified limits and barriers to adaptation in Australia's forests include: competition for land, physical limits of organisms, knowledge gaps, cost of actions, existing markets and social perceptions ***(see Section 7.4)***.
- Adaptation actions can be grouped into: land management options, specific silviculture practices, social and community skills and planning options. There are a number of adaptation tools currently in use by forest managers including software for modelling and decision support, specific silviculture practices, planning, policy and investment ***(see Section 7.5)***.
- Other options for further strengthening of Australia's adaptive capacity include: adopting Indigenous or local level knowledge, improved knowledge transfer, flexibility in decision making. Improved understanding of other disturbance factors, and monitoring change ***(see Section 7.7)***.
- In order to prioritise responses to climate change impacts, land managers and policy makers will need to assess the costs and benefits of adaptation actions. We identified three broad categories of socio-economic values that need to be assessed and this can be done by estimating traditional industry values (timber and tourism), estimating new industry values (carbon sequestration) or estimating non-market values ***(see Section 7.6)***.
- In adapting to the impacts of climate change there are a number of potential social and economic adjustments of perception and practice that might need to be made for managers and communities associated with forests. Many of these were identified in stakeholder

interviews and indicate that some adjustment of perception is already happening ***(see Section 7.7)***.

Vulnerability

In general, those forests with the greatest vulnerability will be those with existing stresses, those with the highest exposure to extreme events, existing plantations in long rotations and reserves with inadequate management.

For most regions, temperatures are predicted to warm and rainfall is likely to decrease. For some regions growing conditions could in fact improve which might have positive implications for plantations and environmental plantings as well as agriculture, but create potential land use conflicts. The greatest negative impacts are likely to be felt in those regions with existing stressors (e.g. the Mediterranean Woodland and Brigalow Belt) or with unique or high biodiversity and a reliance on a cool climate for some species (e.g. Subtropical moist forest, Tropical rainforest and Cold forest and grassland).

- **Tropical Savanna** – Although growth is not likely to be strongly affected, a number of natural vulnerabilities exist in this region: exposure to extreme weather events; risk of pest/disease/weeds, changing fire regimes and increasing severity of dry season. There is potential for expansion of closed-forests in mesic savanna, while xeric savannas are likely to experience tree death in times of drought.
- **Brigalow belt woodland** – The increased availability of CO_2 in the atmosphere may compensate for water limitations and maintain plant growth levels. Extensive past clearing and resultant biodiversity loss could make this region particularly sensitive to climate change impacts and new disturbances (e.g. weeds). Vine thickets are particularly vulnerable to any increased fire risk. An increasing focus on conservation outcomes will be needed.
- **Tropical rainforest** – Increased frequency and intensity of storms and cyclones are expected. On balance, there may be little change in plant growth in some areas and a reduction in other. There is reasonable potential for new species (both weed and tropical native species) biodiversity loss, natural disasters and reduced tourism.
- **Tropical forest and woodland** – The impact on plant growth and productivity is likely to be a complex response to a number of variables. While increasing temperatures and decreasing rainfall have the potential to increase water stress in plants and reduce growth at dry times of the year, an increase in CO_2 could increase productivity in high nutrient areas and improve water use efficiency. Plantations or plantings will need to adapt species choice and management tools. There could be increased risks from new species, and new fire risks. Coastal inundation threatens mangroves and wetlands.
- **Temperate sub-humid woodlands** – There is potential for increased plant growth and productivity, but some plantation species are expected to decrease in productivity. Decreased frost and warmer conditions may allow new species to establish or thrive. Existing degradation issues will be compounded by climate change.
- **Subtropical moist forests** – Increased growth is likely, particularly summer growth in the southern half of the region. Areas of high nutrients could experience increased productivity under elevated CO_2 as well as increased water efficiency. Drought, fire and weed potential will increase. Loss or change of the character of high value biodiversity highly likely.
- **Temperate moist forests** – There is good indication that plant growth is likely to increase and water efficiency could improve. Fewer frosts could allow establishment of new species. Drought will elicit species-specific responses. Implementation of plantation management to deal with drought (e.g. species selection, density of planting) to avoid drought stress, to avoid drought impacts. Expect an increase in vegetation cover. Climate tolerance of species thought to be limited, may result in migrations or species loss. Fire is likely to be a significant threat to both biodiversity and forest land use.
- **Cold forest and grassland** – Increased water stress is expected in summer in the Alps. There is predicted to be some increased plantation productivity for some species. There is an extremely high risk of loss of high altitude species with loss of snow, higher temperatures and

altered distributions for other species. Phenological events are likely to change. There is expected to be an increased fire risk. Considerable impacts on the tourism industry are also likely.

- **Mediterranean woodland** – Plant growth is expected to be reduced, although at a local scale, the availability of groundwater may advantage some species. There is an increased drought mortality risk. There is an expectation that the distribution of species will be affected, with some at risk of local extinction. There is projected to be an increase in fire risk conditions, although fuel loads may be reduced. In general climate change is likely to exacerbate existing land degradation issues.

The vulnerability analysis for forests in each of the four classifications used in this assessment (conservation forests, environmental plantings, productive native forests and plantations) highlighted those regions with the most vulnerable forests of each category ***(see Section 9).***

- **Conservation forests** – The Brigalow Belt and Mediterranean Woodland were identified as requiring urgent attention because of the potential of climate change to worsen existing stressors. The Cold Forest and Grassland region and Subtropical Moist Forests region were identified because of their unique biodiversity, cool climate dependent species and remnant or limited distributions.
- **Environmental plantings** – In this category of forest, the Mediterranean Woodland was identified as the highest priority for attention because of the high potential value of environmental plantings for connectivity and ecosystem services to a landscape already compromised by a number of pre-existing stressors.
- **Productive native forests** – Forests in the Mediterranean Woodland, Cold forest and grassland and Subtropical moist forests were identified for urgent attention. As for conservation forests, the existence of other stressors and high biodiversity-cold climate dependence of these forests make them the most vulnerable. It should be noted that this assessment was not limited to timber extraction areas.
- **Plantations** – Not all regions currently support plantations. For those with existing plantations, the Mediterranean Woodlands required the most urgent attention. Where new industries were planned or possible under future conditions (e.g. the Tropical Savanna), priority for attention is likely to increase to meet the demands of new industries.

An adaptive future

With an assessment of the vulnerability of Australia's forests completed and presented in this report, we identify some actions that might take the management of Australia's forests forward into an adaptive future under climate change:

- There is some scope for incremental adjustment of existing policy in order to adopt climate change adaptation principles and actions for Australia's forests and the ways these frameworks might be adapted are considered ***(see Section 10.1)***. More severe or extreme climate change might require the introduction of more novel or innovative governance structures that might incorporate a principle of climate change adaptation and consider new categories of land use such as carbon conservation areas or climate change adaptation areas ***(see Section 10.2)***.
- Increased future resources are expected to include a national capacity to oversee adaptation among forest managers, the adoption of financial mechanisms to encourage cost-benefit analysis of actions, increased knowledge, expertise and people-power ***(see Section 10.3)***.
- There is a need for new research focussing on improved modelling frameworks, improved understanding of plant distributions, understanding of how elevated CO_2 and water availability interact and social research. In addition to new knowledge, it is essential that effective transfer of knowledge is carried out through engagement activities ***(see Section 10.3.4).***

Key messages and policy directions

The scale of the problem and the current level of scientific knowledge, mean that there is a great deal of uncertainty in the impact of climate change on Australia's forests. At a coarse scale, the key outcomes of climate change on Australia's forests are likely to be:

1. Changes to the nature of Australia's forests.
    a. Rates of growth could either increase or decrease.
    b. Species composition could change through changes in interspecies interactions and shifts in species distributions.
    c. The areas that forest types occupy could change.
2. Climate change will compound other and existing stressors.

Based on the available information, the assessment recommends the following key policy directions for an adaptive future in managing Australia's forests:

Create a vision of the future adapted forest

Forest management needs a clear management goal for adaptation under climate change. Previously this has been a principle of ecologically sustainable development, with the condition, composition and biogeography of forests pre-European settlement the usual benchmark. Under climate change this may no longer be appropriate.

Recognise the role of forests in mitigation

Implement mitigation policies that recognise the role of forests in carbon management. This includes setting a price on carbon. A number of co-benefits of such policies can be considered and might include offsetting of other socio-economic impacts of climate change such as renewed vigour in marginal industry, reforestation of lands formerly used for agricultural and pastoral purposes, improving the profitability of marginal areas and increased non-use benefits around habitat, water quality and micro-climate.

Invest in decision-making tools and research

In order for governments to make informed decisions about the best adaptation strategies they will require effective decision-making tools. While the uncertainty associated with climate change projections and impacts is an obstacle to planning adaptation, the risk of not acting has the potential to be more damaging than acting on the best available evidence.

Coordinate efforts at the national level

While the impacts of climate change will differ among regions, many adaptation responses will cross regional and state borders. This will require national coordination. The development of biological links or corridors across the landscape, for example requires national coordination to ensure the right locations are included and gaps are filled. Potential policy instruments already exist at the regional level such as the Regional Forest Agreement that might be adapted to meet this need.

Promote co-benefits of forests

There is scope to expand and coordinate programs to maximise the multiple benefits from forests. The Forest Vulnerability Assessment demonstrated the contribution of Australia's forests to multiple ecosystem services. By managing for multiple functions, investment can be maximised.

Audit impacts and respond when needed

Monitoring changes in and impacts on Australia's forests is essential. This activity must include inbuilt markers or trigger points at which new or changed adaptation actions should occur. This approach is beyond simple monitoring, with inbuilt markers designed to trigger the need for changes in adaptation strategies. This applies to both natural and social systems.

Understand and respond to community concerns

The support and confidence of the wider community will be important for successful implementation of planned adaptations, particularly if innovative policy or legislative changes become necessary. There will need to be a two-way flow of information, one informing people, and another identifying community and stakeholder views

Invest in targeted research

There are many uncertainties and research gaps that are important to address in order to support and improve the adaptation response of forest managers to climate change. These must be addressed through a carefully targeted research program. Specific research areas are listed in ***Section 11.4***.

Agree to prioritise actions

Governments and industry bodies need to develop and agree to the means by which actions that address the impacts of climate change on forests will be prioritised. For example, in fire management of forests should priority be given to protection of large conservation forests over lifestyle forests? Because many of the socio-economic impacts of climate change are diffuse and indirect and some are intangible, it will be difficult to decide on priority areas for governments and industry bodies to address and so agreement on indicators of change would be helpful.

Part A: Introduction and Background

Overview

This report presents a final synthesis of the Forest Vulnerability Assessment project. The project was established to improve our understanding of current knowledge of the likely biophysical and socio-economic consequences of climate change on Australia's forests; and to improve our understanding of existing vulnerabilities, actions and information gaps in order to improve adaptive capacity.

In Section 1 we outline the terms of reference and definitions that were set in formulating the assessment.

The assessment utilised a basic vulnerability assessment framework which considers *sensitivity*, *exposure* and *adaptive capacity*.

Forests in Australia were defined as:

> *… an area, incorporating all living and non-living components, that is dominated by trees having usually a single stem and a mature or potentially mature stand height exceeding two metres and with existing or potential crown cover of overstorey strata about equal to or greater than 20%. This includes Australia's diverse native forests and plantations, regardless of age. It is also sufficiently broad to encompass areas of trees that are sometimes described as woodlands.* Australia's State of the Forests Report (Montreal Process Implementation Group for Australia, 2008)

Forest management types were categorised into four groupings:

- conservation forests,
- native production forests,
- plantations, and
- environmental plantings (*see Section 1.2.1*).

A set of climate scenarios were adopted against which the assessment was carried out. The scenarios included a general trend of warming throughout Australia and variable rainfall response, with an increase in the number of extremely hot days and decrease in frost days (*see Section 1.4*).

An agro-ecological framework, which classifies Australia into ten regions based on climate and vegetation classifications, was adopted as the basis of a regional vulnerability assessment and is described in this section (*see Section 1.3*).

1 Introduction to the Forest Vulnerability Assessment project

In this part of the report we introduce the scope and method of the Forest Vulnerability Assessment project. It describes the terms under which the project was undertaken and defines important terms on which the assessment was based.

Introduction to the Forest Vulnerability Assessment: Key points

- This project was established to improve our understanding of current knowledge of the likely biophysical and socio-economic consequences of climate change; and improve our understanding of existing vulnerabilities, actions and information gaps in order to improve adaptative capacity.
- This report is the fifth of five reports and provides a synthesis of the findings of the first four reports. In addition it provides a regional assessment of forest vulnerability based on those reports.
- The assessment overlaid four categories of forest management type on Australia’s forests. The chosen categories were plantation, productive native forests, conservation native forests and environmental plantings.
- The largest forested area in Australia falls under the category of “productive native forest”. There is no explicit legal impediment to harvesting in this forest category as defined in the State of the Forest report definition adopted here. Only a very small area, however, is actually harvested, with controls on clearing through legislation and lease conditions. Large areas of these forests are arid or semi-arid lands on which the dominant activity is grazing. These areas are generally referred to as “rangelands”.
- A set of climate scenarios were adopted against which the assessment was carried out. The scenarios were based on the 2007 IPCC A1FI scenario (worst case) of future greenhouse gas emissions and high climate sensitivity to these increasing emissions. Two time periods were used: 2050 and 2070.
- The method of making a regional assessment of forest vulnerability is described here. Our assessment used an existing agro-ecological framework (Hobbs and McIntyre 2005) in conjunction with a well established vulnerability assessment framework. The result of the regional assessment is presented in Part D of this report.

1.1 Project description

In 2006 the Natural Resource Management Ministerial Council (NRMMC) identified the need for a national assessment of the vulnerability of Australia's forests to climate change and a framework for adaptation to these putative impacts. The National Climate Change Adaptation Research Facility (NCCARF) through the Commonwealth Department of Climate Change and Energy Efficiency (DCCEE) was approached to carry out a comprehensive preliminary assessment of the vulnerability of Australia's forests to the impacts of climate change. The Forest Vulnerability Assessment (FVA) was carried out by four research groups, each producing a stand-alone report (work package). In addition a Synthesis Report (this report) was produced to summarise and synthesise the assessment outcomes. These technical reports are complemented by a summary report for policy makers and a brief executive summary. The work packages are listed in Appendix 1.

A Steering Committee of university, federal and state government stakeholders were engaged to adopt the FVA brief and set the parameters for this study. Here we introduce the general terms of reference for the project.

1.2 Purpose and approach

The primary aim of the Forest Vulnerability Assessment project was to provide forestry policy makers and forest managers in Australia with information that assists the sector to adapt to climate change. In particular, the project sought to provide governments, NRM managers and the business sector with:

- an improved understanding of current knowledge of the likely biophysical and socio-economic consequences of climate change for Australia's native and planted forest regions;
- an assessment of the vulnerability of Australian forests from the perspectives of both resource use and ecosystem services – identifying particularly vulnerable forests and communities in major forest areas;
- an overview of what is already being done in Australia in regard to understanding and managing climate related risks for forests; and
- guidance on key gaps to assist climate change adaptation.

Methods

Work Packages 1 to 4 each undertook an extensive review of literature and policy from a range of sources (including peer reviewed journals and technical reports) to provide a critical analysis of this material to determine the vulnerability of Australia's forests to climate change impacts. In addition, a process of stakeholder engagement and survey was undertaken (full description of methods can be found in Wood et al., 2010) to determine stakeholder attitudes, practices and planned actions under climate change; and a qualitative study of community understanding and perceptions of climate change and the role of forests (Cockfield et al., 2010).

Finally, a regional assessment of vulnerability was undertaken and is presented here in this the synthesis report. Using the Hobbs and McIntyre (2005) framework (Figure 1.1), we assessed the regional variability of climate impacts in order to identify regional vulnerabilities and adaptation recommendations.

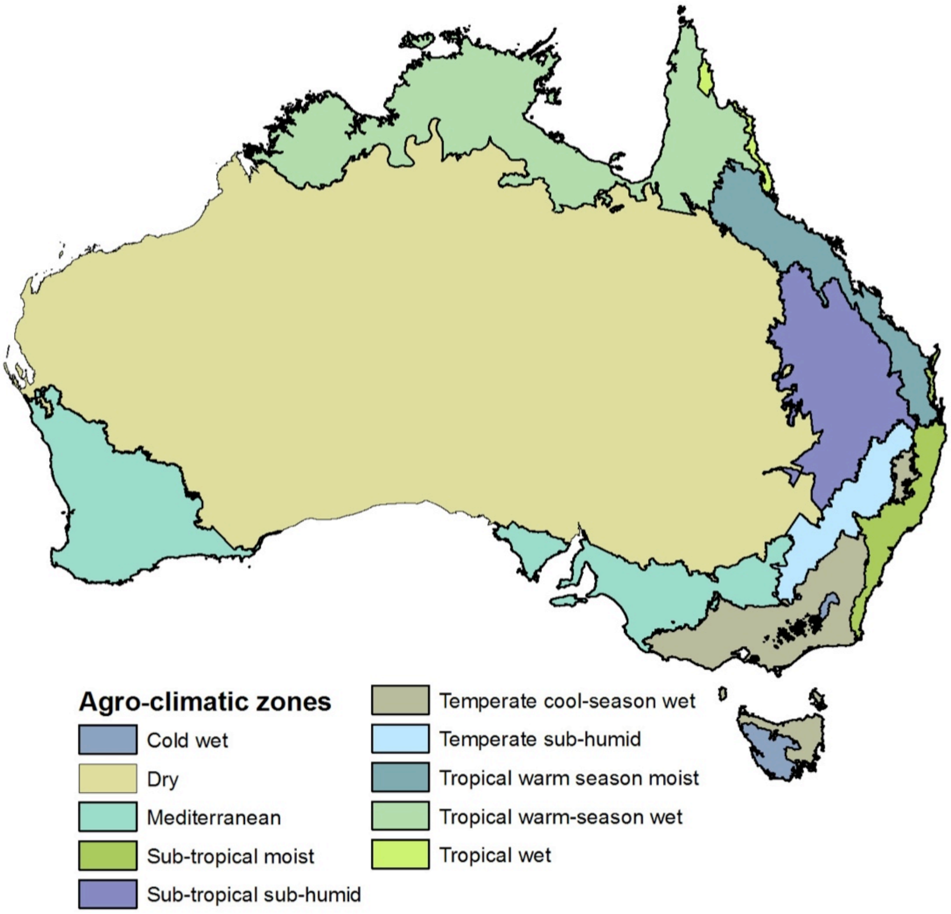

Figure 1.1 Agro-ecological regions developed by Hobbs and McIntyre (2005) and used here as a framework to assess the regional impact of climate change on Australia's forests.

The assessment was undertaken in four steps:

1. Description of each region, including current forest coverage, land use, social and economic constraints/opportunities and existing environmental threats.

2. Description of potential environmental changes and impacts at a national scale (summarised here in Section 4 and reported in associated Work Packages).

3. An assessment for each region of climate change impacts on forests extrapolated from the national assessment using existing data where available but also a subjective assessment where specific data is unavailable.

4. Identification of key vulnerabilities and adaptation options for each region. Again a subjective analysis based on a critical analysis of existing information.

The result of this analysis is presented in Part D of this report.

It is worth noting that strategies to address the mitigation of climate change have not been specifically addressed in this assessment with the exception of the potential consequences of incentives to establish forest-based sinks. That is, we consider how efforts to sequester carbon may be usefully considered along with efforts to maintain or even increase the area and quality of both the production and conservation forest estates. Obviously, strong mitigation policies and actions would reduce the level of climate change response, but it is highly likely that current changes in climate will continue to accelerate in response to existing elevated greenhouse gas concentrations due to a lag in the response of the global climate system to emissions and the report responds primarily to this eventuality.

1.2.1 Definitions of forests and forest uses for the purpose of the project

The scope of the project was largely set by the definition of **forests** used. We adopted the definition used in the 2008 *Australia's State of the Forests Report* (SOFR) (Montreal Process Implementation Group for Australia, 2008). This definition includes both native forests and plantations:

> *A FOREST is an area, incorporating all living and non-living components, that is dominated by trees having usually a single stem and a mature or potentially mature stand height exceeding two metres and with existing or potential crown cover of overstorey strata about equal to or greater than 20%. This includes Australia's diverse native forests and plantations, regardless of age. It is also sufficiently broad to encompass areas of trees that are sometimes described as woodlands. (Montreal Process Implementation Group for Australia, 2008)*

Based on this definition, the assessment includes a large part of Australia's **mallee** ecosystems (defined as dominated by multi-stemmed eucalypts – any one of about 25 species depending upon location) and encompasses very large areas of tropical savannah and woodland (also referred to as **rangelands**), where trees are spread out in a more open landscape and grazing is the predominant land-use. Inter-tidal, salt tolerant forests, often referred to as mangroves, also fall within this definition of forests. What many people would traditionally regard as forests – expanses of tall, closely spaced trees – comprise a relatively small part of the country's total forest estate.

Estimates of the area covered by forest and used both here and in the State of the Forests 2008 report are those estimates produced by the National Forest Inventory (NFI). The NFI builds the national forest-cover map by compiling state and territory forest mapping information using eight agreed broad national forest types (including eucalypts with 11 subtypes – see Appendix 2 and Figure 1.2). The resultant map and its associated data are the accepted national data agreed to by the Australian Government and the states and territories to be used for national and international reporting on Australia's forests. The NFI forest data incorporate the best available forest typing, floristic and structural information to make sure that vegetation counted as forest meets the national forest definition. It should be noted that additional areas of woody vegetation that have been identified by the National Carbon Accounting System, but excluded from the NFI calculations are of relevance to this assessment (see Box 1).

Australia's forests are dominated by eucalypt (including the genera *Eucalyptus, Corymbia* and *Angophora*) and acacia forests; making up about 89% of all native forest types (see Appendix 2 and Figure 1.2). Both these forest types support an enormous diversity of species with over 700 eucalypt species and almost 1000 *Acacia* species (Montreal Process Implementation Group for Australia, 2008) as well as a diversity of other plant species. Other important forest types cover smaller areas. These include rainforest that supports a high diversity of flora and fauna as well as *Melaleuca* wetlands and mangroves that perform essential and unique ecosystem functions.

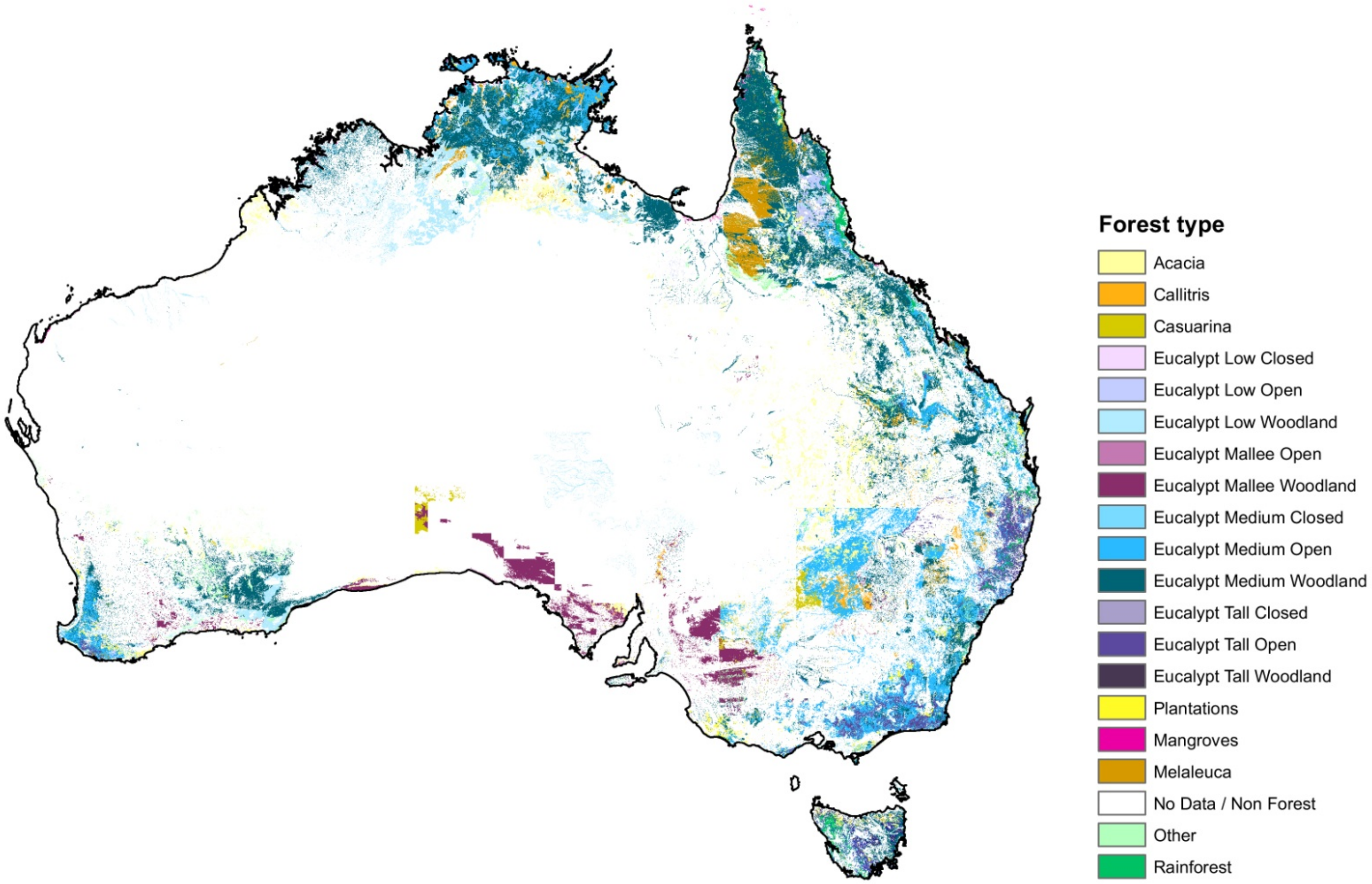

Figure 1.2 Australia's broad forest types used to assess forest vulnerability under climate change.

The SOFR 2008 report also used the National Forest Policy Statement (Commonwealth of Australia, 1992) definition of **plantations**:

> *Intensively managed stands of trees of either native or exotic species created by the regular placement of seedlings or seeds which we adopted for this assessment.*

Box 1 Differences between state and national forest mapping for State of the Forests Report 2008 and National Carbon Accounting System estimate of woody vegetation. Source: Montreal Process Implementation Group for Australia, 2008.

Estimates of forest cover for Australia range from 107 million hectares (National Carbon Accounting System – NCAS) to 149.4 million hectares (National Forest Inventory – NFI). This report uses the latter of these two definitions. The measurements differ according to the parameters used to determine what qualifies as forest. The forest definition adopted for both Australia's greenhouse gas inventories and the NFI incorporates a height of two metres and crown cover of 20%. Unlike the NFI, however, a minimum forest area of 0.2 hectares is adopted for greenhouse gas emissions reporting (Commonwealth of Australia, 2010). This excludes, for example, rangelands of the Northern Territory and Queensland that carry sparse but ecologically significant tree stands.

The Australian Greenhouse Office (AGO) developed the National Carbon Accounting System (NCAS) for the purposes of reporting on Australia's carbon emissions. One part of the NCAS is a time-series of national woody-cover data layers based on Landsat satellite imagery from 1972 to the present; the primary end use of the final data is to determine vegetation cover change for the purpose of estimating net greenhouse gas emissions over time. The estimate of total woody vegetation cover derived by NCAS was 108 million hectares for 2005, which is considerably lower than the 149 million hectares total forest cover estimated in the NFI, although there is considerable overlap between the two datasets. The difference is due to the different methodologies used to compile the data. Each dataset has been developed for – and are best suited to – specific purposes: the AGO dataset for tracking changes in woody cover and the NFI forest data (which includes information on forest type, structure, height and extent) for reporting on a broader range of indicators for SOFR, including biodiversity and conservation values. Information on vulnerability of forests to climate change will have relevance to both these datasets.

In summary, Australia's forests may be considered as a continuum with large-scale industrial plantations at one extreme and native forests which include mallee, savannah, woodland and mangroves at the other. In order to place the Australian forest estate firmly into a management context, we superimposed a set of forest type categories reflecting the way forests are used:

- Plantations or farm forests
- Productive native forests
- Conservation native forests
- Environmental plantings

Table 1.1 Total area ('000 ha) under three of the four categories of forest type used in this report including the percentage of Australia's total area under each type based on the 2008 State of the Forests reporting. The coverage of environmental plantings has not been quantified. Source: Montreal Process Implementation Group for Australia (2008).

Forest Type	ACT	NSW	NT	QLD	SA	Tas	Vic	WA	Aus	% of forest area
Plantation/ farm forests	10	345	26	233	172	248	396	389	1818	1
Productive native forests	5	21 060	30 994	48 005	4826	1996	4332	13 797	125 052	83
Conservation native forests	108	5148	16	4576	4029	1121	3505	3868	22371	16
Total forest	133	226 553	31 036	52 814	9024	3364	8233	18 054	149 215	100

Plantation/farm forests

In this category are all those planted forests largely destined to be harvested for economic benefit at some time in the future. They include major broad-acre plantings of exotic species such as pines as well as smaller farm forestry plantings utilising a variety of species from construction to cabinet timbers.

In the 2010 National Forest Inventory update (Gavran and Parsons, 2010), there was a reported 2.02 million hectares of plantations of which 1.02 million hectares was pine (softwood) and 0.99 million hectares of hardwood of various species and mixtures. This is an increase of 49 658 hectares of new plantations from that reported in the 2008 (Montreal Process Implementation Group for Australia, 2008). The area of plantation estate in Australia has continued to expand, with planting of hardwoods the greatest area of expansion (e.g. from 29% of all plantations in 1999 to 49% in 2009). There are several regions of plantation activity (Figure 1.3) with the largest proportion of the national estate being in Victoria and Western Australia. Timber extraction industries in Australia (both in native production forests and plantations) contribute approximately 1% to Australia's GDP and is not a major sector in Australia's economy (Table 1.4). It is however, regionally important, particularly in southern and eastern high rainfall areas.

There are no recent survey data for small-scale private (farm) forestry but as at 2000, farm forestry comprised approximately 5% of plantation area (Wood et al., 2001) and by 2006, approximately 12% of the area was managed by means other than investment funds, schemes or timber corporations (Department of Agriculture Fisheries and Forestry, 2008).

The majority of plantations are privately owned (62%), one-third (33%) are publicly owned and a further 5% are jointly owned (Gavran and Parsons, 2010).

Table 1.2 Total plantation area (hectares) by state and territory in 2009. Source: Gavran and Parsons (2010).

	Hardwood	Softwood	Other Categories	Total
ACT	0	7870	0	7870
New South Wales	92 541	28 7820	2821	383 182
Northern Territory	29 599	2239	0	31 838
Queensland	63 618	190 663	2108	256 389
South Australia	58 669	123 419	457	182 545
Tasmania	231 992	77 098	100	309 190
Victoria	202 703	220 009	1438	424 150
Western Australia	311 823	110 934	2305	425 062
Total	990 946	1 020 051	9229	2 020 226

Table 1.3 Ownership of Australia's plantation estate by industry category in 2009. Source: Gavran and Parsons (2010).

Industry Category	Percentage ownership
Superannuation funds	13.1
Timber industry companies	7.1
Farm foresters and other private owners	9.7
Managed investment schemes	35.7
Governments	34.4

Table 1.4 Overview of timber extraction forests (native and plantation) from 2001-2008. Source: Australian Bureau of Agricultural and Resources Economics (2009a).

		2001-2	2002-3	2003-4	2004-5	2005-6	2006-7	2007-8
Volume of log production (‘000 m^3)	Native	9829	10 314	10 090	9866	8575	8551	8940
	Broadleaved plantation	1112	1594	1819	2936	3779	4052	4607
	Coniferous plantation	13 356	13 911	14 589	14 196	14 379	14 580	14 913
Value ($M)	Native	576	618	627	640	588	570	635
	Broadleaved plantation	58	81	102	172	237	273	341
	Coniferous plantation	703	777	839	842	847	869	895
Value ($M)	Imports		4086				4271	4412
	Exports		2091				2355	2471
Wages	Value ($m)	2528	2764	2902	3020	3145		
	% of all manufacturing	5.9	6.2	6.3	6.2	6.2		
Employment	Nos (‘000)	82.8	83.3	90.6	83.5	83.0	83.4	76.8

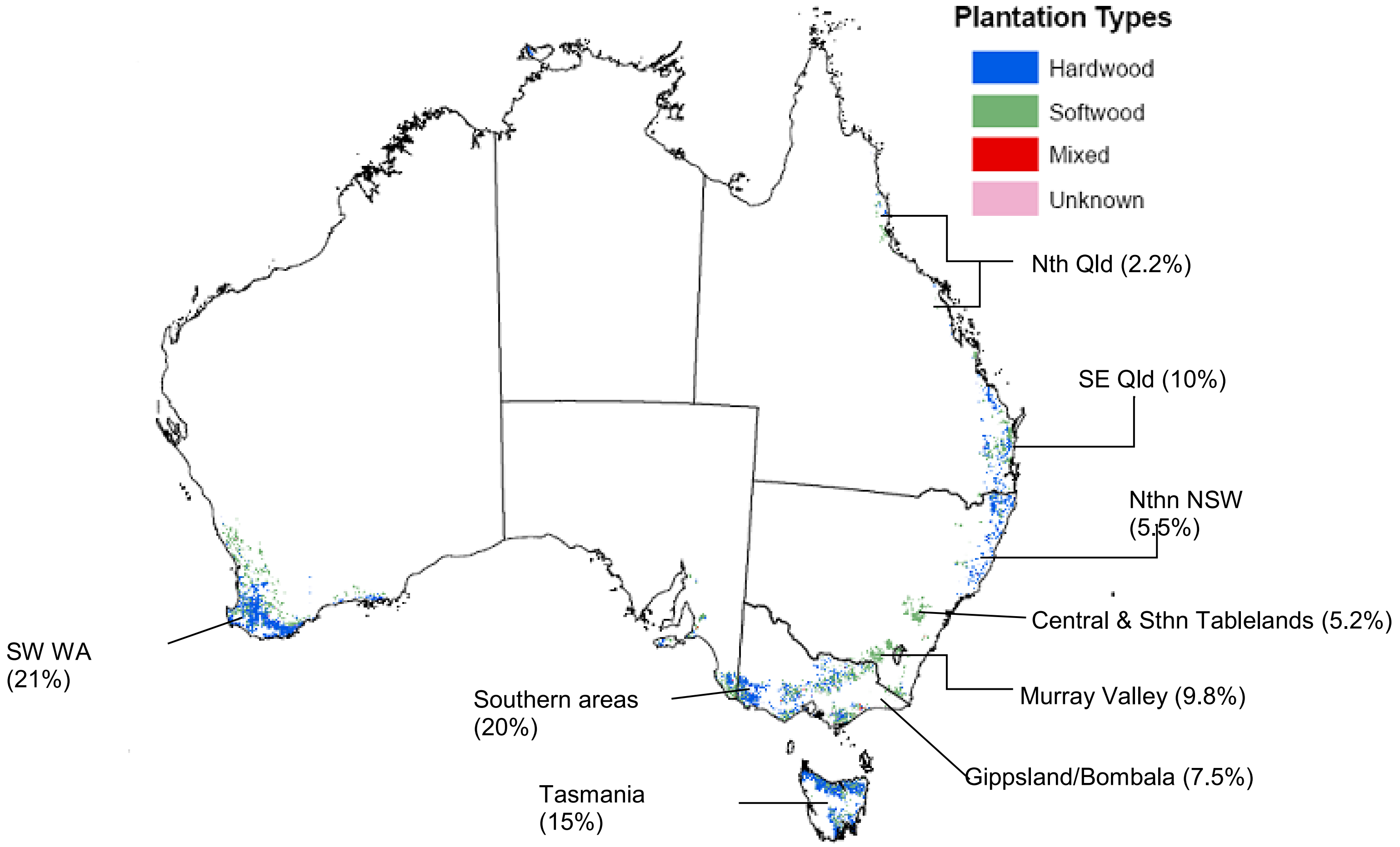

Figure 1.3 Major Australian plantation regions. The percentage area each region makes up of the national estate is shown in brackets. Source: Bureau of Rural Sciences (2008).

Productive native forests

Under this category we include those naturally occurring forests which may be periodically harvested for timber or other forest products or used for other agricultural purposes while retaining the essential ecological characteristics of their undisturbed predecessor forests.

Of the 149 million hectares of forest in Australia, 147 million are native forest (Montreal Process Implementation Group for Australia, 2008). Under the Montreal Process definition, native forests available for harvesting (wood and non-wood products) are defined as “those native forests in which harvesting is not illegal” and some 112 million hectares or three-quarters of Australia’s native forests were classified as not legally (in a strict sense) excluded from timber harvesting or tree clearing in the 2008 State of the Forests Report, (Montreal Process Implementation Group for Australia, 2008). Only forests in nature conservation reserves are specifically excluded from tree removal – although for most other lands, permits are required to undertake clearing (see below).

For the purposes of the FVA, therefore, we have categorised those forests in which “harvesting is not illegal” as productive native forests. In practice, however, very little of this area is currently used for timber supply, with more than half (65 million hectares) being leasehold land used for grazing. Tree clearing is generally not a permitted activity under most pastoral leases. In addition, in Queensland and New South Wales the clearing of vegetation is controlled legislatively (Vegetation Management Act Qld 1999 and Native Vegetation Act NSW 2003) with permits required for tree clearing and areas under remnant vegetation in “endangered”, “of concern” or “threatened” categories prohibited from tree clearing but available for other land uses such as grazing. Productive native forests, as defined here, are represented by three tenure types – multiple-use public forests, leasehold and freehold (private) lands.

Harvesting of native forests is largely restricted to multiple-use public forests with some contribution from leasehold and private lands. These forests make up 9.4 million hectares of the legally unrestricted harvestable area of 112.6 million hectares. This is down from 13.4 million in 1998 (Department of Agriculture Fisheries and Forestry, 2008). There is relatively limited commercial harvesting of native forests in the Northern Territory and none in South Australia or the Australian Capital Territory (Montreal Process Implementation Group for Australia, 2008). The Queensland Government has signalled its intention to phase out native forest harvesting in favour of hardwood plantation development (Montreal Process Implementation Group for Australia, 2008) with the South-East Queensland Forests Agreement providing for the ending of timber harvesting in native State forests and timber reserves in the South East Queensland Bioregion by 2024.

Although wood products can be harvested from private land, this is distinguished from farm forestry, in which seed or seedlings are purposefully planted for future harvest.

It should be noted that the area of forest attributable to different forest management classes tends to reflect information available on land tenure rather than specific land use or vegetation type. A very significant area of what is classified as “productive native forests” is the drier, sparse “woodland” forests, with approximately half on leasehold (usually pastoral leasehold) lands and half privately owned. For leasehold lands, there are generally no specific harvesting rights associated with the lease conditions, but tree clearing has been a common pastoral practice employed in an effort to increase pasture production (Burrows, 1990).

Rangelands Much of the land that can be classified as productive native forests makes up the arid area of Australia commonly referred to as “the rangelands” (Box 2). The rangelands are those areas where the rainfall is too low or unreliable and the soils too poor to support regular cropping (Bastin and ACRIS Management Committee, 2008). The area traditionally defined as rangelands includes areas of savannah, woodlands, shrublands and wetlands that fall under the definition of forest used in this assessment. The primary use of these areas is grazing with the trees or forests providing services such as shade and shelter, nutrient input, salinity control, biodiversity and amenity rather than any harvestable product.

Box 2 The Australian rangelands. Source: Bastin (2008).

The rangelands encompass tropical woodlands and savannas in the far north; vast treeless grassy plains (downs country) across the mid-north; hummock grasslands (spinifex), mulga woodlands and shrublands through the mid-latitudes; and saltbush and bluebush shrublands that fringe the agricultural areas and Great Australian Bight in the south. Across this gradient, seasonal rainfall changes from summer-dominant (monsoonal) in the north to winter-dominant in the south. Soils are characteristically infertile. Great climate variability and the dominating influence of short growing seasons distinctly characterise rangeland environments.

The Forest Vulnerability Assessment includes rangelands because they support vast areas of forest (savannas, woodlands and shrublands). Although legally possible (in contrast to conservation parks where it is explicitly excluded), rangeland forests are generally not utilised for timber extraction. Most rangelands are under Pastoral Leases that do not allow for clearing, or only allow clearing of regrowth. Rangelands are important pastoral country while supporting significant biodiversity.

Rainfall variability is one of the major drivers of change in the rangelands. Managing short-term (seasonal and yearly) variability within the context of longer-term climate change will be a key challenge.

Existing stressors in rangelands include the pressures placed on land by grazing use. This includes selective clearing to improve pastures (but note the control of these activities through legislation), soil compaction and the resulting water runoff, destruction of waterbodies and riparian vegetation through stock pressure and increased erosion through disturbance and tree loss. These pressures will interact with climate change to create worsening or new problems (e.g. desertification due to decreased water up-take, warming and decreased rainfall). The “safe” livestock carrying capacity (LCC) required to maintain resource condition is strongly dependent on climate and this will need to be modified as the climate changes (McKeon et al., 2009). The impact of grazing on species diversity and composition are dependent on seasonal climate conditions (Watson et al., 2007).

These forests, do also present opportunities to ensure multiple benefits (e.g. biodiversity protection, carbon storage) through new management strategies. Change in land-use is highly likely for areas of rangelands as marginal lands become non-viable. Henry et al., (2002) reviewed the potential for the rangelands to contribute to greenhouse gas abatement and this role is likely to become extremely important in these forests.

Photo: Terry Reis

Conservation native forests

Native forests on which no harvesting is legally permitted and over which conservation controls are in force are defined here as conservation native forests. This includes the many categories of forest reserves designated to serve as areas for the maintenance of environmental quality, biodiversity conservation and/or tourism. In some states this also includes forests designated as “wilderness”, and urban forests protected from development and forests under time limited covenants, such as those managed under the Environmental Stewardship Program (ESP).

Forests in nature conservation reserves are located around Australia and cover a broad range of vegetation types. Australia has 22.37 million hectares of nature conservation reserve (Montreal Process Implementation Group for Australia, 2008).

Environmental plantings

This last category encompasses artificially constructed forests with a diverse set of roles from restoration and maintenance of environmental health to provision of shelter-belts, biodiversity corridors, erosion control or amenity.

Amenity plantings are primarily for human enjoyment and comfort and seek to provide shade, screening and windbreaks. Amenity plantings may also direct vehicular or pedestrian traffic or to enhance urban living.

Ecological plantings uses species local to an area (indigenous species) and primarily provides habitat to native animals. The use of locally indigenous species conserves the character of a region both biologically and visually but could also include some urban backyard plantings.

Environmental plantings may also be established for the purpose of carbon sequestration (carbon offsets) and reduction of salinity or serve several of these purposes.

1.3 Applying an agro-ecological regional classification

While climate change will have a global impact, the response of individual ecosystems will very much depend on its local or regional circumstances. To capture this regional variability, the FVA applied a second layer of landscape classification using the 10 zones proposed by Hobbs and McIntyre (2005) (Figure 1.1) in order to carry out a qualitative assessment of regional forest vulnerability under climate change (Section 8). There are of course, several organising frameworks that could be used for a regional assessment of forest vulnerability (e.g. states and territory boundaries) any one of which might be better suited to different sectors but will likewise result in generalisations fine scale variation.

The Hobbs and McIntyre (2005) climate scheme is an agro-ecological classification, originally developed to use the minimum number of variables (i.e. climate and vegetation, moisture index, growth index and seasonality) that are most meaningful to the Australian landscape and its management. Climate classes were aligned to existing bioregions (Thackway and Cresswell, 1995) and the vegetation classification was broadly based on the presence or absence of a tree-layer and whether the understorey was grassy or shrub-dominated. The Hobbs and McIntyre (2005) framework also considered human interaction and management in assigning regions. The resulting framework consists of ten regions described in Table 1.5.

Table 1.5 Description of the ten regions identified by Hobbs and McIntyre. Source Hobbs and McIntyre (2005), Metcalfe et al., (2007), Murphy et al., (2008).

Region	Climate	Location	State	Description	Important industries
Cold forest and grassland	Cold, wet	Tasmanian highlands and Victorian and NSW alpine area.	Tasmania Victoria NSW	Cold winters with short summers warm enough to support significant growth.	Water harvesting, hydroelectricity, tourism and nature conservation.
Temperate moist forest	Temperate, cool-season wet	Tasmanian lowlands, southern Victoria, NSW.	Tasmania Victoria NSW	Cool wet climate; Moisture Index high in winter-spring, moderate in summer; Growth Index high in spring.	Forestry, improved pasture (sheep, beef, dairying), horticulture.
Mediterranean Woodland	Mediterranean	Southwest WA, southern SA, northwest Victoria, southern NSW.	WA SA Victoria NSW	Warm climate; Moisture Index high in winter low in summer; Growth Index moderate in winter.	Winter cereal cropping, improved pasture (sheep) forestry, horticulture.
Temperate subhumid woodland	Temperate, subhumid	NSW western slopes	NSW	Cool winter and moisture limiting summer. Moisture Index moderate to high year-round; Growth Index high in autumn to spring.	Summer and winter cereal cropping, cotton, sown pasture, rangeland, horticulture.
Brigalow belt	Subtropical, subhumid	Northwest plains of NSW and Qld Brigalow Belt.	NSW Qld	Mild winter with Moisture Index and Growth Index moderate year-round.	Summer cereal, cropping, cotton, sown pasture, rangeland, horticulture.
Subtropical moist forest	Subtropical, moist	Coastal southern Qld and NSW (climate is more temperate in southern NSW).	Qld NSW	Moisture Index and Growth Index moderate to high year-round. Both indices are lower in winter in southern regions and lower in spring in northern regions.	Horticulture, sown pasture (dairying), rangeland, forestry, horticulture, coastal development.
Tropical Savanna	Tropical, warm-season wet	Northwest WA, northern NT, and Cape York Peninsula.	WA NT Qld	Moisture Index and Growth Index high in warm season, very low in cool season.	Potential for field crops not realised; predominantly rangeland (cattle), Indigenous land use, horticulture.
Tropical forest and woodland	Tropical, warm-season moist	Coast and hinterland areas of Queensland (subtropical in southern Qld).	Qld	Characterised by a long growing season and a cooler dry season than the tropical savannas. Moisture is the main limiting factor to crop growth and the Growth Index is lowest in spring.	Sugar, horticulture, improved pasture and rangelands (cattle).
Tropical rainforest	Tropical, wet	Limited areas on the east coast of northern Qld.	Qld	Moisture index and Growth Index high all year, J1 has short dry season.	Conservation, sugar cane, horticulture.
Arid grassland and shrubland	Dry	Large central portion of the continent.	NT SA WA Qld	Warm to hot and dry. Moisture Index and Growth Index low all year. Southern regions wetter in winter (E6) and northern regions wetter in summer (H).	Major use rangeland (sheep, cattle), Indigenous land use, some irrigated horticulture. Unsuitable or marginal for rainfed crops.

1.4 Development of climate change projections for the project

Actions to mitigate and planning for adaptation tend to rely on modelled predictions of how the planet's climate will respond to changing atmospheric levels of greenhouse gases. There are several limitations involved in the modelling process and in climate models this includes four areas of uncertainty as identified by Hughes (in Steffen et al., 2009):

1. The projected rate of production of greenhouse gases (emissions scenarios, see Box 3)
2. The relationship between the rate of greenhouse gas emissions and their atmospheric concentrations
3. The rate and magnitude of the global warming for a given change in concentration in greenhouse gases
4. Identifying region-to-region differences within global climate change scenarios.

The difficulty of anticipating future greenhouse gas emissions means that projections of climate change vary among models. For the purpose of the FVA project, it was determined that the working groups would use a single set of climate change projections. The "worst case" A1FI emissions scenario was chosen because it best represents current emission trends and climate observations. It follows that the A1FI emissions scenario is likely to provide the most realistic set of impacts and adaptation recommendations[1].

Climate modelling was carried out using the SimCLIM modelling software (Warrick, 2009). There are three areas within the SimCLIM model where different ranges of data can be selected to capture different levels of uncertainty. They are:

- **Climate sensitivity** which determines the *magnitude* of global warming in response to a given change in greenhouse gas concentrations.
- **Greenhouse gas emissions** which determine the *rate* of change of greenhouse gas concentrations and associated radiative forcing (capturing uncertainties 2 and 3 from the Steffen et al., 2009, list – see above).

Box 3 IPCC emissions scenarios

Predicting the amount of greenhouse gases emitted in the future is probably the most difficult aspect of climate change prediction. It is for this reason that the IPCC, the principal organisation analysing, synthesising and reporting on climate change, have developed four major emission scenarios with variations within each. The four emissions scenarios are:

A1. Very rapid economic growth, new more efficient technologies, a global population that peaks in the mid-21st century and declines thereafter. This scenario is divided into three sub-groups based on alternative directions in technology change: **A1FI** – fossil intensive; **A1T** – non-fossil energy sources; and **A1B** – a balance across all energy sources.

A2. Economic development (primarily regional) with per capita economic growth slower, more fragmented technological change than A1. Human numbers continue to increase.

B1. Rapid change in economic structures towards a service and information economy, reduced material intensity, introduction of clean, efficient technologies for energy production. Population growth as per **A1**. Global solutions and equity among peoples.

B2. Economic development localised, less rapid and more diverse technologies that **A1** or **A2**. Intermediate economic growth, human population continues to rise but at a slower rate than **A2**.

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[1] Note that the "worst case scenario" could also be considered conservative under current trends in emissions, political willingness and observed impacts. Emissions are presently tracking on or above levels of warming projected using the A1FI emissions scenario (Allison et al., 2009).

- **Spatial patterns of change from general circulation models (GCMs)** which determine the *regional differences* in changes in temperature, precipitation and other climate variables.

For this project the following specifications were applied for all scenarios:

- Climate sensitivity – **high**
- Emission scenario – **A1FI** (highest future emissions)
- General circulation model – the median value of an ensemble of 21 equally weighted GCMs

Two time horizons were selected for the project, 2030 and 2070, to provide a mid- and long-term scenario in each case. Projections were made for annual rainfall, seasonal rainfall (all seasons for the southern half of Australia and wet and dry seasons for northern Australia), February maximum temperatures, days over 35ºC and days over 40ºC and frost days (days with minimums less than 0ºC).

A full description of the SimCLIM methods is provided in Appendix 3.

The resulting scenarios are summarised in Section 4 with the complete set of mapped projections included in Appendix 4.

1.5 The structure of the Forest Vulnerability Assessment

In this synthesis report we provide an assessment of the vulnerability of Australia's forests to climate change using a well-established vulnerability framework (Figure 1.4). The basis of the framework is that ***vulnerability*** (or potential impact) of a forest system or region to a particular impact will depend on its ***exposure*** to that impact (i.e. degree, duration and extent of the impact) and a system's or a region's ***sensitivity*** (i.e. the extent to which the impact can be absorbed). In addition, vulnerability can be lesser or greater depending on the system's ***adaptive capacity.***

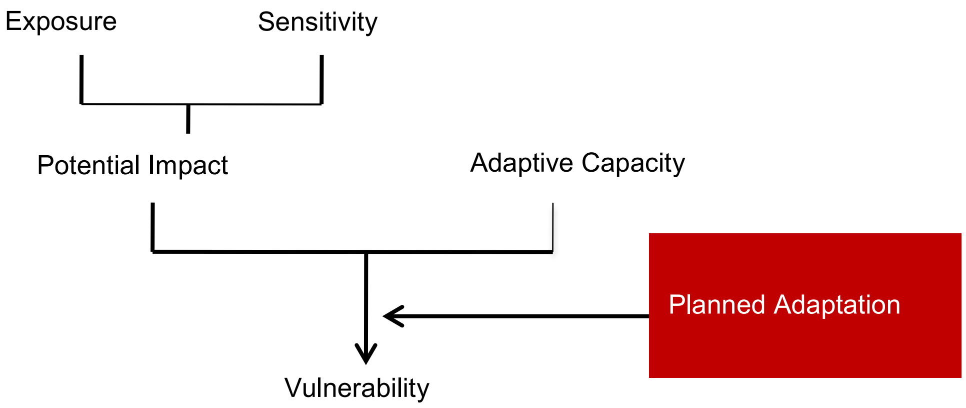


Figure 1.4 A framework for understanding vulnerability of the forestry sector to climate change. Source: Adapted from Schroter and ATEAM-Consortium (2004).

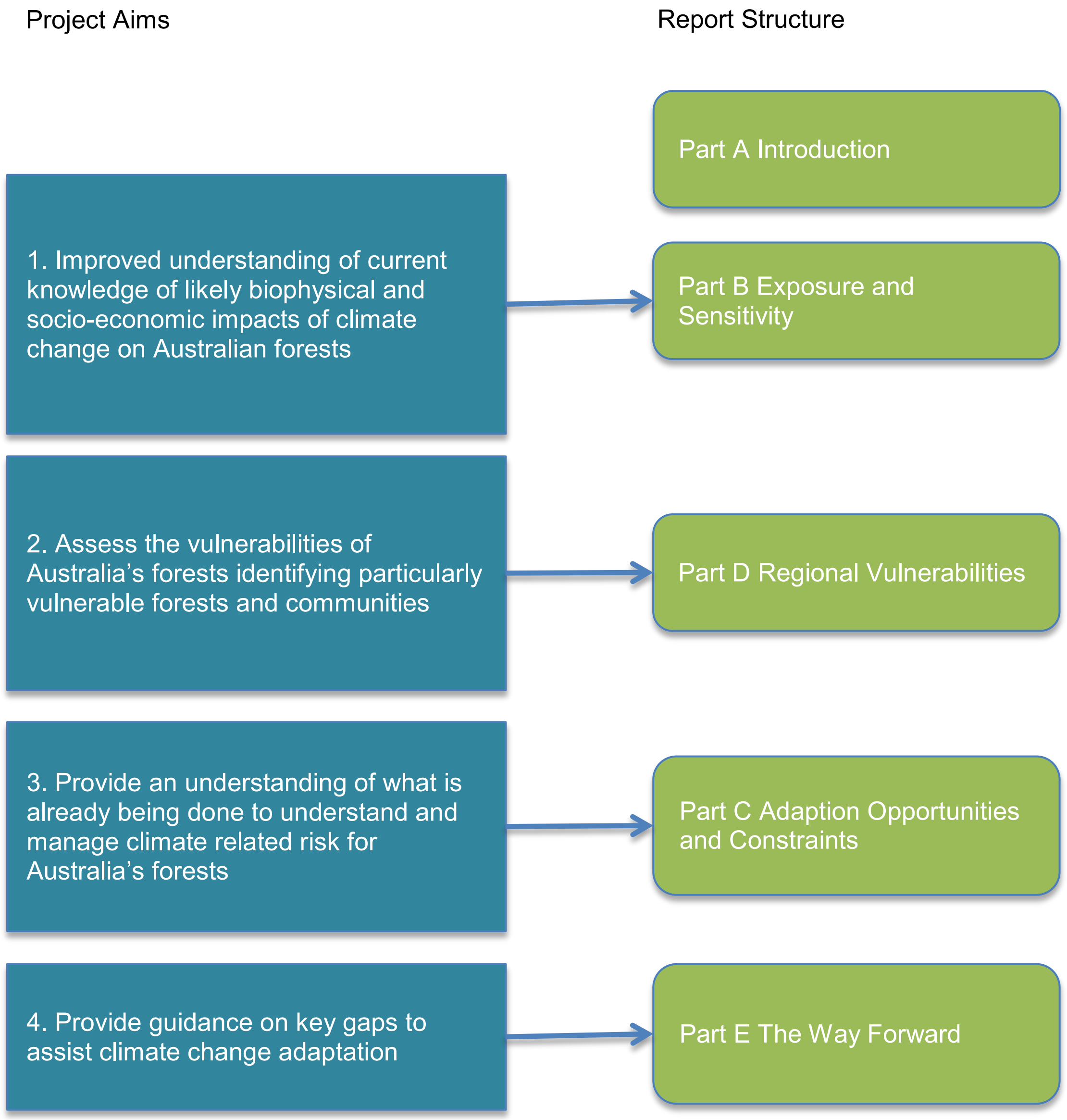


Figure 1.5 The major parts of this report shown against the primary aims of the *Forest Vulnerability Assessment* project.

Report Structure

This report is structured to address the project aims as shown schematically in Figure 1.5. Part A of the report has introduced the project methods and reporting framework provided to the assessment team. We then summarise the impacts of climate change on forests in the Part B. In the Part C of the report we look at the concept of adaptation and adaptation actions that could be used by the forest sector. In Part D we consider impacts and vulnerabilities of individual regions of Australia. In the final section, Part E, we consider options for adapting to and managing the problems facing forests under climate change and provide a set of policy recommendations.

It should be noted that this report summarises the findings arising from individual Work Package literature reviews. While we mention some key literature, individual Work Package reports should be consulted for a detailed discussion of all reviewed literature (available at www.nccarf.edu.au).

Part B: Exposure and Sensitivity

Overview

In the Part A of this report, we outlined three inter-related factors that are typically associated with the assessment of vulnerability to climate change. They are:

- Exposure to impacts
- Sensitivity to impacts
- Capacity to adapt to impacts

In Part B we consider the first two – exposure and sensitivity – in relation to Australia's forests.

Exposure The exposure of forests to changes in climate will depend on global trends in greenhouse gas emissions and local variability in climate response. Precise predictions of changes in climate cannot be made because of uncertainty surrounding the change in greenhouse gas emissions, the rate of climate change associated with certain levels of emissions and regional differences in climate change. Nonetheless, climate modelling and scenarios have identified climate change trends for the medium to long term, that need to be considered when managing forests.

- There is high confidence that temperatures will increase over most of Australia, with an increase in mean maximum temperatures of between 3.5 - 4.5ºC in the hottest months by 2070.
- Rainfall patterns are more difficult to predict but there is some confidence they will vary across Australia. The scenarios used in this assessment predict wetter wet season and drier dry season in Australia's north. In the southern half of Australia the scenarios predicted decreased winter rain.
- There is a high level of confidence that the weather will become more highly variable, with increased storm frequency and severity, fewer frost days, increase in the number of extremely hot days and longer, drier drought conditions (*see Section 2*).

Sensitivity There is likely to be significant variation in how individual organisms, species, communities and ecosystems will be affected by climate change. In addition, species will be directly affected by changes in climate at an individual level, with flow-on effects to ecosystem structure, composition and function. Changes in climate will also create indirect effects that will impact on forests such as fire, introduced species and diseases. When multiple impacts and flow-on effects are considered, the potential responses are complex. Direct effects of climate change on individual trees were considered:

- **Increased atmospheric CO_2** While there is evidence that Australia's forests have the physical capacity to increase productivity or growth in response to increasing atmospheric CO_2, the availability of water and nutrients will change this response. In nutrient poor sites there may be no increase in carbon uptake and growth. There is sound evidence that water use efficiency can improve under increased CO_2 availability. What is unclear is whether this will translate into improved drought tolerance among forest trees (*see Section 3.2.1*).

- **Rising temperatures** The effect of rising temperature on individual species will depend on (i) whether the organism is currently living at a temperature above or below its optimal temperature, and (ii) its capacity to acclimatise. For example, a plant living at a temperature cooler than its optimal temperature is likely to improve its growth and survival under warmer conditions. Rising temperatures are also associated with reduced frosts. Again this has both positive and negative implications with species that are currently precluded from frost susceptible areas being potentially more successful in these areas as the number of frost days diminishes. There is some evidence that less frost days could reduce acclimation to these conditions increasing the negative impact of frosts when they do occur (*see Section 3.2.2*).

- **Rainfall** While predicted changes in rainfall for specific regions remains quite uncertain the assessment considered the existing evidence for potential sensitivities. The impact of drought will depend (i) on the duration and severity of the drought conditions, (ii) the drought tolerance of individual species, and (iii) avoidance strategies of individual species (e.g. use of groundwater). Where rainfall increases, forests may increase water uptake to a point after which runoff will increase (*see Section 3.2.4*).

- **Fire** As with the direct effects of temperature and rainfall, the response of individual species to fire will depend on its sensitivity to fire. In addition, the impact of fire on forest communities will depend on the season, frequency and severity of fires (*Section 4.5.1*).

For individual species, changes in environmental conditions may alter phenological or life cycle events. The evidence from Australia is limited and mixed, but any changes may interrupt interactions with other species such as pollination, frugivory and parasitism. Potential outcomes may be either positive or negative for individual species (*see Section 3.3*).

Impacts on individual organisms and species will have flow-on effects to species interactions and ecosystems. The key changes to ecosystems are:

- Changes in species distributions – Range shifts are most likely to be polewards or to higher elevations. For some species this may represent an expansion of range, for others a reduction. Range is not just determined by climate and predicting future ranges of species currently relies on this as the primary parameter (*see Section 4.2*).
- Changes in community compositions – The composition and diversity of forest communities is likely to change with shifting distributions, local extinctions and introduction of new species. Some introductions could be existing or new weed species, although some weed species are predicted to become a reduced threat in some areas (*see Section 4.3*).
- Changes in forest structure – Again shifting distributions, local extinctions and the introduction of new species is likely to result in changes to forest structure. Current evidence of changed forest structure has been associated with increasing CO_2, temperature changes, rainfall patterns, grazing and fire, but it is difficult to point to a single causal link (*see Section 4.4*).

- Disruption of biotic processes – There is potential for both spatial mismatches (e.g. distribution shifts, local extinctions) and temporal mismatches (e.g. change in life cycle timing) to change the interactions between species (e.g. pollinator and plant; herbivore and food source) (*see Section 4.4*).

Introduction

There is now little doubt that changes in the earth's climate have occurred that are closely correlated with increases in greenhouse gases (e.g. carbon dioxide, methane). Credible mechanisms linking increases in atmospheric concentrations of greenhouse gases with a warming "greenhouse" effect have been proposed and substantiated (IPCC, 2007b). The most important greenhouse gas, in terms of its effect on climate is carbon dioxide (CO_2). In 1750, prior to industrialisation, atmospheric concentrations of CO_2 were 280 ppm as compared to a global mean of 379 ppm measured in 2005 with more than half the increase occurring in the past 50 years (IPCC, 2007b). The current rate of increase is approximately 1.7-1.9 ppm per annum. The projection of future CO_2 concentration depends on emissions trajectories and the strength of oceanic and terrestrial sinks. Government policy and individual actions in the future can strongly affect the trajectory of greenhouse gas emissions. For example, estimates for atmospheric CO_2 in the year 2099 range from 600 ppm under a low-emission scenario up to 1100 ppm under high emission scenario (Stitch et al., 2008).

Changes in the composition of atmospheric gases will trigger changes in the earth's physical environment (carbon dioxide, temperature, rainfall). These physical changes or "climate change" will affect the physiological processes of plants and animals (metabolic response, photosynthesis, water efficiency). Individual organisms may also respond by modifying their behaviour such as timing of life cycle events, dispersal, migration, reproduction and evolutionary adaptation. All organisms have the capacity to deal with a certain level of environmental variability, however beyond physiological thresholds, responses may change dramatically and death could result (Steffen et al., 2009).

In this part of the report we consider the potential impacts of rising atmospheric greenhouse gas emissions on Australia's forests. The impacts of climate change will occur at a number of levels from environmental impacts, through to impacts on individual species, species interactions and ecosystem function, and on through to impacts on human society. These impacts can be categorised as part of exposure or sensitivity for the purposes of determining vulnerability:

Exposure

Exposure is the climate variability or change to which a system is exposed.

Environmental impacts are those that arise from increased greenhouse gas concentrations to which an organism is exposed. They include changes in carbon dioxide, temperature and rainfall regimes, fire regimes and sea temperature.

Sensitivity

Sensitivity is the degree to which a system is affected, either adversely or beneficially, by *climate variability* or change. The effect may be direct (e.g. a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g. damages caused by an increase in the frequency of coastal flooding due to sea-level rise) (IPCC, 2007).

Individual species impacts are the direct changes to the biology of organisms and their environment. Examples of changes include timing of life cycle events (phenology) and physiology.

Impacts on species interactions and ecosystem services determine species distribution, composition of biodiversity found in forests, the success of pests, weeds, pathogens as well as species synergies (mutualisms, predation and competition). These impacts ultimately determine the make-up of biodiversity.

Impacts on societal values reflect the views, expectations and goals of stakeholders; as well as broader economic and social impacts.

Each of these levels can “cascade” into the next with the effect of compounding impacts. But indirect effects or feedbacks can also occur through mitigation and adaptation.

It is worth noting that both climate change and the responses of biological, socio-economic and governance systems to its impacts operate on wide time and broad spatial scales (e.g. Medlyn and McMurtrie, 2005). Available information on impacts, to-date, is limited by the scale of the potential impacts. The little information available – often only from a particular taxon or region – must suffice for first pass vulnerability assessments and estimations of impacts at other locations and while there will be regional variability, existing information can provide initial planning guidelines. The constraint of limited information for all regions and all organisms was encountered in the FVA, but the report strives to represent the best information available at the time, with an expectation it should be up-dated in the future.

2 Exposure – Environmental Impacts

In this section of the report we look at the environmental changes associated with future climate change. This includes changes in the weather, changes in fire risk and changes to the soil.

Exposure – Environmental impacts: Key findings

- Using a scenario of high emissions, high climate sensitivity and the median of 21 GCM ensembles we developed the following scenario of future climate for Australia:
    - Annual rainfall increases in the tropical north and decreases elsewhere.
    - In northern Australia, the wet season gets wetter, the dry season gets drier.
    - In southern Australia, widespread decreases in rainfall occur during winter.
    - Mean maximum temperature in February increases by 3.5 - 4.5ºC over most of Australia by 2070.
    - The number of days with extreme maximums would increase over most of Australia by 2070.
    - The area of Australia experiencing minimum temperatures less than 0ºC by 2070, would be restricted to the mountainous ranges of NSW and Tasmania, particularly across the NSW border with Victoria.
- Additional research has predicted increased frequency and severity of storms, decreased snow cover, changes to potential evapotranspiration and intensification of the ENSO cycle resulting in longer drier drought conditions.
- Other environmental changes include increased fire weather leading to more frequent fires and changes in soil chemistry and moisture.

2.1 Scenarios of future climate

Current changes in climate are producing unprecedented atmospheric and weather conditions. Measures of change include warming temperatures, increased atmospheric carbon dioxide (CO_2) and rising sea levels. In its most recent report, the Intergovernmental Panel on Climate Change (IPCC) stated that the global average surface temperature of the earth had increased by 0.74 ± 0.18°C since 1906 (IPCC, 2007b). Although warming has occurred across the globe, change has been greatest in the northern high latitudes (IPCC, 2007b). With a global average sea level rise of 1.8mm/year from 1960-1983 and 3.1mm/year since 1983, rising sea levels are consistent with warming trends (Steffen et al., 2009).

We present here scenarios of the future climate, including a set of future temperature and rainfall conditions, modelled on a set of assumptions of future emissions and environmental response selected specifically for use in the FVA project (see Section 1.4 and Appendix 3 for a description of the methods used). The resultant scenarios are consistent with those produced by other key authorities in Australia (CSIRO and BOM, 2007).

By assuming high climate sensitivity, high future greenhouse gas emissions (A1FI) and using a median ensemble of 21 general circulation models (GCMs), the future scenarios of climate developed for this report consists of the following climate trends:

- **Annual rainfall increases in the tropical north and decreases elsewhere.** The decrease in rainfall (mm) would be greatest in the southwest corner of the mainland and the west coast of Tasmania (Figure 2.1).

- **In northern Australia, the wet season gets wetter, the dry season gets drier.** Although in terms of the annual average the scenario suggests large areas of northern Australia get wetter, the seasonal distribution may mean additional rainfall when it is least needed (the Wet season), and declines during the dry season (April - October) almost uniformly across the northern part of Australia, when it is most needed by forests. There would be small areas on the coast of Western Australia and eastern Australia that would experience less wet season rain. These trends worsen into 2070 (Figure 2.1).

- **In southern Australia, widespread decreases in rainfall occur during winter and spring** except southern Tasmania that would experience a slight increase in rainfall in winter. A slight increase in rainfall would be experienced in a large portion of the southern part of Australia in both summer and autumn. *The west and southern coasts show decreases in rainfall in all seasons.*

- **Mean maximum temperature in February increases by 3.5-4.5 degrees over most of Australia by 2070.** By 2070, vast areas of interior Australia in particular would be facing *average* daytime temperatures in February in excess of 39ºC (Figure 2.2).

- **The number of days with extreme maximums would increase over most of Australia by 2070.** The north-northwest coast of Australia would experience as many as 40 – 42 days with temperatures greater than 35ºC in 2030 becoming as many as 163 - 175 *additional* hot days (>35ºC) in 2070. Days over 40ºC would increase by as many as 16 - 17 days in 2030 in northwest Australia and as many as 60 - 63 days in 2070.

- **The area of Australia experiencing minimum temperatures less than 0ºC by 2070 would be restricted to the mountainous ranges of NSW and Tasmania.** This would reduce the number of frost days nationwide.

In addition to changes in temperature and rainfall patterns, future climate change will affect other environmental conditions and the weather. Several predictions have been made as part of the wider body of climate change science and these represent important changes for forests in the future. Table 2.1 provides a summary of these changes.

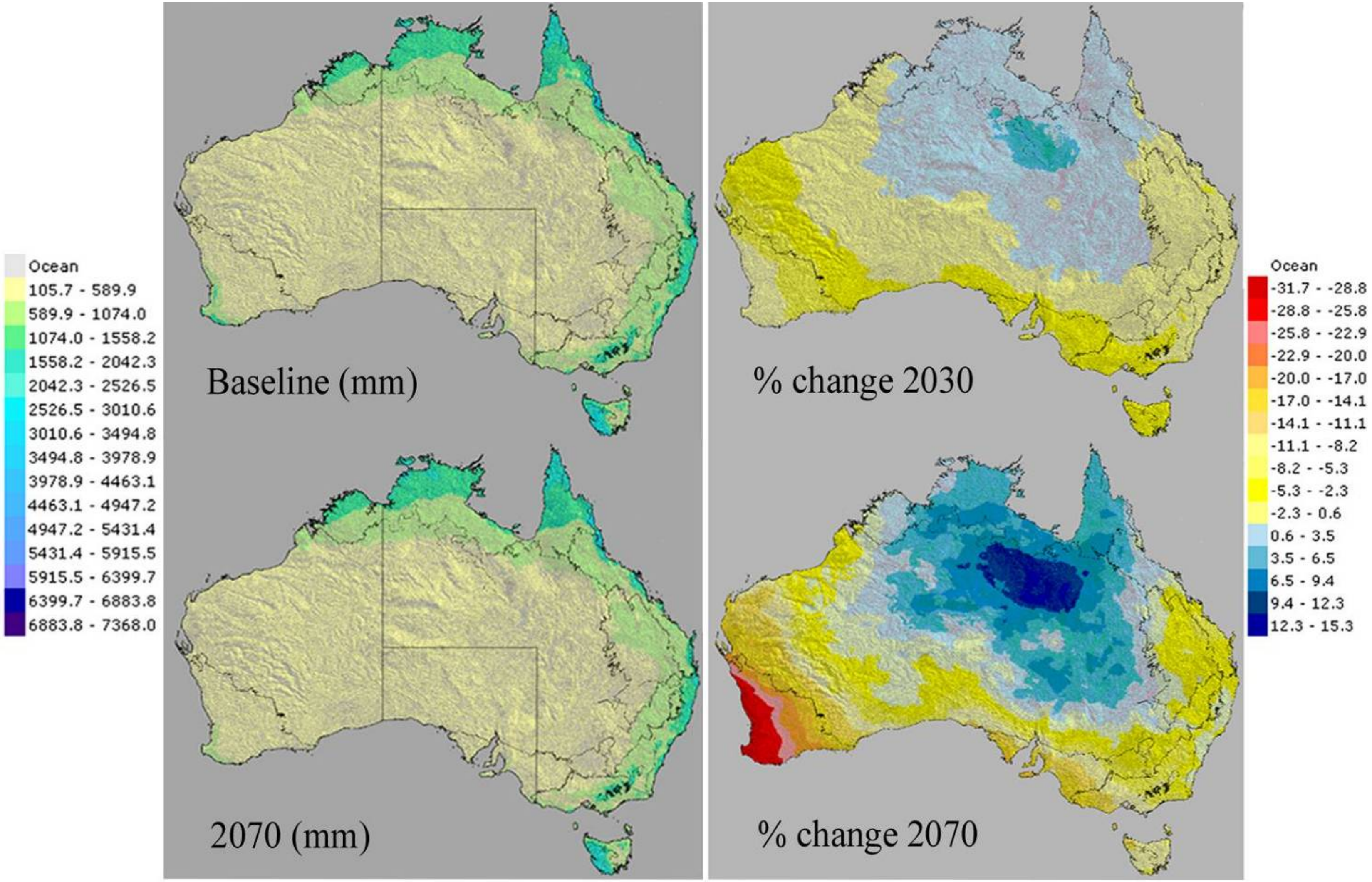


Figure 2.1 Projected annual precipitation in 2070 across Australia created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current (baseline) annual precipitation (based on 1961-1990 data), change in precipitation from baseline to projected rainfall in 2030 and 2070 (mm) are both shown.

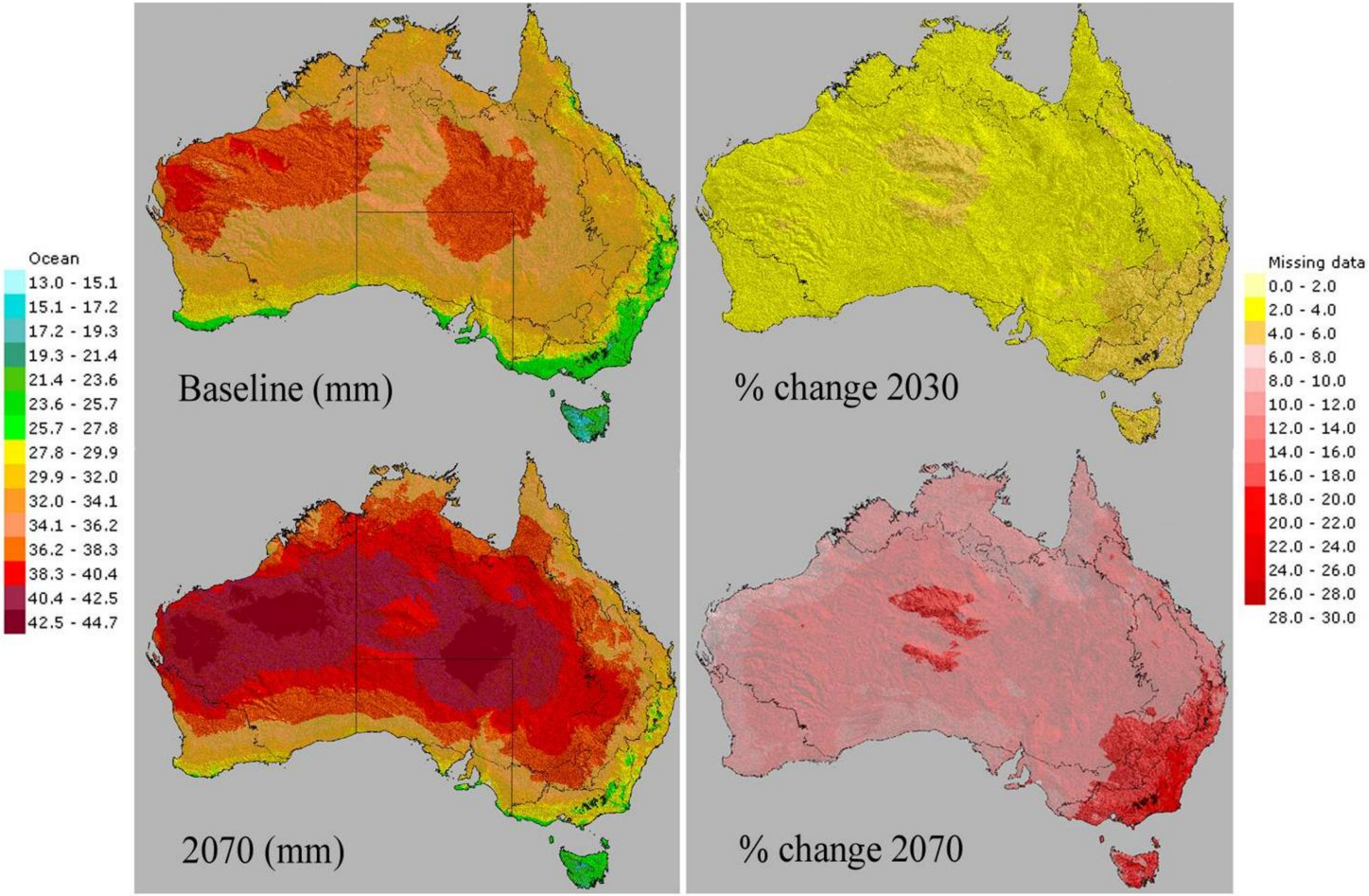


Figure 2.2 Projected February maximum daily temperatures across Australia in 2070 created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current (baseline) annual precipitation (based on 1961-1990 data), change in precipitation from baseline to projected rainfall in 2030 and 2070 (mm) are both shown.

Table 2.1 Recent changes in environmental conditions quantified and attributed to climate change and those predicted to continue or occur over the remainder of this century. Modified from Steffen et al., (2009).

Variable	Changes observed to the present	Predicted future changes from the scientific literature
Temperature	Australian temperatures have increased by approximately 0.9ºC since 1910 with the greatest proportion of warming occurring since 1950 than over the entire historical record. In the last fifty years there has also been an increase in hot days (35ºC or more) and a decrease in cold days (less than 5ºC).	Increase in temperatures Australia wide of approximately 1ºC by 2030 with the greatest increases occurring in inland Australia. By 2070 increases by as much as 4ºC will occur.
Rainfall	Regional variability: rainfall increases northern third of WA and NT and declines across eastern seaboard and southwest WA.	There remains considerable uncertainty about the patterns of future rainfall. In the scenarios used here seasonal increases and decreases occur in different areas. Overall the majority of Australia will experience annual drying.
Solar radiation	Net radiation decreasing (McVicar et al., 2008).	Little change, although a tendency for increases in southern areas of Australia particularly in spring and winter.
Relative humidity	No data	Small decreases expected over most of Australia.
Potential evapotranspiration	No data	Best estimate projections reported by CSIRO (2007) were for an increase in potential evaporation of 6% in the south and west, and 10% in the north and east, under the A1FI scenario by 2070. New research demonstrating non-stationarity in other climate variables affecting the process of evaporation, particularly wind speed (see Roderick and Farquhar, 2004, McVicar et al., 2008, Donohue et al., 2010) suggests that these projections need to be re-performed using all the forcing meteorological variables (net radiation, vapour pressure, wind speed and air temperature).
Wind	Decreasing wind speeds (stilling) over 88% of continent (McVicar et al., 2008).	Increases in most coastal areas except a band around 30ºS in winter and 40ºS in summer where decreases are projected
Frost	Changes in frost occurrence may have increased plant productivity. Risk of late frost increased in southern areas due to changes in synoptic circulation.	Overall decrease in the number of days experiencing 0ºC or less minimum temperatures.

Variable	Changes observed to the present	Predicted future changes from the scientific literature
Snow	Mean snow cover has declined significantly over the period from 1960-1974 to 1975-1989 in the Australian Alps.	Decreases in snow coverage and depth and average length of season. Models also predict a tendency for maximum snow depth to occur earlier in the season.
Storms	Decline in tropical cyclones along east coast of Australia, but increase in number of very intense systems.	Increases in storm intensity by 5 - 10% and/or frequency of events. An increase in the proportion of rainfall occurring in intense events might lead to increased local flooding. Tropical cyclones initiated further south.
Fire	Some evidence of increased fire regimes (Williams et al., 2009b).	Higher temperatures, regional reduction in rainfall, decreased relative humidity and greater plant growth and therefore fuel load are together likely to increase both the frequency and intensity of wildfires. The number of extreme fire weather days will increase. Changes in the season of fire might also occur.
Sea – level rise	Rise of 1.2 mm per year from 1920 to 2000 with large regional variability.	By 2100 the global average rise of sea level of between 18 - 59 cm has been projected. Melting of ice-sheets might push these levels to the upper range of predictions.
Ocean temperature	Warming of all three oceans surrounding Australia.	Higher sea surface temperatures. An increase of 0.6 - 0.9ºC increase in the southern Tasman sea and off the north-western coast, with 0.3 - 0.6ºC elsewhere.
Ocean acidity	Changes observed – 0.1 pH increase in acidity.	Increases in ocean acidity due to increased oceanic absorption of carbon dioxide will occur, with the largest increases in the high- to mid-latitudes.
East Australian Current (EAC)	Increased in strength by 20% since 1978.	The strength of the EAC may continue to increase, resulting in warmer waters extending further south with possible impacts on severe storms.
El Niño-Southern Oscillation (ENSO)	Variability in ENSO, increased frequency of El Niño events. Higher temperature and rainfall for SOI values.	ENSO may intensify with the El Niño phase of the ENSO may tend to become drier and the La Niña phase wetter.

2.2 Other environmental change

While changes to long-term climate trends are the most obvious changes under increasing greenhouse gas emissions, but these climate changes will alter other environmental conditions including fire and soil condition.

Climate change is expected to produce hotter, drier years and increased fuel loads that are generally associated with an increased fire risk. The impact of any resulting fires on forests will depend on fire frequency, fire intervals (i.e. time elapsed between fires), the intensity of individual fires and the region or forest type in which the fire occurs. Given the highly variable nature of all these factors and the complicated interaction between them, it is difficult to make local predictions about the impact of increased fire risk. Williams et al., (2009b) undertook a sensitivity analysis at the national scale as well as with specific regional case studies. In their analysis they determined that increased fire danger indices may result in shorter intervals between fires, particularly in southern Australia.

Increasing temperatures and changes in precipitation will influence soil moisture, soil processes and water availability. For example, the use of water by trees, particularly under elevated CO_2 can affect soil moisture and this is discussed further in Section 4.5.2. Rising temperature has a significant effect on soil processes, with consequences for productivity and ecosystem carbon storage. As temperature increases, soil microbial activity increases, increasing the rate of decomposition of soil organic matter. It is generally accepted that rising temperature will result in a loss of stored carbon via this mechanism (Kirschbaum, 2000). However, increased temperatures can also accelerate N mineralisation and therefore stimulate plant growth (Simioni et al., 2009). A meta-analysis of the impact of warming by 0.3 to 6.0°C on soil processes across a range of sites in the northern hemisphere reported that soil respiration increased by 20%, net N mineralisation increased by 46% and productivity by 19% (Rustad et al., 2001). However, it is uncertain whether these northern hemisphere responses will be similar for Australian forests, as there have been no studies of soil warming effects on Australian forest ecosystems. Simulations of temperature impacts on ecosystem carbon sequestration suggest that enhanced plant growth can outweigh loss of soil carbon in some circumstances, leading to a net increase in total ecosystem carbon storage with rising temperature (Medlyn et al., 2000).

3 Sensitivity – Impacts on individual trees

In this section of the report we review the impacts of climate change on individual plants. The effects of environmental change, including elevated carbon dioxide, rising temperatures, changed water availability, decreased frosts and increased extreme heat are all considered. Impacts on individual species translate into more complex ecosystem responses which are considered in Section 4.

Sensitivity – Impacts on individual trees: Key findings

- The impacts of increased CO_2, higher and extreme temperatures and changed water availability are complex to assess because of (i) the different responses of individual species, (ii) the interaction of environmental factors and (iii) flow-on effects.
- CO_2 has the potential to increase forest productivity but large positive responses to rising CO_2 can only be expected in Australia where soils are fertile.
- CO_2 effects are predicted to be higher when water availability is limiting, but experimental evidence for this effect is scant. A key unknown outcome is whether forest water use will be decreased at high CO_2, or whether leaf area will increase to compensate, resulting in higher productivity but no change in water use.
- Plants have a peak response to temperature, in general, so that rising temperature affects different plants differently, depending on whether they are currently growing above or below optimum growth temperatures. Growth of plants species in cool climate systems (e.g. Tasmania) is likely to respond positively whereas growth in species in warm climate systems might respond negatively (e.g. north Queensland). In addition, plant species have some capacity to acclimate which might negate the impact of warming temperatures up to a point. Given that optimum growth temperatures tend to be quite broad, and plants can acclimate to growth temperatures, growth effects are likely to be small for 1 - 2ºC warming, beyond this however effects could be quite marked.
- Extreme events (frost and extreme heat) may have a significant impact on plant growth. Fewer frost events and less severe frosts could significantly affect productivity and species distribution. Extreme heat is likely to cause some damage depending on the complex interplay between CO_2 concentration, photorespiration, water stress and leaf temperature.
- Drought reduces productivity – initially through stomatal closure (short term response), then through reduced leaf area (longer response), finally can cause mortality,
- Effects of drought are highly variable depending on individual species’ tolerance to drought.
- Given the close ties between climate and lifecycle events, changes in climate are expected to alter the timing of these events. Most existing evidence is from the northern hemisphere, but we would expect species specific changes in the timing of flowering, fruiting, leaf flush, emergence and reproduction in forest associated organisms.

3.1 Introduction

So far in Part B we have looked at the affect increased atmospheric greenhouse gas emissions are likely to have on the physical environment including changes in weather, soil and fire regimes. We now look at the scientific evidence of the response of individual plants and animals to projected climate related environmental change, starting first with increased availability of carbon dioxide and then considering changes in climate conditions.

It is worth noting at the outset of this section, that there are various types of scientific evidence that are used to understand and predict climate impacts on individuals, with four major categories: manipulative experiments, observational studies, ecophysiological models and bioclimatic models (See full review in Medlyn et al., 2010). Each type of scientific evidence have inherent strengths and weaknesses, but if we are to anticipate the impact of climate change on forests, then each method offers an important contribution and in combination, builds a stronger portfolio of evidence.

3.2 Plant physiology

Plants require nutrients, light, energy and water to grow. The limited supply of any of these individual elements can affect the metabolism (photosynthesis and respiration) and growth of individual plants. Plant growth, therefore, is limited by the availability of these elements. Likewise, an increased availability of any individual element can increase plant growth – provided none of the other elements are in short supply. For example, plants in rainforests generally have sufficient moisture for growth year round, but growth is limited by a lack of light availability under the canopy. The creation of a gap in the canopy through a tree fall allows light into the understorey and improves growth conditions for understorey plants or seedlings in that light gap. The impact of increased or decreased availability of CO_2, water, energy or nutrients under climate change in any region will depend then on the availability of other resources and this needs to be borne in mind when considering the impact of climate change on plant physiology in the following sections.

3.2.1 Carbon dioxide (CO_2)

Plants use carbon dioxide as part of the respiration process. Increasing the availability of CO_2 can therefore change the respiratory behaviour of plants. This may result in:

- increased photosynthesis, and
- reduced stomatal conductance.

These physiological responses have several flow-on effects to plant growth (productivity), carbon storage and plant survival, as well as leaf chemistry which has further flow-on effects for herbivores.

Plant productivity – nutrient availability An increased availability of CO_2 can benefit plant productivity with increases in both above- and below-ground biomass. Growth trials conducted in Australia, have shown strong positive growth responses to elevated CO_2 in some trials. The variability of responses is inherent to individual species and/or local environmental conditions with the capacity for elevated CO_2 to increase growth rates dependant on the availability of other elements required for plant growth (e.g. nutrients). There appears to be an interaction between the response to elevated CO_2 and soil fertility in particular, with above-ground increases in growth most likely in fertile sites, potential for soil carbon storage only as fertility decreases and no increase in growth or carbon storage at infertile sites.

Plant productivity – water availability There is consistent experimental evidence that at elevated CO_2, reduced stomatal conductance (see Box 4) improves water efficiency. The logical outcome of this evidence would be that plants growing at elevate CO_2 should be less stressed in drought conditions. To-date, however, this effect has been rarely demonstrated in forest trees. This makes the results of this experimentation difficult to relate to Australia's water-limited, broadleaf forests where this interaction is of crucial importance.

Box 4 Stomatal conductance

The lower, and sometimes upper, surfaces of leaves are dotted with stomata (tiny pores) that allow the entry of CO_2 needed for photosynthesis, but that also play a role in the diffusion of oxygen out of the leaf during photosynthesis. Water vapour evaporating from the moist interior cell surfaces can also escape via the stomata. This evaporation of moisture can cool the leaf, but excessive loss of water can damage the leaf.

Stomatal conductance is the speed at which water evaporates from pores in a plant, and is directly related to relative size of the stomatal aperture. Basically, the higher the evaporation rate, the higher the conductance (i.e. water evaporation) from the leaf. Humidity, the hydration status of the plant, CO_2 availability and light intensity can all affect the rate of stomatal conductance.

Plant productivity – temperature Reduced stomatal conductance reduces evaporation of moisture from leaves – the process through which leaves are cooled – increasing leaf temperature as a consequence. Increased leaf temperature can change the effect of frost damage and heat damage on leaves. For example, higher leaf temperatures were found to reduce the frost hardiness of *E. pauciflora* (Barker et al., 2005). In addition, elevated CO_2 increases the temperature at which ice nucleation occurs in plant tissue that increases the temperature at which freezing stress occurs. We would expect elevated CO_2 and warm temperatures to reduce frost hardiness and raise the threshold temperature at which frost damage occurs.

Acclimation is the process by which tolerance to an environmental stress is increased. It is usually triggered by an environmental stress itself. For example, cold acclimation is triggered by exposure to low temperatures, and plants in this state experience minimum growth but increased freeze tolerance (Woldendorp et al., 2008). De-acclimation is the reverse of this process. So, for example, in the case of cold acclimation, de-acclimation would trigger increased growth and decreased freeze tolerance. Elevated CO_2, along with rising temperatures, results in delayed acclimation and advanced de-acclimation, potentially reducing the length of time during which plants are frost tolerant, but increasing their growing season (Woldendorp et al., 2008).

It is unclear whether rising CO_2 will alleviate or worsen the impacts of extremely high temperatures (i.e. heat stress and water stress). Based on our understanding of plant physiology, we expect increased CO_2 to affect plants in three ways that might impact on the plant's ability to deal with water and heat stress. First, increases in atmospheric CO_2 can increase photosynthesis by decreasing photorespiration. Suppressed photorespiration would ameliorate water stress. Second, increased CO_2 can increase water-use efficiency by decreasing stomatal conductance (Wang et al., 2008). Finally, increased leaf temperatures due to reduced stomatal conductance would exacerbate heat stress. The only Australian study to look at this issue actually demonstrated an increase in photorespiration under increased CO_2 (contrary to what would be expected) with the result that heat stress was exacerbated (Roden and Ball, 1996).

Leaf chemistry Elevated CO_2 impacts leaf chemistry, particularly the nitrogen content and carbon to nitrogen ratio in leaves. Two effects are possible. First, decreased palatability may result in less pest damage and second, decreased nitrogen availability might increase feeding by chewing herbivores (see also Section 4.4.2).

Conclusions Elevated CO_2 has been shown to increase plant productivity in controlled experimentation. However in Australian forests, this response to elevated CO_2 will depend on nutrient and water availability at particular sites. Nutrient availability can constrain increased productivity under elevated CO_2. In addition, there are likely to be important interactions with elevated CO_2, water availability and water use for forests. CO_2 effects are predicted to be higher when water availability is limiting, but experimental evidence for this effect is scant. There is some sentiment among the scientific community that rising CO_2 will lessen drought stress in some instances, although experimental data do not yet confirm this. An outstanding question is whether forest water use will decrease at high CO_2, or whether leaf area will increase as a result of higher productivity leading to no change in water use. From the perspective of plant health, water savings are likely to only be of benefit if productivity or leaf area does not increase.

3.2.2 Temperature

Temperature affects nearly all plant biological and chemical processes and as such, changes in temperature are likely to impact on many mechanisms associated with plant growth. Evidence of the physiological responses of plants to temperature changes is discussed below.

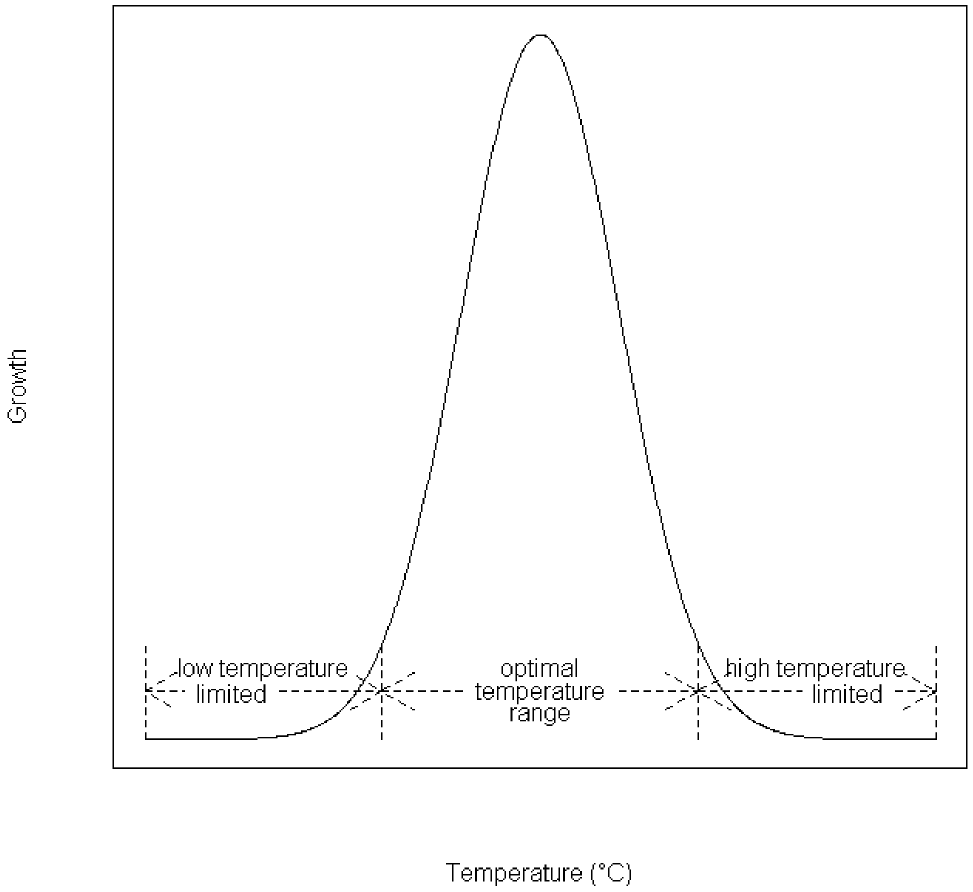


Figure 3.1 Idealised diagram of the impact of temperature on plant growth. When temperatures are above or below the optimal range, growth will be temperature limited. Within the optimal temperature range, high growth rates may be achieved (assuming nutrients and water are available). The optimal temperature range is likely to vary with location and species provenance: for example, it is likely to be markedly different for alpine compared to semi-arid species.

Plant growth Individual plant species have an optimal temperature for growth (Figure 3.1) beyond which growth is limited and prolonged exposure to temperatures outside the optimal range may lead to partial damage or whole-of-plant death. Accordingly, the response of individual plant species to increased temperatures will relate to this inherent temperature tolerance. Species that are currently growing in conditions at the upper limit of their optimal temperature growth tolerance will fare worse under increased temperatures than those at the bottom of their range. Those that experience increased growth under elevated temperatures may not simply accelerate their growth, but follow different development pathways. For example, Way and Oren (2010) found that trees growing at elevated temperatures had more biomass allocated to leaves and less to roots and grew taller for a given stem diameter.

Photosynthesis Temperature affects the rate of photosynthesis in plants. Optimal photosynthetic rates are achieved within a range of temperatures specific to each plant species (similar to the optimal temperature range discussed above). The temperature conditions of the region a plant originates from (as distinct from the conditions under which it was grown) will influence this optimal range. For example, the optimal temperature for photosynthesis is higher for northern temperate rainforest plant species than those found in Tasmania (Hill et al., 1988) and higher again for tropical rainforest species (Cunningham and Read, 2003). This effect can also occur among individuals of a single species that originate from different regions (Slatyer, 1977).

The optimal photosynthesis temperature can be altered through acclimation. For example, the optimum temperature of photosynthesis for a plant will change depending on the temperature at which the plant was originally grown (Slatyer and Morrow, 1977). It is not possible, therefore, to predict long-term responses to rising temperature based on short-term measurements of temperature responses. The long-term temperature response depends on the degree of acclimation that the species is capable of, which is considerably more difficult to establish.

Although the optimum photosynthesis temperature can increase with growth temperature, it is generally less than increases in growth temperature. Due to the broad range of temperatures optimal for high photosynthesis rates and the capacity of plants to acclimate, therefore, increases in temperature of 1 - 3ºC are unlikely to directly reduce photosynthesis (Körner, 2006).

Respiration Rates of respiration in plants increase near-exponentially with increased temperature. For most plant species, however, respiration rates acclimate to the temperature at which the plant was grown and the long-term response of respiration rates to increased temperatures is weaker than expected (Atkin and Tjoelker, 2003). Despite this, there is some evidence that for any given plant species, respiration doesn't fully acclimate to temperature changes resulting in some reduction in carbon uptake and growth.

Extreme temperatures Extreme temperatures can cause damage to leaves (leaf necrosis), reduced productivity or even plant mortality. The temperature thresholds of individual species vary considerably and relate to the climate conditions associated with their place of origin. For example, in desert, arid or semi-arid environments, vegetation remains undamaged by frequent temperatures over 45ºC (Jiang and Zhu, 2001). The onset of heat-induced tissue damage is known from temperatures greater than 45ºC, but this is of course species dependent.

Leaf mortality and damage have been reported for a range of species and habitats, including rainforests (Cunningham and Read, 2003) and sclerophyllous mallee-heathlands (Groom et al., 2004). The thickness of leaves of different species, and the exposure to wind, sun and bare soil affect the susceptibility of individual species to heat-induced leaf damage. Preconditioning or growth under warmer conditions can increase photo-protective pigments and reduce the risk of heat damage.

Extreme temperatures are thought to be an important determinant in species distributions and changes in these extremes might influence shifts in plant distributions under climate change. Frost has a major impact on the growth of many plant species and inhibits the distribution of frost-susceptible species to areas prone to frost. Future climate scenarios suggest that the number of days with temperatures less than 0ºC in a year would decrease (Section 2). It would be expected that this should result in reduced frost impacts on productivity. However, absolute minimum temperatures remain almost as low under future climate change as current lows (Woldendorp et al., 2008) – resulting in less frequent, but equally high impact frost events. Trees deal with freezing conditions through acclimation. If these conditions are experienced less frequently, then acclimation may be delayed and individual tree species could in fact be more vulnerable to frost damage (Woldendorp et al., 2008). There is also potential for increased vulnerability if leaf temperatures increase under elevated CO_2 (see Section 3.2.1) (Loveys et al., 2006, Barker et al., 2005).

Conclusions How a plant responds to warmer temperatures will be affected by (i) the species optimal-growth temperature range, (ii) its inherent photosynthesis temperature range, and (iii) its respiration response. In addition, these species-level characteristics can be altered in individual plants through acclimation and extreme temperature events. In light of this, it is more useful to consider the impact of rising temperatures on plant growth by considering responses from the whole plant perspective rather than at the level of individual impacts. So, rather than a simple answer to the impact of temperature rise on plants (generally), the question must be framed for individual plants or categories of plants. For example, rising temperature affect will depend on whether a plant is currently growing at, above or below its optimum growth temperature range. Growth of plants in cool climate systems (e.g. Tasmania) is likely to respond positively whereas growth in warm climate systems might respond negatively (e.g. north Queensland). In addition, plants have some capacity to acclimate that might negate the impact of warming temperatures up to a point. Most importantly for plant response to climate change is the fact that current plant distributions do not necessarily reflect the capacity of species to tolerate different temperatures and this is explored further in Section 4.2.

How changes in temperature affect growth in the field is complicated by many factors that co-vary with temperature e.g. air vapour pressure deficit (VPD) increases with temperature. Yet much of our evidence comes from pot studies and too little information from growth in the field. It is important to have more field-scale data of temperature impacts on growth to improve our understanding.

3.2.3 Water availability

Extended periods of drought is a feature of Australia’s climate. Future climate scenarios suggest changed seasonal rainfall patterns, with widespread reductions in rainfall for most of Australia. In addition, higher evaporative demands will result from higher temperatures and the variability of El Niño is expected to increase and produce worsening drought conditions. All of these factors have the potential to impact on water availability to Australia’s forests. It is important to note, however, that water availability to plants is not solely determined by rainfall. Topography, aspect, and soil depth, texture and structure can all influence water availability (Mendham et al., 2005, Battaglia and Williams, 1996) and these will be important to consider when predicting impacts of reduced rainfall in an area.

Physiological response to drought With few exceptions, (notably mangroves) reduced water availability leads to reduction in the rate of photosynthesis and ultimately growth in plants. Limited water availability (or drought) is dealt with by plants in a number of ways depending on the length of time in which water is limited. In short-term (several days) or moderate levels of reduced water availability or drought, plants control water use by reducing stomatal conductance. In the medium term (weeks or months) leaf area is reduced, and biomass allocation or growth patterns change and more growth occurs in roots than aboveground plant tissue. During the longer-term (months or years) or at high levels of drought intensity, the pipes that constitute the xylem pathway collapse and become non-functional, leaf shedding takes place and finally death occurs. The timing of rainfall has a significant influence on mortality and productivity of forests. If annual rainfall totals remain constant but reduced precipitation occurs in the dry season, this will reduce growth and potentially lead to water stress during those periods.

Box 5 Leaf area index

Leaf area index (LAI) is defined as the total one-sided area of leaf tissue per unit ground surface area (Watson 1947). Under this definition LAI is a dimensionless quantity characterising the canopy of an ecosystem.

Leaf area index (or the ratio between leaf area and ground area) drives the within and below canopy microclimate, determines and controls canopy water interception, radiation extinction, water and carbon gas exchange and so knowing something about LAI is important for understanding many of the physiological processes of trees.

Changes in the leaf area index (e.g. frost, storm, defoliation, drought) are accompanied by changes in plant productivity.

As with temperature, different plant species respond differently to water availability. This differential response has the potential to change community composition as water availability changes (either quantity or timing) and affects particular species in a negative or positive way.

Leaf area and productivity Water availability has a strong influence on leaf area index (LAI – see Box 5) that is in turn correlated to forest productivity. Both increased LAI or tree cover with increasing rainfall (Hutley et al., 2001, Fensham and Guymer, 2009) and conversely reduced leaf area with decreased water availability (Pook et al., 1997, Battaglia et al., 1998) have been reported. Glass-house based experiments have consistently shown that reduced stomatal conductance (and therefore reduced water availability) and leaf area lead to reduced plant productivity (Austin et al., 2009, Battaglia and Williams, 1996). The response is however highly variable among different plant species (Drew et al., 2009, Battaglia and Williams, 1996).

Monitoring of plant responses to drought events has demonstrated that while drought can cause marked reductions in leaf area through leaf shedding, the timing of rainfall surrounding such events can have a dramatic effect on the extent of leaf loss.

Drought mortality A number of mechanisms have the potential to cause plant mortality during drought: hydraulic failure (stems can no longer transport water) and carbon starvation (insufficient photosynthesis because stomata are closed) (McDowell et al., 2008). Drought related mortality is generally highest in more arid locations such as sun facing aspects, well-drained soils or ridge tops (McDowell et al., 2008).

Prolonged drought can result in different rates of mortality among species with some evidence that drought susceptibility differs among species (Fensham et al., 2009) and across ecosystems (Battaglia et al., 2009). In addition, seedlings and tall trees appear to be particularly vulnerable to drought mortality. Again, the difference in drought susceptibility (as with temperature responses) has the potential to change community composition of forests. Assessment of thresholds of drought risk mortality has been made for a limited number of plant species and a number of thresholds determined (Brodribb, 2009). This result is highly significant in terms of predicting distributional limits of native plants and predicting the conditions under which death is likely to occur during drought (Brodribb, 2009).

Plant death as a result of drought has several implications for the functioning of forest ecosystems. Overstorey mortality reduces photosynthesis, potentially causing ecosystems to become a CO_2 source (i.e. emitting carbon, rather than capturing it) during drought conditions. Understorey mortality may increase growth in the overstorey, altering plant succession pathways and species composition as a result. Reductions in leaf area affect the quantity of solar radiation reaching the ground. This in-turn influences evaporation, transpiration and soil processes such as nutrient cycling, mycorrhizal activity and erosion. The consequences of these changes on subsurface hydrology remain untested (McDowell et al., 2008).

Conclusions Drought reduces plant productivity with extended drought having the potential to cause plant mortality and a number of flow-on effects. The effects of drought are highly variable depending on individual species' tolerance to drought and the timing of rainfall events. Not enough is known about thresholds for drought mortality and better forest monitoring systems are needed to learn more about when drought death is likely to occur.

3.2.4 Conclusions – Physiological impacts of climate change

The physiological impacts of climate change on individual trees will reflect a complex interaction of changes in the physical environment, local environmental conditions, existing (genetic) tolerances of individual species and the capacity of individuals to acclimate to changed conditions. In addition, individual environmental factors will interact to potentially magnify or negate other impacts or create flow-on effects. A summary of these interactions is presented in Table 3.1

Several example scenarios of plant response pathways can be imagined. One example is given below. In this case the response of growth to increasing temperature (Figure 3.2). If an additional and interacting factor was added (e.g. decreased or increased water availability) then the response pathway is likely to become complicated.

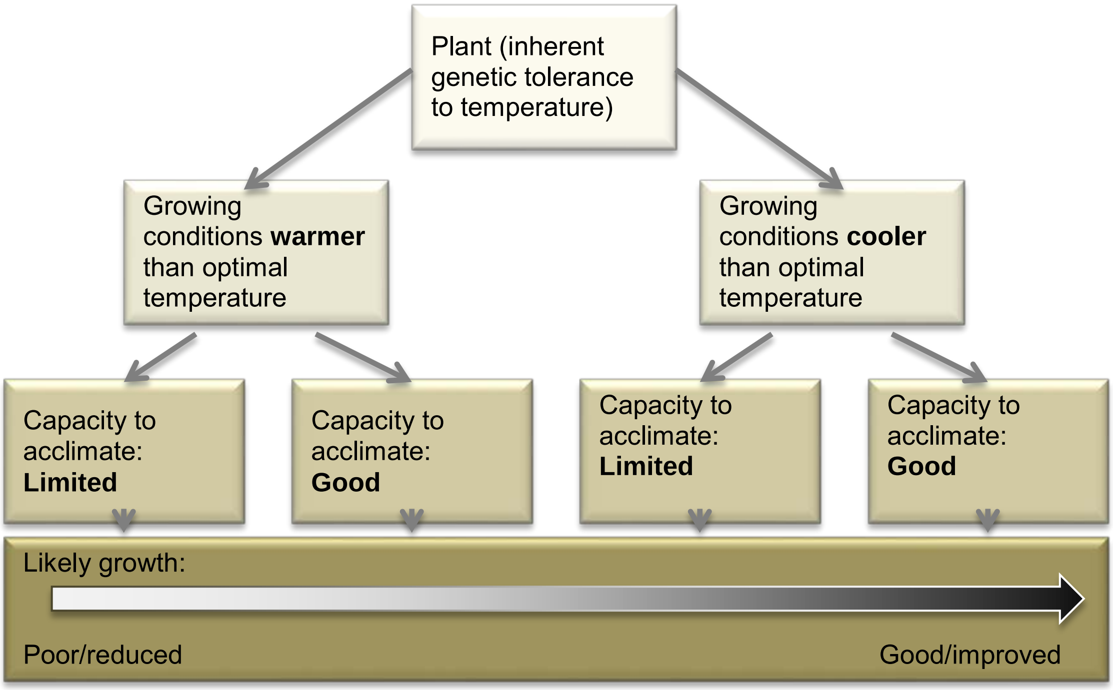


Figure 3.2 A scenario of plant growth under increasing temperatures. The response is clearly dependant on a plant's genetic characteristics, its ability to acclimate and the temperatures of the locality at which it is growing.

Table 3.1 Experimental evidence of interaction between environmental factors under climate change that influence plant growth and survival.

Climate change	Impact on the physiology of individual trees	Interactions		
		Nutrients	Water availability	Rising temperatures
Carbon dioxide (CO_2)	Increased productivity. Change leaf chemistry. Reduced stomatal conductance. Lowered freeze tolerance, reduced acclimation.	Strong interaction effect, decreased nutrient availability limits growth stimulated by CO_2 increase. Expected to restrict response of trees in Australia to elevate CO_2.	At high CO_2, water use efficiency increases. Experimental evidence mixed. Larger leaf area (CO_2 response) cancels effect of increased water efficiency.	Mixed evidence. Increased heat stress (reduced stomatal conductance) OR decreased heat stress (suppressed photorespiration).
Rising temperatures	Change in rate of photosynthesis.	Accelerated nitrogen mineralisation due to warmer soil temperatures can stimulate plant growth (Simioni et	Lack of available water at high or extreme temp., leaves cannot cool through transpiration, leaf temperatures more likely to reach	N/A

		al., 2009).	extreme values.	
Water availability	Drought reduces plant productivity. Mortality depends on thresholds of individual species.	None reported.	N/A	N/A

3.3 Lifecycle timing

Phenology is the timing of biological events. For plants this includes leaf flush, flowering, fruiting and for animals this includes reproduction and emergence. The timing of these events is generally thought to have evolved to maximise the success of individual species. Influences at this evolutionary time-scale include:

- interactions with other organism (biotic),
- inherited traits (phylogenetic), and
- physical limitations of environmental factors (abiotic).

These evolutionary drivers of phenological patterns are considered the "ultimate" while climate is considered an important "proximate" or immediate cue/trigger to phenological processes (Biesmeijer et al., 2006). For example, in seasonal tropical forests many tree species flower at the end of the dry season, the trigger is believed to be an increase in overnight minimum temperatures and lengthening period of time with little or no rainfall. But the timing of flowering means that fruiting will occur when conditions are optimal for seed germination at the onset of the wet season – a potential evolutionary cause for plants to evolve to flower in response to climate signals that precede the wet season.

A number of climatic factors have been identified as cues to phenological events and these include rainfall, solar irradiance or photoperiod and temperature. Many of these abiotic cues are interrelated, and an organism may respond to changes in one or a combination of factors. Individual species respond differently to environmental cues. Any change to these cues has the potential to disrupt interactions between organisms.

Climate change Considerable evidence of changing phenological patterns as a result of rising temperatures exists from the northern hemisphere where marked seasonal changes occur. In particular advanced flowering dates for spring flowering (Primack and Miller-Rushing, 2009), and increased growing season length (Gordo and Sanz, 2009), although considerable variation in these trends exist. Most taxa examined flowered 3 - 5 days earlier for each 1°C increase in temperature, but early-flowering taxa (i.e. those species that flower early in the flowering season) generally responded more strongly, flowering as many as 9 days earlier for each 1°C increase in temperature (Miller-Rushing et al., 2007). Both increases and decreases in the number of flowers produced have been recorded (Hegland et al., 2009).

Likewise animal life histories have demonstrated advanced emergence and migration dates in response to changing climate (Parmesan, 2006). For example, temperature is known to be critical to insect development and activity (Hegland et al., 2009).

While temperature is the key trigger of phenological change in many studies, other climate change factors have also been demonstrated to alter phenological or life cycle events (Table 3.2). Moisture or water availability is also known to be an important cue to phenological events. For example, the few studies conducted in arid, semi-arid, and dry tropical regions indicate that moisture is a dominant trigger for the plants in these regions (Penuelas et al., 2004, Franks et al., 2007). These studies indicate that precipitation from the previous wet season is an important trigger for flowering.

As already noted, much of the published evidence of changed phenologies is derived from the northern hemisphere where temperature is the main limiting factor to growth and development of both plants and animals. Australia by contrast has less dramatic seasonal changes for a large part of the country, with the northern half of Australia experiencing a wet and dry season rather than the traditional four seasons and this may alter the climatic cues to many species.

Existing phenological studies from other tropical areas demonstrate that phenological patterns are markedly different and the climate cues differ considerably from those experienced in the northern hemisphere (van Schaik et al., 1993). The El Niño - Southern Oscillation (ENSO) is the greatest source of interannual climate variability in the tropical region (Wright and Calderon, 2006), has a marked effect on Australia's climate (Nicholls, 1991) and the cyclic nature of El Niño is considered a key factor in triggering general flowering in south east Asia (Wright et al., 1999, Wright and Calderon, 2006). In Australia, the general (or mass) flowering phenomenon is not a major feature of flowering phenology although many species do not flower in every year. It is likely that the El Niño cycle is also an important cue to flowering intensity for many areas of Australia. Given the inter-related set of climate conditions associated with ENSO, it is difficult to distinguish a single climate factor (light availability, temperature or rainfall) as the primary cue for flowering in El Niño controlled systems making it difficult to predict phenological changes in Australia in response to climate change.

Phenological studies in Australia are very limited but from what little evidence there is, it is clear that individual species respond to different climate variables in different ways (Keatley et al., 2002). An improved understanding as to how the phenology in important forest species will respond to climate change is required. Changed flowering and fruiting responses may have consequential impacts in terms of faunal survival and breeding and plant reproduction and success.

Table 3.2 Predicted impacts of climate on phenological or life cycle events in plants.

Climate factor	Phenological response	Interaction with rising temperatures
Carbon dioxide (CO_2)	Increase abundance of flowers(Munoz et al., 2005).	Increase phenological shifts (Walther et al., 2002).
Rising temperatures	Advance timing of flowering, leaf unfolding, fruit ripening, fruit harvest, leaf fall (Fitter and Fitter, 2002, Primack and Miller-Rushing, 2009, Gordo and Sanz, 2009). Warmer autumn may benefit late flowerers by extending season suitable for germination. Extended growing season (Gordo and Sanz, 2009). Reduced growth and plant size affects reproductive output. Increased area of seedling survivorship. Upslope flowering contractions (Walther and Grundmann, 2001, Walther, 1997, Crimmins et al., 2009).	N/A
Water availability	Reduced plant vigour, declining nectar production. Decreased bud development, flowering and seed crop (Ashton, 1975, Keatley et al., 2002).	Timing of flowering, rainfall and temperatures affect flowering. High temperatures and low soil moisture could initiate a second dormancy in eucalypt seeds.

4 Sensitivity – Impacts on species interactions and ecosystems

In this section we consider evidence of the impacts of climate change on the complex interactions between individual species and within ecosystems.

Sensitivity – Impacts on species interactions and ecosystems: Key points

Climate change could impact on ecosystems through (i) changes in species distributions, (ii) changes in community composition, (iii) changes in forest structure, and (iv) disruption to biotic processes.

- Plants and animals are likely to alter their distributions in response to changing climate conditions, however the magnitude of this movement is difficult to predict because:
    - Individual species have different tolerances and capacity to acclimate.
    - As well as climate, species interactions influence their distributions and this effect is difficult to quantify.
- Changes in forest community composition may occur due to:
    - Species loss through changes in distribution.
    - Local extinction through climate stressors (fire, drought,temperature increase, biotic interactions).
    - Introduced species such as pathogens, weeds and pest species. Changes in the prevalence, abundance and competitive success of these species will depend on individual responses to climate factors. Direct impacts of climate change on pests or pathogens and their host can be predicted with some confidence if their responses to temperature and moisture changes are understood. It is expected that some species will become a greater, and some a lesser, threat. Weeds are likely to have similar physiological responses to climate change as other plants. Some will be expected to expand their distribution while others will retract.
- Forest structure is liable to change through altered species composition and changes in crown cover or density through improved or diminished growing conditions. There is some evidence of changes in vegetation density across Australia attributed to climate, clearing and fire. Increases in density may be counteracted by periods of tree mortality during drought over time.
- Biotic interactions such as pollination, herbivory and predation are vulnerable to changes in the timing of lifecycle events and the distribution of organisms. Mismatches in the timing or location of individual species could interrupt mutualisms, but might also create new beneficial interactions.
- The extent of the impact of fire on a forest will be determined by the fire frequency, intensity and the season of burning. Key impacts include species loss, changes in floristic composition, changes in vegetation structure and cover, death of individual organisms and alteration of the water balance.

4.1 Introduction

Australia's native forests have several unique features:

- a high proportion of endemic plant species,
- the dominance of two large tree or shrub groups (*Eucalyptus* and *Acacia*),
- high species diversity, and
- a variety of structural types from multi-stemmed mallee and shrub dominated woodlands to sclerophyll forests and rainforest (Barlow, 1994).

The diversity and uniqueness of the flora is reflected in the diversity and uniqueness of the fauna associated with the forests. It is the complex interaction of individual species in these forest systems that provide an array of functions within the forests (e.g. decomposition, pollination, herbivory) and an array of services to human society (e.g. water quality, pollinators, pest population control). In the previous section of this report we considered the impact of changing climate on the physiology of individual organisms – in particular trees. Here we consider the likely impacts on whole forest ecosystems.

4.1.1 Climate change and Australia's biodiversity

The evolution of Australia's unique and diverse flora and fauna (its biodiversity) is a consequence of Australia's climatic history (Barlow, 1994, Steffen et al., 2009). Individual species are well adapted to aridity, warm temperatures and climate variability including drought (Steffen et al., 2009). However, despite this "evolutionary adaptiveness" changes to the climate are already impacting on biodiversity (see a comprehensive review of these impacts in Steffen et al., 2009). Biodiversity is a term generally used to encompass the variety of life on earth (Steffen et al., 2009). Biodiversity is an important concept in the discussion of forest vulnerability under climate change as biodiversity is acknowledged to play a critical role in ecosystem function and resilience.

It is much more difficult to predict the impact of changing climates on plant-animal interactions, ecosystems and regions than on individuals and individual species because of the multiple effects of interactions. Hughes (2000) provides a plausible example of potential pathways of ecosystem or community change flowing from the response of individual organisms to direct (i.e. increased atmospheric CO_2 concentration) and indirect (i.e. increased temperatures, changes to rainfall and extreme events) impacts of climate change. Hughes suggests that organisms may respond in one of four ways:

- Physiological responses (discussed here in Section 3)
- Phenological responses (discussed here in Section 3.3)
- Shifts in distribution (see below, Section 4.2)
- Adaptation *in situ*

Individual organisms facing direct and indirect impacts of climate change will potentially employ strategies or mechanisms that will alter the impact. These include:

- *Acclimation* – This gradual habituation to slow changes in climate have been discussed for plants in section 3.1. Animals may also respond through similar physiological or morphological responses.

- *Behavioural change* – This could come about through use of or survival in a microhabitat. For example a widespread species may become restricted to a cooler south-facing slope.

- *Phenotypic plasticity* – This is the range of phenotype responses and may include developmental changes (e.g. number of stomata) or phenological (life cycle events).

- *Genetic adaptation* – This applies to populations and involves natural selection. This is more likely to occur in organisms with a short generation times and large populations. Trees, generally have long generations with either large or small populations (Steffen et al., 2009).

While genetic adaptation is a long-term response, the other three strategies allow for short to medium term responses to rapid changes in environmental conditions. Ultimately, however, we would expect any one of these responses or impacts to potentially lead to changes in interspecies interactions (e.g. reduced or increased competition, alteration of predator-prey or parasitic relationships and decoupling of mutualisms). Changes in interspecies interactions could in turn lead to extinctions or further adjustments in distribution. Ultimately, the expected outcome for Australia's forests is a change in community composition or structure in one or a number of the following ways:

- Changes in species distributions

- Changes in community compositions (including introduced species)

- Changes in forest structure (vegetation density, dominant structural type)

- Disruption of biotic processes (e.g. mutualisms)

Steffen et al., (2009) note that biological systems are likely to experience rapid or dramatic transformations after long periods of little change, with changes usually occurring at tipping points or critical thresholds with an expectation that organisms and ecosystems are most likely to respond to extreme events (e.g. loss of lemuroid possums following heatwaves in North Queensland, *pers. comm.* Stephen Williams). The impact of extreme events tends to be at odds with our capacity to predict climate change as averages.

Indirect influences of climate change will impact on the intensity and magnitude of existing biotic and abiotic stressors such as fire. In addition the pressures of pre-existing disturbances or threats such as fragmentation, vegetation clearing, pests and weeds, changes in water resource availability, urbanisation and mining are likely to increase the vulnerability of systems to climate change. Indeed, the natural ecosystem and biodiversity sector has been identified as one of the most vulnerable to climate change (Parry, 2007). It is important to note that predicting impacts on ecosystems and species interactions represents a major gap in knowledge because of the complexity and multiplicity of impacts. In this section we consider the existing literature of impacts on ecosystems and species interactions.

4.2 Changes in species distributions

The distributions of individual organisms reflect differences in life history, behavioural traits and interactions with other organisms associated with particular environmental conditions (Jepsen et al., 2008). Both temperature (Piessens et al., 2009) and moisture, for example, are important influences on insect life-histories. Organisms experiencing environmental change may tolerate the change *in situ* (i.e. individuals acclimate, change behaviour or populations adapt). They may also shift their distribution. Many studies have shown that climate change results in shifts in the latitudinal and altitudinal ranges of affected species (Steffen et al., 2009). Steffen et al*., (*2009) suggest two ways that species might change their distribution. First for more mobile organisms, environmental change might cue individuals to disperse to new more suitable areas. The second way is a more gradual change in which small numbers of individuals naturally disperse during part of their life cycle and can survive in new locations under new climate conditions. In the case of plants, dispersed seeds and seedlings might become increasingly successful in new areas. Ultimately this will result in a gradual change in distribution of that species. Range contractions and population fragmentation might also occur as a result of localised extinctions. Changes in distributions, it should be noted, rely on the availability of suitable habitat within dispersal ranges. So while, new areas may be climatically suitable for a species, if individuals cannot disperse to it, then predicted range shifts are unlikely. For most Australian plants, dispersal is dependant on biotic vectors (e.g. birds, mammals) or physical mechanisms for movement (e.g. mechanical expulsion of seed, wind movement). Seeds dispersed by animals are likely to be moved greater distances than those relying on mechanical means. Plant dispersal is often slow, with short transfer distances and lengthy growth periods before new plants become reproductively mature.

Globally, range boundaries have been documented to shift to higher elevations or towards the poles in a variety of regions. Documented evidence of distribution shifts largely come from northern hemisphere studies (Parmesan, 2006) where conspicuous range expansions have occurred for animal species in particular and where greater historical records are available. In Australia, most evidence is based on predictive modelling (e.g. Beaumont and Hughes, 2002) using either bioclimatic modelling or ecophysiological modelling. These two techniques and their limitations are discussed in Box 6 and in more detail in Medlyn et al., (2010).

Most modelling undertaken so far is restricted to plantation forests and species or common, large overstorey tree species, and does not necessarily represent all forest types. Bioclimatic modelling tends to show that Australian tree species will be highly vulnerable to climate change, whereas, with the exception of south-west Western Australia, ecophysiological modelling tends to show relatively minor or even a positive impact of climate change on forest productivity. The contrasting outcomes of these two modelling methods demonstrate a critical need to improve our understanding of the drivers of species distributions and translate that knowledge into predictive tools.

Box 6 Predicting future distributions – how do we know where species will go?

Predicting future distributions of both plants and animals currently relies on modelling techniques. There are two primary modelling techniques used to predict the distribution of organisms under future climates – ecophysiological models and bioclimatic models.

Ecophysiological models These models are based on a mechanistic understanding of plant function. Typically they include a representation of how CO_2, temperature and water availability affect plant production on a day-to-day basis. Forest growth rates can be predicted for a given climate, species and soil type and productivity of individual species at a given location determined. Ecophysiological models rely on knowledge learnt from other types of studies. They are probably the best source of information about likely future climate effects on vegetation at the "human" timescale but are limited by the quality of available input information.

Bioclimatic models Bioclimatic modelling uses the current geographical distributions of species and/or ecosystems and relates them to the local climate, including temperature and rainfall of those locations to calculate a climatic envelope for that species. Future climate projections can then be used to determine future areas with climates that will support that climate envelope. The approach can be used for any taxon. There are a number of limitations to this type of model. First, the models do not directly predict carbon or water cycling and do not account for the effect of elevated CO_2. Second, climate is not likely to be the only factor limiting an organism's distribution, and species may be more tolerant than indicated by the output of these models.

Which models are best?

Both types of model have limitations. Bioclimatic models may overstate species vulnerability to changes in climate, or omit key processes. Likewise, ecophysiological models may also omit key processes that affect responses to climate. Although both model types look at the impacts of climate change, they both focus on different aspects of tree response. Bioclimatic modelling focuses on species existence, whereas ecophysiological modelling estimates ecosystem productivity. It is possible for ecosystem productivity may be maintained or even increased under climate change even though biodiversity decreases due to species loss and replacement.

It should be noted that species established, or growing out of their climatic range will not necessarily go extinct. Forestry trials around the world have demonstrated that many acacias and eucalypts are able to survive in different temperature environments from their native ranges (Mina and Sinha, 2008). For example, *Acacia mearnsii* is only found in regions with mean annual temperatures below 17.5°C but has successfully been grown in plantations at temperatures up to about 23°C elsewhere. Its success in new environments might be attributed to reduced competition with other species (Gaston, 2003).

Booth and Jovanovich (2005) simulated climatic regions suitable for growth of Australian tree species in current and future climates. They updated their climate distribution descriptions with reports from overseas growth trials of individual species, in particular from Africa (Booth et al., 1988), so their climatic limitations may better reflect a plant's inherent (rather than imposed) climate tolerance (i.e. its fundamental niche). Their projections showed marked changes in the distributions of several species by 2070, although the modelled distributions of some species did not change greatly. The addition of overseas trial data on the climate sensitivity of species, beyond that in other bioclimatic models, reduced climate sensitivity of individual species.

Changes in other environmental variables will also influence distributions. For example, a reduction in the number of frost days may allow frost-intolerant species to move into regions from which they previously were excluded (Bell and Williams, 1997).

4.3 Change in forest community composition and diversity

Climate change is likely to drive changes in the community composition of Australia's forests. While natural drivers (climate and geography over geological time) have shaped Australia's unique biota;

existing and past disturbance pressures (e.g. vegetation clearing, pest and weed introductions, changed fire regimes) have also operated and continue to operate, to profoundly alter the composition and ecosystem structure of our forests. Climate change pressure is likely to exacerbate these pressures and continue to drive such changes. Changes in diversity can occur at either the genetic or species level and these changes in the species make-up of a community will have flow-on effects to whole communities or ecosystems, particularly through interspecies interactions (e.g. predator-prey interactions, pollination, decomposition, herbivory, competition).

Changes can also occur at the genetic and species level. Genetic changes can occur through the isolation of inter-breeding sub-populations or the loss of sub-populations. The outcome is likely to be the reduction of genetic diversity that in turn can reduce the adaptive capacity of a species. At a species level, community composition can be changed through loss of species (extinction), changes in the relative abundance and distribution of species, and the introduction of new species (e.g. pests and weeds) (Steffen et al., 2009). Species loss, changed distributions and changed species interactions are likely to result in changes in community composition. An example of this might include the impoverishment of some communities with a relative increase in weediness (Steffen et al., 2009). Similarly, plantation forests, which only have one tree species, provide many vacant niches for weeds and pests as well as little competition for new species. These mechanisms and processes of change further in the following sections.

4.3.1 Species loss, changes in relative abundance and distribution of species

We have already considered the potential for the distribution of species to change under climate change in Section 4.2, but it is important to note that this has important implications for community composition with localised extinctions and introductions altering the community composition of forests. This in itself has further flow-on effects to species-species interactions and ecosystem function. Where species are unable to shift their distribution in response to climate change (e.g. lack of habitat connectivity, limited dispersal capacity) then species are more vulnerable to extinction and there are plenty of examples of past extinctions as a result of changing environmental conditions. Steffen et al., (2009) provide a review of the changes in distribution of Australia’s fauna under disturbance pressures since the arrival of Europeans to Australia, with climate change described as a new and different stressor, but one that is likely to continue to alter the abundance of individual species, with evidence of biodiversity responses to changing climate already reported. Of course, plant species are often long-lived, and the turnover of species of plant is likely to take very long time periods.

Loss of species can occur through a number of climate related stressors including drought related stress (see Section 3.2.3), fire (see Section 4.5.1) and negative interactions or mismatches with other species (see sections below). Of course the loss of some species and the ecosystem function they perform, may be countered with increases in the abundance of, or introductions of, other species. In addition, responses can vary across time and the ultimate outcome may not be immediately discernible or fixed across time. For example, Fensham et al*.,* (2009) note that drought-related mortality was preceded by a net increase in tree cover over five decades of above-average rainfall. Their conclusion is that any increases in woody biomass as a result of climate change (i.e. increased atmospheric CO_2) during some years will likely be negated by drought mortality in others (Fensham et al., 2009).

Box 7 Mangroves. Source: Poloczanska (2006).

Mangrove communities fringe most of the coastline of Australia. They support a diverse flora and act as a buffer between land and sea to filter terrestrial discharge and decrease sediment loading. They play a significant role in nutrient and carbon recycling, support fish and fisheries and maintain the integrity of the coastline.

As with many other ecosystems, the overall impact of climate change will be the result of several interacting variables. Rising sea-level is seen as a key threatening process under climate change with the sea expected to inundate many mangroves. However, if rates of sedimentation exceed sea level rise the present position of a mangrove area may not be altered. Increases in plant growth through CO_2 enrichment may be tempered by loss of nutrients and changes in salinity levels due to increased freshwater input during storms or decreases during drought.

Mangroves themselves provide protection to coastal areas from storms and coastal erosion. Protection of mangroves will be critical in adaptive management strategies for coastal areas.

4.3.2 Introduced species

The introduction of new species to Australia or undesirable species to new areas has been a major driver of change to biodiversity in Australia (Steffen et al., 2009) and has posed major economic threats to productive forests (e.g. rangelands, state forests) and commercial plantations. Understanding the link between tree diseases, weeds or pests and changes in climate requires an understanding of:

- the basic biology of the pest or pathogen and its host,
- how each might respond to different climate variables, and
- the interaction between pest and host.

Of course the greatest difficulty in this exercise is the complexity of interactions whereby multiple climatological and biological factors are varying simultaneously in a changing environment (Hodkinson, 2005). We now consider the various categories of introduced species and evidence of climate change impacts.

Pathogens

Pathogens are any disease-causing agent but in particular: viruses, bacteria, fungi or other micro-organisms. Escalation of pathogen or disease outbreaks is common under particular environmental conditions (see Table 4.1) or with decreased health or increased susceptibility of the host (e.g. tree stress during drought). Projected changes in climate will directly impact on the development of pathogen species and also influence the likelihood and/or severity of outbreaks indirectly by affecting the susceptibility of their plant hosts (Old and Stone, 2005).

Based on existing examples of pathogen response to climate factors, direct climate change effects are likely to be highly variable. With warming, some pests and pathogens may be able to occur at higher altitudes and latitudes than under current conditions

Box 8 Types of pests and pathogens

There is a broad functional and species diversity of pests and pathogens but they can be broadly categorised. In the case of pests by their functional group (and the damage they cause):

- Defoliators
- Leaf chewers
- Leaf miners
- Sap feeders

In the case of pathogens by their broader taxonomic groupings:

- Fungi
- Bacteria
- Viruses

(Kliejunas et al., 2008, Dale et al., 2001) and some range expansion would be expected (Charkraborty et al., 1998, Harvell et al., 2002, Garrett et al., 2006). Improved suitability of environmental conditions for some pathogens has the potential to shorten life histories and accelerate pathogen evolution increasing the risk of new disease complexes (Mina and Sinha 2008). For example, higher winter temperatures have been found to increase the survivorship of overwintering rust fungi (Garrett et al., 2006).

Compromised health in host trees increases their susceptibility to pathogens (Desprez-Loustau et al., 2006). For example, many stem canker and dieback pathogens are more successful when attacking stressed trees. The key stressor under climate change is likely to be water or drought stress with these trees known to experience greater damage by many pathogens (Kliejunas et al., 2008, Mina and Sinha, 2008). Most fungal pathogens can grow at water potentials much lower than most plants, protecting the pathogen from experiencing drought stress when a host species suffers.

The susceptibility of host trees is likely to be greatest where any factor is limiting or unfavourable (Kliejunas et al., 2008) such as at the edge of their natural range, in fragmented areas of forest or in plantations (Mina and Sinha 2008). For example, pathogen outbreaks are mostly recorded from monoculture plantations rather than undisturbed native forests (Carnegie et al., 1997, Park et al., 2000). Increased growth and vegetation densities occurring under climate change may increase vulnerability by facilitating pathogen transfer.

Effects on native host-pathogen and introduced host-pathogen systems are likely to differ due to co-evolutionary history. Introduced pathogens tend to lack natural enemies and can therefore increase to more severe epidemics.

Amongst the most common forest pathogens in Australia, there is limited existing knowledge of the conditions under which these pathogens are likely to increase or decrease (Table 4.1). For those for which there is some information, a combination of particular temperature and moisture conditions can increase the severity of outbreaks.

Table 4.1 Common pathogens of forests in Australia, variables that the disease responds to where known and its current known distribution.

Pathogen/Pest species	Current distribution	Hosts	Responses				
			Tree stress	Temperature	Drought	Increased rainfall	Future risk area
Armillaria luteobubalina	WA	Karri, jarrah and wandoo forests *Banksia brownii, B. occidentalis, B. verticillata*	unknown	unknown	unknown	unknown	unknown
Armillaria hinnulea	NE Tas., West coast Australia	*E regnans* *E. nitans*	unknown	unknown	unknown	unknown	unknown
Mycospaerella/ Teratosphaeria	Tas, Vic, WA	Native eucalypt forests	unknown	unknown	unknown	unknown	unknown
Mycosphaerella septosporum (needle blight)	Moist periphery of Australia (Watt et al., 2009)	Pinus spp.	Constrains distribution of host and therefore pathogen	Temperatures greater than 5ºC during wet weather allow disease spread	Increased rainfall increases disease risk	Drought not a factor	unknown
M. cryptica	SE South Australia, SW Vic, Tas, southern NSW	50 eucalypt species (E. nitens, E. globulus)	unknown	unknown	unknown	unknown	unknown
Phytophthora cinnamomi	Australia wide	Broad range of host species	unknown	Increased summer moisture increased severity of pathogen; Warmer winters expand outbreak area.	Reduced rainfall days reduced infections Increased rainfall in NT and western Queensland (uncertainty)	Infected drought stressed trees may be better able to contain lesions (e.g. E. marginata but not in Proteaceae)	Cool high altitude areas Vic & Tas; central highlands Victoria (*E. regnans* & *E. nitens* where flat areas with poor drainage); SEQ, NSW and East Vic decreased rainfall will not change vulnerable zone

Insects and insect pests

Outbreaks of insect species tend to be most damaging in single-species (monoculture) plantations than multi-species forests. Insects are likely to respond to climate change in much the same way as plants (Table 4.2). Insects are likely to respond directly to climate change through:

- limiting or changing the distribution of insects directly by influencing survival and fecundity (Chen et al., 2009),
- changes in growth rates and development (life history), and/or
- evolution or adaptation.

Evidence of insect species range shifts is clearly seen in outbreaks of warm adapted insect species at cool upper latitudes where warmer weather allows increased populations in new areas (Stireman et al., 2005). In particular, outbreaks occur if unabated by predators due to differential climate tolerances of pest and predator (Hoffmann et al., 2008). Conversely, an increased incidence of hot and arid conditions has the potential to decrease the populations of some insects with evidence of local extinction of some herbivores under hot conditions despite recovery of host plants (Bradshaw et al., 2007). These changes in distribution also have implications for beneficial insects that play a role in ecosystem function. For example, insect parasitoids that help control herbivorous pests have become less common and effective under drier conditions in South Australia (Kriticos et al., 2009).

Direct effects of climate change on insect growth will vary among individual species depending on the sensitivity of their growth rates to change (Bale et al., 2002), the life-stage at which they experience these changes (Hodar and Zamora, 2004), and their ability to capitalise on, adapt to, or escape from, unfavourable conditions (Morecroft et al., 2002).

Other evidence of temperature related responses of insects include: a decrease in cold-related mortality (Bentz and Mullins, 1999), shorter generation times (Ungerer et al., 1999), reduced growth rates, fecundity and survival when optimal growth temperatures are exceeded (Rouault et al., 2006), interruptions to the life cycle of diapausing insects (Logan et al., 2003) and increased mortality in eggs and young larvae with excess heat (Rouault et al., 2006). Limited evidence of responses of common Australian tree pest species to climate variability exists (see Table 4.2).

Indirect effects may also occur through impacts on interacting species, including species that act as food sources, predators, competitors or through host availability or host plant palatability. In particular changes in the chemical and physical composition of plants as a result of increased CO_2, increased temperatures and reduced water availability could alter the diet of pests. Predicted responses include: increased feeding rates to compensate for lower nitrogen concentration, unpalatable leaves, toughness or increased thickness of leaves with low water or higher carbon content. The feeding guild of an insect determines how much an insect herbivore will be affected by host changes, for example performance may be unaffected or enhanced as in the case of some phloem and whole cell feeders, or it may suffer as in leaf chewers (Bezemer and Jones, 1998, Docherty et al., 1997) and leaf miners (Steel et al., 2008). Changes in the feeding habits of insects have potential implications for the effectiveness of weed biocontrol agents (Scott et al., 2008).

Herbivores may respond to climate change induced dietary constraints by increasing feeding rates, extending development times, reducing adult body size or changing host species. At early-stages of development leaf chewing insects, may be more vulnerable due to weak mouthparts that reduce their capacity to feed on tougher leaf tissues brought about by a higher C-N ratio. This example is a situation in which rapid adaptation could conceivably occur due to higher offspring numbers and relatively short generation times.

Table 4.2 Common Australian forest pests and recorded responses to changes in environmental conditions and areas considered vulnerable to outbreaks under climate change. Note: no data was found for increased rainfall for any of these species.

Pest	Current distribution	Host species	Tree stress	Rising temperatures	Increased drought	Vulnerable areas
Chrysomelid beetles	Few reports from native forests All states where eucalypts are grown commercially		Increased insect attack in flooded plantations *E. dunnii*	Higher winter temperatures potentially speed up life cycle or greater overwintering success	unknown	Expanded distribution matches plantation expansion
Ips grandicollis	NSW, SA, WA	Pinus	Fire damaged trees susceptible to attack	Longer breeding period, greater survival of overwintering individuals	Drought stress increases host vulnerability to attack	Increased drought, fire incidence *Pinus radiata* increased vulnerability to outbreaks as likely to experience greater drought stress Southern tablelands of NSW increase susceptibility
Sirex noctilio	Victoria, Tasmania, NSW, Queensland		Tree stress attracts the wasp (storm damaged, drought and heat stresses trees are vulnerable)	Heat stress	Drought stress	Southern tablelands of NSW expected to experience severe droughts and increase susceptibility to *Sirex* attacks
Longicorn beetles	Qld and Nthn NSW		unknown	Stressed trees susceptible to attack	unknown	No information

Introduced plant species

Weeds, by their very definition are fast growing, highly effective dispersers, tolerate a range of environmental conditions, are afforded high phenotypic plasticity (the ability of an organism to change any observable trait in response to changes in the environment), and have short juvenile periods (Fisher et al., 2009). This allows them to adapt to a wide range of environments and be very opportunistic in their dispersal. In planted forests – either plantations or amenity plantings – weeds are generally a problem at the establishment stage. They create difficulties in the preparation of sites for planting and compete with young trees reducing the rate of growth. They can affect forestry maintenance activities such as thinning and maintaining access, rights-of-way and road margins, as well as increasing the risk of fire. In both productive and conservation forests, areas of disturbance favour weed establishment, through high light levels and the relatively high water and nutrient availability (Webster et al., 2005).

Weed species, like all plant species, will potentially experience changes in distribution or range, changes in physiology and phenological behaviour under climate change (see earlier sections for reviews of these effects). Changes in distribution depend largely on the optimal climatic conditions under which a species grows. As temperatures increase, we would expect tropical and sub-tropical weed species (e.g. *Acacia nilotica* – prickly acacia) to expand their range further south to areas previously too cold for their success (Kriticos and Filmer, 2007). Likewise, those species in cool locations (montane and alpine species) will retract in both latitude and altitude as temperatures increase (e.g. *Cytisus scoparis* – scotch broom) making control methods more effective as these species reduce in range and vigour (Murphy et al., 2008). Range expansions in weed species are generally efficient as they tend to have very effective dispersal methods and generalised pollination systems (Policy et al., 1993) although this will vary among species. While expansion can be rapidly facilitated by favourable germination conditions, range contraction may demonstrate time lags as some species will be able to persist in favourable microhabitats, or as non-reproductive perennial vegetation (Paterson, 1995). In addition, introduced species that do not currently pose a threat (also known as sleeper weeds) may become invasive with sudden and dramatic responses to changed climatic conditions or extreme events associated with climate change (Dukes and Mooney, 1999). Seeds of weed species may also exist as ‘sleeper cells’ in soil seed banks and these plants may respond as the condition of native vegetation deteriorates due to disturbance e.g. increased fire frequency or intensity, or intense drought (Kriticos, 2008). Southern regions of Australia are forecast to expect an overall 20% increase in weed species threat (Ziska and Teasdale, 2000, Ziska et al., 2004).

Major disturbance caused by cyclones such as Larry in 2006 (see Box 9) provide ideal conditions for rapid recruitment and the spread of invasive species (Fisher et al., 2009, Metcalfe et al., 2007). Severe tropical cyclones are likely to become more frequent in the future (Australian National University, 2009) and will create increased opportunities for weed outbreaks.

Elevated CO_2 has the potential to increase weed plant growth and water use efficiency (Stirling and Cornelissen, 2007). However, several factors associated with individual species will determine growth responses. Among weed species there is a prevalence of C4 photosynthetic plants which have been shown to have a smaller growth rate response to increased CO_2 than C3 plants (Johns and Hughes, 2002). Resource availability will also be important in determining weed growth under climate change (Kriticos et al., 2009) with increased competition for nitrogen to maintain C:N ratios as atmospheric CO_2 increases will favour leguminous species (e.g. *Genista monspessulana* – cape broom and *Ulex europaeus* – gorse). Improved water use efficiency under elevated CO_2 may allow some species to invade drier sites (e.g. *Cryptostegia grandiflora* – rubber vine). In drought-prone areas, the length of growing season is unlikely to be affected by increased water-use efficiency of plants and is unlikely to have a significant effect on distribution (Scott et al., 2008, Potter et al., 2009). Any increased growth will include increased root biomass that might in turn lead to the dilution of herbicides and reduce the effectiveness of current weed management techniques (Steel et al., 2008).

Given the high economic cost of weeds, considerable effort has been put into predicting future weed threats. We summarise information on common forest weeds and the increase or decrease of threat to Australian forests under climate change in Table 4.3. It should be noted that much of this weed work relies on the bioclimatic modelling approach. As discussed in Section 4.2 bioclimatic modelling is limited by its focus on current climate and current distributions and should be taken as indicative of one scenario only.

Box 9 Weed invasion of rainforests after cyclone

Severe tropical Cyclone Larry crossed the coast of far north Queensland on 20th March 2006. Damage on the coastal lowlands and tablelands was extensive with some areas losing nearly 100% of their canopy. The cyclone moved inland unusually fast and maintained its intensity cutting a broad swathe through the upland World Heritage Area forests that normally escape the worst impacts of cyclones. Although cyclones are a common occurrence in the Wet Tropics of Queensland and an important determinant in the biodiversity and forest structure as well as an important regulator of hydrology, energy and nutrient regimes, Cyclone Larry created the perfect conditions for the recruitment of light-demanding weed species.

A survey of the rainforest following Cyclone Larry showed the relationship between disturbance and weed recruitment. Pre-existing disturbances (roads, power lines, forest edges and agriculture) were a source for weed seed up to 500 m away. Cool climatic conditions of the higher altitudes may have inhibited germination and development of tropical weeds. The results of manipulative experimentation suggest that herbaceous weeds may be transitory in a recovering rainforest, but that woody invasive species have the capacity to persist.

Cyclone Larry was the second strongest cyclone on record in the Wet Tropics since records began in 1858. Although there is a great deal of certainty in the modelled projections for changes in tropical cyclone frequency, there is evidence that the severity of cyclones and associated precipitation will increase over the rest of the century. The example of Cyclone Larry demonstrates that severe cyclones will increase the threat of invasive weed species. In addition, increasingly severe disturbance such as cyclones will change the community structure of rainforests as aggressive early colonising native species will also benefit. This may result in the expansion of scrub vegetation or “cyclone scrub” under which there is limited regeneration of tree and shrub species and thus lower overall diversity (Metcalfe et al., 2007).

Table 4.3 Common weed species of Australian forests, their current distributions and factors that increase or decrease their threat to an area.

Weed species	Current distribution/status	Increased threat	Decreased threat
Cytisus scoparius (scotch broom)	Cool temperate regions including the Great Dividing Range of south-east Qld, NSW and Vic Widespread in Tas	unknown	Contraction of distribution (Scott et al., 2008)
Genista monspessulana (cape broom)	Widespread in Vic and south-east NSW	Leguminous species favoured in competition for nitrogen favoured by increased atmospheric CO_2 Likely to migrate southwards and potentially outcompete native plants that similarly require southward migration (Boardman 1994)	unknown
Ulex europaeus (gorse)	Widespread in southern Vic and Tas	Leguminous species favoured in competition for nitrogen favoured by increased atmospheric CO_2	Their potential distribution (e.g. coastal southern Aust.) may be contracted (Ivens 2006)
Acacia nilotica (prickly acacia)	Central Qld including arid and semi-arid inlands (could potentially invade most of northern Aust.)	Increased water efficiency due to increased atmospheric CO_2 concentration potentially invading more xeric inlands and expand distribution polewards (Kriticos et al., 2003b)	unknown
Cryptostegia grandiflora (rubber vine)	Eastern and northern Qld (except Cape York Peninsula) Its distribution restricted to areas with summer rainfall of 400 – 1400 mm	Increasing temperature enables tropical and sub-tropical species to expand distribution polewards (south in Australia) and inland (west), potentially invading all mainland states except Victoria (Kriticos et al., 2003a) Invade drier sites due to improved	unknown

Weed species	Current distribution/status	Increased threat	Decreased threat
		water-use efficiency under elevated CO_2 conditions	
Chromolaena odorata (Siam weed)	Locally restricted (early stages of establishment) (Tully, Qld)	Increasing temperature enables tropical and sub-tropical species to expand distribution polewards (south in Australia), probably along coastal regions where rainfall is not a limiting factor (Kriticos et al., 2005)	unknown
Buddleja davidii (buddleia, butterfly bush)	Tas., scattered distribution in southern Aust.	unknown	Contraction of distribution with increased temperature (Kriticos and Filmer, 2007).
Billardiera heterophylla (blue-bell creeper)	Open forest and woodland of south WA, scattered distribution in SA, Tas, NSW and Vic	unknown	Range contraction as climate conditions are no longer suitable (Johns and Hughes, 2002) Improved control as range and vigour is reduced
Cotoneaster glaucophyllus (Large-leaf Cotoneaster)	South-eastern coastal regions of mainland Aust. (south-east Qld, NSW, Vic and SA) and south west of WA. Widespread in Tas	unknown	Range contraction as climate conditions are no longer suitable (Kriticos et al., 2009)
Leycesteria formosa (Himalayan honeysuckle)	Cool high rainfall regions including southern Vic and northern Tas	unknown	Range contraction as climate conditions are no longer suitable (Setterfield et al., 2005) Improved control as range and vigour is reduced

Weed species	Current distribution/status	Increased threat	Decreased threat
Rubus fruticosus (blackberry)	Humid and subhumid temperate regions including south-eastern coastal regions of mainland Aust (Qld, NSW, Vic, SA) and south-west of WA Widespread in Tas	unknown	Short-term conditions remain suitable, range contraction as climate conditions are no longer suitable in the long term (Tommerup and Bougher, 2000, May and Simpson, 1997)
Asparagus aethiopicus (basket asparagus)	South-east Queensland, coastal NSW, scattered distribution in south-west WA, and coastal SA and Vic	Expanded range? Its predicted distribution is largely unknown due to taxonomic problems between *A. aethiopicus* and *A. densiflorus.* (Scott and Batchelor 2006)	unknown
Bidens pilosa (cobbler's pegs)	Widespread in all Aust mainland states, grows in a wide range of habitats including disturbed areas	Increasing temperature enables tropical and sub-tropical species to expand distribution polewards (south in Australia)	unknown
Heliotropium amplexicaule (blue heliotrope)	Widespread in south-east Qld, northern NSW, scattered distributions in Vic and southern SA	Expand distribution polewards (south in Australia) in the short term (Steel et al., 2008)	Contraction of its potential distribution as climate conditions are no longer suitable in the long term (Steel et al., 2008)
Acacia karroo (karroo thorn)	Locally restricted distribution (early stages of establishment) in south-east Qld, NSW, Vic, SA and WA before eradication, with potential distribution covering southern half of Australia	Expanded range (Bougher, 1995)	Poleward shift in its potential distribution (but the size of high risk areas is predicted to remain large) (Scott et al., 2008)
Retama raetam (white weeping broom)	Locally restricted (early stages of establishment) distribution in south-west WA and south SA	Expanded range (O'Connell and Grove, 1996) Reported as weed species with the highest risk of establishment in Aust. due to climate change (Scott et al.,	Poleward shift in its potential distribution (but the size of high risk areas is predicted to remain large) (Scott et al., 2008)

Weed species	Current distribution/status	Increased threat	Decreased threat
		2008)	
Equisetum arvense (horsetails)	Locally restricted distributions (early stages of establishment) currently in central coastal NSW Potential distribution in cool to warm temperate regions including south-east Qld, coastal NSW, Vic, SA, south-west WA and Tas	Expanded range (Claridge et al., 1996) Reported as weed species with the highest risk of establishment in Aust due to climate change (Scott et al., 2008)	unknown
Echium plantagineum (Paterson's curse)	Widespread in south-east Qld, NSW, Vic and southern SA, scattered distribution in south-west WA and Tas	Reduced effectiveness of biocontrol agent as leaf thickness increases under high temperatures and elevated CO_2 (Perry et al., 1985, Simpson, 1996)	Contraction of its potential distribution as climate conditions are no longer suitable in the long term (Steel et al., 2008)
Asparagus asparagoides (bridal creeper)	Tasmania, Victoria, SA, NSW and WA, Mediterranean woodlands region	Range increases in highland areas of Victoria, NSW and Tasmania by 2080	Decreased range in dry warm climates (Gehring et al., 1998, Rygiewicz et al., 2000, Kernaghan and Harper, 2001, Shi et al., 2002, Scott and Batchelor, 2006)
Andropogon gayanus (gamba grass)	Australia's tropical woodland savannas	Increased growth under elevated CO_2. Predicted to modify fire regimes and species composition (Staddon et al., 2004)	unknown

4.4 Changes in forest structure

Forest structure, can change concurrently with changes in the dominant vegetation type (through distribution shifts, introductions or extinctions), changes in crown cover or the density of vegetation (through improved or diminished growing conditions).

There exists some evidence of small increases in woody biomass and tree cover in Australia. Examples include evidence of expansion of closed forests, with a 42% increase in total coverage, in the Australian monsoon tropics over five decades of monitoring (Brook and Bowman, 2006), an increase by 5 - 9% in woody vegetation cover across Victoria from 1989 to 2005 (Lunt et al., 2010), and a 21% increase in "persistent" vegetation Australia-wide (Donohue et al., 2009). It is apparent, therefore, that ecosystem boundaries are changing, however the causes of these changes are uncertain and the influences of CO_2, temperature, rainfall, previous disturbance, grazing and fire regimes are difficult to separate.

Reported localised changes in density have been attributed to subsets of these factors (see review in Medlyn et al., 2010). In general, there appear to be small increases in woody biomass and tree cover across the northern part of Australia. In drier regions these increases are likely to be related to rainfall patterns and can be negated by severe drought. In wetter regions, the increases can be explained by fire activity in some cases, but in other cases distinct drivers could not be identified, leaving open the possibility that the changes are due to rising carbon dioxide and increased rainfall. Land cover change in the southern half of the continent has generally been attributed to land use and land management change rather than landscape-wide climactic factors. Only one study has attributed these changes to climate change. Encroachment of *Eucalyptus pauciflora* forest into sub-alpine grasslands in Victoria's high country, was attributed to rising temperatures (Wearne and Morgan, 2001) although a later study suggested that the observed shift in tree-line (5 m) was much less than expected from the warming that has already occurred (Green, 2009).

The impact of climate change on individual species will have flow-on effects to interactions between species. These indirect impacts are likely to be greater than direct effects because of the capacity for flow-on effects of one species to impact on all species with which it interacts. Species to species interactions include: herbivory, competition, predation, parasitism, pollination, and other mutualistic relationships.

Species to species interactions that benefit *both* species are referred to as mutualisms (e.g. pollination). Mutualistic relationships generally represent long-term evolutionary processes and can be critical to the success of one or both species. Disruptions to mutualistic relationships can come about through changes of distributions or alterations of life-cycle events. Unequal changes on the organisms in the mutualism relationship can create spatial or temporal mismatches with the decoupling of the relationship a possible outcome (Hughes, 2003).

4.4.1 Reproductive biology

Successful pollination, fertilisation and seed development, as well as seed dispersal, are essential forest functions that in a large proportion of plant species require an interaction with an animal to be successful. Much of the evidence of climate change impacts on reproduction is from elsewhere in the world, but the principles are likely to apply in Australia.

We have already considered the potential for lifecycle events to be altered by climate change (Section 3.3) and these lifecycle events are strongly tied to the reproductive biology of plants. Changes in the timing of life history events in plants and animals might create *temporal* mismatches between plants and their pollinators. For example, if warmer temperatures advance the first date of flowering for a plant species, pollinators with different temperature thresholds may not be available to visit these early flowers. Such reduced visitation may result in reduced reproductive success for the plant. It may also mean reduced survival for flower visitors relying on that species for feeding, particularly if flowering finishes before the end of the animal's feeding period. The length of flowering period will be critical in determining the potential for temporal mismatches, with those species with short flowering durations likely to be the most vulnerable. In addition, changes in species distributions may create *spatial* mismatches in mutualistic interactions. For example, if warming means a pollinator restricts foraging to areas further up-slope than the distribution of a plant relying on that species for pollination, there will likely be diminished reproductive success for that plant species. Any of these changes could result in pollinator declines, changes in plant or pollinator behaviour or growth (e.g. flower morphology) and declines in reproductive success. These mismatches will similarly apply to other mutualistic interactions.

Despite the potential for decoupling of plant-animal mutualisms such as pollination, studies on multi-species plant-pollinator assemblages (i.e. generalist systems) indicate that the overall structure of pollination networks probably are robust against perturbations caused by climate warming (Hegland et al., 2009, Dupont et al., 2009). While decoupling of plant-animal interactions is one potential consequence of climate change, opportunities for new interactions may also arise. Climate change may thus have unforeseen consequences to the structure and dynamics of plant-animal interactions (Dupont et al., 2009).

Evidence from Australian forests is extremely limited, but what little evidence there is points to a less pronounced impact of climate change on reproductive success than in more seasonal northern hemisphere studies. Australia plants appear to be more opportunistic in the triggering of flowering events in response to climate. The generalist or specialist nature of plant pollinator interactions is likely to be critical in determining the effect of climate change impacts on successful pollination.

4.4.2 Herbivory, parasitism and predation

Mismatches as discussed above, may also occur in other plant-animal interactions such as parasitoid to host and herbivore to host interactions. Plant-herbivores and parasitoids have important roles in forest function. Plant-herbivore interactions have been considered under the heading of pest insects (Section 4.3.2) and while that focussed predominantly on pest species, similar impacts will be experienced by native herbivores and this may have important implications for biodiversity, particularly if herbivore numbers are reduced. One of the key outcomes under climate change is the change of dominant species due to climate advantages or disadvantages to competitors. Such disruptions have the potential to change the character of forests or the outbreak of pest or weed species.

The natural checks and balances of competing species interactions has long been used for effective biocontrol. Often these biocontrol systems work within a narrow set of environmental conditions and climate change has the potential to disrupt these relationships. For example, climate modelling of the common bridal creeper suggests a reduction of its distribution in the future. However, the impact of climate change on its biocontrol agent (rust fungus – *Puccinia myrsiphylli*) has not been established. The use of biocontrol agents relies on the natural balance of species interactions and consequently, assessments of climate change impacts on either host or control agent will be inconclusive unless climate mediated changes to the interactions between host and control agent and other organisms are also investigated.

4.4.3 Mycorrhizal fungi

Macrofungi play an important role in the decomposition of organic matter, nutrient recycling and nutrient uptake by plants via mycorrhiza formation (see Box 10) and this is especially important in the ecology of Eucalypt forest communities in areas of nutrient poor soils such as those found in southwest WA (Blackman et al., 2009). Mycorrhizal fungi and their mutualistic host relationship is influenced by changes in soil moisture, temperature and fire regime – all of which are likely to change in a warming world.

Mycorrhizae can decrease the effect of drought on the host plant, enhance drought tolerance and help seedlings recover from drought more quickly. Evidence of the physiological response of mycorrhizae to water stress, however, is contradictory with some reports finding declines while others observed a positive relationship or no significant association (see review in Medlyn et al., 2010). This mix of results is likely to reflect differences in individual fungal taxa, difficulties in quantifying the fungi and the variability of water deficit conditions imposed. It appears, however, that irrespective of the nature of the response, water deficits can cause shifts in mycorrhizae community composition (Vernes et al., 2001).

Box 10 Mycorrhizal fungi. Source: Stern (2006).

More than three-quarters of all seed plants have various fungi associated with their roots. The association is mutualistic in that both the fungi and the plant benefit from the presence of the fungi.

The fungus is able to absorb and concentrate phosphorous more readily than the root hairs of the plant. Phosphorous is stored in a granular form until it is used by the plant. The fungus also often forms a mantle of threadlike strands that facilitate the absorption of water and nutrients.

In return the plant provides sugars and amino acids that the fungus requires to survive.

Increased temperatures sometimes increase root colonisation and mycorrhizal hyphal production (Staddon et al., 2004). Several researchers have found significant relationships between air and/or soil moisture, temperature and ectomycorrhiza colonisation rates (e.g. Antibus and Linkins, 1992) but responses are site specific (Swaty et al., 2004).

A number of the chemical and physical changes that result from fire have the potential to affect soil fungal communities. Slow accumulation and reduced leaf litter following fire reduces soil moisture and therefore fungal diversity and the ability to recolonise. There is evidence that while some species are reduced or lost during fire, others are stimulated to fruit and some species are only found after fire. The recovery of fungal spores and fruiting bodies is also dependent on the frequency, season and intensity of fires, the highly variable distribution of heat during a fire and the mortality of host species.

An increase in drought or fire causes a shift in plant/fungus communities, and influences the composition and the diversity of the mycorrhizal community. The close causal link between mycorrhizal relationship and tree health may exacerbate climate change impacts on forests through complex feedback loops. For example, as mycorrhizal communities are affected and the mutualistic relationships are weakened or break down, trees become less resilient to adverse conditions such as water stress, heat or pests. This may lead to more frequent tree death, the build up of forest fire fuel and a greater likelihood of more frequent and hot fires with detrimental consequences for mycorrhizal communities.

4.5 Direct and indirect influences of climate change on ecosystems

4.5.1 Fire

Fire plays a pivotal role in the Australian landscape. Paleological records demonstrate the importance of fire in determining vegetation distribution (e.g. Lynch et al., 2007) with peaks in the charcoal record generally associated with onset of ENSO conditions (Kershaw et al., 2003) and the expansion of eucalypt woodland at the expense of rainforest (Hope et al., 2004). As a result many plant species and communities have adapted to fire over time, although a significant portion remain highly sensitive to fire.

Climate change may affect fire regimes across the Australian landscape through changes to temperature, rainfall, humidity, wind and the level of atmospheric CO_2 (Williams et al., 2009b). Under climate change, it is likely that fire risk will increase and that the season, intensity and frequency of fires will change, particularly in areas experiencing higher temperatures and lower rainfall. Scenarios of future climate show that the southern part of Australia will experience much of this drying and warming and that this will be the regions that experience an increase in extreme fire danger days.

The vulnerability of forests to fire in a CO_2 rich and warming world can be considered under the vulnerability framework as follows:

- ***Exposure:*** fire frequency, intensity, scale and season.

- ***Sensitivity*** of species. Evidence from the literature indicates the most sensitive species are woody species that sprout from seed (cf. resprouters) and have low dispersal rates, and animals with low dispersal ability or are ground dwelling or understorey dwelling species.

- ***Adaptive capacity***: well established or researched understanding of fire; implementation of fire management plans that have good biodiversity outcomes, existence of fire refuges.

Under this framework, those areas that experience more frequent, intense fires or unseasonal fires and are dominated by fire sensitive species with limited fire management practice would be the most vulnerable to the negative impacts of fire.

The prevalence and role of fire varies between regions in Australia as a result of different drivers (e.g. climate driven, fuel load driven). It might be expected that climate change will affect different regions differently as a result of these drivers. Williams et al., (2009b) predict that regions where the drivers of fire are climate related (e.g. temperate forests of south-east Australia) maybe more affected by climate change than those areas where fire is driven by fuel or ignition rather than climate (e.g. the tropical savanna region of northern Australia).

In addition, flow-on factors that may increase fire risk include increased fuel loads as a result of increased vegetative growth (CO_2 fertilisation – see discussion in Section 3.2.1) or increased leaf loss during dry periods (leaf litter accumulation), and changes in forest structure. The progressive dominance of introduced species can reduce canopy and floristic diversity and has been identified as a cause of increased fire frequency (Steel et al., 2008). For example, lantana (*Lantana camara*) will potentially increase fuel loads in *Araucaria* vine forests and vine thicket communities (Steel et al., 2008). On the other hand, drought may reduce growth (reduce fuel loads) and decrease moisture (reducing fire spread). How these factors will interact and influence fire regimes in the future is difficult to predict (Williams et al., 2009).

Key impacts of fire in forests include: species loss, changes in floristic composition, changes in vegetation structure and cover, death of individual organisms, and changes in water balance (see Section 4.5.2). Under climate change similar fire impacts are expected as are currently experienced. However, local changes in fire frequency, intensity and season will determine the severity of impacts felt in individual regions of Australia and these are considered in greater detail in Section 8.

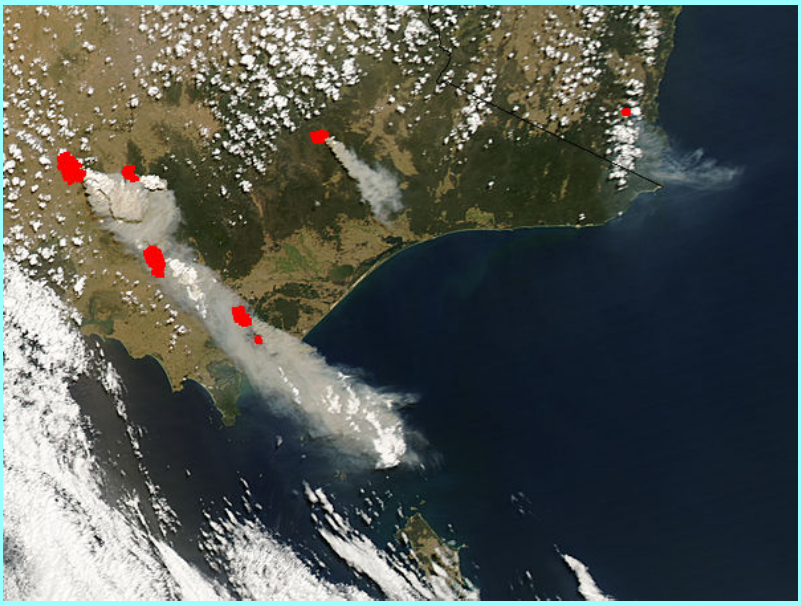
There are complex feedback interactions between fire and biodiversity that can be both positive and negative. Williams and Bradstock (in Steffen et al*.,* 2009) identify as a result, that the risk to biodiversity differs across the country. In particular, they suggest that the biodiversity values of sclerophyllous vegetation of south-eastern and south-western Australia appear to be at higher risk than those of the savanna woodlands of northern Australia.

The impact of fire on forests has been studied in Australia for some time, reflecting the importance and often catastrophic effects of these events. Recent “mega-fires” in ACT, NSW and Victoria (see Box 11) have increased concerns about the impact of fires on communities, the forest industry and the environment and placed current fire management practices under increased scrutiny (Walsh et al., 2006). Fire is also an important management tool and considerable study has gone into balancing its use across a number of management outcomes (e.g. weed control, biodiversity, hazard reduction).

Box 11 The “Black Saturday” fires of southern Australia

In February 2009 fires in Victoria devastated 30 000 hectares of land, including 70 national parks and reserves, destroying forests, homes and lives. Record temperatures were reached in the hours before the fires and demonstrated the climate conditions that increase the risk of extreme fire events. The following excerpt from the Australian Bureau of Meteorology describes those conditions.

> *The presence of a slow-moving high pressure system in the Tasman Sea, combined with an active monsoon trough, provided the conditions for dry hot air of tropical origin to be directed over the southern parts of the continent. On Saturday strong northerly winds, ahead of an approaching cooler south-westerly change, brought this hot air to southern Victoria. The combination of strong and gusty winds, low humidity and record high temperatures led to extreme fire conditions ahead of the change, while the change in wind direction exacerbated the dangers in fire behaviour.*



Satellite imagery (3 pm EDT) on Saturday 7 February 2009 showing the smoke plumes from fires, including the dense cloud column ascending to high altitudes from the Kilmore fire.

4.5.2 *Forest water use*

We have already considered species differences in rates of water use and drought tolerance among individual plants (see Section 3.2.3). However at a stand level there is some evidence that co-occurring species may use different strategies to access all available rainfall (Pekin et al., 2009, O'Grady et al., 2009, Zeppel and Eamus, 2008) – improving water-use efficiency at the forest level.

Increased water availability can lead to increased water use, while decreased water availability can impact on the productivity and survival of plants. The impact of changes in rainfall on plant water use, will however, depend strongly on whether an ecosystem is energy limited or water limited. For example, in the tropics of northern Australia, where energy is more limited than water (which is in abundant supply), reduced rainfall is unlikely to influence plant water use and productivity. However it is likely to reduce run-off rates with the potential for significant impacts on river flows and associated ecosystems. By contrast, in water-limited ecosystems, reductions in rainfall are likely to have dramatic impacts on stand water use (Zeppel et al., 2008).

Different regions facilitate water access to plants via cloud formation, groundwater and soil moisture in addition to precipitation. For example, in some areas of rainforest, cloud contact is a significant source of water, providing as much as 66% of water inputs to forests of the Wet Tropics region of north Queensland (McJannet et al., 2007b). An increase in the height of cloud formation and increased evapotranspiration resulting from climate change, would impact on this water source in those areas reliant on this source.

There are many groundwater dependent ecosystems in Australia (e.g. some riparian zones). Evidence suggests that the presence of groundwater can increase tree water use and leaf area (Benyon and Doody, 2004) as well as reduce water stress (Carter and White, 2009). There is some potential that the presence of shallow groundwater may mitigate the impact of drought providing increased resilience to groundwater dependant ecosystems during short-term droughts. This advantage is likely to be lost under prolonged droughts when groundwater resources may become depleted.

The water balance of a forest changes dramatically after fire (Wood et al., 2008). Water use of the forest stand immediately after fire is very low, and runoff into streams and rivers is high. Research from catchments dominated by ash forests in Victoria shows that in the years and decades after fire, forest growth recovers and stand water use increases, leading to a level of runoff that can be significantly lower than before the fire event (Marcar et al., 2006). If fire frequency increases or changes season, this could have significant long-term impacts on runoff, regional water resources and stream health.

The response of stand-level water use has important implications for the modelling of hydrological processes in determining the water availability at a landscape level in order to plan for and manage water resources under climate change.

4.6 Conclusions – Impacts on species interactions and ecosystems

We have considered in this section of the report the broad categories of impacts on forest ecosystems. Species distributions are likely to change, with predicted expansion and contraction of species based on inherent climate tolerance affected by inter-species interactions, length of generation times and dispersal methods and barriers. One of the key obstacles to predicting the shift in species distributions is our limited understanding of the complexity of drivers (both climatic and non-climatic) of a species current distribution. And while we can say that we expect some species distribution shifts and make a best estimate of direction, there are considerable contingencies and unknowns associated with these predictions. Likewise, changes in ecosystem composition are certain, but which species and where is not. Changes depend on inherent tolerances, species-species interactions and adaptive capacity in response to environmental conditions.

Forest types

Thus far, we have largely considered climate change impacts on forests in general. However, climate change impacts will also vary across the four forest management types established at the outset of this project. The impacts are summarised by these forest types in Table 4.4 and across regional subsets of forest in Part D.

Table 4.4 Summary of climate change impacts on different forest management types.

	Impact	Key impact for plantation forests	Key impact for environmental plantings	Key impact for conservation forests	Key impact for native production forests
Environmental impacts	Rainfall	Seasonal changes in rainfall affects tree establishment	Seasonal changes in rainfall affects tree establishment	Reduced rainfall	Reduced rainfall
	Temperature	Warming	Warming	Warming	Warming
	CO_2	Increased growth, increased water efficiency? Depends on soil quality	Increased growth, increased water efficiency? Depends on soil quality	Increased growth of some species (vines?)	Increased growth, increased water efficiency? Depends on soil quality
	Water availability/ Hydrology	Water stress risk in drying areas and seasons	Establishment and growth compromised in drier areas	Drought stress increase in some areas	Drought stress increase in some areas
Individual species	Tree growth/ productivity	Increased growth if high nutrient soils	Increased growth if high nutrient soils	Potential increased growth probably cancelled out by other effects (moisture, herbivory, competition) although some species in some areas could benefit	Potential increased growth probably cancelled out by other effects (moisture, herbivory, competition) although some species in some areas could benefit
	Drought sensitivity	Species intolerant, reduced growth	Species intolerant, reduced growth	Some vulnerable areas could be highly sensitive, particularly wet areas (e.g. wetlands)	Species dependant, some areas will experience water stress and tree mortality
	Frost tolerance	Risk of increased frost damage though less frost days	Susceptibility depending on species selection	Risk of frost damage disturbance in some areas as no longer acclimate to cooler weather	Risk of frost damage disturbance in some areas as no longer acclimate to cooler weather
	Phenology	Low impact unless used as seed source	Changes in life cycle events have the potential to prevent natural regeneration	Likely to see change Potential for mismatches in mutualistic relationships, has	Likely to see changes Potential for mismatches in mutualistic relationships, has

	Impact	Key impact for plantation forests	Key impact for environmental plantings	Key impact for conservation forests	Key impact for native production forests
				potentially serious implications for ecosystem function and biodiversity	potentially serious implications for ecosystem function
	Carbon sequestration	If productivity increased, improved resource	Increased opportunity	Existing value, increased resource value	Existing value, new resource value
Species interactions & Ecosystem services	Mutualisms	Loss of pollination service, reduced reproduction Low impact unless used as seed source	Loss of pollination service, reduced reproduction	Loss of pollination service, reduced reproduction Breakdown of mutualism affects function	Loss of pollination service, reduced reproduction; impact on mychorizal fungi in eucalypt forests experiencing more fire
	Pathogens	Increased risk of new and worsening diseases; improved resilience to disease in some areas	Increased risk if increased rainfall and high density plantings	New outbreaks in new areas	New outbreaks in new areas
	Pests	Increased risk of worsening outbreaks; new pests in some areas	Increased risk of worsening outbreaks; new pests in some areas	Lower risk than plantations and plantings, but tree stress could make some areas highly vulnerable.	Lower risk than plantations and plantings, but tree stress could make some areas highly vulnerable
	Weeds	Increased risk of more weeds, especially in temperate/subtropical areas	Increased risk of more weeds, especially in temperate/subtropical areas	Risk will depend on health of reserve and management resources New risks for areas with increased fire risk	Risk will depend on health of forest, pre-existing disturbance or use and management resources New risks for areas with increased fire risk

	Impact	Key impact for plantation forests	Key impact for environmental plantings	Key impact for conservation forests	Key impact for native production forests
	Biodiversity	Loss of biodiversity could reduce resilience to weed, disease and pests Neighbouring vegetation could have strong effect	Loss of biodiversity could reduce resilience to weed, disease and pests Limited function with limited biodiversity	Loss of species and diversity, changed composition of forests, reduced ecosystem services	Loss of species and diversity, changed composition of forests, reduced ecosystem services Could limit non-forest product values

5 Societal values

In this section of the report we consider the values, expectations and goals of stakeholders such as forest policy makers when considering what climate change might mean to them. Using the biophysical impacts of climate change on forests, an analysis of the socio-economic impacts of climate change on the four broad forest type categories was performed and is summarised here. In addition this discussion is informed by a review of social and economic literature and a case study of communities in two forest-dependent communities.

Societal values: Key points

- Forest managers must manage for multiple-outcomes. Based on interviews of stakeholders, their perception of climate change issues include climate related, social and economic issues and governance issues. Their identified current responses to climate change ranged from no action to changes in management practices to very targeted policy development and planning.
- Socio-economic impacts of climate change could include changes in land use and from that changes in production, output and community structures and viability, changes in intrinsic values of forests (production, habitat), changes in carbon storage (and value) and changes in ecosystem function values (e.g. salinity control).
- The socio-economic impacts of climate change will differ among the different forest types, with some being much more indirect, and therefore perhaps less obvious but not necessarily less important. For example, changes in the location and quantity of timber and bio-fuel production will flow through to community outcomes, whereas the impacts of changes in the composition and extent of conservation forests on humans could be highly variable amongst individuals and difficult to determine.

5.1 Stakeholder values, expectations and goals

This report has so far set out the impacts of climate change on individual organisms and ecosystems in Australia's forests over the next few decades and beyond. Climate change will exacerbate already existing challenges for land managers. Land-managers hold considerable knowledge, experience and understanding of managing forest ecosystems, as well as the future responsibility for managing the consequences the impacts described in this report. While the project was largely a data-mining and synthesis exercise, we set out to understand the values, expectations and goals of stakeholders as well as the extent to which climate change adaptation is being considered in current planning and management, and what type of information forest managers and policy makers will need. This was carried out through a survey at the project outset (see full results of the survey in Wood et al., 2010).

Semi-structured interviews were completed with 34 stakeholders that were identified across a broad cross section of forest management, policy and researchers and covering participants from all states and territories. The set of questions were structure to capture the following about the interviewees, their organisation, and forest system:

- General knowledge and awareness of the biophysical impacts of climate change.
- Key vulnerabilities and sensitivities to climate change impacts.
- Identification of adaptive capacity and existing planned adaptation.
- Perceived constraints to adaptation.
- Current issues, forest management contexts, strategies and tools.
- Current and proposed involvement in carbon sequestration markets.
- The relative importance of key biophysical drivers to their system.
- General demographics.

Many of the forest managers that were surveyed as part of this project identified their role with multiple forest-types (e.g. plantation, native forest, conservation forest) and uses (e.g. grazing, timber production, conservation, carbon storage, recreation) reflecting the diversity of management outcomes for many of Australia's forest managers.

The key issues or concerns raised by stakeholders that were perceived as forest and climate change related can be categorised under three broad headings:

1. Biophysical issues – the physical impact or changes that climate change will create in Australia in the future.
2. Socio-economic issues – the social and economic impacts that flow on from the bio-physical impacts.
3. Governance issues – the types of policy or governance required to manage change or policy obstacles to managing physical and socio-economic changes.

Many of the issues (summarised in Table 5.1) represent persistent and on-going vulnerabilities and complex interactions that will become more challenging to manage under climate change.

The survey demonstrated that the extent to which stakeholders are currently planning for climate change impacts and adaptation varies considerably. The range of responses can be classified as follows:

1. Mention of specific action plan or similar initiative for climate change that deals with climate change adaptation – either in use or currently being prepared.

2. Reference made to a broader strategy document within their sector that incorporated climate change within it.

3. No mention of a specific policy, but dialogue revealed specific policies and actions being taken or developed on climate change adaptation.

4. Minimal or no plans to develop adaptation measures.

In addition to specific strategic planning, a number of managers are undertaking changes in management practices. Examples include growth trials and movement of planting areas to more favourable climatic conditions.

Table 5.1 Australian forest management issues arising under climate change identified during stakeholder interviews grouped by forest management outcome. Note many forests are managed for both outcomes.

Issue	Forests managed for production	Forests managed for conservation
Biophysical		
Biodiversity		Loss of biodiversity Species loss and extinctions Change community composition Loss of ecosystem services Change to intrinsic value Recruitment Changed phenology Succession Distribution and movement across the landscape Connectivity, buffers and fragmentation Seed sources
Water	Catchment health	Drought and drought mortality Water points
Soil conditions	Soil moisture Salinity Erosion	Soil moisture
Ecosystem health Impact of climate change	Temperature change	Implication of climate change Maximising resilience of reserves Intensity and frequency of extreme weather events
Rainfall variability	Unpredictability of rainfall makes planning management activities more difficult Seasonal variation	
Changing fire regime Reduced frequency of weather conditions suitable for controlled burns	Impact on carbon sequestration Smoke management Burn windows Fuel loads	Fire frequency and intensity very important issues
Difficulty of managing fires Pest and disease	Invest in tolerant species Part of management strategy	Feral animals Disease Concern of increased weed expansion – very difficult to manage

Weeds		
Socio-economic issues		
Carbon trading	Manage forests for wood outcomes versus carbon trading	
Adequate conservation status Socio-cultural impacts		Indigenous livelihoods Heritage values Aesthetic values Recreation Dependent industries
Community expectations		Public support Community awareness and engagement Funding and funding cycles Maintenance/management of infrastructure
Productivity	Remain productive Establishment rate Current narrow species range Timber shortages Supply agreements Potential production from germplasm used	
Species climate capacity	Species selection Genetics	
Land	Land clearing policies/moratoriums Land availability Allocation of state lands for forestry Conflicting land use Land use change/competition with agriculture	Land use conflict and availability Buffer zones
Human capacity	Staffing and personnel/skill level	Population growth Skills and knowledge gaps Specialist monitoring
Governance		
Policy certainty	Confused regulatory environment Recognition of carbon stored in harvested wood products State of managed investment schemes Rights and protections of investors Ephemeral tax issues Jurisdictional variability of governance Perverse policy Bio-energy	Inconsistency/incompatibility between and within jurisdictions Perverse policy Recognition of biodiverse carbon

5.2 Socio-economic impacts

In order to understand the potential social and economic impacts related to Australia's forests, resulting from climate change, we extrapolate from the biophysical impacts reviewed in Part B. Information to support this is reviewed from the existing body of published literature (see Cockfield et al., 2010 for the full literature review).

There are four limitations to the review.

1. First, is the dependence of existing social and economic research and knowledge on the biophysical impacts of climate change? For example, once particular growth impacts are known, then changes in output and regional economic impacts can be estimated using, for example, input-output models (Munday and Roberts, 2001, Eiser and Roberts, 2002, Thomson and Psaltopoulos, 2005). As discussed earlier in this report, the study of biophysical impacts is a rapidly evolving research area, and understanding of the interaction of variables, such as temperature and CO_2 levels is yet to be made. Currently, however, there are few studies from which reliable estimates can be made.

2. Second, a significant proportion of the literature to date has come from other countries where conditions are very different to those experienced in Australia. For example, some studies suggest that warming may favour forest production in some areas (Sohngen et al., 2001, Schjolden, 2004, Boisvenue et al., 2006, Sohngen, 2008), whereas there is much more caution in relation to outcomes in Australia as shown earlier. Nonetheless, these studies did provide ideas on the types of impacts to be considered.

3. Third, most studies to-date have been about the identification of possible socio-economic impacts, rather than estimation of the likelihood or extent of those impacts in particular situations. In order to consider ways in which the extent of impacts might be considered, we reviewed some social studies of forest communities, undertaken for other purposes.

4. Finally, and related to the previous point, the methods that can be used to identify and estimate the extent of more intangible impacts, (e.g. intrinsic and existence value of forests undergoing changes) are subject to considerable debate as to validity and the extent to which local findings can be generalised. There is also a tendency for socio-economic studies to be dominated by the more "measurable" elements, which favours those things that can be more easily monetised or at least quantified.

Consequently, the results of the socio-economic review are more heavily weighted towards studies of production forests, simply because of the available literature, rather than a statement of relative importance. The analysis is based on three key assumptions: there could be changes in (i) species growth rates and ranges; (ii) the composition and appearance of some forests; and (iii) the viability of some forests and remnants.

Based on these assumptions, the climate change impacts on forest-dependent socio-economic systems could include:

- changes in the production of timber, pulp and bio-fuel and the locations of production, as forest managers seek the best available conditions, or cease production altogether;

- changes in habitat quality and viability, with a special concern for situations where climate change interacts with other threatening processes and landscape factors to accelerate forest fragmentation and degradation;

- changes in the appearance, and therefore perception, of some forests because of the changes in composition, habitat quality and viability, forest patch sizes and pest and disease impacts;

- changes in carbon sequestration rates resulting from changes in growth rates and stem numbers and changes in sequestration stocks (stored carbon), a function of the total biomass of forests;

- changes in soil salinity in response to changing forest distribution, composition and salinity control services particularly in landscape locations critical to hydrological processes; and

- changes to water quality because of potential loss of trees in riparian systems and their filtration and regulation services.

In addition, the flow-on impacts include:

- Growth in some forest-based communities and accelerated decline in others because of:

    - changes in output and therefore regional income (see for example Rush Social Research, 1997, Powell et al., 1999); and

    - the cumulative effect of relocation and re-establishment decisions.

    These would be medium to long-term effects as investment and location decisions would be made at the end of particular harvesting cycles, but with the effects accumulating over time.

- Some change in the aesthetic pleasure and spiritual sustenance derived from particular forests, especially iconic ones, due to changes in forest composition and appearance. Forests can have psychological benefits for individuals and groups, based on appearance, cultural meanings and the knowledge that forests are part of valued ecosystems (Winter, 2007, Winter and Lockwood, 2004, Xu and Bengston, 1997).

- Possible changes in tourism preferences due to changes in forest appearance, composition and habitat quality (Turton et al., 2009).

- Increased competition between farmers, rural “life-stylers” and forest managers (Barr, 2008, Schirmer et al., 2008) for land in higher rainfall areas that could drive land prices higher.

A (social) community is considered vulnerable to climate change if there is a high probability of “severe adverse consequences” including loss of livelihoods (Parson et al., 2003). Vulnerability occurs at the interface of the ecological and social systems of Australia’s forests. Climate change impacts will, in most cases, interact with other socio-economic pressures and so any research activities and planned adaptation responses will need to take these interactions into account. These other socio-economic factors or pressures include:

- Changes in vegetation management in production landscapes. Clearing, accelerated by higher commodity prices, for example, could lead to landscape fragmentation, reduced forest connectivity and an increase in the vulnerability of remnants. This is especially the case in fertile areas, suitable for large-scale agriculture. The associated intensification could also increase the threat to forests from agriculture by-products (e.g. herbicide use). Conversely, the conversion of land to less intensive use, such as property ownership for lifestyle, aesthetic or conservation reasons (Barr, 2008, Schirmer et al., 2008) could see reforestation or in some cases, spontaneous regeneration.

- Intensive grazing of forest areas (especially in the rangelands), affecting recruitment, ground cover, soil condition and tree viability. That is, economic pressures, combined with climate change impacts on pasture production, may result in over-grazing.

- Tree clearing regulations, which can have a number of effects, including increasing forest density, increased fire risks depending on landholder management and increasing presence of pest species.

- Policies and regulations to encourage plantations and/or discourage logging in native forests. This formally started in the early 1990s, with resource assessment reviews and, although the impacts vary by state and region, the relative proportion of plantations has increased. This, along with the growth of Managed Investment Schemes (MISs), has led to an increasing demand for land in higher rainfall areas, especially in the southern and south-western regions. With drier conditions in southern areas traditionally too wet for cropping demand for cropland has also increases in direct competition to plantation development.

- The trend for encroaching urbanisation in coastal areas resulting in loss of forest, but also counter-demand for forested areas for amenity and conservation values (e.g. Land for Wildlife). “Tree-change” areas may benefit from forest regrowth due to the shift from agriculture (grazing) to lifestyle land-use.

- Depopulation of inland rural areas (Bureau of Rural Science, 2008), especially in regions with a narrow economic base and limited social and cultural appeal, as is the case with some forest-based communities. This problem is exacerbated by the structural change that affects most primary industries whereby mechanisation displaces labour.

- Increased demand for bio-energy (bio-mass fuels and electricity) and the demand for carbon-sinks resulting from renewable energy policy. There is as yet little demand for this in Australia but it is an area for future consideration.

5.2.1 Framework to assess socio-economic impacts

In building a framework on which to assess the socio-economic impacts of climate change on forests, we can first classify the socio-economic values of forests as “ecosystem services”. A simple definition of ecosystem services is *those things provided by natural systems that yield benefits to people*. A simple categorisation was used in the analysis to match the project brief. The aim is to capture the benefits directly linked to people. These services may be of value to society because they can be consumed (e.g. food, firewood, medicine) or sold (i.e. provide a direct income, e.g. timber); they may also provide flow-on income in the form of wages to industry workers. These are direct services and have a very tangible economic and therefore social value. There are also the regulatory services that beneficially affect other processes. Examples of these types of services would be the lowering of water tables by a forested area that is preventing salinity problems in catchment areas and thus sustaining agricultural production, or perhaps riparian forests that contribute to filtration and regulation of surface water flowing into waterways (Table 5.2).

The biophysical impacts of climate change on forests have the potential to alter the socio-economic value of the ecosystem services that forests provide. The value and direction of change, however, will be dependent on a number of factors including location, forest type and forest use/s. In the following sections we summarise these values and value changes by the four forest types defined for the FVA project (see Section 1.2.1).

Table 5.2 Ecosystem services (or products) provided by forests that benefit human society. The services are categorised as providing direct benefits in that they can be either directly consumed or sold (income) or provide flow-on income (e.g. wages). Some services regulate other processes that provide social benefits. Modified from Millenium Ecosystem Assessment (2007).

Type of service	Service	Direct consumption	Direct income	Flow-on income	Enables other system services
Consumption goods	Timber	√	√	√	
	Bio-energy	√	√	√	
	Food	√	√	√	
	Medicines	√	√	√	
System regulation	Carbon sequestration		√	√	√
	Water table		√	√	√
	Micro-climate*				√
	Flood control				√
Filtration	Water quality	√	√	√	√
Protection	Soil				√
Regeneration	Soil				√
Psychogenic services	Recreation	√	√	√	
	Spiritual sustenance	√	√	√	
	Existence value	√			
Services to other species	Habitat	√	√	√	√

*Very limited discussion in this project given the limited availability of research

5.2.2 Plantation forests

Forest plantations in Australia offer two ecosystem services that can be readily valued and are likely to be affected by climate change – timber, bio-fuel or related products and carbon sequestration (Table 5.3). The climate change impacts on both these services is difficult to predict and will vary between regions (considered in greater detail in Part D of this report) but potential impacts and changes to their value are listed in Table 5.3. There is potential for increasing management challenges (e.g. weeds, pests) and costs (e.g. new species development, relocation) but there are also significant opportunities for plantations including new products. The greatest challenge is the long time-frames associated with planning for these changes and the uncertainty associated with impacts. For example, the planting of a new species relies on some prediction of climate several years in advance, although the use of climate ranges (i.e. climate variability) is not unusual in plantation management. Forest production activity is likely to decline where profitability declines due to slower growth rates and higher loss due to fire and pests.

In addition, plantations can have some habitat and micro-climatic value and this will need to be considered in large-scale adaptation planning exercises.

Increases in plantation area will likely occur where conditions become more favourable, as discussed earlier. This will be a much broader range of areas if there are incentives to establish forest-based carbon sinks. The net socio-economic value of plantation expansion will depend on what they replace. There may be a loss of grazing production and for some people, the loss of a preferred agricultural landscape.

Table 5.3 Climate change impacts on the socio-economic values of ecosystem services in plantation forests including farm forests.

Service	Key climate change impacts	Change in value
Timber	Changed climatic suitability of growing conditions in some regions. Reduced productivity in marginal areas or those at the limits of environmental tolerance. Increased growth (possibly) in more favoured areas. Increased (or decreased) disease vulnerability and increased fire risks.	Changes in regional output. Some areas gain and others lose. Accelerated economic adjustments already occurring in timber regions. For some, loss of employment, depending on what land use is substituted Similarly, some potential increased regional economic activity. Increased management costs related to fire protection and pest control.
Bio-energy	Increased demand	Potential to "value add" to timber production and possibly some new plantations. See for example experimental trials of mallee plantations (Wu et al., 2008).
Carbon sequestration	Some species/regional growth rates increase, some slow. Potential for climate change to adversely affect carbon sequestration plantations. Potential for loss of carbon from established forests with warming, as soil carbon mineralisation increases with warming. Tree mortality could reduce carbon sequestration.	Changes in sequestration rates Increased value of trees for carbon storage which could be tangible with a carbon price. Potential for change in land use demand for plantations if carbon is priced. Changes in sequestered carbon stocks which may affect achievement of international commitments/targets.
Water table	Trees lost from/established in	Increased/decreased water-table control and decrease in salinity but may decrease

Service	Key climate change impacts	Change in value
	particular locations. Potential changes in plant water use would affect water table.	pasture/crop production.
Micro-climate	Trees lost from/established in particular locations.	Increased/decreased stock shelter, domestic wind protection but may decrease/increase pasture/crop production.
Water quality	Trees lost from/established in riparian areas.	Increased/decreased water filtration, bank protection, but may decrease/increase pasture/crop production. May be some impact on flood levels.
Soil	Increased/decreased forest cover.	Net gains/losses depend on alternative land use, but generally plantations will result in a slow increase in soil composition and protection value.
Spiritual sustenance	More/less forests in the landscape.	Changes in psychological benefits depend on how particular plantations are seen and what values people presume to be inherent in the forest. There is some resistance to increasing plantation area (see above) but other plantations may provide recreational and aesthetic benefits for some.
Existence value	More/less forests in the landscape.	
Habitat	Increased/decreased forest cover.	Highly dependent on scale, species, proximity to native forests and landscape context but native species will have some value.

One of the socio-economic issues most difficult to predict for plantations under climate change is potential change in land use or land demand. There already exists a major strategy to increase the area of plantations (Plantations Australia: The 2020 Vision) and, for a variety of reasons, a reduction in the production of timber from native forests. In addition there is a convincing argument that there might be some conversion of agricultural lands to forest (Burns, 2009), particularly if the relative productivity of agriculture decreases and there is demand for carbon sequestration. On the other hand, in some situations there may be increased plant growth under elevated CO_2 that could counteract negative impacts on agriculture yields. Indeed, there is alternative evidence suggesting that agricultural production could increase (Gunasekera et al., 2008). In this case the forestry takeover is uncertain and agriculture may successfully compete with forestry.

The coastal high-rainfall regions of Australia are seeing an increasing land demand from growing population centres and the demographic changes in smaller coastal towns brought about by the influx of tree- and sea-changers. The economic value of these competing interests will become central to the expansion or contraction of each interest in these high rainfall areas. Critical to the plantation forest industry will be development of a market value of carbon sequestration under any future government schemes.

5.2.3 Environmental plantings

The impact of climate change on the socio-economic values of environmental plantings will be largely influenced by the purpose of the planting. For example, planting for restoration purposes will experience many of the value changes outlined for conservation forests whereas those planted for carbon offsets will be affected by the potential future incentives for sequestration as discussed above in Section 5.2.2. It might be expected that establishment costs may be greater due to unfavourable climatic conditions, reduced growth and increased vulnerability to invasive species in some areas. Environmental plantings have the potential for higher non-timber values than do plantations because of the capacity for selecting species and species mixes to enhance habitat values and because there is no clearing (harvesting) phase which would sharply decrease habitat value and carbon stocks.

On the other hand, standing conservation forests can have a value advantage over environmental plantings if a conventional economic analysis, using discounting, is applied. If habitat value increases with complexity (i.e. diversity and structure) and complexity takes time to develop, then the increasing value of an environmental planting is offset by the time taken to achieve a more complex state. If climate change accelerates or inhibits the growth of complex environmental plantings, then the implicit net present value changes. In summary, environmental plantings can have multiple benefits but potential trade-offs between the various wanted outcomes also need to be considered (Maron and Cockfield, 2008).

Table 5.4 Climate change impacts on the socio-economic values of ecosystem services in environmental plantings.

Service	Key climate change impact	Change in value
Food and medicines	Slow growth rates and increased mortality. Increased plantings due to incentives.	Possible long-term food and medicinal benefits with selected plantings (e.g. bush foods). These benefits could decrease with slow growth and increased mortality but increase if there were incentives to plant a greater area.
Carbon sequestration	Increased economic value of this service.	Increased value of trees for carbon storage. Actual value will depend on government policy, world carbon price, food price and future demand for other forest products. Potential for change in land use demand. Changed household and regional income, depending on previous land use.
Water table	Trees lost from/established in, particular locations.	Increased/decreased water table control and decrease in salinity but may decrease pasture/crop production.*
Micro-climate	Trees lost from/established in particular locations. Can target the most appropriate species for shelter effects.	Increased/decreased stock shelter, domestic wind protection but may decrease/increase pasture/crop production.*
Water quality	Trees lost from/established in riparian areas. Can target the most appropriate species (for water table management).	Increased/decreased water filtration, bank protection, but may decrease/increase pasture/crop production.**

Soil	Increased/decreased forest cover.	Net gains/losses depend on alternative land use, but generally plantations will result in a slow increase in soil composition and protection value.**
Recreation	Trees lost from/established in particular locations. Can target high appeal species.	Potential increased value, especially where plantings add to more mature and accessible forests.*
Spiritual sustenance		
Existence value		
Habitat	Trees lost from/established in particular locations. Can plan the forest structure to some extent.	Potential increased value*

* Values will vary depending on purpose of planting and time since planting.

**Generally much higher values than for the plantations, because of the capacity for selecting species and species mixes and because there is no clearing (harvesting) phase when values would drop sharply and then increase through the next cycle. However, generally lower values than for conservation forests because of the time to develop the beneficial characteristics. There will also be trade-offs between the various wanted outcomes where there is targeted planting. For example, better windbreak species may not be the best habitat species or good habitat species may be slower growing and sequester less carbon.

5.2.4 Conservation forests

These are existing or natural forests that have a legally binding conservation purpose. Ownership may, however, be public (e.g. national parks) or private with the forest under a covenant or agreement and a significant number are managed by Indigenous owners (Department of Agriculture Fisheries and Forestry, 2008). The services at greatest risk in these forests are those underpinning recreation and tourism, clean water and air, and those less tangible non-use services and intrinsic values provided by forests and their biodiversity. Changes in the diversity, species composition and structure of these forests may have a negative impact on recreation and spiritual values. In addition the increased vulnerability to invasive species and disease may increase management costs. Climate change impacts on Indigenous managed forests may expose Indigenous societies to a number of worsening vulnerabilities including reduced health as wild foods diminish and reduced income from recreation or tourism values.

Dependant on the conservation goals of an area of forest, there are limited management options, so unlike plantation forests, selection of new species, for example, is not compatible with the goals of conservation. Options for management are mostly centred around reducing other stressors (e.g. weed control, reduction of disturbance) but may also include identification of refugia which will include areas not currently under conservation protection. These actions require significant investment.

Table 5.5 Climate change impacts on the socio-economic values of ecosystem services in conservation forests. This includes public reserves (e.g. National Parks) and privately-owned reserves, remnant vegetation (e.g. shelter-belts, corridors) and Indigenous managed forests.

Service	Key climate change impact	Impact on value
Food	Reduced populations of wildlife/plants traditionally harvested for food.	Further impoverishment of Indigenous communities. Reduced general health of Indigenous peoples due to change of diet. Overseas studies have identified peoples with high dependencies on non-timber forest products (see for example Peters et al., 1989, Anderson et al., 1991, Knowler and Canby, 1998, Mallick, 2000).
Medicines	Reduced populations of wildlife/plants traditionally harvested for medicines.	
Carbon sequestration	Increased value where growth rates increase and decreased where growth rates decrease. Reduction in area due to threatening processes.	Increased/decreased sequestration rates. Changes in stock of carbon, depending on the interaction of stem density and growth rates.
Water table	Loss of trees from critical landscape areas.	Soil salinity increases
Micro-climate	Tree mortality	Increase in wind erosion and wind irritation to humans. Reduced livestock welfare and production due to wind chill or heat exposure.
Water quality	Tree mortality (especially in riparian areas)	Reduced water quality (depending on the subsequent ground cover).
Soil	Tree mortality	Increased risk of soil salinity
Recreation*	Change in composition/quality of forests due to increased fire, disease and pests. Damage to infrastructure (flood or fire). Population decline in vulnerable communities. Increased management needs (weeds, pest, disease, fire).	Decreased attractiveness to visitors. Loss of income. Particularly high impact for Indigenous owners. Increased cost in maintaining forests (e.g. weed control) and infrastructure (e.g. repair flood damage). Reduced secondary expenditure benefits to local businesses. Increased insurance costs (associated with elevated risks and possible discomfort). Reduced employment. Increased management costs (increased employment).
Spiritual	Changed character through species	Reduced spiritual (e.g. Indigenous

Service	Key climate change impact	Impact on value
sustenance	loss, composition change (both plants and animals), change of hydrological flows, increased fire damage.	cultural/religious practices) and amenity value.
Existence value‡	Change in habitat, increased fire risk, increased vulnerability to invasive species and disease.	People perceive there to be a loss of natural capital and a loss to the nation/humanity/biosphere.
Habitat	Change in habitat, increased fire risk, increased vulnerability to invasive species and disease. Decreased connectivity of habitats. Increased density due to regrowth or increased productivity. Increased management needs (weeds, pest, disease, fire).	Loss of refugia for bio-control agents beneficial to agriculture. Increased habitat value in some areas. Increased management costs (increased employment).

* Applies to public conservation lands and Indigenous managed forest, but generally not private conservation forests.

‡ Value depends on knowledge of forest types and extent. Higher value of “iconic” forests and well-known areas (e.g. Daintree).

§ Value applies to remote areas managed by Indigenous owners.

5.2.5 Native production forests

These forests include those on state-owned and private land where some degree of harvesting is legally permitted. They are frequently used as grazing lands, particularly in the rangelands. These forests have the potential to produce the broadest range of ecosystem services, from timber and agricultural production through to existence value, depending on location and appeal. In addition, there is also the greatest potential for trade-off between use and non-use values. For example, extensive clear felling of an area could, at least for a time, reduce aesthetic, existence and spiritual values, while increasing regional economic output. Conversely, a reduction in timber harvesting from native forests would increase the sequestration value of forests, depending on the interaction of growth rates, stem density and forest age, but employment and settlement patterns may change as a result. On the other hand, if governments opted to increase the number of conservation managers to manage pest and fire threats then there may be some offsetting increase in employment.

The extensively managed rangelands, which cover some 80% of the continent, have received little investment largely because the landscapes are perceived to be relatively intact. However, recent State of the Environment reports suggest that rangeland ecosystems are in slow decline and extremely vulnerable to inappropriate land uses, fire management practices and invasive weed species. Biodiversity conservation options in the rangelands have the potential to be highly cost-effective and could alleviate the need for large remedial investments in the future (Smyth et al., 2006).

Other new industries include clean energy markets in the rangelands region (Pittock, 2011).

The relevant impacts of climate change will, therefore, overlap with some of those of both plantations and conservation forests (Table 5.6).

Table 5.6 Climate change impacts on the socio-economic values of ecosystem services in native production forests

Service	Key climate change impacts	Change in value
Timber	Reduced climatic suitability of growing conditions in some regions. Reduced productivity in marginal areas or those at limits of environmental tolerance. Winding down of production. Increased (or decreased) disease vulnerability. Increased growth.	Accelerated economic adjustments already occurring in timber regions. Loss of employment. Increased management costs. Some employment gains but probably marginal and long term.
Bio-energy	Increased demand for biomass (Sedjo and Sohngen, 2009).	Some value added to by-products and increase in marginal profitability.
Food	Change in phenology. Increased density.	Reduced capacity for beekeeping or grazing.
Carbon sequestration	Increased value where growth rates increase and decreased where growth rates decrease. Reduction in area due to threatening processes.	Changed annual value of sequestration. Carbon release and loss of carbon stock in mature forests.
Water table	Tree mortality (disease pests).	Increase risk of soil salinity.
Micro-climate	Tree mortality (disease pests).	Increase in wind erosion and wind irritation to humans. Reduced livestock welfare and production due to wind chill or heat exposure.
Water quality	Change in hydrology.	Reduced or increased water flows to catchment.
Soil	Tree mortality (disease pests).	Increased risk of soil salinity.

Service	Key climate change impacts	Change in value
Recreation	Change in composition/quality of forests due to increased fire, disease and pests. Damage to infrastructure (flood or fire) Population decline in vulnerable communities. Increased management needs (weeds, pest, disease, fire).	Decreased attractiveness to visitors. Loss of income. Particularly high impact for Indigenous owners. Increased cost in maintaining forests (e.g. weed control) and infrastructure (e.g. repair flood damage). Reduced secondary expenditure benefits to local businesses. Increased insurance costs. Reduced employment. Increased management costs (increased employment).
Spiritual sustenance	Changed character through species loss, composition change (both plants and animals), change of hydrological flows, increased fire damage.	Reduced spiritual (e.g. Indigenous cultural/religious practices) and amenity value.
Existence value	Change in habitat, increased fire risk, increased vulnerability to invasive species and disease.	Perceptions of loss of natural capital or national assets.
Habitat	Change in habitat, increased fire risk, increased vulnerability to invasive species and disease. Decreased connectivity of habitats. Increased density due to regrowth or increased productivity. Increased management needs (weeds, pest, disease, fire).	Loss of refugia for bio-control agents beneficial to agriculture. Increased habitat value in some areas. Increased management costs (increased employment).

5.2.6 Conclusions

It is clear that for all forest types, the social and economic impacts of climate change will result in both positive and negative outcomes. As with understanding the physiological and ecosystem impacts, there are many interacting factors and pathways that could occur producing numerous future scenarios and few generalisations. It does demonstrate that in addition to the primary impacts (e.g. loss or increase of production, loss of biodiversity and associated values, loss or changes in ecosystem services) there are several flow-on effects including: growth in some forest-based communities and accelerated decline in others because of changes in output and therefore regional income and the cumulative effect of relocation and re-establishment decisions; possible changes in tourism preferences due to changes in forest appearance, composition and habitat quality; and increased competition between farmers, rural “life-stylers” and forest managers for land in higher rainfall areas with associated market price changes of land.

6 Impacts of climate change – Knowledge gaps

In this section of the report we consider gaps in knowledge identified through our review of the literature on impacts. Given the variability of responses among organisms and among facets of society, the knowledge that we have is limited. Consequently we have identified some broad areas of knowledge needs.

Knowledge gaps: Key points

Key gaps in knowledge about the *biophysical impacts* of climate change are:

- Information of impacts and processes at a scale relevant to assessing vulnerability. This includes experiments in the field (versus pot studies) and scaling of impacts from single species to whole ecosystems and landscapes.
- Critical information on the interaction of impact factors (e.g. the competing affect of increased CO_2 and decreased water availability) and cascading of effects (e.g. increased growth and fire potential).

Key gaps in knowledge about the *socio-economic impacts* of climate change are:

- Understanding community opinions and connections to issues associated with Australia's forests. This includes the role of forests in Indigenous communities, the community response to extreme events and climate change in general.
- Very limited work has looked at the sufficiency of existing policy instruments nor the cost and benefits of adaptation actions through existing institutions and policy frameworks or new models for responding to the challenges of climate change.

There are two key difficulties in understanding climate change impacts. First, the scale at which it will occur. Climate change, unlike any other environmental problem has the potential to impact on every aspect of our society and natural systems. Second, such broad impacts are associated with considerable uncertainty – largely as a result of the complex interaction of factors and scales of response. Present levels of uncertainty are hard to reduce. Modelling of future climates, like most risk-assessment exercises, must make a number of assumptions that may or may not occur (e.g. reduction in greenhouse gas emissions). Biotic and societal responses to future climate scenarios require an understanding of the response (i.e. physiological as well as interactions). The sheer scale of the problem simply reduces precision and relies on the progress of technological and scientific understanding. In this section of the report we identify those gaps in information identified through the course of the project literature review.

6.1 Biophysical

The following knowledge gaps were identified from the literature review of biophysical impacts of climate change on Australia's forests:

- With much of our information coming from pot studies of plants, there is too little information about plant responses to growth in the field (temperature and growth). There is a great deal of uncertainty about the application of up-scaled information from pot to field.

- Australia lacks good models and model projections for plant physiological responses to climate change, with the exception of the work done by Battaglia et al., (2009), which is limited to plantation forests of southern Australia. In addition, there is a lack of suitable data sets for model testing. For example, next to no intensive measurements of net primary productivity, limited forest inventory system, diminishing number of permanent sample plots, a total of two long-term eddy covariance datasets and a very limited paleo record.

- The impact of climate change on soil moisture is currently uncertain.

- There is a limited understanding of the counterbalancing effect of increased carbon and water availability. Models need to incorporate responses to CO_2 in addition to evaporative demand and rainfall. It is also important to understand the implications of tree water use for catchment and landscape scale hydrological processes.

- We do not know enough about plant thresholds for drought mortality. Improved understanding of the physiological mechanisms causing drought mortality and better understand the impact of drought on plant function and particularly on the physiological mechanisms that underlie plant responses during, and in recovery, from water stress is essential.

- There is almost no information on phenological or lifecycle event responses to changing climate. We need to better understand the drivers of phenology in Australia and the impact of changing climates on pollinator mutualisms.

- The drivers of plant distribution, including the influence of non-climatic factors (i.e. species-species interactions) are not well understood. A great deal of reliance of existing climate envelopes has been used for modelling future distributions of species, but there is much evidence that this is a conservative estimate of distribution and that other factors have a part to play.

- Our understanding of ecosystem processes and species interactions and the consequences of biodiversity loss for ecosystem function is very minimal.

- Long-term monitoring that is essential in assessing and understanding the impacts of climate change on forests is not available.

- There is a mismatch between predictions of vulnerability coming from bioclimatic and ecophysiological models. Bioclimatic models, based on observed climate envelopes, found that many Australian species have narrow ranges with the ultimate conclusion that forest trees will be very vulnerable to climate change. On the other hand, ecophysiological models, based on mechanistic understanding of climate impacts on plant processes, have predicted widespread increases in forest production. The difference between these two approaches reflects the fact that we do not understand, at a very fundamental level, what limits species distributions.

- While there is excellent information about the biology of many weed species, there is limited knowledge of the weedy potential of sleeper species under climate change.

- Research is very fragmented, with few attempts to integrate across different strands of research. As a consequence, there are currently no reliable projections for climate impacts on native Australian forests and woodlands.

6.2 Socio-economic information gaps or research needs

- Improved understanding and engagement with the community is needed. This includes research to better understand community perceptions of climate change as part of any education campaign supporting future adaptation strategies. There is also potential to develop scenarios that can be used to show some of the potential effects of climate change on forests, preferably using visualisation techniques, following Sheppard (2005) and Ford et al.,(2009) that will assist in determining people's responses to the visual changes in forests, whereas now these changes are diffuse and difficult to describe.

- Research into the attitudes of people living in fire-prone areas as to their intentions under climate change will assist with planning in these areas.

- Improved understanding of the attitudes of prospective forest managers under a regime of priced sequestration or alternatively, incentives for sequestration is needed. This should particularly target potential small-scale growers.

- Further research into the design and optimal mix of regulation, incentives and creation of virtual commons (voluntary cooperative management of natural assets) (Ostrom et al., 1992) in managing dynamic landscapes is required.

- An increased understanding of the legislation and regulations under which plantation industries could operate to mitigate fire risk, ensure better pest management and ensure plantation operators do not transfer impacts of their operation onto the communities in which they operate.

- Information on the net primary production or biomass of potential plantation species in different parts of Australia under climate change. This would assist resource holders to estimate carbon rent value and make appropriate land use decision.

- Conducting a longitudinal study of socio-economic indicators to assess the reliability of using these to measure the change impacts on local forestry communities.

- Examining the dependency of Indigenous people on non-wood-forest-products (NWFP), identifying major NWFPs, analysing the impact of climate change on those species and exploring the possible adaptive options.

Part C: Adaptation opportunities and constraints

Overview

The vulnerability of Australia's forests to climate change will depend on first their exposure and sensitivity (reviewed in Part B), and second their adaptive capacity. In this section of the report we consider not only the adaptive capacity of forests but also opportunities and constraints of adaptation.

Adaptation opportunities and constraints: Key points

While natural systems such as forests have some capacity to adapt in an ecological sense, the focus in this report is on the adaptation measures available to humans.

- In a socio-economic context *adaptation* refers to responses to actual or expected climatic changes in physical, economic or social conditions, by humans, individually, in a group or as an organised authority which moderates harm or exploits beneficial opportunities.
- The current international and national approach to managing natural assets is that of sustainable development. Australia's key policy on forests, the National Forest Policy Statement is built on this principle. The Regional Forest Agreements are the key instruments through which this policy is intended to be implemented.
- Australia's natural systems have a limited innate capacity to adapt to climate change, beyond which adaptation will be constrained by: rates of evolutionary change versus rates of climate change; contractions of suitable habitat; limited capacity to migrate (e.g. fragmentation of suitable habitat prevents dispersal); and extreme events diminish capacity to recover.
- In human systems there is considerable capacity to adapt. The adaptive capacity of Australia's forest management is strengthened by several well developed systems such as: a well developed economy; extensive scientific knowledge; practice of sustainable forest management and technical capabilities; disaster mitigation strategies and plans; and well developed biosecurity procedures. In addition there are existing relevant policies in place.
- Identified limits and barriers to adaptation in Australia's forests include: competition for land, physical limits of organisms, knowledge gaps, cost of actions, existing markets, and social perceptions.
- Adaptation actions can be grouped into: land management options, specific silviculture practices, social and community skills, and planning options. There are a number of adaptation tools currently in use by forest managers and include software for modelling and decision support, specific silviculture practices, planning, policy, and investment.
- Australia's adaptive capacity can be further strengthening by: adopting Indigenous or local level knowledge, improved knowledge transfer, flexibility in decision making, improved understanding of other disturbance factors, and monitoring change.
- In order to prioritise responses to climate change impacts, land managers and policy makers will need to assess the costs and benefits of adaptation actions. We identified three broad categories of socio-economic values that need to be assessed: estimating traditional industry values (timber and tourism), estimating new industry values (carbon sequestration), or estimating non-market values.
- In adapting to the impacts of climate change there are a number of potential social and economic adjustments of perception and practice that might need to be made for managers and communities associated with forests. Many of these were identified in stakeholder interviews and indicate that some adjustment of perception is already happening.

7 An adaptive future

Some of the effects of climate change are already happening while some are inevitable and will become more severe if rates of greenhouse gas emissions continue to increase. Even if emissions, in the most optimistic scenario, were to remain at the 2000 levels, the IPCC estimates we will still experience some unavoidable warming (IPCC, 2007b). Given progress to date on mitigation strategies, there are likely to be some impacts for which adaptation is the only available response if negative effects are to be avoided or minimised.

Land management actions in response to pending climate change impacts might take one of four forms:

1. Same land use, change nothing, continue doing what was always done.

2. Same land use with changed practices (e.g. species selection, increased weed control efforts) to minimise negative climate impacts.

3. New land use to reduce or avoid adverse climate impacts.

4. Land “abandonment” to avoid adverse climate impacts. Abandonment in this case means ceasing active management of land.

Of these responses, the second and third require planning and action, and are considered adaptation responses. The first is also associated with planning, however it may not be an appropriate adaptation response if monitoring indicates adverse changes are the outcome. The fourth response may or may not constitute an adaptation and this will depend on the level at which the response is considered. For example, abandonment of some properties in favour of focusing on others may be successful for a community as a whole.

There is evidence of limited adaptation to changes in climate already taking place in many sectors (Parry, 2007) and the management of forests and forested land (e.g. rangelands) has a long record of adapting to climate variability through a range of practices (for a full review see Wilson and Turton, 2010). Indeed, in practice, adaptations tend to be on-going processes which reflect a number of factors rather than a discrete action to specifically address climate change (e.g. sustainable development) (Parry, 2007).

Climate change, as we have outlined in the first half of this report, however, presents new and novel challenges or the escalation and interaction of pressures, some of which will be beyond the experience of the forest and land management sector.

7.1 What do we mean by adaptation?

There are a number of formal definitions of adaptation that have been published, but one of the most commonly cited comes from the IPCC and it is an appropriate definition for this assessment. Adaptation is defined as:

> *Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects.* (IPCC, 2007a)

We note that adaptation can take a number of forms (defined in Box 12) – including anticipatory and reactive actions of society and the reactive adaptation responses of biological organisms or processes.

Adaptation can occur in physical, ecological or human systems (Parry, 2007). Parry et al., (2007) identify adaptation actions as involving:

- changes in social and environmental processes,
- perceptions of climate risk, and
- practices and functions to reduce potential damages or take advantage of new opportunities.

Types of adaptive responses by society may include:

- structural or infrastructural changes,
- regulation,
- the provision of incentives and disincentives to induce desired responses, and
- education and persuasion.

Adaptation is an ongoing process that requires monitoring, reassessment of impacts and procedures against objectives and a response (that may include no change required) (Figure 7.1). All of these steps feed into the adaptation process.

In this section of the report we refer to adaptation in a socio-economic context. We consider current adaptation practices, adaptive capacity and the opportunities and limits of adaptation within forest management as a response to climate change using both a review of current literature and interviews with stakeholders.

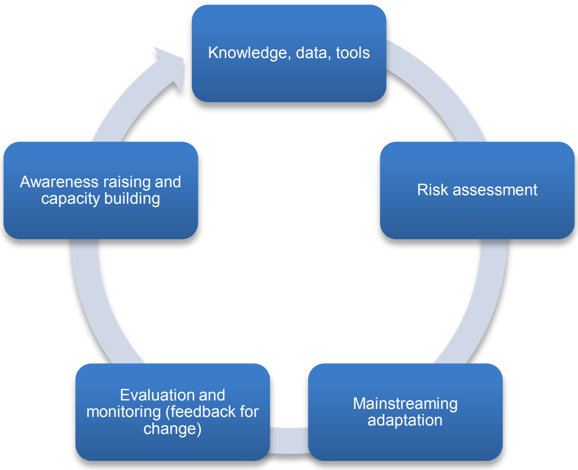


Figure 7.1 The cycle of the adaptation process. Warrick (2000, 2006) cited in Parry (2007).

Box 12 Definitions and types of adaptation

In a natural system, *adaptation* refers to biophysical and evolutionary adjustments of an organism or ecosystem to climate change that moderates harm or exploits beneficial opportunities.

Adaptation in a socio-economic context refers to iinitiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. (IPCC, 2007a).

Anticipatory adaptation is adaptation that takes place before the impacts of climate change are observed.

Autonomous adaptation is adaptation that does not constitute a conscious response to the impacts of climate change, but is triggered by ecological changes in natural systems and by market or welfare changes in human systems (Easterling et al., 2007). These responses are generally carried out by individuals, family groups and businesses in response to changed circumstances.

Planned adaptations involves coordinated responses and are the result of deliberate policy decisions, based on awareness that conditions have changed or are about to change and that action is required to maintain or achieve a desired state (Easterling et al., 2007). Responses may be long-range responses, contingent or tactical (Smit and Pilifosova, 2001) reflecting the time-frame over which the response is intended.

7.2 Current approaches to forest management

7.2.1 Background: international and national policy drivers

Forest management, through private actions and public policy, can influence the functioning of forests and the behaviour of humans toward forests. It is worth noting that historical approaches to land and forest management in Australia, have played a significant role in current land condition and legislative structures and will play a significant role in planning for climate change adaptation. Traditionally, management of forests and forested lands has been the responsibility of their owners- whether private sector or public sector owners – enabling a relatively unrestricted determination of the strategies and policies according to which these forest resources should be managed. Over the last fifty or sixty years, however, the way forest resources are managed has been increasingly constrained by government policy, legislation, or both.

European settlement in Australia was accompanied by a need and a desire to populate the land through traditional agriculture. Extensive land clearing and granting of private rights over land was part of empire and then nation building. It was not until late in the twentieth century that attempts were made – particularly through the involvement of the legal system – to restrain and regulate the use of land and the use of forest resources. Society, both on a national and international level, is re-evaluating the value it places on ecosystem services (i.e. carbon, water, biodiversity) and this is reflected in practice, policy and legislation. On public land, for example, this has seen the rise of national parks and the evolution of a policy and legal framework to accommodate it, while some private landholders are paid habitat managers.

Although there is no international convention that mandates how forests are managed, Australia's international responsibilities are critical in indicating how the forests located within Australia should be managed and the international community has increasingly recognised principles by which forests should be managed, through principles of international law, principles of sustainable development and international conventions. While principles guide and inform, there is a duty for signatory countries to comply with obligations – even obligations of a fairly general kind – founded in international conventions and treaties. In the absence of a specific international convention relating to forest resources any obligations imposed upon Australia are derived indirectly from those dealing with, for example, wetlands, world cultural and natural heritage, desertification, and climate change. It is however the evolution of the principle of sustainable development that has been embraced by the international community and that underlies the way natural resources, including forest resources, are managed.

Sustainable forest management has been defined as:

> *the stewardship and use of forest and forests land in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national and global levels, and that does not cause damage to other ecosystems.*

This comprises the fundamental concept of stewardship in a context of intergenerational equity, environmental conservation and protection, and the multiple functional characteristics of forest resources.

In 1992, the international community adopted a set of principles for the management of forest resources in Agenda 21 (Johnson, 1993) developed by the United Nations Conference on Environment and Development. Australia followed suit, when the Council of Australian Governments promulgated the National Strategy for Ecologically Sustainable Development (Australia Ecologically Sustainable Development Steering Committee, 1992) and the National Forest Policy Statement (Commonwealth of Australia, 1992).

The National Strategy provides the following challenge for managing forest resources:

> *To ensure Australia continues to refine and improve mechanisms for the ecologically sustainable management and use of its forests, by bringing together the commercial and non-commercial values of forests in such a way as to improve the material and non-material welfare of all Australians, and to ensure that all forest values can be utilised on a sustainable basis.*

This involves, as the National Strategy itself recognises, a balance between the conservation values and the productive or commercial values of forest resources. The National Strategy sets out three fundamental objectives with respect to Australia's forests in which the overriding objective is clearly sustainability and the three elements of ecologically sustainable development are incorporated: namely the economic, the social and the ecological values associated with forest resources.

There is a degree of overlap between the principles of the National Strategy and the National Forest Policy Statement (NFPS) and an overall consistency between these principles and those acknowledged by the international community. The NFPS sets out its vision together with goals for its implementation and represents an agreement between the Commonwealth and the States/Territories. The essential elements are these:

- the retention of forests and their associated biological diversity,
- the expansion of commercial plantations,
- managing forests for all their values and uses,
- conserving forest values,
- using forests in an ecologically sustainable manner, and
- managing private native forests in an ecologically sustainable manner.

Since these agreements on sustainable development, other international agreements have been made that deal more specifically with climate change and are relative to forest management. For example, the Convention on Climate Change 1992 and the Kyoto Protocol 1997 may be particularly relevant in indicating how Australia's forest resources should be managed. It is apparent from global developments that forests have a key part in both mitigation and adaptation.

A key element of the National Forest Policy Statement (NFPS) is the development of Regional Forest Agreements (RFAs). The RFAs aim to balance conservation of Australia's forests with economic production and recreation. The plans are 20-year agreements and there are ten agreements in place in NSW, Victoria, Tasmania and Western Australia. One has not been signed for Queensland but the Queensland Government is reducing native forest logging and encouraging the establishment of plantations. The Commonwealth Government takes a national coordinating role, with the state and territories retaining constitutional responsibility for forest management.

In 2002 the Regional Forest Agreement (Commonwealth) Act was established to support the RFA process. The act provides the following main objects:

- To give effect to certain obligations of the Commonwealth under Regional Forest Agreements.
- To give effect to certain aspects of the Forest and Wood Products Action Agenda and the National Forest Policy Statement.
- To provide for the existence of the Forest and Wood Products Council.

Neither the NFPS or RFA policies consider adaptation to climate change as a separate issue but both have embedded in them strategies to address climate change impacts. Several other national policy documents that concern specific aspects of Australia's forests include the *National Agriculture and Climate Change Action Plan* (2006), the *National Biodiversity and Climate Change Action Plan 2004-2007*, *Plantations for Australia: 2020 Vision (1997)*, and the *National Indigenous Forest Strategy (2005)*. The *National Indigenous Forest Strategy* (NIFS) was developed to encourage Indigenous participation in the forest industry. The strategy aims to support business partnerships between the forestry industry and Indigenous communities to provide long-term benefits to both. Other relevant policies are listed in Appendix 6.

There is currently little state level policy designed specifically for the adaptation of forestry to climate change. However, many policies related to water management, environmental sustainability and climate change are in place across the different States and Territories. These address climate variability and forests and are relevant to climate change adaptation.

7.2.2 Existing legislation

Statements of policy are directed at the conservation and ecologically sustainable development of forest resources. They do not by themselves create any rights or duties within the legal system that must be formulated in legislation. But the legal arrangements are for the most part fragmented, sectoral and largely without reference to climate change, its causes and its impacts. The reasons are perhaps the constitutional arrangements in Australia, its common law background and the tendency for the legislature to respond to specific issues rather than to deal with them comprehensively. We now review Australia's existing legal framework relevant to its forests.

Australian law

The Commonwealth government does not have any explicit powers to create legislation with respect to natural resources and the environment under the Constitution. Any involvement of the Commonwealth in the management of these resources is indirect through the exercise of other powers such as: providing financial assistant to the States, regulating interstate and overseas trade, regulating the trading activities of corporations, or implementing its international obligations in exercise of the external affairs power (e.g. international convention obligations).

Depending on the circumstances, the Commonwealth may be involved in how forest resources are managed in relation to matters of national environmental significance, for example, under the Environment Protection and Biodiversity Conservation Act 1999 (Commonwealth) and in relation to the natural resources of the Murray Darling Basin in accordance with the Water Act 2007 (Commonwealth). In the case of the Environment Protection and Biodiversity Conservation Act 1999 (Commonwealth) climate change is specifically listed as a key threatening process.

It is also open to the Commonwealth and the States to come to an agreement on how forest resources are managed either through Commonwealth funding or through the arrangements recognised by the Regional Forest Agreements Act 2002 (Commonwealth). Commonwealth legislation relevant to forests tends to be cross-sectoral (rather than specifically addressed at forests) (Table 7.1).
Natural resources and the environment are for the most part managed operationally in accordance with the laws of the States and Territories. Although largely superseded by a detailed set of statutory arrangements, the common law remains at the foundation of these statutory arrangements. In addition, in 1992 the High Court of Australia recognised the existence of common law native title [Mabo v Queensland (No 2) 175 CLR 1] Thus the common law, including native title, sits side by side with the statutory arrangements for managing land, forests, water and biodiversity.

The natural resources of the States have been managed for many years under the relevant legislation in accordance with a number of functions. The relevant functions are:

- Allocation – Granting an interest in land or a right of access to forest resources or to other natural resources.

- Planning – Stating the desired outcomes to be achieved by granting access to natural resources or by using natural resources either by the private or public sector.

- Protection – Regulating activities or proposed activities that impact upon or are likely to impact upon the environment.

- Conservation – Managing components of the natural environment (e.g. protected areas) on an ongoing basis to ensure that their intrinsic values are maintained for the future.

- Use and development – Permitting or requiring forest resources to be used and developed in particular ways and for particular purposes.

- Commodification – Recognising or creating interests in forest resources capable of being traded, for example sequestered carbon.

The legislation supporting these functions and regulating their performance applies either across all natural resources sectors (cross sectoral legislation) or to one sector in particular (sectoral legislation). Cross-sectoral legislation applies to forests and forest resources to the extent that they are in fact a resource or an element of that which the legislation has general application. For example, conservation legislation provides for the conservation of forest resources to the extent that these forest resources are in fact part of the natural environment in question. Cross-sectoral legislation applicable to Australia's forests and their functions are listed in Table 7.1.
Forest resources in Australia are thus managed in accordance with both the sectoral legislation that deals directly with forest resources (Table 7.2) and the cross-sectoral legislation that in appropriate circumstances impacts upon how forest resources are managed.

Cross-sectoral statutory arrangements for managing forests

The productive values and functions of forests were the focus of statutory arrangements during most of the twentieth century but the recognition of other values – such as the conservation of soil, the prevention of degradation of land, and the protection of water catchments – has emerged through the range of cross-sectoral statutory arrangements directed at these new values and elements of ecologically sustainable use and development of forest resources (see review of state legislative arrangements in Table 7.1). The range of cross-sectoral arrangements can be classified under four functions of law, namely:

- Allocation – All states govern the grant of interests in land (tenure). Generally the grant is preceded by an assessment of the characteristics and an evaluation of land use which could include forestry or conservation.

- Planning – Once allocation is made the land holder may determine a use that constitutes a development for which some form of planning permission is required. Likewise a change of landuse may require a development approval and this will depend on if the planning regimes focus on land or natural resources in general.

- Protection – Statutory arrangements for the protection of the environment have very focused outcomes that are to protect the environment from harm.

- Conservation – Conservation of the environment and specific components, comprise a set of arrangements for recognising the values of nature and for managing them on a continual basis.

Table 7.1 List of the various cross-sectoral statutes and their function.

Jurisdiction	Function
Commonwealth of Australia	
Natural Heritage Trust of Australia Act 1997	Conservation
Environment Protection and Biodiversity Conservation Act 1999	Protection & Conservation
Australian Capital Territory	
Nature Conservation Act 1980	Conservation
Land (Planning and Environment) Act 1991	Planning
Environment Protection Act 1997	Protection
Heritage Act 2004	Conservation
Planning and Development Act 2007	Planning
New South Wales	
Soil Conservation Act 1938	Protection
National Parks and Wildlife Act 1974	Conservation
Heritage Act 1977	Conservation
Environmental Planning and Assessment Act 1979	Planning
Wilderness Act 1987	Conservation
Crown Lands Act 1989	Allocation
Threatened Species Conservation Act 1995	Conservation
Native Vegetation Conservation Act 1997	Protection
Protection of the Environment Operations Act 1997	Protection
Native Vegetation Act 2003	Protection
Northern Territory	
Territory Parks and Wildlife Conservation Act 1976	Conservation
Heritage Conservation Act 1991	Conservation
Pastoral Land Act 1992	Allocation
Waste Management and Pollution Control Act 1998	Protection
Planning Act 1999	Planning
Queensland	
Nature Conservation Act 1992	Conservation
Land Act 1994	Allocation
Environmental Protection Act 1994	Protection
Sustainable Planning Act 2009	Planning
Vegetation Management Act 1999	Protection
South Australia	
Crown Lands Act 1929	Allocation
National Parks and Wildlife Act 1972	Conservation
Pastoral Land Management and Conservation Act 1989	Conservation
Native Vegetation Act 1991	Conservation
Environment Protection Act 1993	Protection
Development Act 1993	Planning
Natural Resources Management Act 2004	Protection
Tasmania	
Crown Lands Act 1976	Allocation
Land Use Planning and Approvals Act 1993	Planning
Threatened Species Protection Act 1995	Conservation
Environmental Management and Pollution Control Act 1994	Protection
National Parks and Reserves Management Act 2002	Conservation
Nature Conservation Act 2002	Conservation
Victoria	
Land Act 1958	Allocation
Environment Protection Act 1970	Protection
National Parks Act 1975	Conservation
Wildlife Act 1975	Conservation
Planning and Environment Act 1987	Planning
Flora and Fauna Guarantee Act 1988	Conservation
Catchment and Land Protection Act 1994	Conservation
Heritage Act 1995	Conservation
Western Australia	
Wildlife Conservation Act 1950	Conservation
Environmental Protection Act 1986	Protection
Land Administration Act 1997	Allocation
Planning and Development Act 2005	Planning

Statutory regimes for forest resources management: state and territory responses

Forest-specific sectoral legislation also exists (see listing in Table 7.2). Sectoral legislation primarily has the following two functions:

- Use and development – Permitting or requiring forest resources to be used and developed in particular ways and for particular purposes.
- Commodification – Recognising or creating interests in forest resources capable of being traded.

State/territory statutory arrangements have increasingly recognised not only the commercial value of forests and forest products but also the importance of what may be described as the bioassets of forests or, in more traditional language, the ecological or environmental services that forests and their ecosystems provide. It also recognises that these may become tradeable assets e.g. carbon, biodiversity, salinity control and water. In other words, the commodification of forest resources has been extended to include not just timber and timber products but also the commodification of bioassets that are a natural feature of forests.

Table 7.2 Specific sectoral statutory arrangements for managing forests.

Jurisdiction	Statute
Commonwealth of Australia	Regional Forest Agreements Act 2002
New South Wales	Forestry Act 1916
	Forestry and National Park Estate Act 1998
	Plantations and Reafforestation Act 1999
Queensland	Forestry Act 1959
South Australia	Forestry Act 1950
	Forest Property Act 2000
Tasmania	Forestry Act 1920
	Forest Practices Act 1985
	Private Forests Act 1994
	Tasmanian Regional Forest Agreement Act 1997
Victoria	Forests Act 1958
	Conservation, Forests and Lands Act 1987
	Forestry Rights Act 1996
	Sustainable Forests (Timber) Act 2004
Western Australia	Conservation and Land Management Act 1984
	Forest Products Act 2000

7.2.3 Conclusions

Current management of Australia's forested land is determined by historical drivers, current international obligations and trends and a variety of national- and state-based legislation and policy. While recent trends have moved toward stronger values of sustainability, there are as yet, few policies or legislative instruments designed specifically to support adaptation of forest management for the threat of climate change. Within existing policies there are some opportunities and solid foundations on which the capacity to meet these objects can be built, but the process of developing policy and implementing legislative change is lengthy.

7.3 Adaptive capacity

The uptake of adaptation options will depend on the adaptive capacity of Australia's forest management systems. Adaptive capacity is understood as "the ability or potential of a system to respond successfully to climate variability and change, and include adjustments in both behaviour and in resources and technologies" (Adger et al., 2007). Assessing adaptive capacity requires a broad understanding of land-use pressures and the organisational, political, economic and social context that impact on land use (Keskitalo et al., 2007).

7.3.1 Natural systems

Natural systems have an inherent, but limited capacity to adapt to climate change, beyond which adaptation will be constrained by:

- rates of evolutionary change versus rates of climate change;
- contractions of suitable habitat;
- limited capacity to migrate (e.g. fragmentation of suitable habitat prevents dispersal); and
- extreme events that diminish their capacity to recover.

The high level of biodiversity in primary forests can provide them with a greater capacity to adapt to disturbance (Thompson et al., 2009). There is considerable evidence that they have greater resilience to a number of threats such as disease and pests. There is also an expectation is that the higher the diversity, the greater the redundancy of individual species in ensuring ecosystem function.

7.3.2 Human systems

Most human systems have considerable adaptive capacity. Some aspects of adaptive capacity are generic, such as human capital, governance structures, education, income and health, while others are particular to specific climate change impacts for example institutions, technology and knowledge (Adger et al., 2007). Australia, in general, has several well-developed systems in place to manage climate change impacts. These include:

- a well developed economy,
- extensive scientific and technical capabilities,
- disaster mitigation strategies and plans, and
- well developed biosecurity procedures (Cole, 2005, Parry et al., 2007).

In the case of Australia's forests, there are several pre-existing social, scientific and policy instruments or practices that enhance the adaptive capacity of Australia's forests. These include the following two factors:

- The forest sector (including those productive forests that are used for pastoral and other activities and conservation forests) operates in a variable climate and as such adaptation is natural and ongoing. Forest management also has a long history of adaptation through experience and corporate knowledge as well as scientific research and implementation (Metcalfe et al., 2007). It is through adaptation to climate variability that the forest sector has in-built adaptive capacity to change.
- Existing policy/planning frameworks. The Regional Forest Agreement (RFA) process and development of strategies and Code of Practice for all states has considerable potential to strengthen adaptive capacity. A number of frameworks to protect biodiversity will also strengthen adaptive capacity. As discussed above, existing policies and plans exist that provide frameworks for building adaptation options.

Additional ways that adaptive capacity might be strengthened, but that are not yet formalised include:

- incorporation of traditional and local level knowledge into policy, planning and management;

- improved knowledge transfer through forums such as Private Forestry Development Committees, national extension and research programmes, scientific communication;
- improved capacity or flexibility of decision makers at all levels to make continual adjustments;
- increasing understanding of other disturbance factors such as weeds, pests, disease and fire; and
- monitoring and reporting change.

7.4 Limits and barriers to adaptation

There are a number of potential limits and barriers to adaptation for Australia's forest sector. Here we consider the limits and barriers identified in the literature and the survey of stakeholders undertaken at the outset of the project, using the same categories as Adger et al., (2007).

Low or diminished adaptive capacity

As already discussed, adaptive capacity plays an important role in determining the vulnerability of a sector or social group and can impact on the up-take of adaptation. With respect to the forest sector, factors that have been identified that might diminish adaptive capacity include:

- scepticism about the actuality or scale of climate change amongst the general population, political actors and resource-dependent communities;
- limited, slow or non-acceptance of adaptive measures at a local level;
- organisational, political, economic and social context that impact on the ability and rights to use land;
- the aging demographic of a community servicing the forest industry;
- market uncertainty and exposure to failed large-scale investment schemes (e.g. Managed Investment Schemes);
- land use competition;
- loss of expertise, under-investment in training;
- lack of local knowledge;
- economic costs (cost of adaptation measures, lack of cost-benefit analysis, insurance costs); and
- policy uncertainty.

Physical or ecological limits

In the IPCC fourth assessment contribution from Work Group II (Parry, 2007), it was identified that there may be a number of critical thresholds in ecological systems, beyond which some systems may not be able to adapt without radically altering their functional state and system integrity (Adger et al., 2007). Our review of the climate tolerances of individual plant species (see Section 3) confirmed that there are physical limitations of individual plant species. This will affect the survival of species at the extremes of their distribution in particular. While some acclimation will occur, there appears to be a limit to this and to survive, species will need to be able to shift their distribution. This of course relies on the availability of suitable areas for establishment. Fragmentation of natural areas is a significant physical barrier.

Catastrophic events, such as fire and storms, pose particularly severe challenges to the physical limitations of forest trees, with damage able to radically alter forest composition and function. Likewise, alteration of forest function and composition through changes in phenology and flow-on effects to plant reproduction present a significant potential barrier to adaption within conservation forests in particular – if the expectation of adaptation is that these forests should maintain the same composition and function.

Existing stressors (e.g. weeds, pests, feral animals, disease, fragmentation and habitat loss) are likely to be compounded under climate change (Steffen et al., 2009) and so reduce the adaptive capacity of some forest systems. This is particularly relevant to conservation forests that will demand investment in management to reduce the impact of these stressors, but also have the potential to increase management costs of planted forests.

Within the production forest sector, the long rotation time for some plantation timbers (e.g. 30 - 40 years for *Eucalyptus* and *Corymbias*) is a major biophysical constraint. Opportunities for replacing growing stock with new genetic stock or a new species are limited in time.

With changed suitability of land for a number of sectors, increased urban expansion, loss of land through sea level rise and the potential need to allow migration of species, competition for land or the sheer unavailability of suitable land presents a significant barrier to adaptation measures for forests under climate change.

Technological barriers

Technology offers significant opportunities to support adaptation measures. In particular, the forest sector relies on remote sensing and modelling technologies. While these are powerful tools, they are limited by uncertainties and cost. These technologies are not developed to the extent that remote sensing can reliably monitor small but critical changes and ground-truthing or on-ground monitoring requires a significant labour input.

Financial barriers

Adoption of some adaptation measures requires significant financial investment. In the forest sector this might include development of migration corridors for biodiversity, for plantations this might include establishment of new locations for timber production. Both of these examples are costly. For example, the Territory Eco-link project aims to create a 2000 km corridor that will link conservation areas. As of October 2009, $2.4 M had been committed to this project (Minister Karl Hampton, http://newsroom.nt.gov.au/index.cfm?fuseaction=viewRelease&id=6166&d=5). Shifting plantation production locations would require significant investment in new infrastructure.

Informational or cognitive barriers

Lack of knowledge or the high level of uncertainty associated with predictive data has been identified throughout this assessment project and is a significant barrier to adaptation. Some knowledge gaps can be addressed with investment in research effort. This would include improved predictive modelling of species distribution shifts, climate modelling and an improved understanding of plant and animal physiology and the influence of species interactions on species success and distribution. The limitation to generating much of this knowledge is more likely to be financial and development or research time, than our capacity to gain knowledge. Nonetheless, climate variability is inherent in Australia's climate system and the uncertainties associated with this are unlikely to be resolved. Acceptance of this uncertainty and a focus on measuring risk is likely to be more constructive in the short-term.

Knowledge transfer and perception of risk will have significant influence on judgement and decision-making. Human cognition is an important barrier to adaptation responses. A case study of community perception (Box 13) demonstrated some of the interpretations of climate change risk and the forest sector in Australia and demonstrates the damaging perception of scientific debate about the certainty of anthropogenic climate change. It clearly illustrates the limited effective transfer of information from scientists to the community-at-large.

We note that the speed of adoption of new techniques or technologies is influenced by education, training and experience. For example, the uptake values for agriculture are between 3 and 100 years (see review in Wood et al., 2010). At present there is a high level of experience and training amongst timber production and plantation forest managers, but this is at risk of decline with diminishing formal forestry training.

Social and cultural barriers

Some consideration of the social and cultural barriers associated with adaptation for Australia's forests was given in the discussion of impacts in Section 5. In particular we note the following potential barriers:

- *Existing or established markets or industry base.* Changes to species selection or forest-derived products (e.g. carbon sequestration, biofuels) as a result of climate change will require a market to support the change.
- *Infrastructure.* Again, new locations, industries or by-products, such as forest biomass for fuels, will require the presence or establishment of infrastructure to support. This may include roads or transport, processing plants and tourist facilities.
- *Planning and policy*. While current planning and policy is moving towards climate adaptation, significant investments of time and knowledge are still required and while it should become a diminishing limitation, will be ongoing as new challenges arise.
- *Community values and perception*. Different groups and people will have different views of climate change and forests. The implication for adaptation is likely to be different preferences for adaptation measures (Adger et al., 2007) and result in variable autonomous adaptation.

7.5 Adaptation actions

The type and prioritisation of adaptation responses to climate change impacts will be largely driven by the management goals for individual forests. At the outset of this report we defined four core forest management types – plantations, production native forests, conservation forests and environmental plantings. In reality, each of these forest types can be managed for multiple outcomes and this was reinforced in interviews with stakeholders. Here we summarise the various management outcomes under two headings – conservation and production:

1. Conservation:
    - Biodiversity
    - Amenity
    - Recreation
    - Spiritual nourishment
2. Production:
    - Industry development and support
    - Support for local community and industries
    - Consumable products
    - Recreation (tourism)
    - Pressure of new or changing markets in

non-timber values (carbon, biodiversity, water)

- Profit
- Amenity (in some cases)

Box 13 Case study of community perceptions of forests and climate change.
Source: Cockfield et al., (2010).

Community members of the Eden/Gippsland region of Victoria and from Tasmania were interviewed to determine their perceptions of climate change and forests in Australia. Participants showed a strong understanding of climate change and believed it was happening locally and globally. However not all respondents believed in the anthropogenic driver of change. It was clear from responses, that while changes in the weather were discussed by the community “climate change” was not in the vernacular. Respondents were most concerned about changes in rainfall patterns, extreme weather, fire risks, and higher sea levels, but were less concerned about increasing temperatures. They were also still concerned about the social, economic and visual impacts of other changes, notably restrictions on native forest logging and the expansion of plantations, particularly those under Managed Investment Schemes (MIS). So while climate change adaptation might be top of the agenda for governments and their agencies, in the minds of some in forests-based communities, there are important and unresolved matters from previous decisions.

The interviews revealed that among the community there was a perception that the scientific community was divided on the reality of climate change. Most relied on the media as their source of information but were also distrustful of this source and expressed a desire for clear, concise credible information and believed that local information (e.g. local council) was the most reliable.

The respondents considered forests important as an employer and to the economy but raised some concerns about the negative community impacts of forestry operations. Concerns about plantation industries included the loss of biodiversity, increased fire risk, introduction or increased risk of pests or ferals, impacts on water quality and the costs of transport. In particular the community perceived a decline in population associated with the change from agriculture to forestry impacted on local services (e.g. medical). In particular, Managed Investment Schemes were seen as offering tax deductions rather than a viable timber production industry that have negative flow-on effects on the community.

Respondents expressed a willingness to adapt to changes in climate and identified a range of adaptations in their current agricultural practices and new opportunities for the future. Forestry was seen as a potential adaptation solution, but that there needed to be meaningful engagement between government, industry and community to develop future management plans for the industry.

During key stakeholder interviews, respondents were asked about their land management tools and strategies. It was apparent that many land managers already have a key set of tools or strategies that are directed at general environmental sustainability in a land management context, but that respondents saw would need to be modified to manage emerging climate change risks (i.e. keep doing what doing but tailor to emerging issues). The identified emerging issues can again be broadly sorted under the conservation and production headings as follows:

1. Production:

   - Species selection (local modelling)
   - Silviculture practices
   - New industries (bioenergy, carbon credits)

2. Conservation:

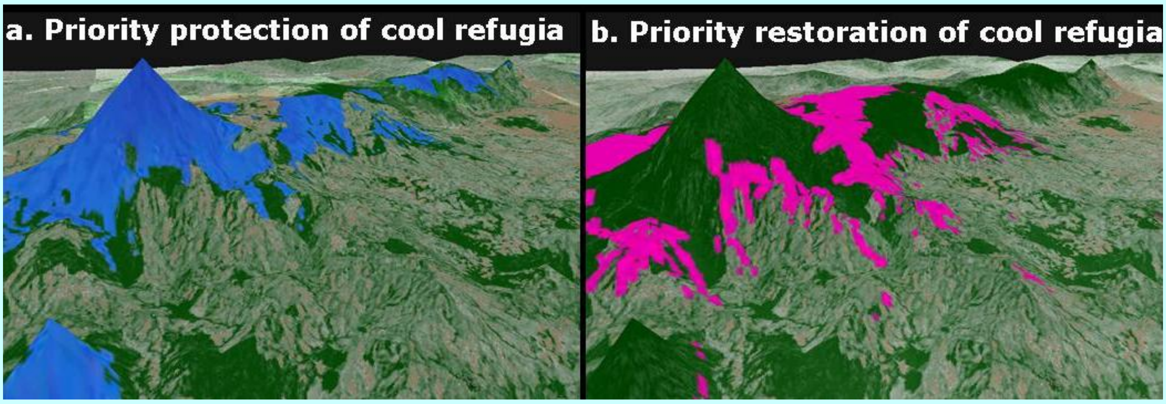
   - Manage additional pressures

Box 14 Adaptive management planning for biodiversity in the Wet Tropics. Source: Shoo et al., (2010).

Adaptation planning for biodiversity under climate change presents numerous challenges including predicting responses of species to environmental change across complex terrain. In the Wet Tropics of Queensland, cool montane habitats are important refugia and sites of high levels of endemism. But simply being at the top of a mountain is not enough to guarantee that an area will be a cool refugia, with other factors determining suitability. The existing network of protected areas may not be adequate to conserve species under future altered climates.

By combining knowledge of the distribution of species and models of the complex processes governing temperature regimes at a micro-scale, Shoo et al., (2010) identify areas of cool refugia that will maximise persistence of endemic species under climate change.

The modelling exercise demonstrated that a high number of endemic species already have core habitat within the coolest 25% of rainforest in the region. It also highlighted important areas of existing forest and degraded land not contained within the existing reserve system. This approach is an instructive example of how land protection and restoration can be prioritized to improve biodiversity outcomes under climate change.



Cool rainforest refugia within a modified landscape. Two major adaptation strategies for habitat management include the protection of existing areas of cool habitat (blue, a), and restoration of foliage cover within deforested areas that formerly supported cool habitat (pink, b). Evelyn-Atherton tablelands are shown in the foreground (Shoo et al., 2010).

The forest management sector has a well-established history of responding to natural climate variability. In analysing stakeholder responses to the project survey, the existence of current adaptation activities or the presence of “changing paradigms” within the forests sector in the face of climate change were sought. Identified changes included:

- linking sustainability of agricultural production with reforestation to better adapt to climate change;

- selecting native species for increased resilience to weather extremes associated with climate change;

- re-addressing fire management practices in native forests to improve water availability for target species;

- location of plantations in areas with higher rainfall to offset predictions for lower rainfall in the future;

- consideration of the likely redistribution of species and ecosystems under climate change and to plan revegetation programs to align with these likely changes; and

- identification of areas in the landscape likely to experience the most pressures from climate change and target for forest restoration.

Table 7.3 provides an illustrative list of the various types of the adaptation options for forest management under climate change that were identified in the literature or through stakeholder interviews. These options can be grouped into four categories:

- Land management options

- Specific silviculture practices

- Building social and community skills

- Planning or policy options

In addition, a number of tools have become available in recent years that can support these adaptation practices including the development of improved forecast modelling, climate modelling, remote sensing technology and decision support software. For example, a participatory planning process was adopted by the Northern Territory Cattlemen's Association to explore the complexity and extent of possible impacts on their industry in the rangelands. The process was facilitated by a system dynamics model, named the Pastoral Properties Future Simulator (PPFS) and demonstrated the benefits of applied systems dynamic modelling for participatory strategic planning in the face of uncertainty (Puig et al., 2011).

It is worth noting that while the focus of this assessment has been adaptation rather than mitigation, the latter is an adaptation option (i.e. by reducing emissions we reduce climate change impacts) and many potential future actions function as both mitigation and adaptation measures. Given that current measurements demonstrate climate change is tracking the worst-case future scenarios, mitigation will be an imperative action to avoid impacts that cannot be adapted to.

Table 7.3 Adaptation options and tools to respond to climate change

Climate change impact	Adaptation options (not mutually exclusive)				Tools (may not yet be available)
	Land management	Silviculture practices	Social and community skills, knowledge and land value	Planning	
General climate change	Protect soil from moisture loss Evaluate costs and benefits of forestry	Agroforestry practices (e.g. top prune against extreme wind events, deep rooted species; change intensity or cutting cycle of silviculture or adopt silvicultural practice to changed climatic condition)	Enhance community awareness of climate change impacts and variability Build regional cooperation Pooling limited resources	Increase public awareness of the value of forests and the need to enhance adaptive capacity Evaluate costs and benefit of forestry Promote agroforestry practices (diversifying production, improved resilience) Take climate change into account when establishing new plantations, including greater weighting to recent climate data Development of appropriate governance institutions Policies aimed at encouraging integration of adaptation into national forest policies and practices	Improved regional level climate change modelling

Climate change impact	Adaptation options (not mutually exclusive)				Tools (may not yet be available)
	Land management	Silviculture practices	Social and community skills, knowledge and land value	Planning	
Local environmental conditions no longer suitable for some species	Selection of land with appropriate growing conditions for production or protected areas Trial new species New cultivars or improved genetic stock	Suitable species/cultivar selection (e.g. drought resistant species) Facilitation of genetic adaptation Promotion of seed exchange and genetic improvement	Indigenous knowledge of natural history	Social change Bioclimatic studies to identify key species	Bioregional and regional ecosystem mapping Remote sensing Data on life history traits, genetic research, tree breeding programs Tree growth models and permanent sample plot records from existing plantations to plan alternative management strategies
Changed distributions of organisms	Selection/planting of vegetated corridors for flora and fauna movement	Translocation		Relocate to arable lands	Biosecurity measures (pests)
Increased risk of soil and nutrient loss (drought or flood)	Reduced impact logging to reduce soil disturbance Mulching	Plant deep rooted species		Pressure to revegetate riparian areas	Revegetation projects

Climate change impact	Adaptation options (not mutually exclusive)				Tools (may not yet be available)
	Land management	Silviculture practices	Social and community skills, knowledge and land value	Planning	
Increased risk of weeds	Reduced impact logging to reduce soil disturbance Changed (timing and frequency) fire, thinning regimes	Consider planting densities Mixed species planting to shade weeds	Engage government at all levels	Improved tools to asses risk Engage governments at levels to respond	Assess risk, address biosecurity measures, code of practice, implement and monitor compliance
Increased risk of pest outbreaks	Longer harvest cycles to avoid disturbance	To grow pest resistant species/strains	Engage government at all levels	Improved tools to asses risk New biological control agents, bioengineering?	
Increased risk of disease	Changed (timing and frequency) fire, thinning regimes to manage pests and fuel loads in fire tolerant species. Tree species selection (for production), breeding of disease resistant strains, move away from monoculture stands Biosecurity methods to restrict movement or create buffer zones	Species selection of disease resistant species	Engage government at all levels	Improved tools to asses risk	Botanical gardens and arboreta resource for future introductions, trials and re-establishment of forests

Climate change impact	Adaptation options (not mutually exclusive)				Tools (may not yet be available)
	Land management	Silviculture practices	Social and community skills, knowledge and land value	Planning	
Increased fire risk	Create buffer zones Reduce fuel loads on edges, keep fire sensitive species away from edges (e.g. Gamba grass)	Grow fire resistant species	Collaboration and learning from Indigenous fire management history (adaptive co-management)	Promote good practices for fire management (e.g. forest types in fire prone areas, proximity to residential areas, extent and type of fuel load) Fire management plans	Updating fire behaviour prediction systems for a changing fire regime
Reduced water availability	Reduced stocking densities at planting or through thinning Application of nutrients to maximise growth and water use	Planting densities, nutrient adjustment	Efficient irrigation at establishment stage, modelling tools, use of drones to assess water needs	Regulated or voluntary efficiency (e.g. water taxes, water restrictions)	Regulation of water restrictions
Extreme rainfall events	Planting tree species with high regulation capacity	Contouring, species selection (e.g. deep rooted species)	Climate modelling – regionally specific	Flood mitigation awareness	Water regulation, flood mitigation
Temperature changes extreme events, wind damage	Forest enrichment – restoration and rehabilitation	Wind barriers, species selection	Climate modelling – regionally specific		Policy support
Habitat loss and species loss	Reduced impact logging Combat stresses/threats (e.g. fragmentation, degradation) Buffers, corridors,	Restoration using seeding rather than planting and enlarge seed zones	Incorporate local forest-related knowledge in decision-making and management Translation of knowledge,	Sustainable management of forests (e.g. bioprospecting industries) Minimise fragmentation (corridor planting)	

Climate change impact	Adaptation options (not mutually exclusive)				Tools (may not yet be available)
	Land management	Silviculture practices	Social and community skills, knowledge and land value	Planning	
	connections and stepping-stone reserves Expand reserves, prioritise protection of likely climate refuges Monitor rare/vulnerable species		both local and scientific Implement Indigenous knowledge (e.g. fire management)	Conservation of primary forest Decision-making support for assisted recolonisations Development of threatened species abatement and recovery plans	

7.6 Assessment of adaptation costs and benefits

Identifying the costs and benefits of adaptation options is an important step in developing climate change adaptation policies. However, as identified in the fourth assessment of the IPCC, the literature on the costs and benefits of adaptation options is quite limited and fragmented.

Assessments of the costs and benefits can be undertaken at a global, national or sub-national/local level. National assessments seek to determine national financing needs of adaptation and facilitate the overall planning and prioritisation of adaptation. At the sub-national or local level, by contrast, assessments assist in the design and prioritisation of specific adaptation policies, options and measures and can more closely resemble traditional economic appraisals (UNFCCC, 2010).

Adaptation costs are usually expressed in monetary terms, while benefits of adaptation measures are usually measured in terms of avoided climate impacts that can be expressed in either or both: monetary and non-monetary terms (Adger et al., 2007). Prioritisation of responses to climate change will require estimating three broad categories of socio-economic values:

1. Traditional industry values (timber and tourism)
2. New industry values (carbon sequestration)
3. Non-market values

Estimating traditional industry values (timber and tourism) – These values are some of the easiest to estimate. The direct and indirect value of timber production and tourism has been routinely established. Economic values include:

- direct income,
- wages (direct and flow-on employment through demand for goods), and
- income through processing and value adding (e.g. furniture making).

Social values might include impacts of the forest industry on its workforce and the broader community including Indigenous people and these in turn might reveal indirect values for economic analysis.

Estimating new industry values (carbon sequestration) – The provision of a monetary value on carbon sequestration is likely to make this an important future “output” of forests in Australia. Tools to estimate the biomass of forests and the sequestration of carbon (e.g. (Richards and Evans, 2005)) form the basis of such estimates. An emissions trading scheme will “reveal” a market value and this will depend on both the market rules and the subsequent demand. Several methods of estimating a sequestration value are available (Cockfield et al., 2010).

Estimating non-market values – This is the area of cost estimation that tends to be most controversial. A number of methods have been developed to elicit a value. Accompanying these methods is a range of decision support frameworks:

- *Benefits transfer* (Bennett, 2000) uses the results of previous studies from one region or situation to another similar area.
- *Threshold value analysis* is used in situations where there is a trade-off between production and conservation benefits. Decisions are made based on whether the gain is thought to be greater than the loss. This estimate might be based on static or dynamic values.

- *Multi-criteria assessment* is a decision-making process based on values clarification, selection and weighting of attributes to be considered, the scoring of the attributes, generation of options, a review of options and a final decision.

In general these decision-making support systems are valuable techniques for allocating resources. In the case of multi-criteria assessments there is considerable potential for its use in participative decision-making. All these methods require considerable knowledge of the biophysical changes under consideration and are most valid when applied to particular locations. Values in this category include ecosystem services (e.g. shade for cattle, clean air and water, nutrients) and intrinsic values (e.g. beauty, existence value, spirituality, recreation).

7.7 Social and economic adjustments

Climate change impacts on forests are just some of many variables in a dynamic system. In relation to forests with marketable values, demand is changing all the time, depending on costs of production, social preferences for building materials or fuels, tourist preferences and so on. There may be indirect effects on demand from climate change, for example regulations that require more renewable energy, hotter weather that discourages/encourages tourism and higher preferences for fire resistant building materials, but the most direct effects are likely to be on the supply side, where there will be changes in growth rates, as discussed in Medlyn et al., (2010) and Cockfield et al., (2010). Changed conditions in other regions of the world may mean a net increase in timber supply with the result that prices in Australia are unlikely to increase. Successful adaptation will require a number of tools (not mutually exclusive) that will include the following functions:

1. Prediction – modelling (species distributions, impacts on human society)

2. Monitoring – remote sensing and ground based inventory

3. Decision support – software programs

4. Investment and market tools – design of market tools and incentives to cover carbon, biodiversity and water markets

5. Long-term adaptation planning tools – early warning systems, disaster risk management

6. Policy tools – planning, legal and institutional arrangements, land management, linkages

7. Information and communication

In adapting to the impacts of climate change there are a number of potential social and economic adjustments of perception and practice that might need to be made for managers and communities associated with both, those forests used for production and those for conservation as outlined below.

Management for production:

- Productivity
- Site conditions
- Stand structure
- Species distributions
- Changes in seasonal operations

Management for conservation:

- Aesthetic (changing appearance, composition, forest type)
- Carbon value
- Changes in habitat value
- Change in reserve value (old growth, heritage, aesthetics, biodiversity, and threatened species)

- Changes in product
- Changes in wood supply
- Changes in cost, demand, prices and benefits.
- Changes in nutrient value
- Changes in Indigenous use.

Many of these were identified in stakeholder interviews, and this suggests that some adjustment of perception is already underway.

Part D: Regional vulnerability

Overview

In the previous part of this report, we summarised what is known about the impact of climate change on Australia's forests ranging from biophysical impacts to societal impacts. Much remains uncertain, considerably more knowledge is needed and definitive forecasts for individual regions of Australia are not possible. What we present here is a review of existing evidence relevant to individual regions of forest. We use this evidence in order to make reasonable judgements about areas of greatest risk. This process allows us to begin assigning priorities for further research and planning activities.

For most regions, temperatures are predicted to warm and rainfall is likely to decrease. For some regions growing conditions could in fact improve which might have positive implications for plantations and environmental plantings as well as agriculture, but potential create land use conflicts. The greatest impacts are likely to be felt in those regions with existing stressors (e.g. the Mediterranean Woodland and Brigalow Belt) or with unique or high biodiversity and a reliance on a cool climate for some species (e.g. Subtropical moist forest, Tropical forest and Cold forest and grassland). This was reflected in the vulnerability analysis for forests in each of the four

8 Regional impacts of climate change

In this section of the report we make a regional assessment of the impact of climate change (exposure and sensitivity) on Australia's forests using a schema of ten agro-ecological zones. We used existing published studies, where available, scenarios of future climate, general literature review, and published expert opinion in order to draw some very preliminary conclusions on the possible impacts of climate change on the forests of each zone. This is intended to provide guidance for further prioritisation and investigation.

Regional impacts of climate change: Key findings

- **Tropical Savanna** – The future climate scenario is for warmer temperatures, more rain in the wet season and less in the dry season. Although growth is unlikely to be strongly affected, a number of natural vulnerabilities exist in this region: exposure to extreme weather events, risk of pest/disease/weeds, changing fire regimes, and increasing severity of dry season. There is potential for expansion of closed-forests in mesic savanna, while xeric savannas are likely to experience tree death in times of drought.
- **Brigalow belt woodland** – In the future climate scenario, rainfall is expected to increase in summer and decrease in winter and spring with an overall annual deficit. The increased availability of CO_2 in the atmosphere may compensate for water limitations and maintain plant growth levels. Extensive past clearing and resultant biodiversity loss could make this region particularly sensitive to climate change impacts and new disturbances (e.g. weeds). Vine thickets are particularly vulnerable to any increased fire risk. An increasing focus on conservation outcomes will be needed.
- **Tropical rainforest** – Under the future climate scenario, rainfall is expected to decrease in winter and spring, but increase in summer. Increased frequency and intensity of storms and cyclones are expected in this region. On balance, there may be little change in plant growth in some areas and a reduction in other. There is reasonable potential for new species (both weed and tropical native species) biodiversity loss, natural disasters and reduced tourism.
- **Tropical forest and woodland** – In the future climate scenario rainfall is expected to decrease in winter and spring, temperatures will increase with the greatest warming to the west and increased exposure to storm/cyclone events. The impact on plant growth and productivity is likely to be a complex response to a number of variables. While increasing temperatures and decreasing rainfall have the potential to increase water stress in plants and reduce growth at dry times of the year, an increase in CO_2 could increase productivity in high nutrient areas and improve water use efficiency. Plantations or plantings will need to adapt species choice and management tools. There could be increased risks from new species, and new fire risks. Coastal inundation threatens mangroves and wetlands.
- **Temperate sub-humid woodlands** – An increase in summer rainfall, winter drying with an overall reduction in rainfall and reduced frost for this region under the future climate scenarios. There is potential for increased plant growth and productivity, but some plantation species are expected to decrease in productivity. Decreased frost and warmer conditions may allow new species to establish or thrive. Existing degradation issues will be compounded by climate change.

- **Subtropical moist forests** – Warmer temperatures and increased rainfall for both summer and autumn were modelled for this region in the climate scenarios. Increased growth is likely, particularly summer growth in the southern half of the region. Areas of high nutrients could experience increased productivity under elevated CO_2 as well as increased water efficiency. Drought, fire and weed potential will increase. Loss or change of the character of high value biodiversity highly likely.
- **Temperate moist forests** – Climate scenarios suggest this area will experience a drier winter and spring representing a change in the seasonality moisture. There is good indication that plant growth is likely to increase and water efficiency could improve. Fewer frosts could allow establishment of new species. Drought will elicit species-specific responses. Implementation of plantation management to deal with drought (e.g. species selection, density of planting) to avoid drought stress, to avoid drought impacts. Expect an increase in vegetation cover. Climate tolerance of species thought to be limited, may result in migrations or species loss. Fire is likely to be a significant threat to both biodiversity and forest land use.
- **Cold forest and grassland** – Based on the future climate scenarios, Tasmania can expect increased rainfall, especially in winter while the Alps areas are likely to become drier. Increased water stress is expected in summer in the Alps. There is predicted to be some increased plantation productivity for some species. There is an extremely high risk of loss of high altitude species with loss of snow, higher temperatures and altered distributions for other species. Phenological events are likely to change. There is expected to be an increased fire risk. Considerable impacts on the tourism industry are also likely.
- **Mediterranean woodland** – This area is already experiencing changes in climate, with further warming and drying the result of the scenario modelling. Plant growth is expected to be reduced although at a local scale the availability of groundwater may advantage some species. There is an increased drought mortality risk. There is an expectation that the distribution of species will be affected, with some at risk of local extinction. There is projected to be an increase in fire risk conditions, although fuel loads may be reduced. In general climate change is likely to exacerbate existing land degradation issues.

8.1 Introduction

While climate change will have a global impact, the response of individual ecosystems will be very much dependant on local or regional circumstances. To capture this regional variability, a qualitative assessment of regional forest vulnerability under climate change was undertaken.

As outlined in Section 1.3, a qualitative assessment of regional forest vulnerability under climate change was made using Hobbs and McIntyre's (2005) agro-ecological zones as an organising schema. In this part of the report we describe the outcome of this analysis for each of the ten agro-ecological zones. For each region we present a review of current knowledge, consider potential future climate change impacts and the vulnerability of each area to negative impacts. In addition the adaptive capacity of the region is considered (see Appendix 7 for more detail).

It should be noted that despite a thorough review of the published literature, information for individual areas is extremely limited. However, in order to inform adaptation in forest-dependent communities, and adaptive management by forest managers and policy makers, it is important that this report provide a critical analysis of current information and a preliminary, but by its nature, speculative, assessment of the vulnerability of forests to climate change. In carefully considering all available information we have developed scenarios of forest vulnerability for each region on the basis of current knowledge. As more research is undertaken in the future and our knowledge of climate change and its impacts improves so will our ability to reassess and revise the vulnerability of Australia's forests to climate change.

Information was drawn from the original analysis of Hobbs and McIntyre (2005), results of the SimCLIM future climate projections (see Appendix 4), a review of the regions undertaken by Dunlop and Brown (2008), the review of literature carried out as part of this assessment (Wood et al., 2010; Medlyn et al., 2010; Cockfield et al., 2010; Wilson and Turton, 2010) and *Landuse of Australia* survey maps. The work of Brown and Dunlop (2008) is also a preliminary and subjective analysis of the impact of climate change on the ten regions and they, too, warn that caution must be exercised in relying on their data.

For each region we highlight the rainfall and temperature scenarios generated for this project in accompanying figures. Note this is intended to demonstrate scenarios of future trends rather than as specific measurements to assess impacts. It is not a substitute for more precise down-scaled modelling predictions that are being developed for various regions, rather presenting the scenario on which the analysis was based.

The distribution of broad vegetation types and tenure types for Australia's forests in each of the ten regions is shown in Figure 8.1 and Figure 8.2.

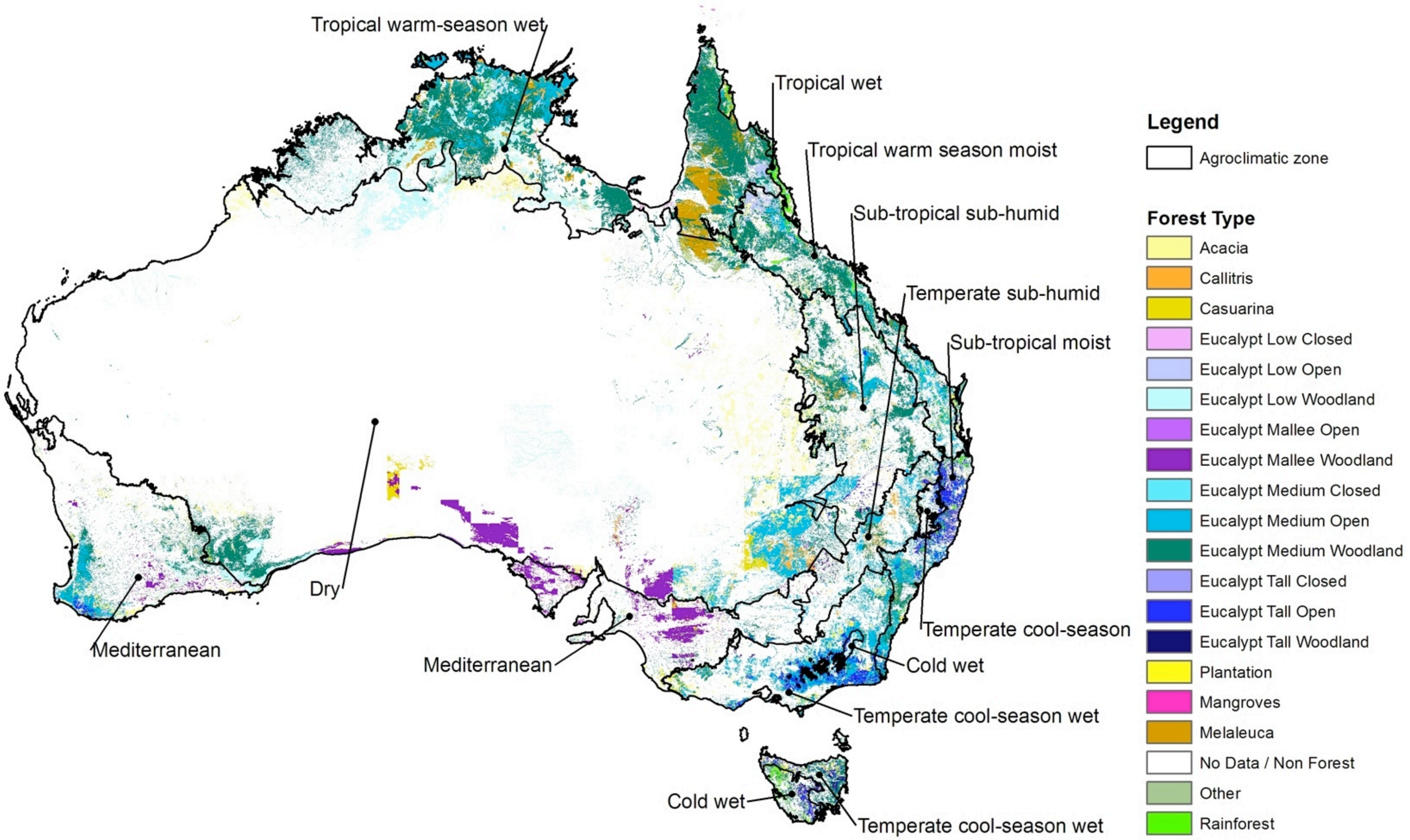


Figure 8.1 Australia's broad forest types shown in each of the ten agro-climatic zones used here to assess forest vulnerability under climate change.

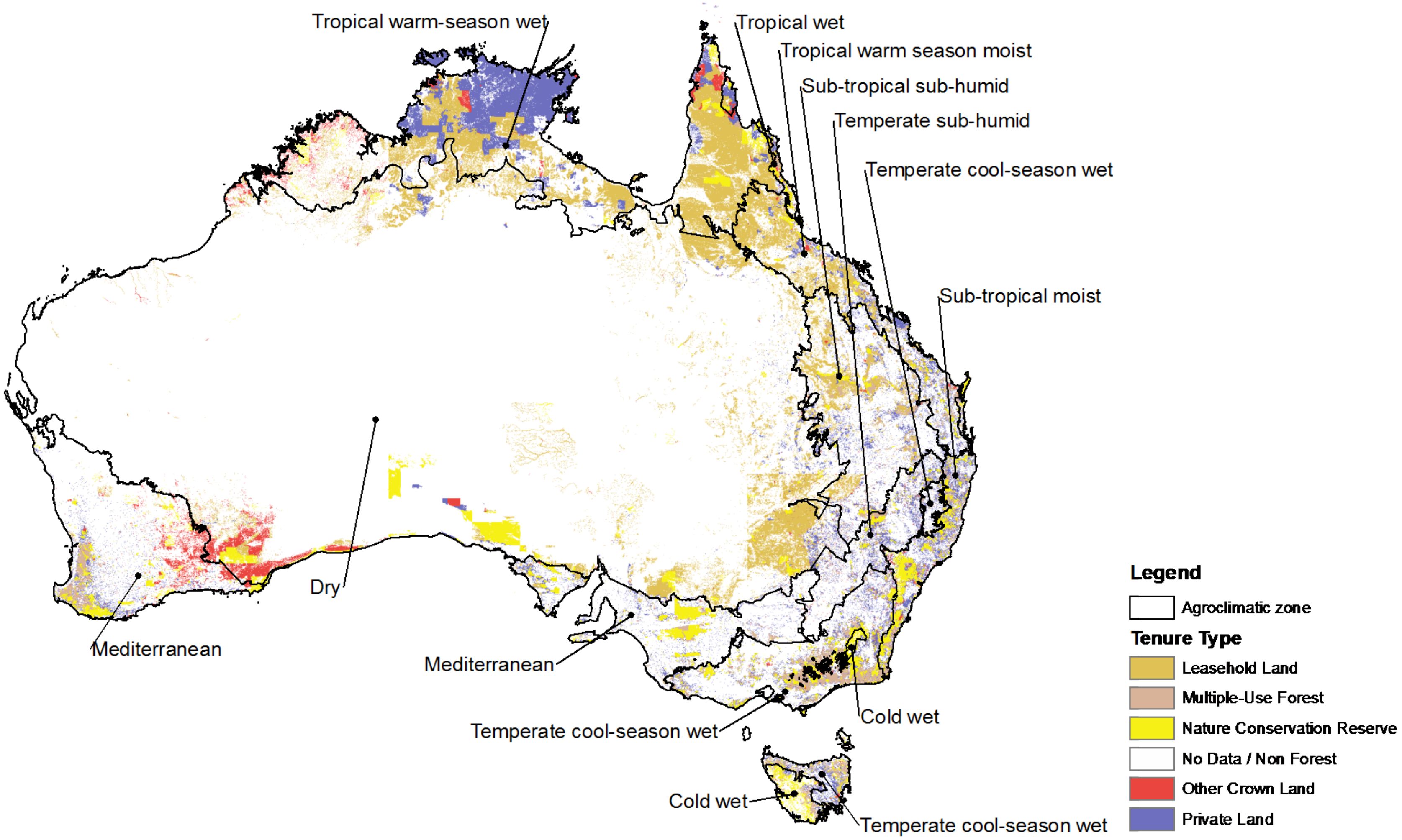


Figure 8.2 Tenure type of Australia's forest shown for each of the ten agro-climatic zones used in this assessment.

8.2 Tropical Savanna

8.2.1 Present

Climate and land-use The Tropical Savanna region extends across the northwest of Western Australia, the northern half of the Northern Territory, and Cape York Peninsula. It currently has a strong wet-dry season pattern of climate with both high moisture and high growth indices in the warm–wet season. In contrast, the cool-dry season has low moisture and growth indices. Land use is predominantly rangelands (i.e. cattle grazing), Indigenous land use and horticultural activities (Hobbs and McIntyre, 2005). Fires are extensive and frequent but with some variability between sub-regions (Williams et al., 2009b). The region features extensive areas of tide dominated mangroves and inland areas of wetland subject to periodic inundation.

Forest types Conservation forests are scattered across the three states (Figure 8.4). Almost all land in the Northern Territory is privately owned or leasehold. Small areas of private plantations exist in the Tropical Savanna region.

Socio-economic Indigenous-owned land includes around 21 million hectares of forest (approximately 14% of Australia's total forest area). Most Indigenous-owned land is eucalypt woodland or open forest in the Tropical Savanna region (Montreal Process Implementation Group for Australia, 2008). The largest scale plantation forestry activity on Indigenous-owned land was established on the Tiwi Islands during the 1960s and has been managed in partnership with a private corporation until recently (Australian Government, 2005).

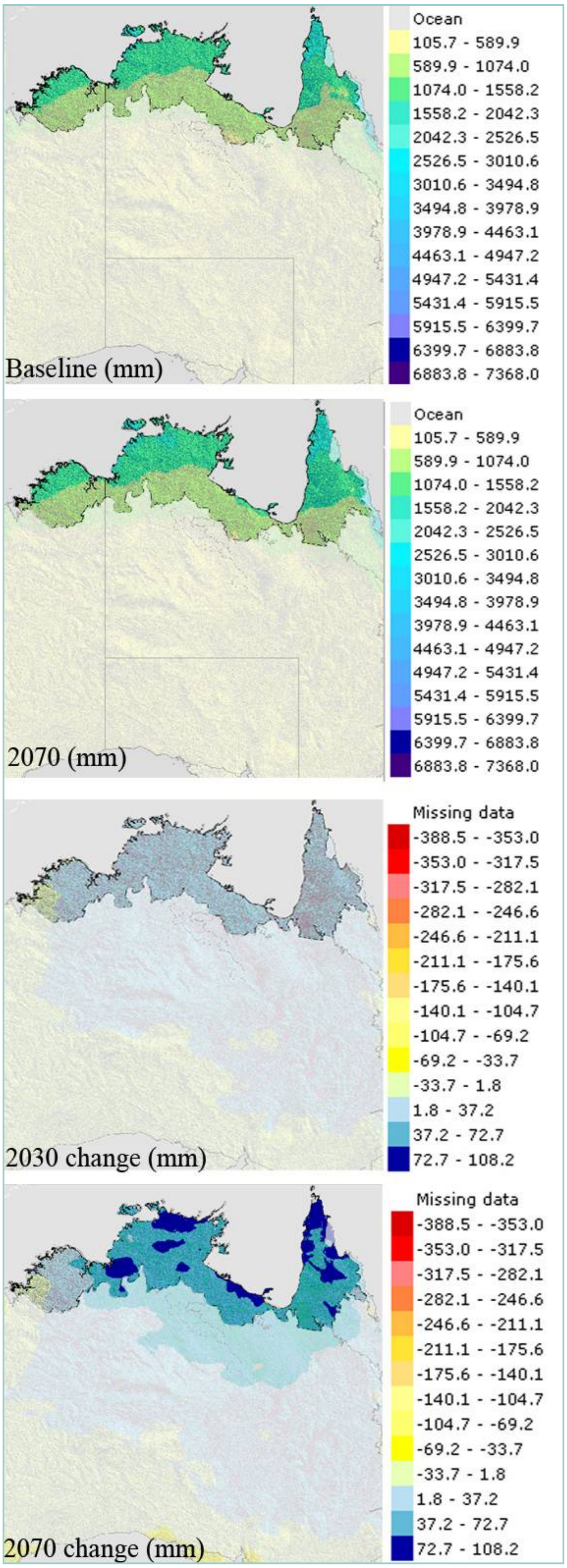


Figure 8.3 Scenario of total annual precipitation in the Tropical Savanna region in 2070 with the change in rainfall totals between the baseline and 2030 and 2070 also shown. Scenario used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

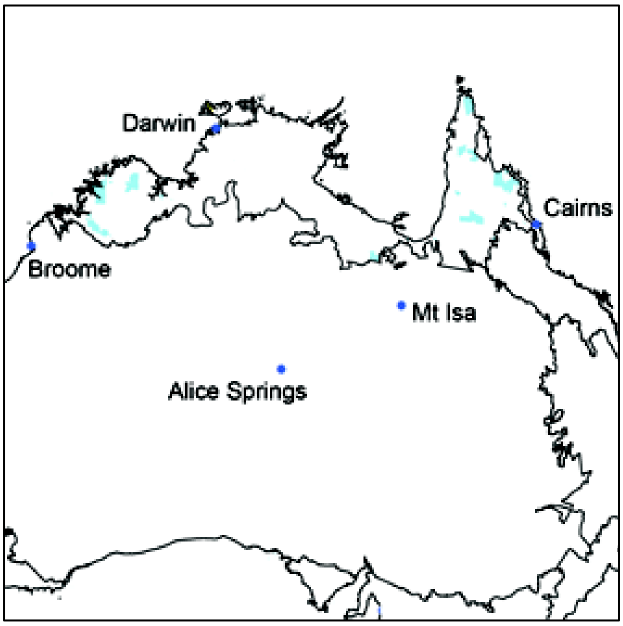


Figure 8.4 The Tropical Savanna region with areas of conservation forest (blue areas) and plantations (yellow areas) where present identified. Source: ABARE – BRS.

Table 8.1 Brief description of the Tropical Savanna agro-ecological zone

Description	Region	Tropical savanna
	Where	North-west WA, northern NT, and Cape York Peninsula
	Climate & growth	Moisture and growth indices high in warm-wet season, both very low in cool-dry season
Landscape characteristics	Ecosystem function	Seasonal wet/dry; local seasonal inundation for some regions; 1-3 yearly cool fires; fast draining (growth needs regular water).
	Climate extremes	Annual, cycle of hot and very wet, warm and very dry; but some inter-annual variation.
	Disturbance	Cyclones. Flooding and fire are very regular. Land clearing for grazing and some cropping.
	Land-use	Extensive grazing; some irrigation and horticulture. Indigenous land use.
	Soil	Many drainage lines, hills, escarpment, soils mainly shallow sandy soils and massive earths.
	Water availability	Dominant driver, timing and duration important; supplies water to northern arid zone; groundwater very important to dry areas.
	Vegetation	Savanna, woodlands and grasslands; Forests and pockets of rainforest. Extensive mangroves, salt marshes and wetlands.
Forest types	Plantation/farm forestry	Limited plantations, some Indigenous-managed plantations
	Productive native forests	None
	Conservation native forests	Some significant areas of National Park e.g. Kakadu National Park; Territory Eco-link a planned major conservation corridor in partnership with community.
	Environmental plantings	Local revegetation projects (e.g. Landcare)
Governance	Policies	The Northern Territory Climate Change Policy (2009); Climate-Change Action Plan for Forestry (Qld); Code of Practice for Forestry (Qld)
	Legislation	Planning Act (NT); Pastoral Lands Act (NT); Forestry Act (Qld); Nature Conservation Act 1992 (Qld); Coastal Protection and Management Act (Qld); local council fire laws (WA)

8.2.2 Climate change vulnerability

Climate exposure

Under the climate scenarios developed for this project, the Tropical Savanna region would experience an increase in annual rainfall totals with more rain likely to fall in the wet season and less in the dry season. Temperatures are highly likely to increase across the year with the dry season expected to experience drier and hotter conditions with a predicted increase in the number of extremely hot days. The area is also likely to experience sea-level increases, increased mobility in shore-lines and increased coastal inundation.

System sensitivity

Biophysical impacts There is some limited evidence of the counterbalancing effect of rainfall, temperature and elevated CO_2 on plant growth in the Tropical Savanna region. The existing evidence is as follows:

- *Maranthes corymbosa* (Berryman et al., 1993) showed increased growth under elevated CO_2 conditions as well as reductions in stomatal conductance of 10 - 30% (Goodfellow et al., 1997) suggesting improved water use efficiency.
- Leaf Area Index (a surrogate measure of productivity) increases with increased rainfall across a rainfall gradient, with differences highest in the wet season (Hutley et al., 2001).
- There may be some trade-off effect between drought tolerance and CO_2 effects. A study in the Queensland section of the Tropical Savanna found a net increase in tree cover over fifty years and was ascribed to above-average rainfall over this period. However, this trend was completely negated by tree mortality during a severe drought (Fensham et al., 2009). The study found that 27% of all tree species (not individual trees) were killed as a result of the drought with different species experiencing higher rates of

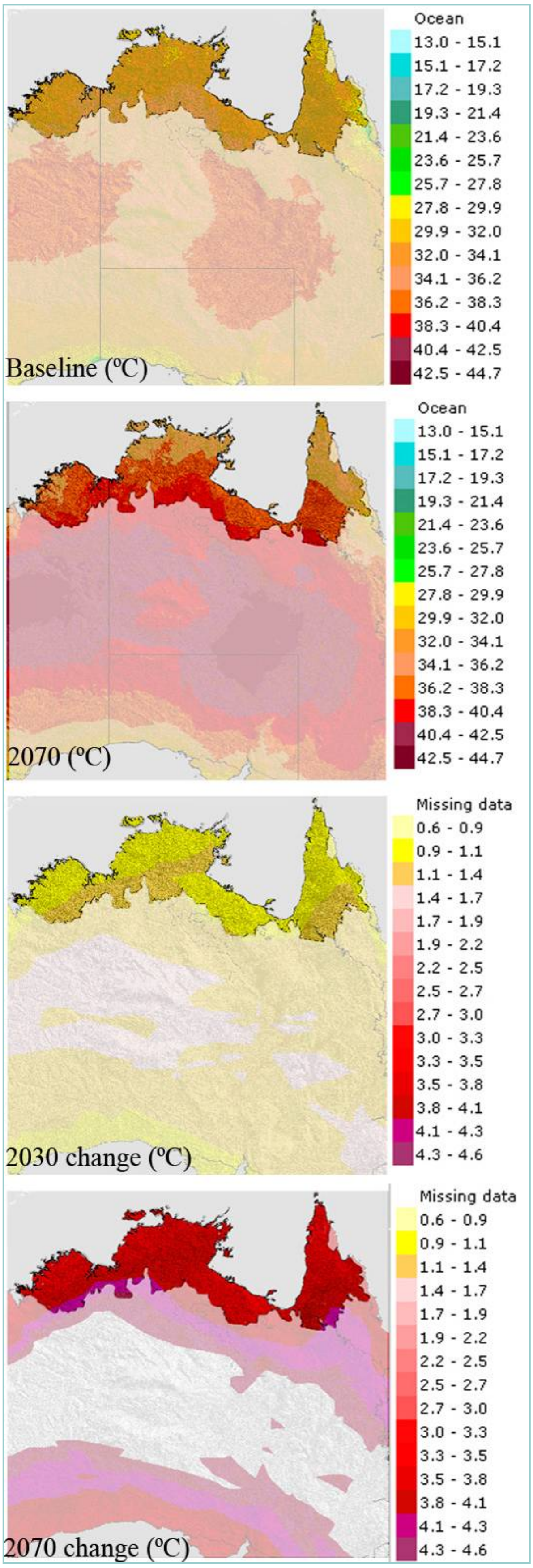


Figure 8.5 Scenario of mean maximum February temperatures for the Tropical Savanna region in 2070 with the change in temperature between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

mortality of individual trees than others. Fensham et al., (2009) conclude that drought-induced tree death seems to be an infrequent, but natural phenomenon in xeric (more arid, mean annual rainfall <900 mm) savanna environments. The frequency of such multi-year droughts is likely to determine the accumulation of biomass in these environments.

- Observational studies from mesic savannas generally suggest that rainforest and closed-forest areas are expanding (e.g. Banfai and Bowman, 2006; Brook and Bowman, 2006) and that tree cover in savannas is increasing (e.g. Lehmann et al., 2008; 2009). This expansion is believed to be a result of elevated CO_2, increased rainfall and fire management (Brook and Bowman, 2006, Bowman et al., 2001). Increases in global CO_2 concentrations are believed to provide a competitive advantage to C_3 trees compared with C_4 grasses (Brook and Bowman, 2006) which is significant in the competitive advantage of closed-forests over grasslands. In more mesic savannas, rainfall is more reliable, and soil moisture reserves are rarely depleted (Bowman and Prior, 2005).

- Tree establishment could be limited by long periods of water stress (5-8 months) and highly irregular and variable rainfall in summer months (Dickinson and Lee, 2005; Bristow, 2004). Likewise, anecdotal evidence suggests the persistence of floodwater for extended periods may decrease seed and seedling survival in this region (*pers. comm.* G. Dickinson, Sep 2009).

- In a seedling establishment study in northern Australia, higher soil temperatures in a savanna compared with a nearby rainforest resulted in reduced soil water availability and reduced seedling survival in the savanna (Bowman, 1993).

- Increased wood density can result from increased temperatures and the seedlings of *E. camaldulensis* showed an increase in wood density at higher growth temperatures (Thomas et al., 2004).

Increases in rainfall are unlikely to influence plant productivity or free water use very strongly as the Tropical Savanna is not currently water limited. However, there is some evidence that tropical trees experience reduced growth under warmer conditions (i.e. trees at their distributional limit). While there is some evidence of increased growth or expanded distribution attributed to increased rainfall and elevated CO_2. Several factors may affect this in the Tropical Savannas:

- Soil nutrient availability is likely to limit productivity increases.

- Sub-regional differentiation between xeric and mesic savannas.

- Changes in growth, vegetation structure and composition are potentially more likely to be affected by increased seasonal dry conditions and extreme events such as storms, extreme heat and tidal inundation.

Extremely high temperatures, in the range 45 - 60 °C, can cause leaf necrosis or plant mortality. The Tropical Savannas can expect an increase in these extremely hot temperatures, and tree mortality may result.

Decreasing soil water availability in the dry season may affect seedling establishment.

Runoff is likely to increase and this may bring additional management implications. There is an increased risk of soil erosion during increased rainfall periods. Changes in hydrology and water balance with a longer dry season will impact on tree growth and species composition. In stakeholder interviews, wind was identified as a key threat in this area.

Mangroves, coastal wetlands and flood plains could be affected by salt intrusion with rising sea levels. This could cause widespread tree death in these vulnerable ecosystems.

Fire is likely to change in seasonality and frequency (Dunlop and Brown, 2008). The flora/fauna of the region are well adapted to fire, but sensitive to fire regime (Bradstock et al., 2002). Change in seasonality, severity (hotter earlier), frequency (less in some areas) and extent of fire due to climate, agricultural practices (more flammable pasture species) and plant species, and reduced Aboriginal burning has affected – and is likely to continue to affect – vegetation composition and structure. For example, the timing of fires can be important for the recruitment of dominant tree species whereas intensity was linked to higher mortality of obligate seeders (as distinct from resprouters) (Bradstock et al., 2002, Prior et al., 2009). Given past adaptation to fire, it is likely that there is less risk to biodiversity than in southern regions but fire management will need to adapt to new climate conditions. Mammals have been identified as fire sensitive, while ants were highly resilient (Bradstock et al., 2002). Increasing fire risk could have differential impacts on the biota of the region.

Evidence in support of increased or decreased pest, pathogen or weed threats is mixed. There is potential for exotic species to spread from the north during the wet season, threatening to introduce new weed species that may be successful in increasingly warm, wet conditions. In this case, weed management will need to be maintained as a priority conservation issue. Increased moisture is a key process in increasing the threat of the pathogen *Phytophthora cinnamommi* that is distributed across the region, although extended dry periods can reduce pathogen risks. Likewise, increased drying, particularly in this very high rainfall region, could result in tree stress and increased vulnerability to pest or pathogen attack. The weed species Gamba grass (*Andropogon gayanus*) is predicted to grow better under elevated CO_2 conditions. Its presence has a number of flow-on effects including changes to fire vulnerability and changes in species composition. *Acacia nilotica* has been shown to increase its water efficiency under elevated atmospheric CO_2 and is expected to expand its distribution into the Tropical Savanna region. Weeds, pests and diseases are obviously potential threats to Tropical Savannas that will require considerable monitoring.

Given that rainfall is variable and highly seasonal, soil conditions are generally poor and local site conditions frequently sub-optimal for growing trees, breeding trials to improve genetic stock of hardwood are being investigated (Dickinson and Lee, 2005). New cultivars, such as hybrids of several species of tropical eucalyptus, have performed well overseas (Dickinson and Lee, 2005) and are options for climate change adaptation. Similarly, high quality timbers such as mahogany and agroforestry crops such as sandalwood are being considered with trials in progress (Dickinson and Lee, 2005)

Social impacts Tourism is an economically important industry in the Tropical Savannas. For example, in Kakadu National Park, the largest number of jobs is provided by tourism followed by conservation and recreation (Bayliss et al., 1997). Some tourist areas might be highly impacted upon by rising temperatures and changed rainfall patterns. For example, in terms of tourism destinations, Kakadu National Park may be most affected with biophysical changes, although the flow-on effects might not be as severe as in other highly developed tourist areas (Cooperative Research Centre: Sustainable Tourism, 2009). Indirect deterrents for visitors may exist, such as high temperatures that may discourage forest/bush hiking and national park visits due to fire danger or physical discomfort. Higher intensity rainfall may be a problem, resulting in floods and damage to infrastructure (including roads, bridges, and accommodation) and a decrease in visitors. Such a downturn would largely affect the livelihood of Aboriginal people (Commonwealth of Australia, 2010, Cooperative Research Centre: Sustainable Tourism, 2009). On the other hand, there could be counter-balancing demand pressures, driven by increased wealth in developing countries and interest in remote areas and Indigenous cultures. Indigenous knowledge of local forest patterns and associated historical landscapes is a valuable source of information. In the Tropical Savanna there is an opportunity to build climate change adaptation strategies for forests based on Indigenous knowledge.

There has been some movement of plantation industries to the north of Australia to areas of greater rainfall (reported in Woods et al., 2010). This may increase the land demand for plantations in this region, increasing land competition with agriculture. Given it is not traditionally a forestry area, there is limited infrastructure to support an expansion of this industry.

Adaptive capacity The Tropical Savanna region experiences conditions or factors that might enhance or weaken adaptive capacity. A strong history of Indigenous knowledge and land management might provide important insights. There is a strong history of fire management in the region and this experience should strength the capacity to adapt to new fire regimes and changing vegetation as a result. The area currently has a strong tourist appeal and the ongoing demand of this industry may present new opportunities for land managers. Existing social and community issues (e.g. poverty, health issues, remoteness) are likely to negatively impact on adaptive capacity. Certainly in a demand for resources, worsening health issues or social issues are likely to take precedence over forest related resource demands.

Forest vulnerability Although growth *per se* is not likely to be strongly affected by climate change, a number of natural vulnerabilities exist in this region: exposure to extreme weather events, increased risk of pest/disease/weeds, changing fire regimes, and increasing severity of the dry season. These vulnerabilities are likely to demand increased management efforts and cost and may impact on tree growth and success.

Adaptation actions for the future Improving or enhancing connectivity between conservation reserves and habitat areas will be important in this region to allow for dispersal and migration of species as the climate becomes sub-optimal in existing distributions. For these environmental plantings and plantations alike, reasonable growth and success is likely provided species suitable to new climates are selected. Increased investment in weed control is likely to be necessary. With good growth predicted, this area may find increased investment in alternative forest products (e.g. carbon sequestration, biofuels) provide new industries or economic benefit. Changes in productivity of grazing lands may change local economic conditions.

8.3 Tropical Rainforest

8.3.1 Present

Climate and land-use The Tropical Rainforest is made-up of a band of year-round high moisture, high growth land on the east coast of far north Queensland. It is characterised by the presence of tropical rainforest, but includes areas of mangrove, wetlands, and salt marshes along the coast and eucalypt forest elsewhere. The area is frequently subjected to cyclones and they are important drivers in vegetation composition and structure. Fires in these forests are generally rare and these forests are considered fire sensitive as a consequence.

The area has a high demand for urban development and agriculture because of its coastal location and high rainfall. It also has a strong conservation demand due to the high biodiversity value and undisturbed nature of large areas of forest.

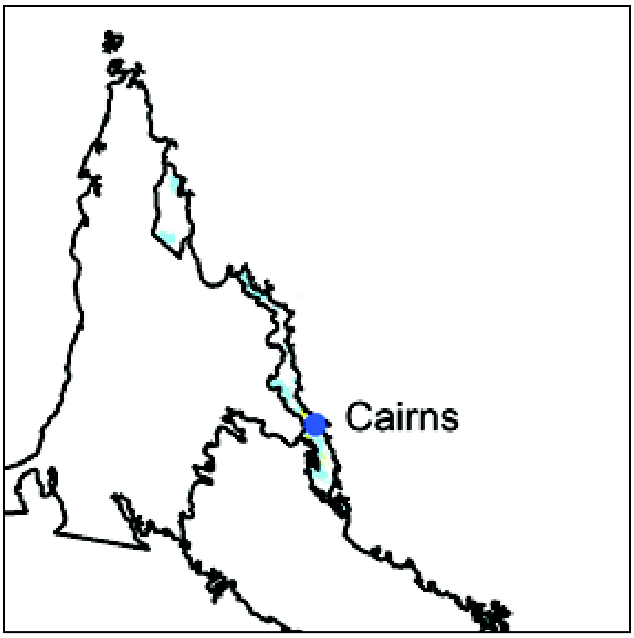


Figure 8.6 The Tropical Rainforest region with areas of conservation forest (blue areas) and plantations (yellow areas) where present. Source: ABARE-BRS.

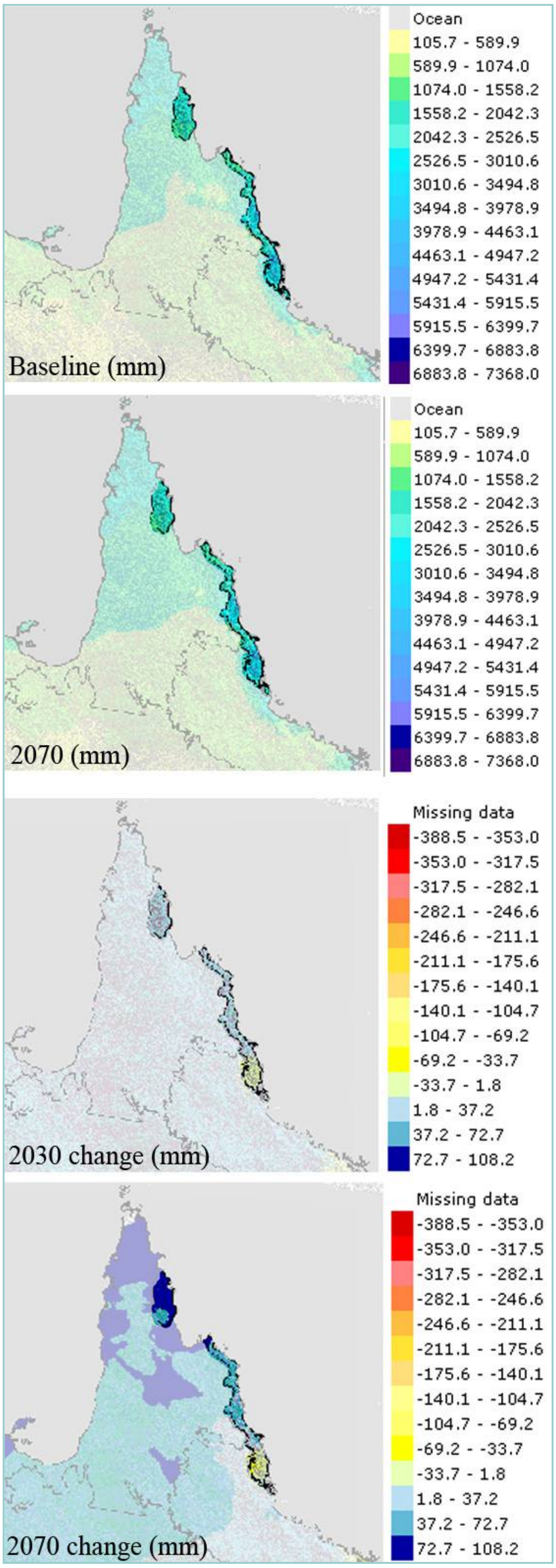


Figure 8.7 Scenario of total annual precipitation in the Tropical Rainforest region in 2070 with the change in rainfall totals between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

Several weed species are significant pests of the Wet Tropics. Significant patch death related to *Phytophthora cinnamomi* has been recorded in high altitude areas (>750 amsl) (Worboys, 2006).

Forest types As already mentioned, there are large areas of conservation forest in the Tropical Rainforest region. Both public and private managed plantations also exist in the region and include Hoop pine plantations and mixed exotic pine plantations. All state owned productive native forests have been transferred to the Wet Tropics World Heritage Area and are now part of the conservation estate. Extensive rainforest restoration activities including revegetation and small farm forestry projects, have been carried out in the Wet Tropics region (Catterall and Harrison, 2006).

Socio-economic The Tropical Rainforest region is a significant forest region for a number of reasons:

- Large areas of forest are protected by World Heritage listing.
- High levels of biodiversity and endemicity (both flora and fauna) are centred in the region.
- Large Indigenous community with strong history of land management.

As a result, the area has high existence, spiritual and recreation values, significant biodiversity value, considerable agriculture value and complex social structures.

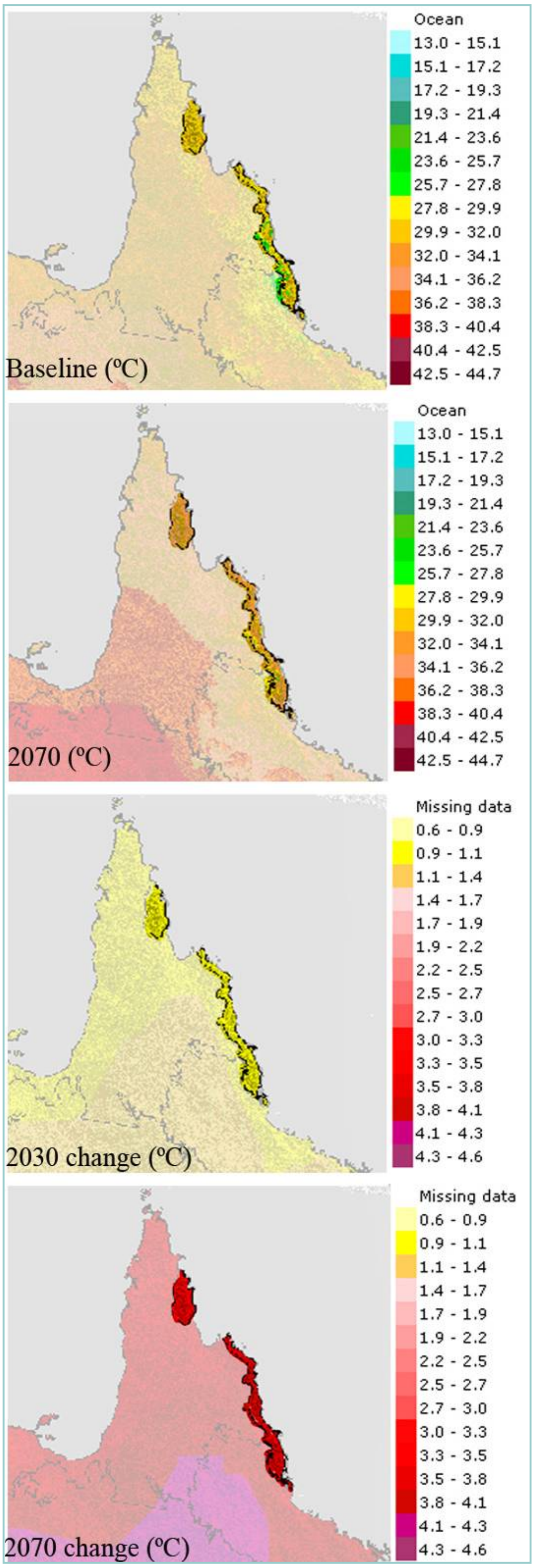


Figure 8.8 Scenarios of mean maximum February temperatures for the Tropical Rainforest region in 2070 with the change in temperature between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models

Table 8.2 Brief description of the Tropical Rainforest agro-ecological zone.

Description	Region	Tropical rainforest
	Climate & growth	Moisture index and growth index high all year, J1 has short dry season
	Where	Limited areas on the east coast of northern QLD
Landscape characteristics	Ecosystem function	Wet, year round growth. Tropical rainforest
	Climate extremes	Hot and wet summer
	Disturbance	Cyclones. Fire very infrequent
	Land-use	Grazing in places. Conservation areas. Sugar cane and horticulture
	Soil	Medium scale topography: coastal plains, hills, tropical mountains in south. Soils mainly structured loams and clays, as well as yellow, red or brown duplex soils.
	Water availability	Surface water a dominant driver
	Vegetation	Rainforest, eucalypt forest. Extensive mangroves, salt marshes and wetlands along the coast.
Forest types	Plantation/farm forestry	Developed industry, both native and exotic tree species Considerable farm forestry
	Productive native forests	Being phased out
	Conservation native forests	Significant and some extensive and iconic protected areas (World Heritage and National Park). High species diversity. High number of endemic species.
	Environmental plantings	Extensive replanting scheme for habitat and connectivity
Governance	Policies	Climate change Action Plan (Qld); Code of Forestry Practice (Qld)
	Legislation	Forestry Act (Qld); Nature Conservation Act 1992 (Qld); Coastal Protection and Management Act (Qld)

8.3.2 Climate change vulnerability

Climate exposure

Climate scenarios prepared for this project suggest temperatures in the Tropical Rainforest region will steadily increase warming by up to 4ºC by 2070. The wet season will see increases in rainfall with decreases in the dry season creating an overall increase in seasonality. More intense and damaging cyclones have been predicted for the region. All these changes increase the risk of flooding and storm surge. Increased sea levels would increase coastal inundation impacting on mangroves, coastal wetlands and flood plains.

System sensitivity

There is limited evidence of growth responses to climate change for Tropical Rainforest species. Based on general findings we would expect that given high rainfall rates, the area is more likely to be energy limited than water limited and that increased wet-season rainfall is not likely to be accompanied by strong positive effects on growth as a result. Given the current year-round moisture availability and growth, less moisture available during the dry season might reduce growth at this time. Reductions in moisture and increased temperature may create water stress for some species depending on retention of soil moisture. This in turn may be dependent on soil depth, topography, aspect, and soil texture and structure (Battaglia and Williams, 1996, Mendham et al., 2005).

Gains in tree productivity could potentially be made through elevated CO_2 in the presence of the naturally nutrient rich soils found in the Tropical Rainforest region. For example, the local species *E. tereticornis* demonstrated improved growth, experimentally, under elevated CO_2 and drought conditions. Further evidence of similar responses by other tropical plant species would be valuable in determining any potential to offset productivity losses due to drought if these plants are grown under elevated CO_2 concentrations.

The Tropical Rainforest region is characterised by high diversity and endemism and the climate tolerance of these species will be crucial in determining their distribution and survival. Hilbert et al., (2001) used an artificial neural network model to predict changes in the distribution of rainforest types in the tropics of Queensland. They found that the climatic range of most forest types was small and concluded that several forest types would be highly stressed by a 1 °C warming with most sensitive to any change in rainfall (Hilbert et al., 2001). Similar modelling exercises have been carried out for vertebrates, with similar potentially catastrophic results predicted (Williams et al., 2003). In addition, changes in species composition could result from warming with large changes in rainforest-woodland ecotones predicted in north Queensland (Hilbert et al., 2001). As noted earlier, these modelling exercises are carried out using existing climate envelopes and may underestimate climate tolerance. However, temperature increases of 4ºC are likely to have a substantial impact on many organisms. In particular, increased temperature poses a threat to high altitude endemic species in this region with many expected to become extinct (Williams et al., 2003). Reductions in the distribution of these species is likely to be replaced by expanded distributions of low altitude species that can tolerate increased rainfall in the wet season and extended dry periods as well as warmer temperatures.

High altitude forests also rely on cloud formation or fog as a water source. It has been hypothesised that climate change could reduce cloud contact with forests by increasing the height of cloud formation and also increasing evapotranspiration (Still et al., 1999). In four of six different rainforest types in the Wet Tropics, cloud interception provided a significant input of water at high altitudes (> 1000 m). Over the three and a half year study period the amount varied between 7 and 30% of total water input but reached as much as 66% (McJannet et al., 2007a). Upper montane cloud forests have a positive net water balance throughout the year and their exceptionally large annual run-off (approximately 6500 mm yr^{-1} at a site with rainfall of 7500 mm yr^{-1}) is a significant source of water for river flows (McJannet et al., 2007a). Any decrease of water availability due to an increase in the height at which clouds form, could reduce water availability to these high altitude areas, as well as reduce water flows to lower catchments. This impact is most likely to be felt during the dry season. Increased rainfall, on the other hand, is not likely to change water use by plants in high rainfall regions, meaning increased runoff. Any increase in runoff is likely to result in increasing risks of erosion and other management issues. These contrasting effects are likely to be felt in different seasons: increased runoff in the wet-season, decreased water availability, and runoff in the dry season.

Extended dry-periods, particularly with increased temperatures may create tree stress. Increased drought stress could expose trees to increased pest and pathogen attack (e.g. Longicorn beetle) and this is likely to be a problem in plantations, in particular. Hotter dry seasons would also be expected to increase evaporation and challenge plant survival during dry periods in moisture dependant areas. Alternatively, longer and wetter wet seasons could increase the spread of *Phytothphora* already found in limited areas of the region. There is also a potential for new species to arrive due to proximity to northern tropics, and increased storm damage allowing growth of pioneer species

Seasonal changes in climate cues have the potential to disrupt phenological events including breeding and flowering. Existing climate related differences in flowering patterns among sub-regions have already been demonstrated (Boulter et al., 2006). Seasonal changes in climate could alter phonological patterns with the potential to impact on mutualistic relationships such as pollination.

High intensity storms or cyclones impact on the structure and composition of forests. Severe Tropical Cyclones Larry and Yasi have both had major impacts on the forests of this region in recent years. Changes may include increased presence or dominance of vine species and increased intrusion by weed species. Any increase in events of this nature will increase these changes.

Tropical Rainforests are currently not fire prone, but warming and seasonal drying and changes in surrounding vegetation (e.g. cyclone recovery, urban or agricultural encroachment, increased weed spread) could increase the fire risk to rainforest regions. While the fire risk is expected to be lower than for the southern states, even small increases in fire prevalence would result in major changes to floristics, structure and function of these forests.

Social impacts High biodiversity is a key feature of the Tropical Rainforest region, creating a high aesthetic and spiritual value. This unique character translates into an extensive tourism industry. Changes in the appearance of forests and loss of iconic species have the potential to impact on this industry (Turton et al., 2009). The tropical northern tourism industry is extremely sensitive to changes in demand, such as those that follow economic downturns so climate change impacts may compound this.

Adaptive capacity The Tropical Rainforest region features extensive areas of conservation forest, and considerable areas of plantation and restoration plantings. This suggests considerable corporate knowledge and experience of establishing and managing these systems that will enhance the capacity to continue managing these systems under the challenges of climate change. In contrast, adaptive capacity could be weakened by policy uncertainty, existing disturbance and recovery (e.g. cyclone damage), and the demands and expectations of the tourism industry. The area also has a strong spiritual or existence value, with many people associating the iconic world heritage listed Daintree forests with the region. With strong ideals about the management of the forests and how it should look driven by this character, it strongly determines the expectations of what adaptation should achieve, potentially constraining adaptive capacity.

Forest vulnerability While plant growth is likely to remain unchanged, increase slightly or experience some loss in the dry season; the loss of biodiversity, particularly of high altitude specialists, is a significant risk to the Tropical Rainforest region. There is already evidence of the risks to high altitude (cool climate) specialists. In the case of these organisms, there are limited refugia available and limited capacity for migration, making some species supported by these forests some of the most vulnerable in Australia.

Although the forests of north Queensland’s Tropical Rainforest region are well adapted to storm events, the increase of extreme events have the potential to pose major impacts on vegetation structure and function.

Adaptation actions for the future There is a great deal of potential to increase connectivity between native forest and conservation areas as well as identifying and protecting refuge areas (e.g. cool climate refugia) for improving the conservation of the unique forests and high biodiversity of this region. Tree growth for multiple benefits (e.g. carbon sequestration and biodiversity) has high potential in this region.

8.4 Brigalow Belt

8.4.1 Present

Climate and land-use The Brigalow Belt region extends from the north-west plains of NSW and into Queensland. The Brigalow Belt experiences mild winters with a moderate moisture index and growth index, year-round (Hobbs and McIntyre, 2005). The area is typified by rainfall of between 500 - 750 mm a year and growth is limited by moisture.

The Brigalow Belt region is characterised by the leguminous tree *Acacia harpophylla* (brigalow) and associated vegetation communities, although large areas are also characterised by a range of ecosystems including eucalypt woodlands and forests, dry rainforest, cypress pine and riparian communities (Young et al., 1999). The region is a major agricultural and pastoral area and as a consequence has been extensively cleared (approximately 50% of the land area). Along the eastern boundary of the Brigalow Belt are scattered patches of semi-evergreen vine thickets. These patches are related to rainforests and are remnants of the extensive subtropical rainforest vegetation that occupied much of the brigalow lands millions of years ago.

Forest types Logging has been a major industry in the southern part of the region since the mid 1880’s. The main species harvested include white cypress *(Callitris glaucophylla*) and narrowleaf ironbark (*Eucalyptus crebra*) both have been harvested from state owned native production forests and private land. Harvesting from private land is now only minimal (Hartley et al., 2000).

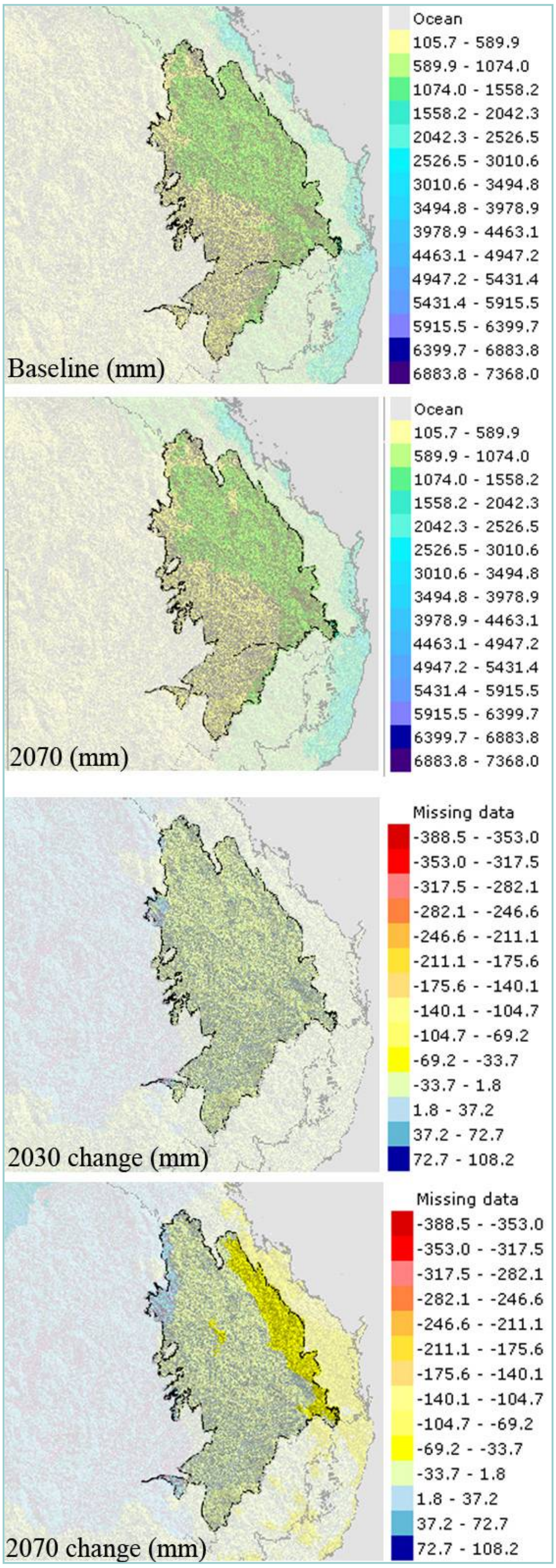


Figure 8.9 Scenarios of total annual precipitation in the Brigalow Belt region in 2070 with the change in rainfall totals between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

Figure 8.10 The Brigalow Belt region with areas of conservation forest (blue areas) and plantations (yellow areas) where present. Source: ABARE-BRS.

The area covers some six million hectares with about 2% protected in conservation reserves. The region has undergone rapid recent change through clearing, altered fire regimes and the introduction of exotic species. Declines in biodiversity have accompanied this and several species have been declared rare or threatened under the *Nature Conservation (Wildlife) Regulation 1994*. In addition many fauna species have undergone severe range reductions, population declines or local extinctions. The conservation of biodiversity in the region has received increasing attention in the management of the region.

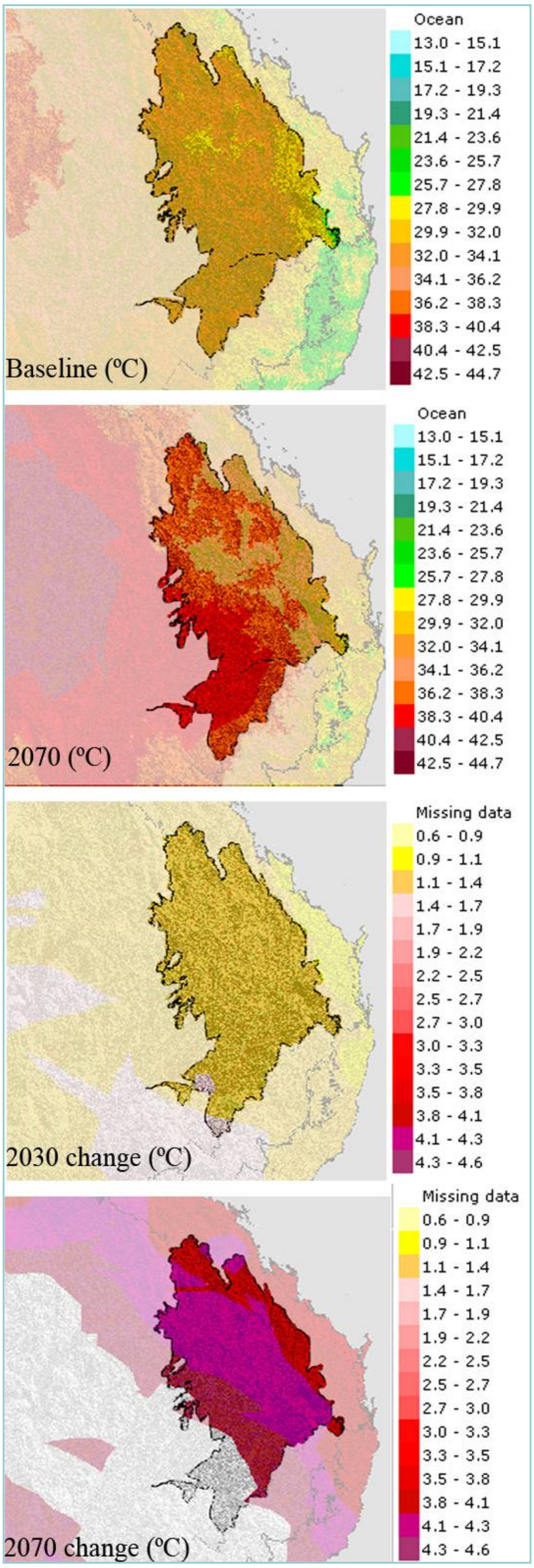


Figure 8.11 Scenarios of mean maximum February temperatures for the Tropical Rainforest region in 2070 with the change in temperature between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

Table 8.3 Brief description of the Brigalow Belt Woodland agro-ecological zone.

Description	Region	Brigalow Belt Woodland
	Climate & growth	Mild winter with Moisture Index and Growth Index moderate year-round. Growth limited by moisture
	Where	North-west plains of NSW and QLD Brigalow Belt
Landscape characteristics	Ecosystem function	All year growth limited by water
	Climate extremes	Prone to floods and drought periods
	Disturbance	Drought and storms. Extensively cleared for cropping and grazing. Salinity, acidification, erosion.
	Land-use	Summer and winter crops, pastures, irrigation, forestry, grazing.
	Soil	Soil water important for growth. Elevated plains and hills; gorges in some areas. Diverse soil types: from massive earths, finely structured clays to yellow, brown or red duplex soils.
	Water availability	Locally important groundwater. Important catchment area; many rivers; farm dams; soil water holding important for seasonal growth.
	Vegetation	Mainly eucalypt and acacia woodlands, some grasslands and forests. Cypress pine forests.
Forest type	Plantation/farm forestry	Some small plantation areas
	Productive native forests	Significant volumes of cypress pine and hardwoods harvested from this region
	Conservation native forests	A number of national parks
	Environmental plantings	Increasing investment in environmental plantings for conservation purposes, some revegetation following mining
Governance	Policies	Climate Change Action Plan (Qld); Code of Forestry Practice (Qld)
	Legislation	Forestry Act 1959 (Qld); Nature Conservation Act 1992 (Qld)

8.4.2 Climate change vulnerability

Climate exposure

Using the climate scenarios developed for this project, we would expect temperatures to increase in the Brigalow Belt line with the majority of Australia, with an increase of 4ºC by the year 2070. Rainfall is projected to increase in summer and decrease in winter and spring with an overall annual deficit. The region could experience a small increase in extremely hot days (>35ºC), with the western portion of the region most affected. The southern half of the region is projected to experience a reduction in sub-zero minimums, with most of the region expected to experience less than four sub-zero days a year by 2070. Increased storm activity could bring more intense storms, more damage and a greater risk of flooding.

System sensitivity

There is very limited evidence of the impact of climate change on plant growth in this region. However, any reduction in moisture availability would be expected to limit growth, particularly in winter active species, although summer active species could benefit from increased moisture availability. Periods of rainfall followed by extensive drought have been shown to increase and then decrease biomass/cover through drought mortality in this area and this could be expected to continue and worsen. Pot trials of *E. tereticornis* showed an increase in growth under elevated CO_2 when moisture was limited, with the species showing improved water conductance. This is a single species pot study, but again raises the question of the potential for increased availability of CO_2 in the atmosphere to counterbalance water limitations. Likewise, chamber tests of growth of *E. camaldulensis* seedlings showed an increase in wood density under warmer temperatures (Thomas et al., 2004). These pot trials of single species emphasise the importance of improving the relationship between CO_2 increases at the stand level.

Extremely high temperatures and extended drought could cause plant mortality. Thresholds for tree mortality are not known for this region.

Extended dry periods can expose trees to water stress and pest attacks (e.g. Cerambycidae/ Longicorn beetles). Plantation species in the Brigalow region would be particularly vulnerable to pest attacks.

Climate changes will favour summer growing (possibly more tropical) species, which could include weed species. In the Brigalow Belt, high habitat fragmentation and extensive agriculture and human settlement provide many sources of weeds increasing the forests' vulnerability to weed invasions. *Acacia nilotica* and *Cryptostegia grandiflora* (rubber vine) have been shown to increase their water efficiency under increased atmospheric CO_2 and are expected to expand their distributions. This would include areas of the Brigalow Belt. The area has a climate conducive to the success of *Phytophthora cinnamomi* and increased summer rainfall might increase the spread of the disease. Any tree planting activity may need to consider planting densities to deal with this threat.

Fire is important in this region to the patterning of forest vegetation, but the impacts are less dramatic than those in taller forests. But more extreme fire weather is likely, particularly in late season autumn and the impact of fire on these forests could well change with increased winds and higher temperatures. Frequency, seasonality and intensity of fires will depend on litter growth and curing. Extended drier and hotter conditions following moist summer growth periods could increase leaf litter build-up.

Socio-economic It could be expected that if some cropping lands become unviable, there will be a change in land use. This could present an opportunity for tree growing on abandoned cropping lands for the purpose of carbon sequestration and/or increased biodiversity conservation and connectivity (Australian Bureau of Agricultural and Resources Economics, 2009b). Outcomes will depend on the interaction of incentives for carbon sinks and state vegetation management laws and conditions. Planting would need to be carried out at the start of the summer-wet season to maximise success.

Brigalow (*Acacia harpophylla*) has a vigorous suckering habit that is generally cleared to increase pasture production. The value of Brigalow regrowth for carbon storage may increase and this may change clearing or management practices. Rules on clearing regrowth, currently under consideration by the Queensland Government, will be a factor.

Adaptive capacity The adaptive capacity of this region is likely to have been weakened by existing disturbance, species loss and vegetation clearing. The area has a strong history of traditional land use values and has been an intensively farmed agricultural area for many years. The native forests are highly fragmented as a result and the region supports some rare and threatened vegetation types. There is some evidence of a capacity to embrace new industries and this experience could enhance adaptive capacity.

Forest vulnerability Extensive past clearing and resultant biodiversity loss could make this region particularly sensitive to climate change impacts. Increasing focus on conservation outcomes will be needed. Vine thickets are particularly vulnerable to any increased fire risk. Given the high level of past clearing the region could be highly vulnerable to any increased pest or disease risk with costly consequences for conservation management.

Adaptation actions for the future Along with ongoing efforts to improve connectivity and reduce the impact of weeds in the Brigalow Belt region, this region will benefit from changing management strategies of land managers. Improved extension and training will improve efforts to embrace co-benefits of forest regrowth, plantings and remnant vegetation.

8.5 Tropical Forest and Woodland

8.5.1 Present

Climate and land use The Tropical Forest and Woodlands region is made up of coastal and hinterland areas of Queensland that extend from tropical regions in the north to subtropical areas in the south. It is characterised by a long growing season and a cooler dry season than the adjacent tropical savannas. Moisture is the main limiting factor to growth with the growth index lowest in spring (Hobbs and McIntyre, 2005). The area experiences a wet/dry seasonal cycle rather than the traditional four seasons. Historically large areas have been cleared for cropping, sugar growing and intensive grazing throughout the region. There is also extensive and increasing urban development along the coastline. The region supports a variety of vegetation types that include rainforest, acacia woodlands and eucalypt forests.

The area infrequently experiences bushfires, but experiences major cyclone disturbance, particularly in the northern half. Weeds are a persistent threat. There are some high altitude areas within the region.

Forest types Forestry is an important industry in the southern coastal area of this region, with extensive harvesting of state forests in the past and a wide establishment of plantations. There are very limited areas of conservation reserve.

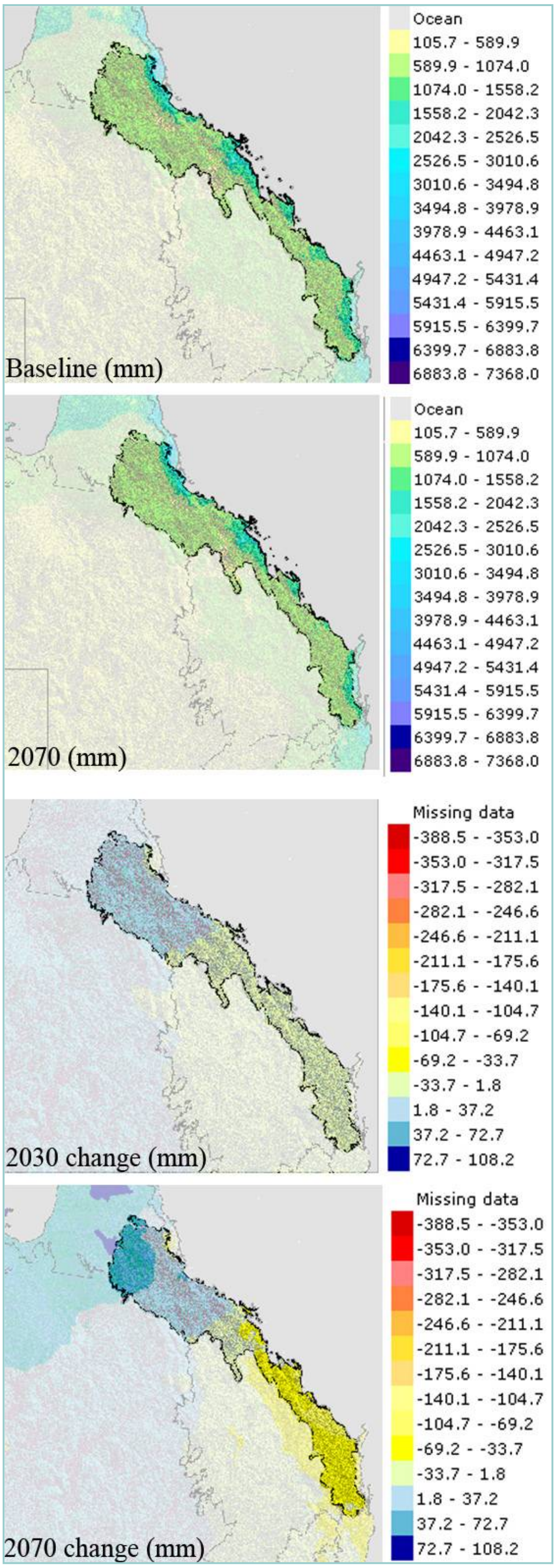


Figure 8.12 Scenarios of total annual precipitation in the Tropical Forest and Woodland region in 2070 with the change in rainfall totals between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

Table 8.4 A brief description of the Tropical Forest and Woodland Region.

Description	Region	Tropical forest and woodland
	Where	Coast and hinterland areas of Queensland (subtropical in southern Qld)
	Climate & growth	Characterised by a long growing season and a cooler dry season than the tropical savannas. Moisture is the main limiting factor to growth and the Growth Index is lowest in spring.
Landscape characteristics	Ecosystem function	Seasonal wet/dry
	Climate extremes	Annual cycle of hot and wet; moderate and dry
	Disturbance	Cyclones. Local flooding. Land clearing for cropping and urban development on coast, and grazing. Fire infrequent.
	Land-use	Sugar, horticulture, other cropping, forestry, intensive grazing
	Soil	Large-scale topography: coastal, plains, slopes to tablelands, tropical mountains in north. Soils mainly yellow, brown or red duplex soils with clays.
	Water availability	Many high volume tropical rivers. Very important local groundwater sources.
	Vegetation	Mainly eucalypt woodlands and forests. Regions of rainforest and acacia forest.
Forest type	Plantation/farm forestry	Plantations are an important industry in the southern portion of the region.
	Productive native forests	Some areas still available for harvest
	Conservation native forests	Recent increase in reserve areas
	Environmental plantings	Some small-scale regional activities
Governance	Policies	No RFA, Climate change Action Plan (Qld); Code of Forestry Practice (Qld)
	Legislation	Forestry Act 1959 (Qld); Nature Conservation Act 1992 (Qld)

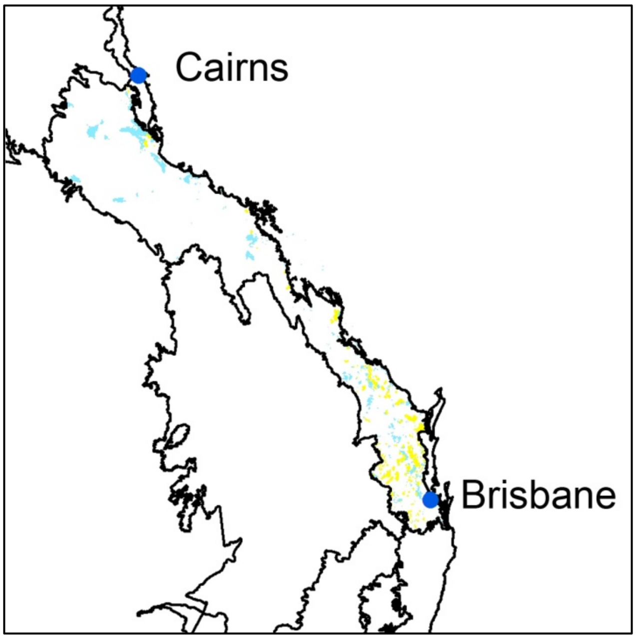


Figure 8.13 The Tropical Forest and Woodland region with areas of conservation forest (blue areas) and plantations (yellow areas) where present. Source: ABARE-BRS.

8.5.2 Climate change vulnerability

Climate exposure

The climate scenario in this region shows an increase in temperatures year round, but not as much as inland areas. Areas to the west of the region would experience extreme summer temperatures with increases of 4.1 - 4.3ºC. Rainfall is expected to decrease in winter and spring. As with most of the northern half of Australia, an increase in the intensity and frequency of storms and cyclones is expected.

System sensitivity

Again, experimental evidence of plant growth response to climate change in this area is limited. Two eucalypt species (*E. tereticornis*, *E. saligna*) from the region have shown increased growth under elevated CO_2 in pot trials but not in one of the species when used in a larger field experiment (Ghannoum et al., 2010). There is also contrary evidence of improved stomatal conductance, with improved water conductance in *E. tereticornis* and no change in *E. saligna*. *Eucalytus camaldulensi* seedlings grown under warm temperatures show an

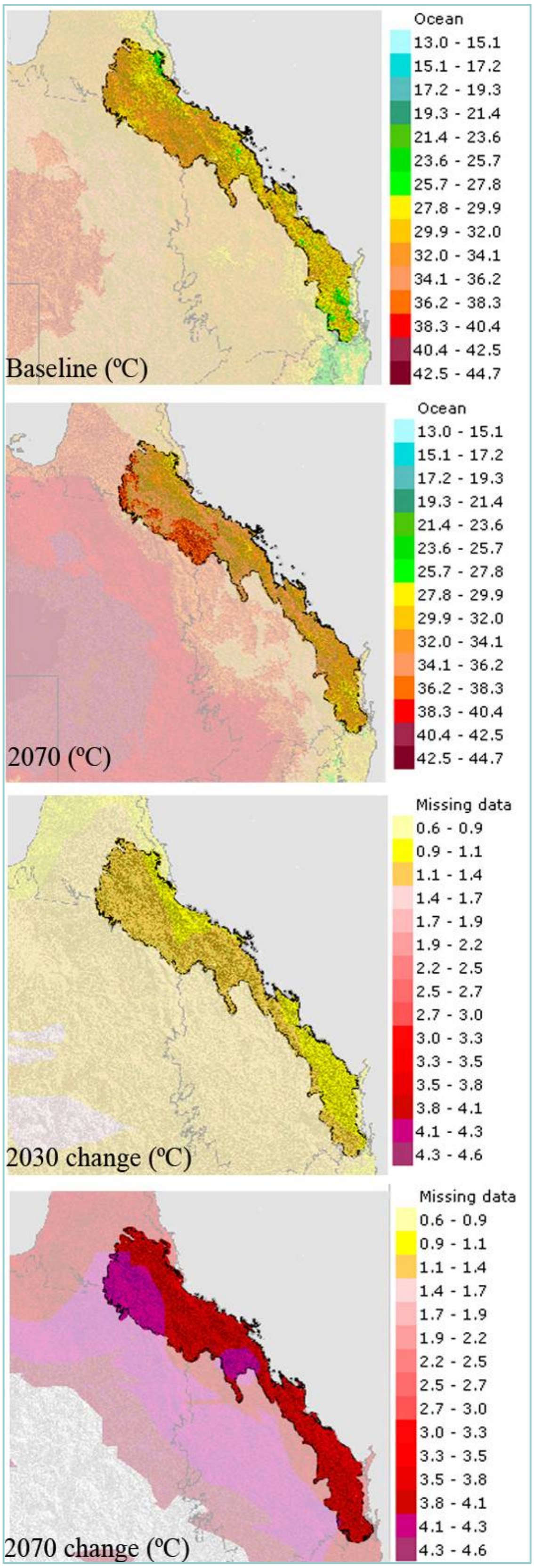


Figure 8.14 Scenarios of mean maximum February temperatures for the Tropical Forest Woodland region in 2070 with the change in temperature between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models

increased wood density.

The impact on plant growth and productivity is likely to be a complex response to a number of variables. While increasing temperatures and decreasing rainfall have the potential to increase water stress in plants and reduce growth at dry times of the year, an increase in CO_2 could increase productivity in high nutrient areas and improve water use efficiency. In reality, this may equate to little change in growth in some areas and a reduction in others in the Tropical Forest Woodlands.

There is reasonable potential for new species (both weed and tropical native species) to arrive and establish due to the proximity of the northern tropics, the extent of disturbance by agriculture and human settlements, increased storm intensity and increased fire disturbance. Existing weed species may respond with an expansion of their distribution, such as is expected for *Asparagus aethiopicus, Acacia nilotica, Cryptostgia grandiflora, Chromolaena odorata,* or contraction e.g. *Cytisus scoparis* (scotch broom) (Scott et al., 2008) and *Cotoneaster glaucophyllus.* The pest insect *Sirex noctilio* may increase attacks in the southern parts of the region if there is an increase in heat and/or drought stressed trees or storm damaged trees.

Fire is currently infrequent in this region, but as with other areas, drier winter and spring climates are likely to increase the potential for more frequent and intense fires. Any increasing risk of fire will be a major threat to forests, particularly to the composition, structure and function. Areas of rainforest in particular would experience major changes to structure and composition following fire, and the risk of this occurring would increase with extended dry periods.

Establishment of new plantations will need to consider species selection and silvicultural practices for drier, hotter conditions given existing moisture limitations. Existing forest plantations could potentially experience decreased growth particularly if species are at the edge of their tolerance range (e.g. cool climate conifers, southern timbers) as well as increased vulnerability to disease. For example, any increase in rainfall would increase the threat of needle blight in pine plantations.

Species distribution changes could be expected. In particular more tropical species could thrive in currently subtropical areas and high altitude specialist species could retract further in range with the potential for losses.

Increased intensity and frequency of storms and cyclones could lead to structural damage of forests and increased establishment opportunities for exotic species. Severe storms and cyclones could create serious damage and losses in plantations in particular.

Sea level rise and coastal inundation have the potential to impact on highly vulnerable mangrove and wetland communities found along the coast of the region. Storm surges in particular are likely to threaten these communities.

Socio-economic The Tropical Forest and Woodland region supports areas of high-density urban settlement with ever-growing populations and demand for land. It also has a well-established forestry industry and a commitment to expand plantation industry in favour of productive native forests. This and other pressures are likely to create a high competition for land and conversion of land uses. This is an area where there has been some interest in small-scale forestry, especially from those where lifestyle is an important part of land ownership (Emtage et al., 2001, Herbohn et al., 2005).

Adaptive capacity The Tropical Forest Woodland region supports a large population, some large conservation regions and an existing forestry industry with a strong history. All of these factors are likely to enhance the adaptive capacity of the region. Adaptation to climate change for plantations will rely on traditions of existing management and this is well established in this region. On the other hand, the coastal location and high urban population could create greater competition for land that would otherwise be suitable for conservation, restoration or new plantation industries.

Forest vulnerability Natural disasters are unpredictable and very difficult to plan for. Some of the effects of these occurrences cannot be controlled for. The possible increase in storms and cyclones is likely to have major impacts on native forest structure and composition, while presenting new disturbance pressures on plantation forests. The area supports a great deal of coast and includes areas of mangroves and wetlands. These unique environments will be highly vulnerable to sea level rise. Large areas of agriculture and urban settlement will make the area very vulnerable to weed invasions.

Adaptation actions for the future Existing plantation areas may need to make adjustments in the species selected for planting to optimise growth under new climates. Extended and new regimes for the control and management of weeds are likely to need to be adopted in response to new weed threats in all forest types. Landscape scale planning to deal with competing land pressures demands would maximise outcomes for social, economic and conservation needs.

8.6 Temperate Sub-humid Woodland

8.6.1 Present

Climate and land-use The Temperate Sub-humid Woodland region is situated on the western slopes of New South Wales. It currently experiences cool winters and moisture limited summers although the moisture index is moderately high year round. Growth is particularly strong in spring and autumn while growth in summer is moisture limited and winter growth is temperature limited. Land use in the region is dominated by grazing and cropping.

Forest types Nature reserves and state forests make up about 2% of the region. There are a limited number of plantations in the region.

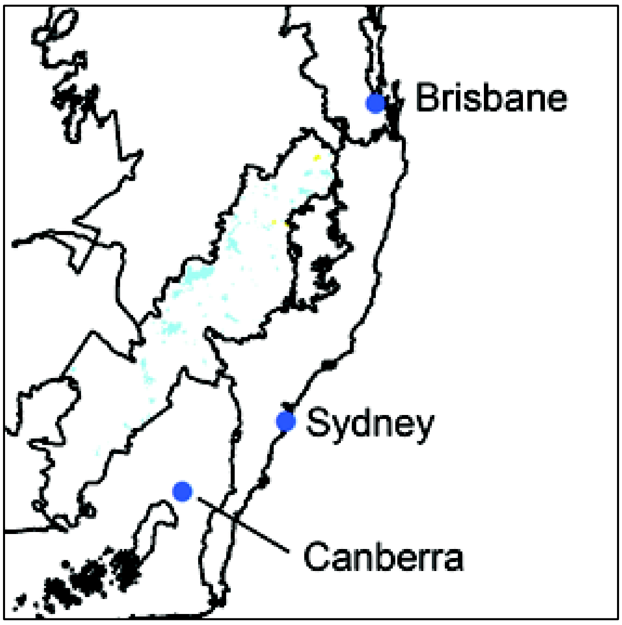


Figure 8.15 The Temperate Sub-humid Woodland region with areas of conservation forest (blue areas) and plantations (yellow areas) where present. Source: ABARE-BRS.

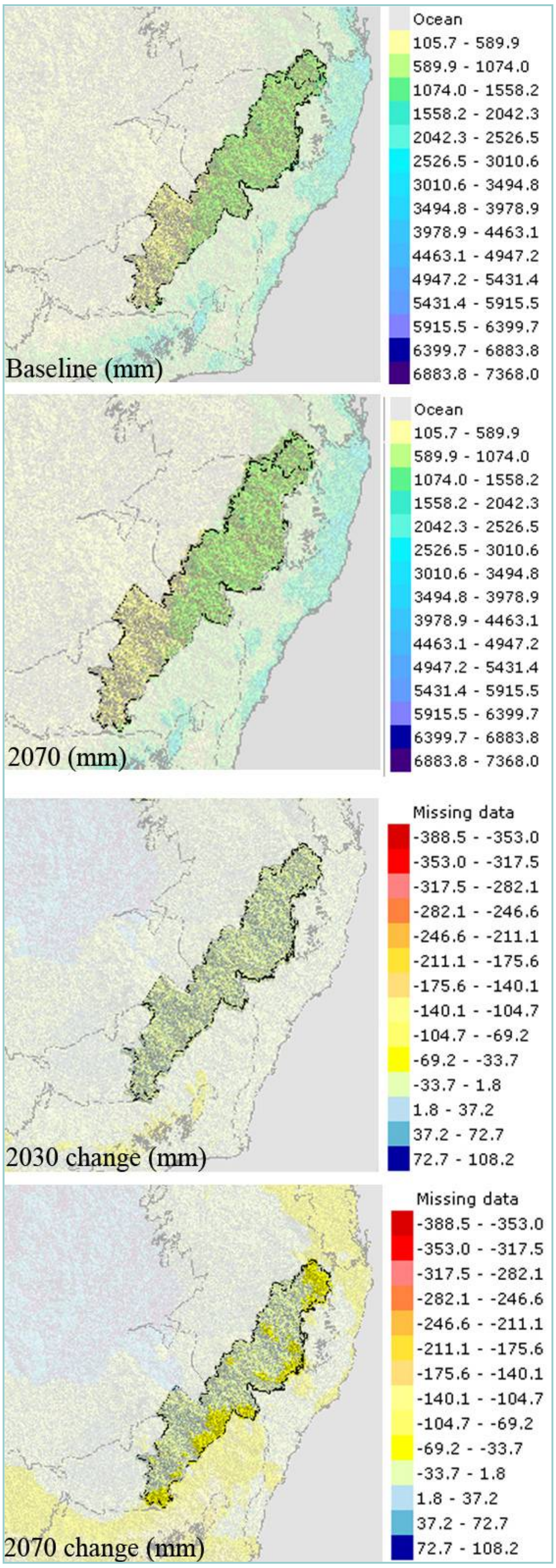


Figure 8.16 Scenarios of total annual precipitation in the Temperate Sub-humid Woodland region in 2070 with the change in rainfall totals between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

Table 8.5 A brief description of the Temperate Sub-humid Woodland region.

Description	Region	Temperate sub-humid woodland
	Climate & growth	Cool winter and moisture limiting summer. Moisture Index moderate to high year-round; Growth Index high in spring to autumn. Most plant growth in summer, although moisture limited; temperature limits growth in winter.
	Where	NSW western slopes
Landscape characteristics	Ecosystem function	Summer growth dominant (but moisture limited); winter growth temp limited
	Climate extremes	Cool/cold winter, frosts; warm summer; drought
	Disturbance	Drought & infrequent fire; extensively cleared & fertilised in parts; grazing; salinity, acidification, erosion
	Land-use	Intensive grazing, summer and winter cropping; irrigation
	Soil	Continuous topographic diversity; rolling hills, gullies, gorges. Soil water important for spring growth. Soils mainly yellow, brown or red duplex clays, and massive earths.
	Water availability	Many wetlands, permanent rivers; farm dams important
	Vegetation	Mainly woodlands, some grasslands and forests
Forest type	Plantation/farm forestry	Very minimal
	Productive native forests	Private holdings
	Conservation native forests	Small proportion of area
	Environmental plantings	Unknown
Governance	Policies	No RFA
	Legislation	*Plantations and Reafforestation Act 1999*; *Plantations and Reafforestation (Code) Regulation 2001*

8.6.2 Climate change vulnerability

Climate exposure

The scenarios used for the project show an increase in summer rainfall, winter drying with an overall reduction in rainfall for the Temperate Sub-humid Woodlands region. Temperatures increased steadily across time, with temperatures increasing by as much as 4ºC by 2070. A projected decrease in the number of days with temperatures less than 0ºC would be expected to result in less frost days in this area.

System sensitivity

There is extremely limited evidence of growth response to climate change and elevated CO_2 in this region. Pot trials of *E. sideroxyon* showed increased growth but no change in stomatal conductance under elevated CO_2 trial (Ghannoum et al., 2010).

There is potential for increased plant growth in summer due to increased moisture availability although how increasing temperatures and evaporation rates will interact with that is unclear. Warmer temperatures in winter could also prompt greater growth at this time of year, although again how this will interact with less water availability is unclear. On nutrient rich soils, elevated CO_2 could potentially increase plant productivity.

Production of *Pinus radiata* in plantations areas of the southern part of the region are likely to decrease unless there is significant benefit from elevated CO_2 or adaptation options in place (Battaglia et al., 2009).

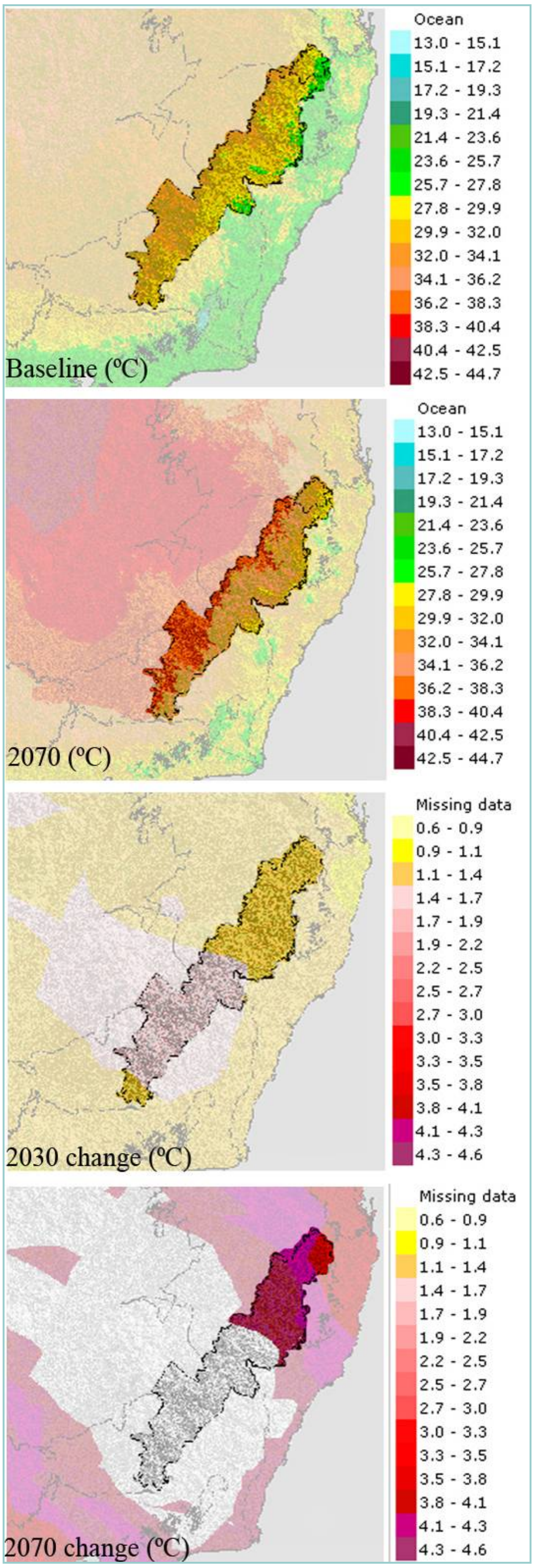


Figure 8.17 Scenarios of mean maximum February temperatures for the Temperate Sub-humid Woodland region in 2070 with the change in temperature between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models

The area currently has a low natural fire frequency. Greater growth and dry conditions could increase fuel loads and generate fire risk conditions. Any fires would have a major impact because species in this region are generally fire intolerant.

Weeds will be a key threat in this region, with improved growing conditions (particularly for frost sensitive species), migration of and improved growing conditions for more northerly species, and existing land degradation. Any increased fire management activities would have the potential to spread and encourage weed establishment.

Limited conservation areas may mean existing biodiversity values will be highly vulnerable under climate change. Environmental plantings could aim to balance carbon sequestration demands and biodiversity values.

Fewer frosts may also increase or improve growing seasons and allow the establishment of more tropical species that are generally limited by frosts. Recent evidence suggests that eucalypts may be more susceptible to frost under elevated CO_2 because leaf temperatures rise when stomata close under elevated CO_2, reducing frost hardiness (Barker et al., 2005, Loveys et al., 2006). The few frosts that do occur have the potential to have a severe impact on plants that have not acclimated to cold temperatures.

Socio-economic Extended growing seasons may make this area suitable for tree growing, although species selection will be critical and will need to consider changing climate conditions into the future. There is an opportunity in this region to expand plantation forestry operations. This will require regional adjustments to this expanding industry and the change of other industries. Careful planning will be required to facilitate the transition of land use. This also contains areas that are attractive to the tree-change landholders who have an interest in aesthetic and conservation forests. Both these opportunities will increase competition for land-use.

Adaptive capacity The Temperate Sub-humid Woodland region has an existing forestry industry and the experience and corporate knowledge of this industry should improve the adaptive capacity of the sector in managing plantations into the future. There are however limited conservation reserves, a number of existing disturbances and considerable fragmentation of native vegetation. These factors will weaken the adaptive capacity of the area with the greatest negative consequences for remnant native forests and their associated fauna.

Forest vulnerability The Temperate Sub-humid Woodland region already experiences a number of land degradation issues including salinity, acidification and weeds. These problems could be compounded under climate change and could require extensive resources to deal with them. The native forests of the region are likely to be highly vulnerable to climate change impacts.

Adaptation actions for the future This area has considerable opportunities to expand and enhance its timber production activity under future climate scenarios. Investment would be required in determining the best species for future climates and markets including investment in growth modelling plus planning for the processing of timbers for any expansion of the timber industry.

For the native forests, there is an urgent need to investigate how to optimise conservation values and ecosystem services. Actions may include investment in strategically selected reserves, conservation corridors, increased investment in management of native forests including minimising existing disturbance factors and planning for future threats.

8.7 Subtropical Moist Forest

8.7.1 Present

Climate and land-use The Subtropical Moist Forests are found on the east coast of southern Australia from south-east Queensland to the NSW-Victoria border. In this area, both the moisture index and growth index are moderate to high year-round, with both indices lower in winter in southern regions and lower in spring in northern regions (Hobbs and McIntyre, 2005). The area has been extensively logged or cleared for farming, horticulture, intensive grazing, forestry or cropping as well as coastal urban development.

In addition to the widespread presence of eucalypt forests, this region supports a unique vegetation type – subtropical rainforest. This forest type is unique to the east coast of Australia and is a remnant of larger, once continuous rainforested areas in Australia's geological history. The subtropical rainforests support a highly diverse flora and fauna with high levels of endemism. Large areas of the region, particularly the rainforest areas, are now preserved in conservation areas and under World Heritage Area listing. There are also small pockets of heath and mangroves, salt marshes and wetlands along the coast.

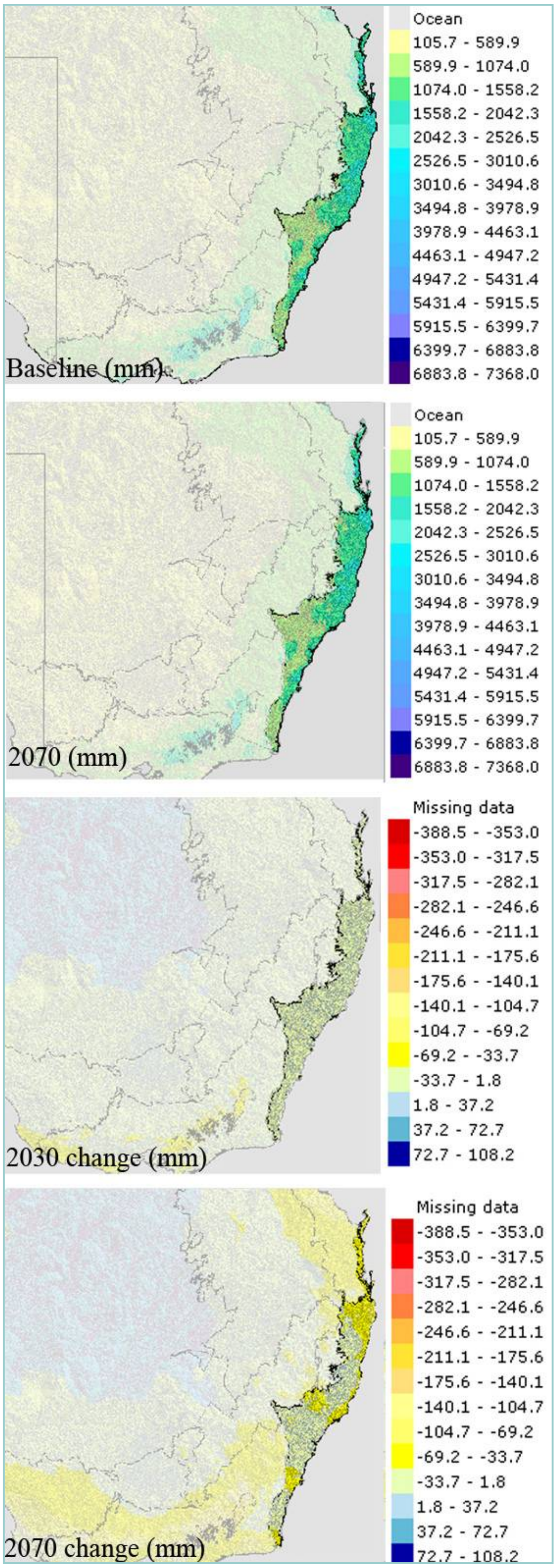


Figure 8.18 Scenarios of total annual precipitation in the Subtropical Moist Forest region in 2070 with the change in rainfall totals between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

Forest Types The area currently supports a number of plantations with typically softwood plantations in the south and hardwood plantations in the north. A number of State forests are still subject to logging, particularly in the south. There has been a change in the composition of the forestry industries with the southern half moving from native forests to a high level of softwood plantations that supply a range of processing activities and an expansion of conservation reserves in the north. There are a large number of conservation reserves.

The region also supports a high population and is a strong economic growth region of NSW. Both tourism and forestry are major industries in some areas of this region.

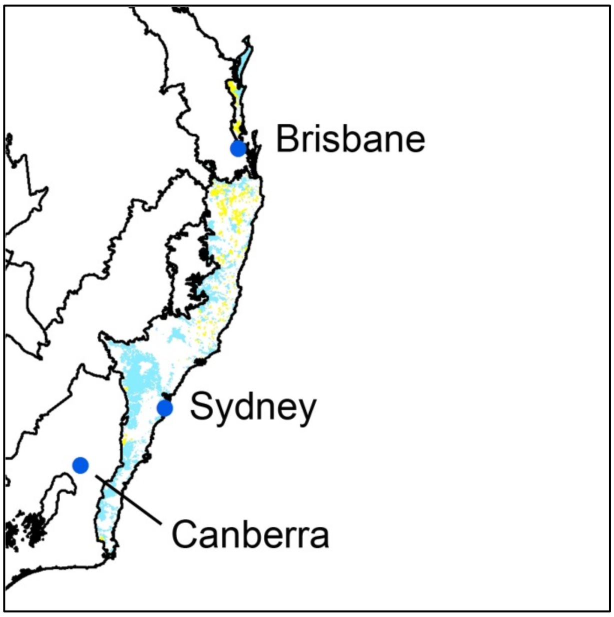


Figure 8.19 The Subtropical Moist Forest region with areas of conservation forest (blue areas) and plantations (yellow areas) where present. Source: ABARE-BRS.

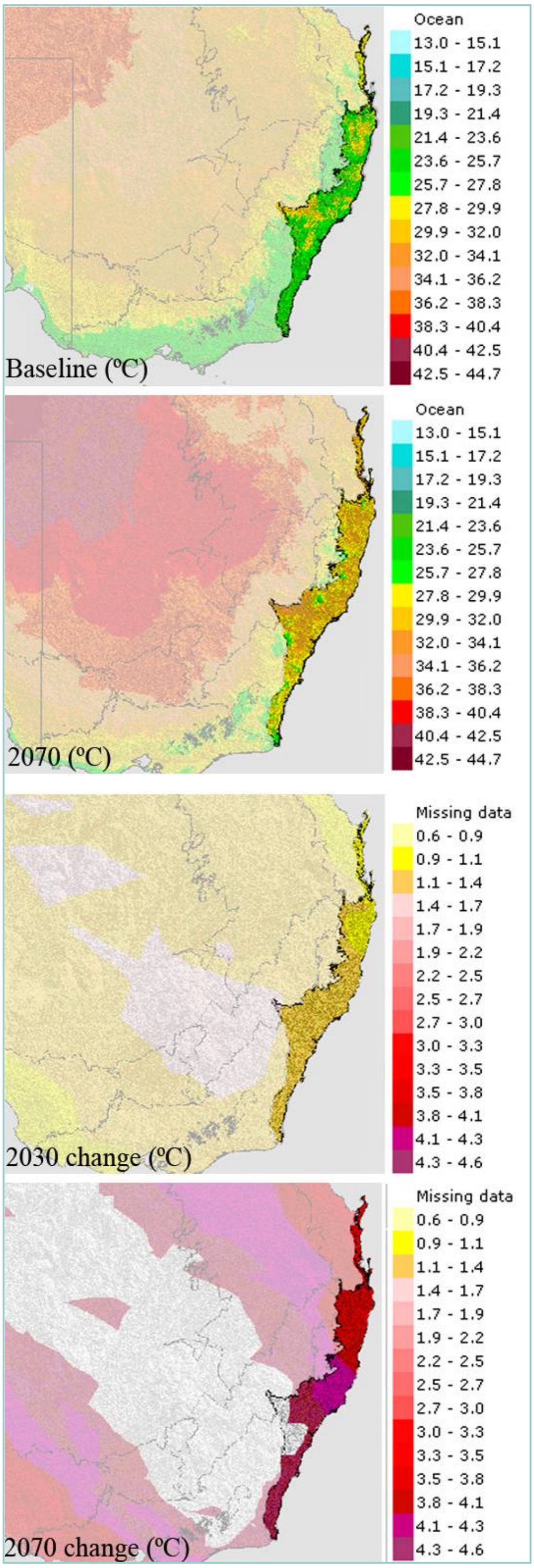


Figure 8.20 Scenarios of mean maximum February temperatures for the Subtropical Moist Forest region in 2070 with the change in temperature between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models

8.7.2 Climate change vulnerability

Climate exposure

Our scenarios of future climate show an increase in temperatures in this area but less so than inland locations. Rainfall increases are projected for both summer and autumn. Additional climate modelling has predicted more intense rainfall and storms, more damage, more flooding and storm surges for this coastal area. This will mean greater variability in water availability with the area likely to expect both flood and drought. Along with sea-level rise, coastal inundation of mangroves, wetlands and salt marshes.

Table 8.6 A brief description of the Subtropical Moist Forest region.

Description	Region	Subtropical moist forest
	Climate & growth	Moisture Index and Growth Index moderate to high year-round. Both indices are lower in winter in southern regions and lower in spring in northern regions.
	Where	Coastal southern-Qld and NSW (climate is more temperate in southern NSW)
Landscape characteristics	Ecosystem function	Year round growth
	Climate extremes	Periods of high rainfall and drought
	Disturbance	Urban development, cropping, grazing, fire, drought, flood
	Land-use	Horticulture, intensive grazing, forestry, cropping, coastal urban development
	Soil	Coastal plains and hills. Shallow loams, structured earths and yellow, brown or red clay duplex soils.
	Water availability	Groundwater locally important in some areas, surface water available in many perennial wetlands, and rivers, however flows are highly variable with local rainfall in small catchment some locally important groundwater sources.
	Vegetation	High diversity. Mainly eucalypt forests, smaller areas of rainforest and heath. Mangroves, salt marshes and wetlands along the coast.
Forest type	Plantation/farm forestry	Important industry
	Productive native forests	Ongoing, but withdrawal of operations from some areas
	Conservation native forests	Highly significant conservation areas
	Environmental plantings	Some local efforts to regenerate and revegetate the “Big Scrub” area
Governance	Policies	Northeast NSW Regional Forest Agreement; Southern NSW Regional Forest Agreement; Climate Change Action Plan for Forestry (Qld)
	Legislation	Forestry Act 1959 (Qld), Nature Conservation Act 1992 (Qld); Coastal Protection and Management Act 1995 (Qld); Plantations and Reafforestation Act 1999 (NSW); Plantations and Reafforestation (Code) Regulation 2001 (NSW)

There is some experimental and modelling evidence of plant growth response to climate change in this region:

- *E. grandis* is a community dominant species of this region. In *E. grandis*, there was no growth response in unfertilised trees but a strong growth response in fertilised trees grown under elevated CO_2 (Diogo, 2002). *E. grandis* seedlings grown at high temperatures from 10 to 35°C for 19 weeks had an increase in wood density of 20% (Thomas et al., 2007).

- *E. tereticornis* showed an increased growth and improved water conductance under elevated CO_2 when drought affected.

- At the Hawkesbury Forest Experiment, carbon and water fluxes were measured on twelve *Eucalyptus saligna* trees in whole tree chambers under ambient and elevated CO_2, and high and low water treatments. Results showed that under elevated CO_2 stomatal conductance decreased, the rate of water use was lower, and water use efficiency increased.

Increased growth is likely, particularly summer growth, in the southern half of the region. Areas of high nutrients could experience increased productivity under elevated CO_2 as well as increased water efficiency that would allow maintenance of growth in low moisture availability periods. Warmer temperatures may also increase wood density.

Extended dry periods will increase the drought risk in the region. In a *Eucalyptus maculata* forest in Kioloa, NSW, severe drought risk was quantified. Foliage retained normal appearance above pre-dawn leaf water potential of -3 MPa but became dull and obviously wilted in the range of -3 to -5 MPa, and was severely wilted and turned brown (mortality) below -5 MPa (Pook, 1986).

New and emerging threats are likely to be fire and the spread of new exotic species into the area. For example, in the Blue Mountains (near Richmond), there are on average 13.3 days when the Forest Fire Danger Index is “very high” or “extreme”. This is predicted to increase to 13.8 - 16.3 days by 2020 and 14.5 - 23.6 days by 2050 (Lucas et al., 2007). The bushfire season may also lengthen from the current duration of early October to mid-January to late July to mid-February by 2050 (Lucas et al., 2007). A 7 - 35% increase in the frequency of unplanned fires could cause significant ecological damage (Bradstock et al., 2008). In the region there are many fire-adapted ecosystems, but also many fire sensitive ones (wet sclerophyll and rainforest) in gullies and other wetter microhabitats. Hughes (2003) suggests that rainforest in this area may be converted into eucalypt forest and grassland, mainly due to changes in land use, fire regimes and climate change.

Production of *Pinus radiata* in plantation areas of the southern part of the region are likely to decrease unless there is significant benefit from elevated CO_2 or adaptation options in place (Battaglia et al., 2009).

Changes in vegetation structure may occur either through increased growth or increased fire. Increased warming could affect species distribution and survival with the most vulnerable species being those cool weather, moisture dependant species that are primarily found at high altitudes and those at the edge of their range (e.g. southern specialists). Correlated to this is the possible expansion of tropical species into the region and expansion of lowland species into high altitude areas. There is a great deal of potential for increased weed spread and success due to agricultural and human settlement and fragmentation. Local and exotic species are expected to re-sort with improved growing conditions. Increased fire management will have potential to spread and encourage the establishment of weeds.

Existing weed species may respond with an expansion of their distribution, such as is expected for *Echium plantagineum, Asparagus asparagoides, A. athiopicus* and *Equisetum arvense.*

Socio-economic Land use change is likely to occur under competing demands for urban expansion tree-change settlement and changing land use (e.g. expanding plantation industry). The forestry industry will need to change species selection and management options to ensure the ongoing profitability of the industry.

Changing growing conditions will require careful species selection for establishing new plantations to ensure tolerance of changing conditions. Existing plantations, particularly recently established plantations, are likely to be the most vulnerable to changing climates, dependant on species selection. Any at the edge of their tolerance would be severely affected.

Adaptive capacity This region already has a strong tradition of forestry and conservation that will increase the adaptive capacity of these forest sectors. In the production forestry sector, there is already a history of adaptation and change with the industry moving from softwood plantations to hardwood in recent years. The successful transition of the industry indicates a strong adaptive capacity. The region does, however, feature some highly vulnerable ecosystems and this will reduce the adaptive capacity of the conservation sector.

Forest vulnerability The greatest vulnerability in this region is the possible loss of high value biodiversity and the tourism activities relying on it. The subtropical rainforests of this region are very unique forest type with a very high diversity of plant and animal species. Many areas rely on particular climate conditions to survive and the change of some these conditions are likely to jeopardise the survival of some of these species. In addition, some areas are already refugia of a geologically past climate, and are likely to support some of the most vulnerable species. There is likely to be considerable land use competition from urban development, agriculture and conservation.

Adaptation actions for the future This area will experience a number of competing land use demands – from urban settlement, farming activities, plantations and conservation. Considerable investment in future land-use planning is required for this region. Planning should focus on establishing the future distribution of vulnerable forest types and the potential for refugia to support them. In addition, the potential for new forest based industries and demands for urban settlement will need to be considered.

8.8 Temperate Moist Forest

8.8.1 Present

Climate and land-use The Temperate Moist Forest region is located in the southeast corner of the Australian mainland and northeast corner of Tasmania. It experiences a cool wet climate with a high moisture index in winter-spring, and moderate in summer. The growth index is highest in spring (Hobbs and McIntyre, 2005). The region experiences regular drought and fire.

The land has been extensively cleared and fertilised for grazing, dairy and cropping.

The vegetation is diverse with a diverse topography from high tablelands to coast. There are large areas of forest and woodland, and smaller areas of grassland in the region.

Forest type Forestry is an important industry in the area with large areas of both softwood and hardwood plantations. There are also a number of conservation areas (Figure 8.22). The area comes under several Regional Forest Agreements. Under these agreements, there was an incorporation of more areas into conservation, but provision for greater economic certainty in the forestry industry.

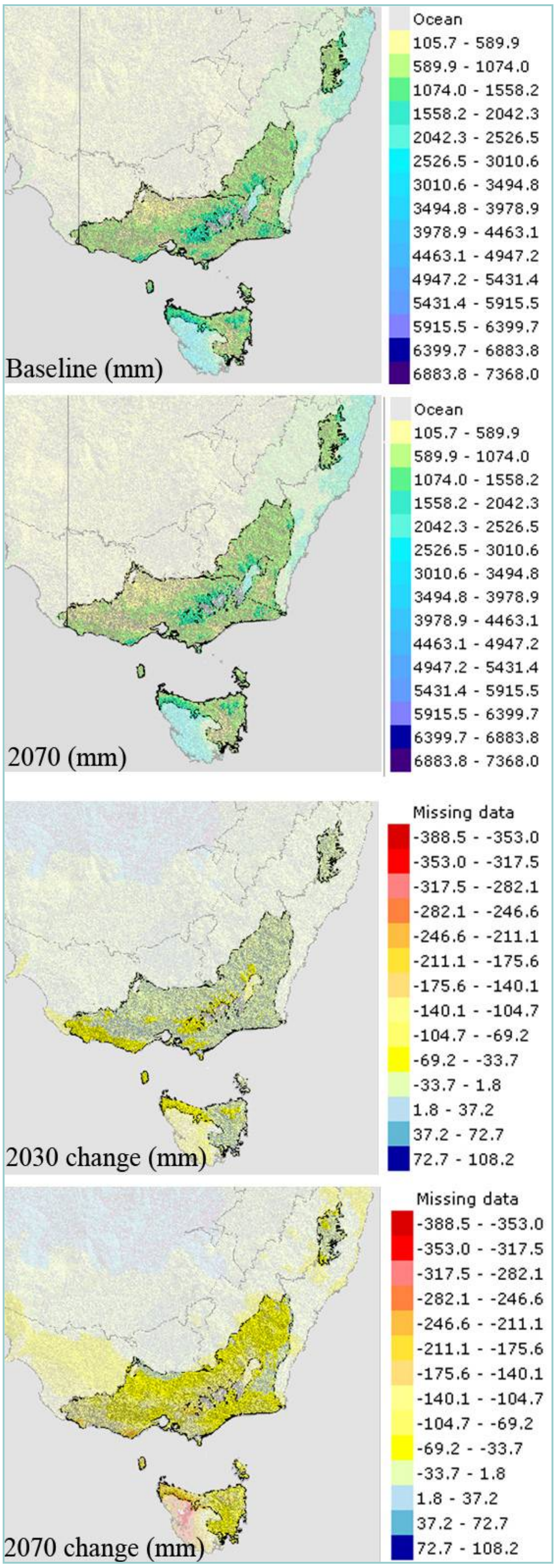


Figure 8.21 Scenarios of total annual precipitation in the Temperate Moist Forest region in 2070 with the change in rainfall totals between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

Table 8.7 A brief description of the Temperate Moist Forest region.

Description	Region	Temperate moist forest
	Climate & growth	Cool wet climate; Moisture Index high in winter-spring, mod. in summer; Growth Index high in spring.
	Where	Tasmanian lowlands, southern, central and eastern Victoria; southern and northern NSW tablelands
Landscape characteristics	Ecosystem function	Cool, high rainfall, high winter-spring growth, regular fire
	Climate extremes	Cool wet winter, frost. Hot summer; drought
	Disturbance	Regular drought and fire. Extensively cleared and fertilised for grazing; forestry, horticulture; regular fire; salinity
	Land-use	Forestry; sheep, beef, dairy; horticulture; cropping; urban development
	Soil	Mainly yellow, brown or red duplex clay soils, with structured earths
	Water availability	Many wetlands and rivers. Many farm dams. Important local groundwater
	Vegetation	Diverse; topographically diverse: high tablelands to coast. Large areas of forest, woodland, and smaller areas of grassland
Forest type	Plantation/farm forestry	Widespread, important and expanding industry
	Productive native forests	Harvesting still occurring
	Conservation native forests	Numerous smaller patches of forest
	Environmental plantings	Unknown
Governance	Policies	Tasmanian RFA; Gibbsland RFA; East Gibbsland RFA; Southern NSW RFA; West Victoria; Central Highland RFA, North East Victoria RFA
	Legislation	Plantations and Reafforestation Act 1999 (NSW); Plantations and Reafforestation (Code) Regulation 2001 (NSW);Forestry Act 1916 (NSW); Forest Act 1958 (Vic); Conservation, Forests and Land Act 1987 (Vic); Forestry Rights Act 1996 (Vic); Sustainable Forests (Timber) Act 2004; Forestry Act 1920 (Tas); Forest Practices Act 1985 (Tas); Private Forests Act 1994 (Tas); Tasmanian Regional Forest Agreement Act 1997 (Tas)

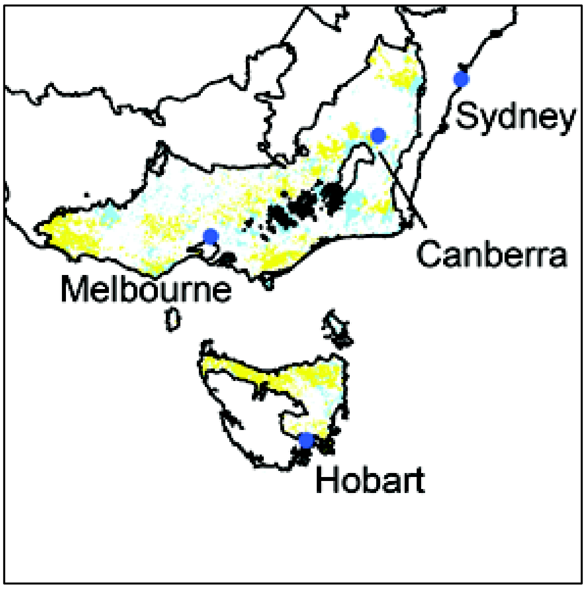


Figure 8.22 The Temperate Moist Forest region with areas of conservation forest (blue areas) and plantations (yellow areas) where present. Source: ABARE-BRS.

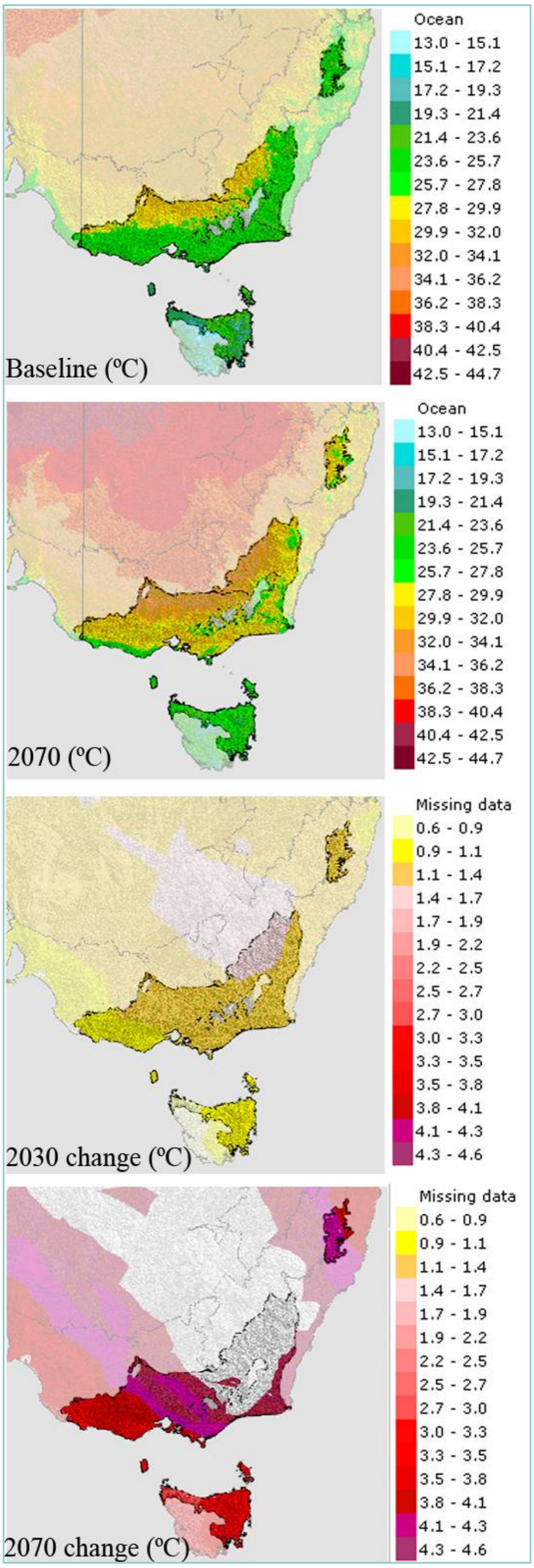


Figure 8.23 Scenarios of mean maximum February temperatures for the Temperate Moist Forest region in 2070 with the change in temperature between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

8.8.2 Climate change vulnerability

Climate exposure

The scenarios of future climate show this area experiencing a drier winter and spring representing a change in the seasonality of moisture. We would expect this to be accompanied by a change in growing season. Increasing sea levels will result in inundation of mangroves, wetlands and salt marshes.

System sensitivity

There is some experimental and modelling evidence of the effects of moisture, temperature and elevated CO_2 on plant growth from species in this region.

- Production of *E. globulus, E. nitens* and *Pinus radiata* in this area could increase, particularly if increased production as a result of elevated CO_2 is realised (Battaglia et al., 2009).
- *E. tereticornis* experienced increased growth and improved water conductance experimentally under elevated CO_2 under drought conditions.
- *E. pauciflora* demonstrated a 45% reduction in stomatal conductance (but no change in stomatal density) under elevated CO_2 and reduced water.
- In the Tasmanian FACE experiment, rising CO_2 was found to negatively impact on production of the major C3 grass species, favouring the C4 species (Williams et al., 2007).

There is some indication from these results that plant growth is likely to increase in this region and water efficiency could improve.

Fewer frost days will have an important influence on plant success, although there is mixed evidence:

- Battaglia et al., (2009) predict increased productivity for *Eucalyptus* plantations in Tasmania due to fewer frost events.
- Recent evidence suggests that eucalypts may be more susceptible to frost under elevated CO_2 because leaf temperatures rise when stomata close under elevated CO_2, reducing frost hardiness (Barker et al., 2005, Loveys et al., 2006).
- An expected increased vulnerability of *E. pauciflora* frost damage and higher mortality than occur in current conditions (Woldendorp et al., 2008).
- A reduction in the number of frost events is likely to allow upwards expansion in the range of *E. pauciflora*, as has been observed by Wearne and Morgan (2001). Similarly, *E. delegatensis* and *E. dives*, normally excluded from higher elevations due to better frost tolerance by *E. pauciflora*, may also expand their ranges into areas previously dominated by *E. pauciflora* (Bell and Williams, 1997).

Reduction of frost days may allow expansion of some species, but the occurrence of occasional frost events could have a severe impact on species.

Increased dry periods have the potential to create drought stress in plants. There is some evidence of responses in this region to dry conditions:

- *E. globulus*, are adapted to short periods of drought stress, although prolonged periods of drought stress lead to mortality (Mendham et al., 2005).

- A plantation study comparing water relations of *E. nitens* and *E. globulus* reported that pressure-volume curves and leaf water potential data indicated that *E. globulus* had greater drought tolerance than *E.. nitens* (White et al., 1996).

- Growth, conductance and assimilation of *E. nitens* and *E. globulus* decreased when pre-dawn leaf water potential fell below ~ -0.5 MPa (White et al., 1996).

- Horner et al., (2009) showed that drought mortality of *Eucalyptus camaldulensis* plantations in Victoria was high in high density stands, whereas low density stands were relatively unaffected by drought.

This evidence suggests that response to drought will be species specific, but in the case of plantation management (i.e. species selection, density of planting) can reduce drought stress problems. Lunt et al., (2010) used information from Australia's National Carbon Accounting System to quantify changes in woody vegetation cover from 1989 to 2005 in native woodlands across Victoria. They found consistent increases of 5 to 9% in woody cover in all ecosystems examined as a result of recent land management practices. Of interest to this assessment is their observation that protracted drought in the last decade did not appear to have reduced woody cover, despite declining forest health observed in riverine woodlands (Cunningham et al., 2007, Cunningham et al., 2009).

Species distributions might change in response to altered climate. In this southern region it could mean the loss of southern restricted species. Alpine species in particular are expected to be lost, eventually. A study on the Victorian Central Highlands used bioclimatic modelling, combined with a semi-mechanistic species distribution model to identify the vulnerability of the regeneration niche of forest species to climate change (Nitschke, 2007). Results showed narrow climatic breadths of the species studied. He concluded that an increase in mean annual temperature of 1.4°C and a decline in precipitation by 5% would be sufficient to cause a significant contraction in 20 species regeneration niches and significant changes in the size and location of species potential ranges.

Kirschbaum (2000) modeled net primary productivity of *Pinus radiata* plantations under climate change and concluded that as temperatures become supra-optimal, productivity will decrease despite an increase in available CO_2, with decreasing rainfall. On balance, the productivity of radiata pine plantations would be expected to decrease in this region.

Fires are likely to be more frequent and intense. Increased fire will be a major issue, both for currently fire-prone and non-fire-prone areas, affecting structure, function and composition. Fire favours shrubs and forbs/grasses.

Research from catchments dominated by mountain ash forests in Victoria shows that in the years and decades after fire, forest growth recovers and stand water use increases, leading to a level of runoff that can be significantly lower than before the fire event (Vertessy et al., 2001, Vertessy et al., 1998, Marcar et al., 2006). In the centuries following, water use and runoff return to pre-fire levels. The potential for changes in fire frequency could alter vegetation composition and structure. Biodiversity values in particular, are at greatest risk from fire.

Warmer climate species are likely to establish, potentially creating new or worsening weed problems. The area will be particularly vulnerable to this due to the highly fragmented landscape and variety of land uses and therefore source of material. Climate changes could signal an increase in summer growing natives such as dominant C4 species and native legumes (warm season growers) and more frost sensitive species. In contrast, drier autumns and winters could disadvantage winter growing annuals, which are a major category of weed in this region e.g. *Leycesteria formosa*, *Buddleja davidii, Billardiera heterophylla* and *Cotoneaster glaucophyllus*.

In a 30 year study of *Phytophthora cinnamomi*, Weste (2003) found the disease declined in low rainfall years in open eucalypt forest and woodlands of southern Victoria and this may be an ongoing trend with increased drying.

Socio-economic The Temperate Moist Forest region has strong economic industries tied to its forests. For example, Gillespie Economics (1997) estimated expenditure on recreation and tourism visits to forested lands in the Eden Regional Forest Agreement (RFA) region in the range of $10 - $15million/yr based on a “macro” approach. Changes in the vegetation composition, species suitable for timber industries, new demands for non-timber industries and increasing management costs will all have socio-economic impacts in this region. Some adaptation efforts already exist in the region with Biolinks (a conservation connectivity programme) adopted by Victoria (2009) and changes in the forestry industry adopted with the RFA process. In these regions there is strong evidence of “transition landscapes” (Barr, 2008, Mendham and Curtis, 2010), with the conversion of land from relatively intensive agricultural use to boutique or semi-subsistence production and lifestyle uses.

Adaptive capacity Much like nearby regions, the Temperate Moist Forest region has a strong tradition of forestry and conservation that will increase the adaptive capacity of these forest sectors. In the production forestry sector, there is already a history of adaptation and change with the industry moving from softwood plantations to hardwood in recent years. The successful transition of the industry indicates a strong adaptive capacity. The region does, however, feature some highly vulnerable ecosystems that are largely fragmented. This will reduce the adaptive capacity of the native forest and conservation sector.

Forest vulnerabilities Fire is likely to be a significant threat to both biodiversity and forest land use. The region has significant fire management issues and how it adapts and responds will be extremely important. The area is already highly fragmented and the environmental problems associated with this will be exaggerated by climate change. Ecosystems that are already very vulnerable are likely to face even greater challenges under climate change

Adaptation actions for the future Planning for change will be important in this region. As part of this, new fire management plans will be needed. In addition land use planning that considers conservation of forests under a future climate and for changed forest industry (e.g. new species, new products, new markets) will be essential to minimise risks under climate change.

8.9 Cold Forest and Grassland

8.9.1 Present

Climate and land-use The Cold Forest and Grassland region is represented by the Tasmanian highlands to the south west of the island and the Victorian and NSW alpine areas. The region is characterised by cold winters with short summers warm enough to support significant growth. The area has snow present during winter while summer can experience water stress in some areas. Land clearing has been very limited. The main land uses are tourism, recreation, dams, water harvesting, hydroelectricity, some grazing and conservation. High intensity fires and prolonged drought have been experienced in some areas of this region in the past.

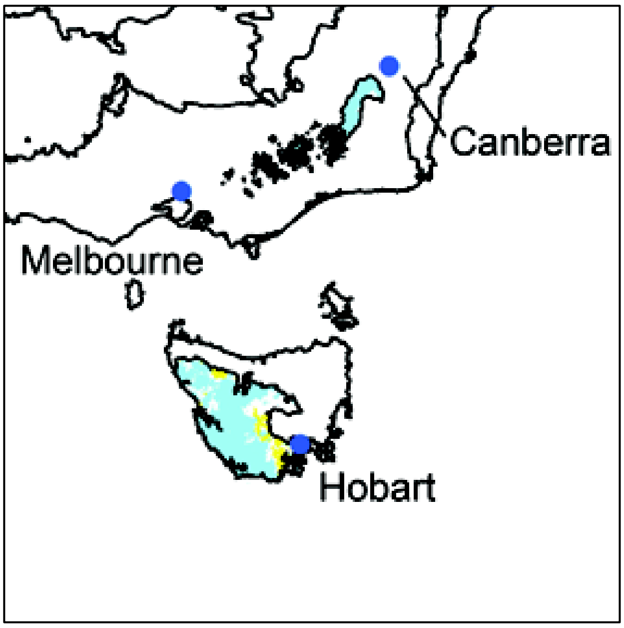


Figure 8.24 The Cold Forest and Grassland region with areas of conservation forest (blue areas) and plantations (yellow areas) where present. Source: ABARE-BRS.

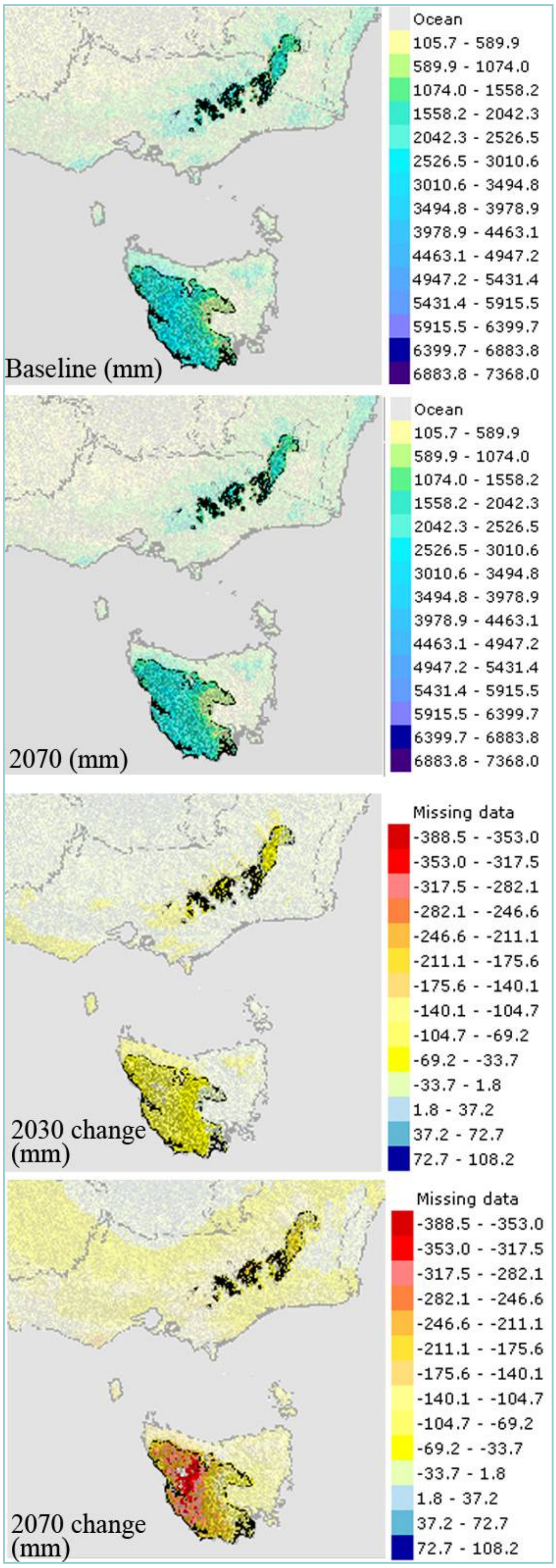


Figure 8.25 Scenarios of total annual precipitation in the Cold Forest and Grassland region in 2070 with the change in rainfall totals between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

Table 8.8 A brief description of the Cold Forest and Grassland region. Modified from Brown and Dunlop (2009).

Description	Region	Cold forest and alpine grassland
	Climate & growth	Cold winters with short summers warm enough to support significant growth
	Where	Tasmanian highlands and Victorian and NSW alpine areas
Landscape characteristics	Ecosystem function	Seasonally cold, snow, high rainfall, altitude significant, seasonal migration
	Climate extremes	Cold, snow, frost, wet spring, summer water stress in some areas
	Disturbance	Very infrequent fire, forestry, some grazing in lower areas
	Land-use	Resorts, tourism, recreation, dams, little land clearing, water harvesting, hydroelectricity, tourism and conservation
	Soil	Diverse topography. Soils mainly yellow, red or brown duplex clay soils, with duplex soils containing much ironstone and gravel
	Water availability	Snow in winter and bogs and fens store much water providing year round flows; wetlands and significant rivers, recreation water harvesting
	Vegetation	Alpine meadows, shrub-lands, woodlands, forest to rainforest in Tasmania
Forest type	Plantation/farm forestry	Small areas, both softwood and hardwood plantations
	Productive native forests	Large areas
	Conservation native forests	Over half of area, mostly rainforest in Tasmania, but almost all of Alps area
	Environmental plantings	Unknown
Governance	Policies	Tasmanian RFA
	Legislation	Forest Act 1958 (Vic); Conservation, Forests and Land Act 1987 (Vic); Forestry Rights Act 1996 (Vic); Sustainable Forests (Timber) Act 2004; Forestry Act 1920 (Tas); Forest Practices Act 1985 (Tas); Private Forests Act 1994 (Tas); Tasmanian Regional Forest Agreement Act 1997 (Tas)

Forest Type Large areas of continuous conservation forest (more than half the region) and many unique species including alpine species are a feature of this region. Some small areas of both softwood and hardwood plantations exist in the region and considerable areas of productive native forest.

8.9.2 Climate change vulnerability

Climate exposure

Based on our future climate scenarios, Tasmania can expect increased rainfall, especially in winter while the Alps are likely to become drier, especially in winter and spring. There is some potential in the Alps for increased plant stress particularly in winter and spring due to reduced moisture availability. Temperatures will increase, with less snow cover, longer growing season and fewer frosts as a result.

System sensitivity

There is very limited evidence of plant growth effects of climate change in this region with a single study finding no clear response. *E. pauciflora* response to elevate CO_2 was: unclear, increased, no change or decreased depending on the level of environmental exposure (Barker et al., 2005, Roden et al., 1999). A modelling exercise suggested that the production of *E. globulus, E. nitens* and *Pinus radiata* in this area could increase, particularly if increased production as a result of elevated CO_2 is realised (Battaglia et al., 2009).

While warming might be expected to increase growth, increased drought or moisture-limited conditions may limit growth in some species. For example, *E. globulus*, are adapted to short periods of drought stress, although prolonged periods of drought stress can lead to mortality (Mendham et al., 2005).

A long-running eddy flux study in a native *Eucalyptus delegatensis* forest at Tumbarumba in the Snowy Mountains has similarly provided insights into effects of drought on forest carbon exchange. In this study, net ecosystem exchange of carbon has been monitored since 2001 (Leuning et al., 2005). During this period, two drought years have occurred. Net ecosystem carbon uptake, which was strongly positive in wet years, was reduced to below zero during the first drought year but unaffected in the second drought year (*pers. comm.* van Gorsel) The reduction in carbon uptake during the first drought year was ascribed to pest damage rather than direct water stress *per se* (Kirschbaum et al., 2007) but demonstrates the potential for relatively mild drought to impact significantly on forest productivity due to pest interactions.

Under future climate change scenarios, the Cold Forest and Grasslands region will experience a decrease in snow cover and the duration of snow cover. There will also be a marked reduction in frost days and this may impact on plant growth:

- Battaglia et al., (2009) predict increased productivity for *Eucalyptus* plantations in Tasmania due to fewer frost events.

- Increased vulnerability of *E. pauciflora* frost

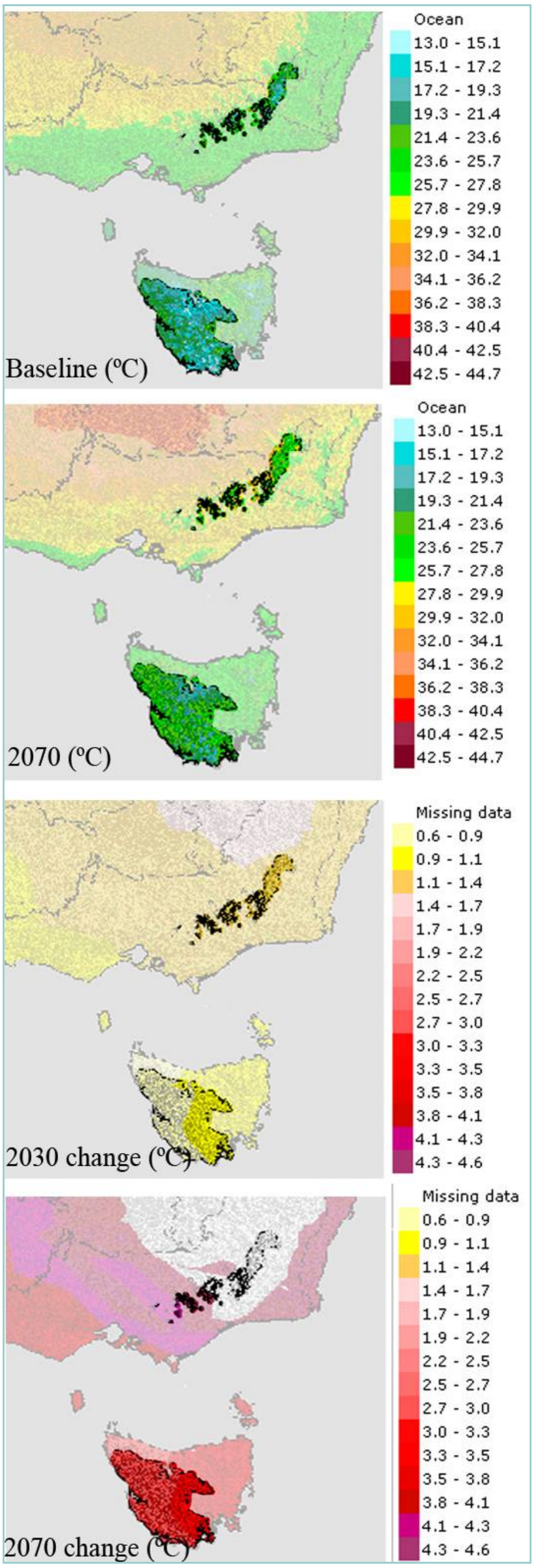


Figure 8.26 Projected mean maximum February temperatures for the Cold Forest and Grassland region in 2070 with the change in temperature between the baseline and 2030 and 2070 also shown. Projections used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

damage and higher mortality than occur in current conditions (Woldendorp et al., 2008).

- Recent evidence suggests that eucalypts may be more susceptible to frost under elevated CO_2 because leaf temperatures rise when stomata close under elevated CO_2, reducing frost hardiness (Barker et al., 2005, Loveys et al., 2006).

- A reduction in the number of frost events is likely to allow upwards expansion in the range of *E. pauciflora*, as has been observed by Wearne and Morgan (Wearne and Morgan, 2001). Similarly, *E. delegatensis* and *E. dives*, normally excluded from higher elevations due to better frost tolerance by *E. pauciflora*, may expand their ranges into areas previously dominated by *E. pauciflora* (Bell and Williams, 1997).

Distribution changes of species is also likely with warming:

- Changes in herb, shrub and tree competition will lead to structural and functional changes (e.g. changed tree lines, microclimate, hydrology) in alpine areas; and changes in the composition and ecology of grazers (e.g. expansion of mammalian grazers to areas previously dominated by insect grazers) may have very significant impacts on the composition and structure of vegetation (Hughes, 2003, Pickering et al., 2004).

- Wearne and Morgan (2001) found that *Eucalyptus pauciflora* forest had encroached into sub-alpine grasslands in Victoria's high country, and attributed this movement to rising temperatures. However, the observed shift in tree-line (5m) was much less than expected from the warming that has already occurred (Green, 2009). It is a common observation that alpine tree-lines are stable, and do not change to match changes in temperature isotherms (Grace et al., 2002). Green (2009) studied seedling establishment following wildfire in the Victorian Alps and found that tree-lines were very stable, despite removal of competing grass biomass. He suggests that there is little seed dispersal uphill, which limits the ability of seedlings to establish above the existing tree-line.

Changes in climate conditions could precipitate the loss of some high altitude species, with considerable potential to disrupt mutualisms, particularly where phenology or life cycle events are triggered by snow melt. Migration of warmer climate species into new areas is highly likely to occur, although note the stability of the tree-line as discussed above. This includes migrations and improved success of weed and pest species with improved growing and establishment conditions for non-alpine species; more overwintering species and elevational range expansion. Increased herbivore and carnivore mammal activity (e.g. brumbies, wallabies, rabbits, cats, foxes) in warmer conditions will have an impact on conservation forests.

Increased growth will produce more fuel, and warmer drier weather will increase fire risk. Based on this, the area could potentially experience more intense and frequent fires. Fire impacts include changes in vegetation composition with the loss of fire-prone species and the possible conversion of woodlands to shrublands and forblands (grassland) (Dunlop and Brown, 2008).

Socio-economic A large part of the economic sector is based on an industry that relies on specific climate conditions. The cost to tourism and the impact of this on the local economy have enormous potential for damage. Increased growing conditions are likely to improve the forestry and other industries. There is likely to be shifts in regional forestry production.

Adaptive capacity The Cold Forest and Grassland region benefits from extensive and well-managed conservation reserves with a long history of conservation. The community in these areas, especially in the highlands of New South Wales are largely built on recreational activities that rely on cold weather conditions and the natural environment. Changes to climate and the loss of some of the natural attributes of the areas have the potential to impact on communities, reducing their adaptive capacity.

Forest vulnerability The Cold Forest and Grasslands region feature some of the most vulnerable biodiversity and at least in part, an economy built on climate conditions. For many cold climate reliant species, warmer temperatures will reduce their success and they will be vulnerable to local extinction. Small areas of plantation could continue to be viable, provided species selection for future climates and markets is considered.

Adaptation actions for the future The uniqueness of this region lies in its natural features. If these change under new climate conditions, “re-branding” of the landscape is likely to be important in maintaining many of the recreation industries reliant on the forests of this area. Increased threats from fire and weeds will need to be addressed with careful planning and management. There is reasonable evidence that any plantation industries in this region can continue to expect good growth. This will rely on appropriate species choice and development of new markets for alternative species if necessary.

8.10 Mediterranean Woodland

8.10.1 Present

Climate and land-use The Mediterranean Woodland region takes in the south-west corner of mainland Australia, southern South Australia, north-west Victoria and southern NSW. The region experiences warm climates with a high moisture index in winter, and low in summer resulting in peak growth in winter and spring.

Fire is a regular event in the Western Australian, South Australian and Victorian parts of the region. Lightning is a frequent fire starter. The area also experiences regular drought.

Native vegetation is open woodland, mallee and heath.

The region has multiple land uses (e.g. cropping grazing, urban development) and has been extensively cleared as a result. There are also a number of serious environmental problems including salinity, acidification, tree pests, tree disease, many exotic species, fragmentation, and biodiversity loss. Climate change effects of reduced rainfall and increased temperatures are already apparent in this region (Williams et al., 2009b).

Forest type The timber industry plays a significant role in parts of the region, particularly Western Australia. The South West Forest Regional Forest Agreement expanded conservation areas in Western Australia as well as investing in the timber industry to develop new opportunities. There are some large areas of conservation forest in the region. Plantations have also been established in some areas.

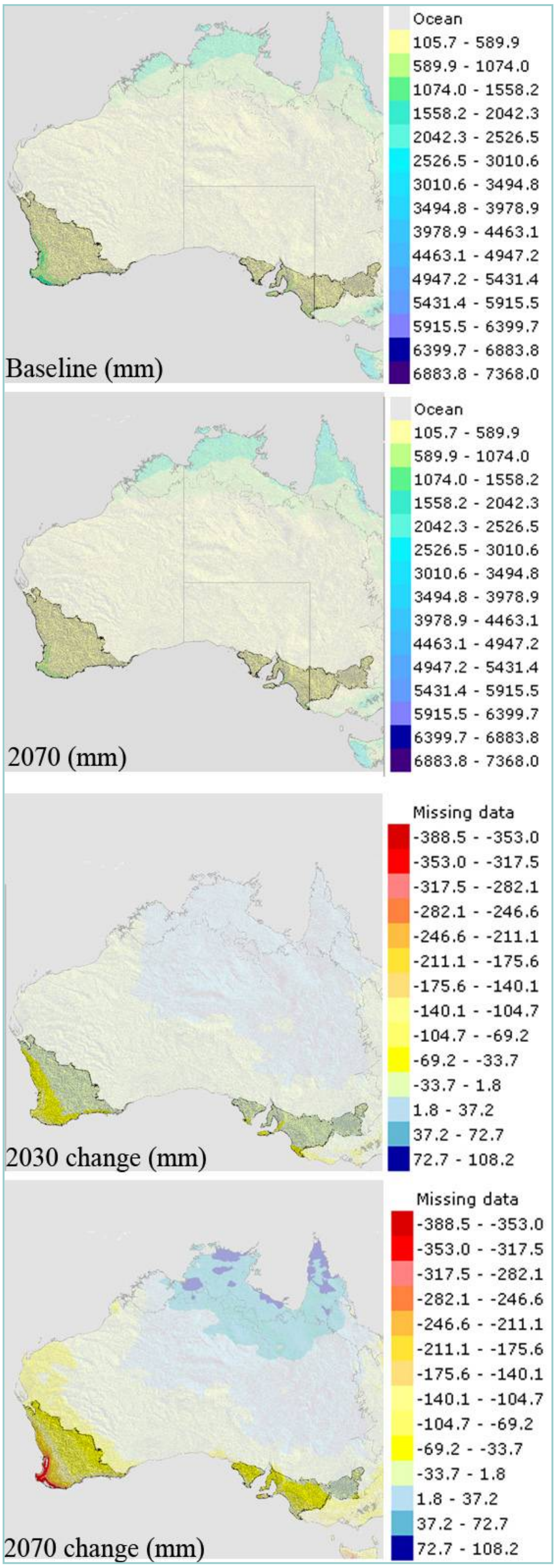


Figure 8.27 Scenarios of total annual precipitation in the Mediterranean Woodland region in 2070 with the change in rainfall totals between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

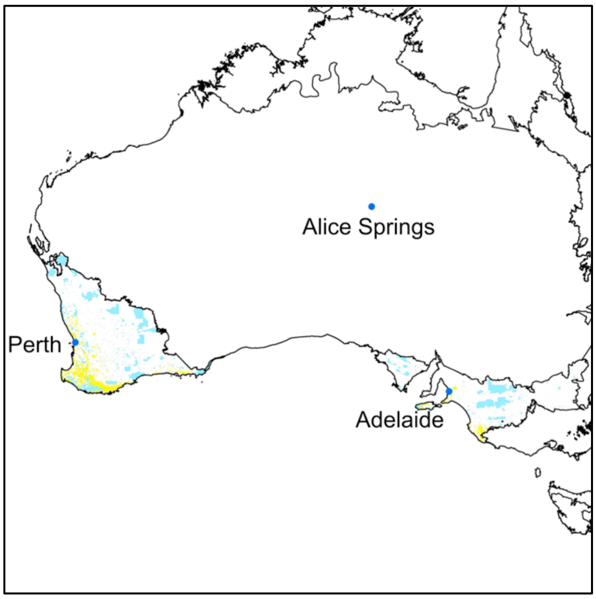


Figure 8.28 The Mediterranean Woodland region with areas of conservation forest (blue areas) and plantations (yellow areas) where present. Source: ABARE-BRS.

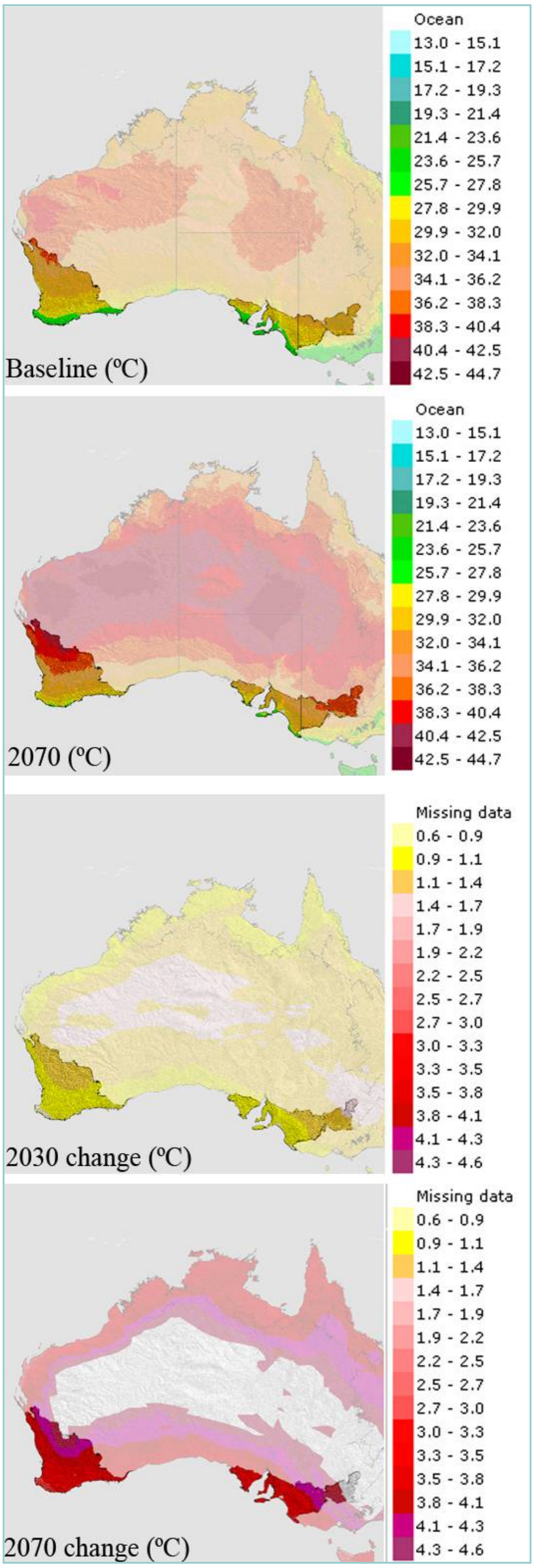


Figure 8.29 Scenarios of mean maximum February temperatures for the Mediterranean Woodland region in 2070 with the change in temperature between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

Table 8.9 A brief description of the Mediterranean Woodland region. Modified from Dunlop and Brown (2008).

Description	Region	Mediterranean Woodlands
	Climate & growth	Warm climate; Moisture Index high in winter, low in summer; Growth Index moderate in winter. Peak growth winter and spring.
	Where	Southwest WA, southern SA, north- west Victoria, southern NSW
Landscape characteristics	Ecosystem function	Winter / spring growth; warm summer; regular fire
	Climate extremes	Cool wet winters, frost; hot summers, drought
	Disturbance	Regular drought and fire. Highly disturbed. Extensively cleared and fertilised for cropping and grazing. Native vegetation grazed. Many exotic species. Salinity and acidification.
	Land-use	Cropping, sheep, beef horticulture, dairy, irrigation; forestry; urban development
	Soil	Local topography but largely flat. Soil and biogeographic history diverse. Mainly yellow, red or brown duplex soils.
	Water availability	Base groundwater flows. Many wetlands, semi-seasonal rivers; farm dams important. Soil water important for spring growth.
	Vegetation	Open forest, woodland, mallee, heath
Forest types	Plantation/farm forestry	Plantation industry
	Productive native forests	Some areas
	Conservation native forests	Very fragmented conservation reserves
	Environmental plantings	Amenity plantings to relive salinity, provide shelter belts and fauna corridors
Governance	Policies	Western Australia RFA
	Legislation	Forest Act 1958 (Vic); Conservation, Forests and Land Act 1987 (Vic); Forestry Rights Act 1996 (Vic); Sustainable Forests (Timber) Act 2004 (Vic); Forestry Act 1950 (SA); Forest Property Act 2000 (SA); Conservation and Land Management Act 1984 (WA); Forest Products Act 2000 (WA).

8.10.2 Climate change vulnerability

Climate exposure

Under the future climate scenario generated for this project, the Mediterranean Woodland region will experience less winter rainfall during what is normally the critical growing period. Temperatures will increase and the area will become increasingly drier. Coastal areas will experience saltwater inundation and sea level rise impacting on mangrove and wetland areas.

System sensitivity

Water availability is likely to be the most critical issue for plant growth and survival in this region. A large body of experimental evidence from this region demonstrates that there are water stress impacts in the region:

- A comparative study in south-west Western Australia examined jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) stands along an aridity gradient (Pekin et al., 2009). Leaf area (and standing biomass) was lower at more arid sites, while sapwood areas were unaffected, suggesting these stands respond to decreased water availability by lowering leaf area relative to sapwood area (Pekin et al., 2009).

- In *E. globulus* plantations of southwest Western Australia across a gradient in mean annual rainfall from 600 to 1420 mm, showed that although carbon isotope discrimination and basal area were strongly positively correlated with water availability, LAI was only weakly correlated with basal area (MacFarlane et al., 2004). The authors concluded that canopy conductance was a more important determinant of growth than LAI in water-limited (but fertilized) *E. globulus* plantations (MacFarlane et al., 2004). These findings are in contrast to a study which reported that LAI in fertilized *E. globulus* plantations across southern Australia increased from 3 to 6 as water stress decreased (Battaglia et al., 1998).

- Both ecophysiological modelling (Battaglia et al., 2009) and bioclimatic modelling (Booth and Jovanovic, 2005) flag plantations in south-west Western Australia as those most likely to be adversely affected by climate change due to severe reductions in precipitation.

- A modelling study conducted in south-west Western Australia, examined the trade-off between productivity and drought in *E. globulus* plantations (Mendham et al., 2005). This report showed that drought risk needs to be managed in high productivity *E. globulus* plantations, however there are several management strategies available to reduce this risk, including site selection, stocking density and reducing the amount of nutrient application (Mendham et al., 2005).

- A study in south-western Australia found that *E. kochii* trees that had shallow access to groundwater had three times higher LAI (3.2 m^2 m^{-2}) than trees over deep groundwater (1.0 m^2 m^{-2}) (Carter and White, 2009). Similarly, a comparison of biomass on two west Australian sites with the same climatic conditions showed that a restored mine site, with higher soil water and nutrient availability than the control site, had higher biomass (Bleby et al., 2009).

- A native forest stand dominated by *Eucalyptus crebra* and *Callitris glaucophylla* exhibited decreased annual stand water use (318 mm) in a drought year with reduced mean annual rainfall (522 mm, 51% of Mean Annual Rainfall, MAR), and 443 mm in a year with above average rainfall (1062 mm, 171% of MAR) (Zeppel et al., 2008). Thus, stand water use increased by 39% when rainfall almost doubled.

- Horner et al., (2009) showed that drought mortality of *Eucalyptus camaldulensis* plantations in Victoria was high in high density stands, whereas low density stands were relatively unaffected by drought. CSIRO studies on *Eucalyptus globulus* plantations in Western Australia have shown similar results (Mendham et al., 2005).

- A study on mallee eucalypts in Western Australia reported that although summer-time water-use per unit sapwood area was 20-30% higher in trees over shallow groundwater compared with trees over deep groundwater, there was little difference in water-use on a leaf area basis, because trees over shallow groundwater had a higher leaf area (Carter and White, 2009). Furthermore, stand water use was four times higher over shallow groundwater than that over deep groundwater (1230 mm yr^{-1} compared with 320 mm yr^{-1}) (Carter and White, 2009).

The evidence strongly points to reduced growth in the Mediterranean Woodland region with increased warming and decreased moisture availability. The availability or depth of groundwater will have a significant impact on this at a local or tree level.

Wood density also may increase as water availability decreases (O'Grady et al., 2009, Pickup et al., 2005, Wright et al., 2006). A series of drought risk trials on *E. globulus* in Western Australia across a rainfall gradient (Mendham et al., 2005) reported that wood density was 20% higher at a low rainfall site (Annual rainfall of 600 mm) compared with a high rainfall site (Annual rainfall of 1000 mm). Increased wood density was also found in seedlings of *E. camaldulensis* that were grown at higher temperatures for 9 weeks (Thomas et al., 2004).

With increasing drought, there is an increased risk of drought mortality. Mendham et al., (2005) conducted a study on the risk of mortality due to drought in south-western Australian plantations, and defined thresholds for mortality risk as follows: moderate drought was defined as occurring when one or more months during the peak LAI period (age 3 to 6 years old) had predicted pre-dawn leaf water potential less than -3 MPa and mean maximum air temperatures higher than 30°C (Mendham et al., 2005). Severe drought was defined as one or more months during the critical period with predicted pre-dawn water potentials less than -3.2 MPa and mean maximum air temperatures higher than 35°C (Mendham et al., 2005).

Distribution shifts could be a potential result of changed climate conditions. A CSIRO study conducted a bioclimatic analysis for 92 species of the endemic genus *Dryandra* and 27 *Acacia* species found in the goldfields region of Western Australia. This study found that both genera had very narrow climatic distributions, with high vulnerability to warming: 66% of the *Dryandra,* and 100% of the *Acacia* species bioclimatic profiles disappeared completely under a 2°C warming, and 59% of *Acacia* species disappeared under a 1°C warming (Pouliquen-Young and P., 2000). Again, the bioclimatic modelling does not account for other controls of distribution but does suggest limited adaptive potential for many of these species.

Even including an assumption of migration, a bioclimatic modelling exercise involving 100 *Banksia* species found that climate change impacts on flora of south-west Western Australia may be large (Fitzpatrick et al., 2008). These results suggest that biodiversity in south-west Western Australia may largely depend on the degree to which the area experiences increased drought and in the ability of species to tolerate decreases in rainfall.

Fire intensity and frequency are likely to also increase as a result of hotter drier weather, although it has been projected that fuel loads will stay the same or be reduced (Williams et al., 2009b). Fire frequency, intensity and scale are likely to increase. Fire risks may threaten biodiversity in this area with reduced growth and reproduction under drought conditions necessitating longer recovery periods between fires (Williams et al., 2009b). If fire frequency increases it might lead to changes in vegetation composition and structure. Plant health could be affected in several ways and for eucalypts the potential for fire to impact on mycorrhizal fungi populations could flow on to plant water and nutrient uptake.

Changed climate will lead to migrations as already discussed, which might include the introduction of new drought-tolerant weed species or the worsening of existing threats. Existing land degradation issues and high levels of fragmentation will exacerbate this situation.

Given the reduced water availability, tree stress is likely to be common. With this comes the risk of more pest and disease problems. In the case of *Phytophthora cinnamomi* drought stress may in fact reduce the threat of this disease. Disease severity is at its greatest at 25-30ºC in jarrah seedlings (Hüberli et al., 2002), for example, with disease severity potentially diminished at temperatures greater than this.

Changes in leaf chemistry in response to elevated CO_2 and reduced water availability may affect leaf palatability to pests. For example, a study of *E. cladocalyx* seedlings grown at two N and CO_2 concentrations demonstrated that the proportion of N allocated to prunasin (a cynaogenic nitrogen based metabolite) increased significantly under the elevated CO_2, despite a decreasing pool of N in these plants (Gleadow et al., 1998). These changes could potentially lead to reduced pest damage as leaf palatability decreases.

Socio-economic Decreased growth of plants and increased management issues (fire, weeds, pests) are likely to make both plantation forestry and conservation more expensive exercises. The potential for changing industries will have implications for communities reliant on forest industries. Incentives for carbon sinks may see some demand for conservation plantings (Burns, 2009) and there are some experiments with coppiced plantations for bio-fuel production (Wu et al., 2008) which may become viable industries in this area.

In south-west Western Australia, foresters have changed land management practices for *Eucalyptus globulus* plantations in response to declining rainfall (Booth et al., 2010). To reduce the risk of drought death for this fast growing species, they have reduced stocking densities at planting (or through thinning) to increase the amount of soil (and therefore soil moisture) available for each tree to minimise drought death. In addition, application of nutrients to match supply with demand has maximised growth and water use efficiency of wood production for given stocking densities (Booth et al., 2010). This provides an exemplar of how the forest industry in WA has already begun adapting to changing climatic conditions.

Adaptive capacity While the Mediterranean woodland region has a strong tradition of forestry that is likely to strengthen the adaptive capacity of this sector, it represents one of the most severely degraded regions in Australia. The region has considerable existing stressors including salinity, habitat loss, fragmentation, weeds, disease and fire. The Mediterranean Woodland region is already experiencing climate change, with decreasing rainfall and increasing temperatures in south-west Western Australia in the latter half of the twentieth century some of the fastest changes recorded globally (Williams et al., 2009b). The region also supports some areas of extremely high and unique biodiversity, with high levels of endemism in some areas. These present some major challenges for this region going into the future.

Forest vulnerabilities Pre-existing land degradation issues are likely to be exacerbated by climate change. Together with a unique and diverse for and fauna, the forests of the Mediterranean Woodlands are extremely vulnerable to the negative impacts of climate change. Both forestry and conservation are likely to be vulnerable, with production forests challenged by weeds, disease and water stress, and the conservation areas with loss of species due to an inability to migrate to more suitable climes.

Adaptation actions for the future While the production timber industry will face new challenges under climate change, it could make adjustments to expand activities to strengthen resilience. This might include moving into biofuels (including conversion of non-viable agricultural lands) and carbon sequestration industries. In order to protect biodiversity and ecosystem function in native forests, there will need to be a vigorous and well-resourced programme of protection and enhancement of conservation areas. Conservation and land-use planning is likely to need to consider increasing resources to viable conservation areas to preserve representative conservation areas as well as conservation for other purposes. There is considerable benefit to be gained from using forest panting to conserve biodiversity, improve connectivity and invest in carbon sequestration.

8.11 Arid Grassland and Shrubland

8.11.1 Present

Climate and land-use The Arid Grassland and Shrubland region covers the large arid interior of Australia. The moisture index and growth index are both low year round. The area experiences high wind erosion in areas and ephemeral reproduction of plants with rainfall an important cue. The vegetation is predominantly shrublands and grasslands. There are some patches of native forests and woodlands which are frequently used for grazing. Fire events are infrequent, occurring once every 10-80 years (Williams et al., 2009a).

Forest type No plantation or logging industries are found in this area. There are a number of conservation areas, but these are largely shrublands or grasslands. There are some areas of high diversity such as the McDonnell Ranges.

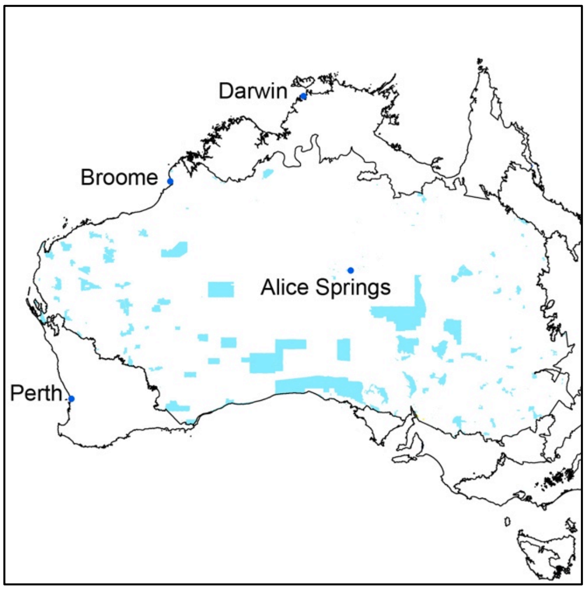


Figure 8.30 The Arid Grassland and Shrubland region with areas of conservation forest (blue areas) and plantations (yellow areas) where present. Source: ABARE-BRS.

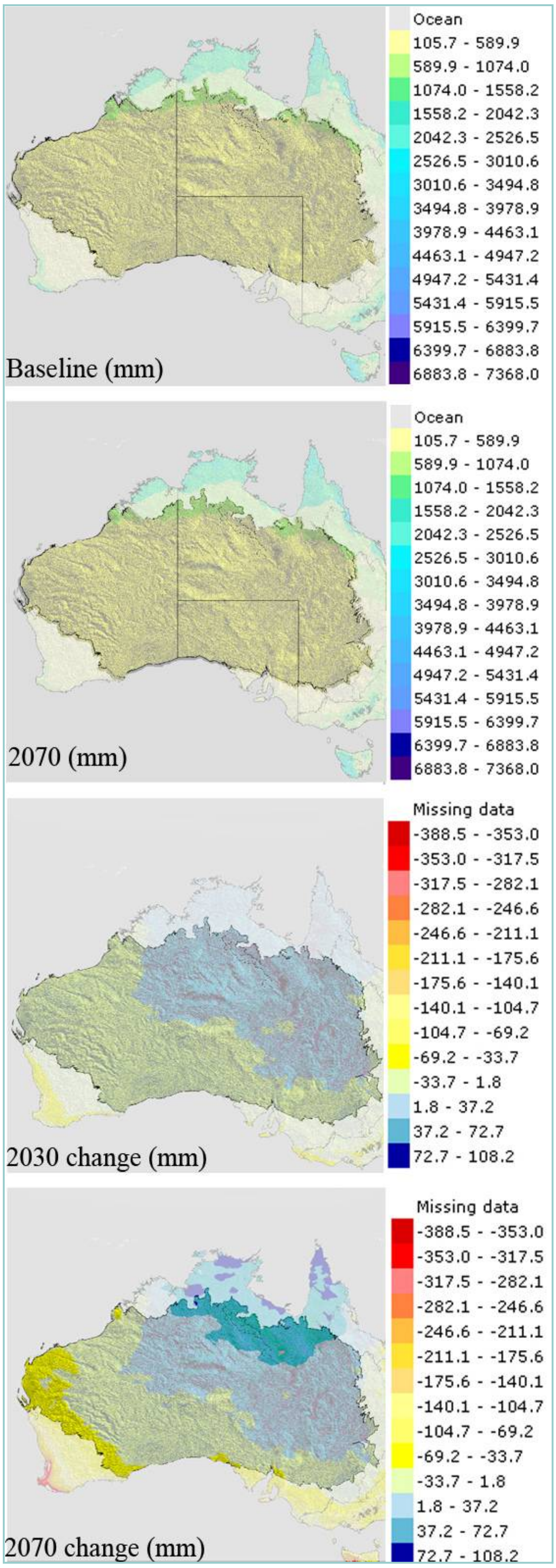


Figure 8.31 Scenarios of total annual precipitation in the Arid Grassland and Shrubland region in 2070 with the change in rainfall totals between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models.

Table 8.10 A brief description of the Arid Grassland and Shrubland region. Modified from Dunlop and Brown (2008).

Description	Region	Arid grassland and shrubland
	Climate & growth	Warm to hot and dry. Moisture Index and Growth Index low all year.
	Where	Large central portion of the continent. Southern regions wetter in winter (E6) and northern regions wetter in summer (H).
Landscape characteristics	Ecosystem function	Rainfall pulses, fire mosaics, grazing; mobile fauna; refuges.
	Climate extremes	Hot, dry, cold
	Disturbance	Fire, grazing, drought, flood; artificial water points supporting native and exotic grazers in low rainfall times.
	Land-use	Extensive grazing /rangelands, large impact; very restricted irrigation. Indigenous land use.
	Soil	Medium and fine scale topography (rocky ranges, low hills, ephemeral lakes/salt pans, as well as extensive areas of low relief); soils mainly sandy soils (deep sandy soils, coarse sandy soils) as well as finely textured clays.
	Water availability	Groundwater locally very important for everyone/everything. Periodic flooding. Waterholes critical for drought refuges.
	Vegetation	Grassland and shrubland
Forest type	Plantation/farm forestry	None
	Productive native forests	Rangelands areas, no timber harvesting
	Conservation native forests	Limited
	Environmental plantings	Unknown

8.11.2 Climate change vulnerability

Climate exposure

Under the scenarios developed here, the greatest temperature increases are expected to occur in the Arid Grassland and Shrubland region. Accompanying this we would expect increased heat stress and water stress. The number of extremely hot days will increase significantly. Rainfall is currently highly variable, with the potential to become more variable but with little overall change in average annual rainfall. The eastern half of the region will experience increases in summer rainfall while in the south and west parts, rainfall will increase in autumn.

System sensitivity

This region is an area highly adapted to very variable, dry and hot conditions, however its tolerance to more drying and extremely hot weather is difficult to predict. There is some limited evidence of extreme temperatures (45-60ºC) causing leaf necrosis or plant mortality, but this requires much further investigation.

A decline in annual rainfall and higher evaporation would likely reduce run-off to rivers and see a tendency for more frequent and severe droughts and increasing competition for water sources. Desertification of significant areas may be a possible outcome. Changes in rainfall may alter phenology, although given the currently highly variable phonological response, this may have a limited impact.

Changes in the seasonality of rainfall could affect the distribution of species with the potential for some weed invasions.

While extreme fire risk weather is likely to increase (i.e. hot and dry conditions), these systems rely on fuel build-up in the understorey following rainfall events to fuel infrequent fires. Any reduction in rainfall will preclude fuel build-up, potentially limiting fire events. Climate change factors are therefore unlikely to significantly change the fire regimes of these areas (Williams et al., 2009a).

Socio economic There is potential for high socio-economic impacts on vulnerable communities and marginal lands. Land abandonment may become more common in this region. There is a considerable area controlled by Indigenous people in this zone and a structured approach to developing professional land managers to help climate change adaptation could see an increase in employment opportunities and the benefits that go with that.

Adaptive capacity The Arid Shrubland and Grassland region already experiences extremes and highly variable climate conditions. This should strengthen the adaptive capacity of the region's forests. Its communities, however, are potentially some of the most vulnerable with a number of health, education and social issues among parts of the community. This may weaken adaptive capacity.

Forest vulnerability Given the existing arid and variable conditions of the Arid Grassland and Shrubland it is difficult to assess the vulnerability

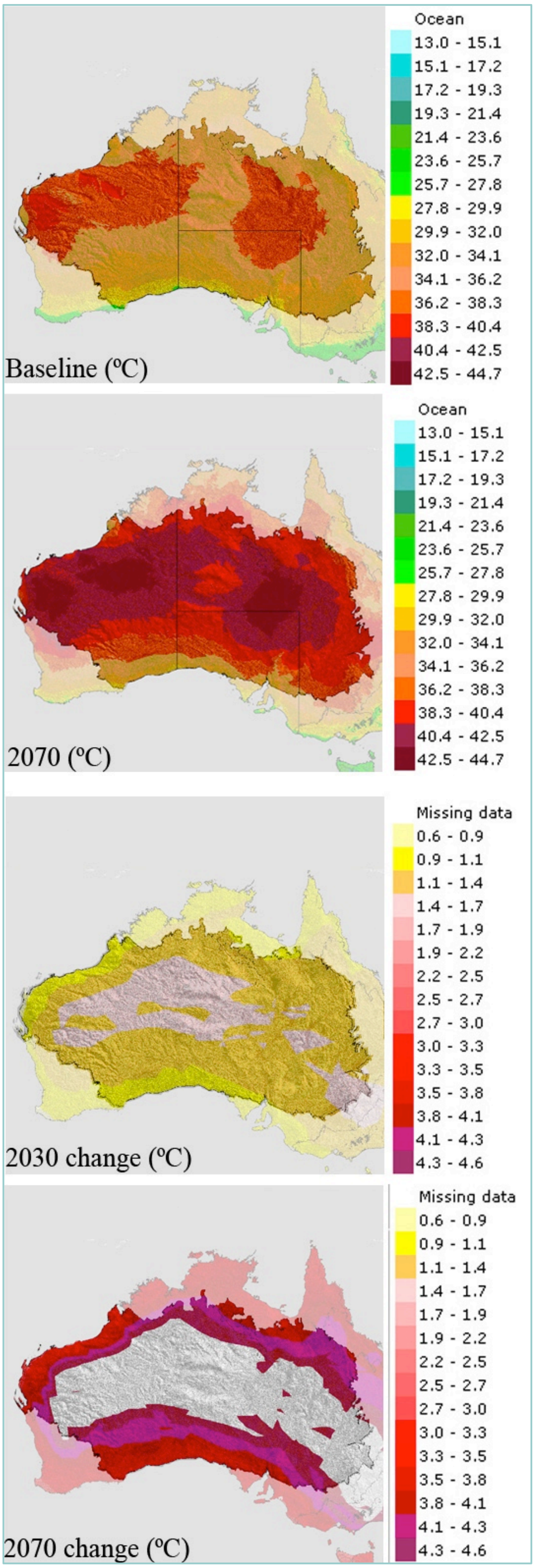


Figure 8.32 Scenarios of mean maximum February temperatures for the Arid Grassland and Shrubland region in 2070 with the change in temperature between the baseline and 2030 and 2070 also shown. Scenarios used a high emissions, high sensitivity scenario with a median ensemble of GCM models

of the plant and animal communities.

Adaptation actions for the future Ongoing conservation and protection of conservation forests will be essential in this region. There is some potential for new industries that depend on forest resources to be developed. Development of new industries should be built with consideration of the social and economic needs of vulnerable communities (both Indigenous and non-Indigenous) to ensure the best outcomes.

9 Comparative regional assessment of vulnerability

This section describes the results of a vulnerability assessment of the four forest types (conservation forests, environmental plantings, productive native forests and plantations) in each of the ten agro-ecological zones.

Comparative regional assessment of vulnerability: Key findings

Key priority areas were identified for each forest type.

- **Conservation forests** The Brigalow Belt and Mediterranean Woodland were identified as requiring urgent attention because of the potential of climate change to worsen existing stressors. The Cold Forest and Grassland region and Subtropical Moist Forests region were identified because of their unique biodiversity, cool climate dependent species and remnant or limited distributions.
- **Environmental plantings** In this category of forest, the Mediterranean Woodland was identified as the highest priority for attention because of the high potential value of environmental plantings for connectivity and ecosystem services to a landscape already compromised by a number of pre-existing stressors.
- **Productive native forests** Forests in the Mediterranean Woodland, Cold forest and grassland and Subtropical moist forests were identified for urgent attention. As for conservation forests, the existence of other stressors and high biodiversity-cold climate dependence of these forests make them the most vulnerable. It should be noted that this assessment was not limited to timber extraction areas.
- **Plantations** Not all regions currently support plantations. For those with existing plantations, the Mediterranean Woodlands required the most urgent attention. Where new industries were planned or possible under future conditions (e.g. the Tropical Savanna), priority for attention is likely to increase to meet the demands of new industries.

This report has so far highlighted what we know, and what remains to be discovered about the potential impacts of climate change on Australia's forests. While there remains a vast amount of uncertainty, there is evidence against which we might make reasonable judgements about areas of greatest risk in order to assign priorities for further research and planning activities. Using the vulnerability framework described by the Allen Consulting Group (2005) we present in the following four tables a comparative vulnerability assessment for each of the four forest types in each of the ten agro-ecological zones used for the regional assessment.

It should be noted that when assessing productive native forests, consideration was not limited to areas with timber extraction activities. These forests were assessed in light of multiple values including grazing, biodiversity and tourism.

Across all forest types, the forests of the Mediterranean Woodlands were identified as the highest priority for attention. This reflects the existing pressure of other stressors on these forests (pathogens, fire, habitat loss, salinity, drying, etc.). The Brigalow Belt's conservation forests were identified as a high priority for the same reasons. Both the conservation and productive native forests of the Subtropical Moist Forest and Cold Forest and Grassland regions were identified as high priority forests for attention. In the case of these forests, their vulnerability lies in the representation of a unique species composition and diversity as well as cool climate reliance by many species.

Table 9.1 A comparative assessment of conservation forests in each of ten agro-ecological zones in Australia.

Agro-ecological zone	States	Vulnerability	Adverse implications	Potential to benefit	Comparative assessment
Arid grassland and shrubland	NT SA WA Qld	Unknown	Species loss	Carbon value Indigenous employment	Merits some attention Improve understanding of climate tolerance
Brigalow belt	NSW Qld	Very High	Increased risk of biodiversity loss, weed and pest threats, fire threat	Change in land use and increased carbon value may allow investment in greater restoration or connectivity programmes	Requires urgent attention Investment in biodiversity, connectivity and understanding existing threats
Cold forest and grassland	Tas Vic NSW	Very High	Loss of unique biodiversity, change in vegetation structure and composition	New tourism value	Requires urgent attention
Mediterranean Woodland	WA SA Vic NSW	Extremely high	Species loss Fire stimulated changes in composition and structure	Uncertain Possible bio-fuels	Requires urgent attention
Subtropical moist forest	Qld NSW	Very High	Species loss and distribution	Increased tourism value Carbon value	Requires urgent attention
Temperate moist forest	Tas Vict NSW	High	Loss of biodiversity Impact on tourism	Increased tourism (cooler than north)	Requires attention

Agro-ecological zone	States	Vulnerability	Adverse implications	Potential to benefit	Comparative assessment
Temperate subhumid woodland	NSW	High	High fragmented reducing movement of species Existing disturbance pressures	Increased tourism value?	Requires attention
Tropical forest and woodland	Qld	High	Fragmented, urban/agriculture interface, change of species distributions may result in increased weeds, loss of high altitude species, change in composition and structure	Improved growth?	Requires attention
Tropical rainforest	Qld	High. Loss of biodiversity, species extinctions	Reduced tourism attraction, change in vegetation type and structure	Existing well-developed framework of conservation	Requires attention
Tropical Savanna	WA NT Qld	High. Increased weediness, change in fire regime	Reduced tourism attraction, change in vegetation type and structure	Expansion of rainforests will increase this habitat	Requires attention

Table 9.2 A comparative assessment of environmental plantings in each of ten agro-ecological zones in Australia

Agro-ecological zone	States	Vulnerability	Adverse implications	Potential to benefit	Comparative assessment
Arid grassland and shrubland	NT SA WA Qld	High?	High temperatures and drought would impact on success and cost of plantings	Amenity value likely to be high (shelter) Some carbon value?	Requires some attention depending on demand
Brigalow belt	NSW Qld	Moderate	Change in species suitability	Increased value of carbon sequestration may allow significant investment in this area, particularly if land unsuitable for cropping High potential for biodiversity value	Requires urgent attention Plan for co-benefit values
Cold forest and grassland	Tas Vic NSW	Moderate	Change in species suitability	Reasonable growth potential. Conservation, ecosystem services and amenity value	Requires some attention Strategic planning
Mediterranean Woodland	WA SA Vic NSW	High	Reduced growth Increased costs of establishment	Increased value and demand Connectivity Ecosystem services values (salinity reduction, amenity)	Requires urgent attention
Subtropical moist forest	Qld NSW	Moderate	Species climate tolerance and selection	Good growth potential Important connectivity/refuge for vulnerable species	Requires attention

Agro-ecological zone	States	Vulnerability	Adverse implications	Potential to benefit	Comparative assessment
Temperate moist forest	Tas Vict NSW	Moderate	Drought stress Species appropriateness Cost of management	Increased growth Opportunity to strengthen conservation links	Requires attention
Temperate subhumid woodland	NSW	Low - Moderate	Species already planted may not tolerate new climate conditions	Increased value for carbon and biodiversity	Merits some attention
Tropical forest and woodland	Qld	Low - Moderate	Increased cost of establishment and management (weeds, natural disasters)	Good growth potential Important connectivity/refuge for vulnerable species	Merits some attention
Tropical rainforest	Qld	High at tree establishment stage, change in vegetation suitability/distribution	Increased cost of establishment may become a disincentive from this option	Increased growth of some species is possible	Requires attention
Tropical Savanna	WA NT Qld	High	Species suitability	Important connectivity/refuge for vulnerable species Co-benefit value	Requires attention

Table 9.3 A comparative assessment of productive native forests in each of ten agro-ecological zones in Australia

Agro-ecological zone	States	Vulnerability	Adverse implications	Potential to benefit	Comparative assessment
Arid grassland and shrubland	NT SA WA Qld	Not applicable	N/A	N/A	N/A
Brigalow belt	NSW Qld	Limited and declining relevance (e.g. cypress pine and ironbark patches)	Declining productivity	Increase conservation areas Enhance habitat connectivity	Requires some attention
Cold forest and grassland	Tas Vic NSW	High	Loss of species	Reasonable growth potential	Requires urgent attention
Mediterranean Woodland	WA SA Vic NSW	Very high	Reduced growth Weed, disease, pest threats Drought Fire damage Existing threats	New values (e.g. carbon, conservation)	Requires urgent attention
Subtropical moist forest	Qld NSW	High	Species distribution or climate tolerance	Good growth	Requires urgent attention
Temperate moist forest	Tas Vict NSW	Moderate	Increased fire threat	New industries (carbon value) Good growth potential	Requires attention
Temperate subhumid woodland	NSW	Low – decreasing activity		Increase conservation area	Merits some attention

Agro-ecological zone	States	Vulnerability	Adverse implications	Potential to benefit	Comparative assessment
Tropical rainforest	Qld	Not applicable			
Tropical Savanna	Qld	Uncertain	Not applicable	New industries (e.g. biofuel, non-wood products, carbon sequestration)	Low
Tropical forest and woodland	WA NT Qld	Low – decreasing industry	Existing disturbance from extraction	Add to conservation reserve, improve connectivity and expand habitat availability	Low

Table 9.4 A comparative assessment of plantations and farm forests in each of ten agro-ecological zones in Australia

Agro-ecological zone	States	Vulnerability	Adverse implications	Potential to benefit	Comparative assessment
Arid grassland and shrubland	NT SA WA Qld	Not applicable	N/A	N/A	N/A
Brigalow belt	NSW Qld	Moderate	Change in seasonal growth patterns. Increased management of weeds	Land use change may provide land opportunities for plantation investment	Requires attention
Cold forest and grassland	Tas Vic NSW	Low - Moderate	Fire exposure Reduced productivity of some species	Good growth potential	Requires attention
Mediterranean Woodland	WA SA Vic NSW	High	Reduced growth Weed, disease, pest threats Drought Fire damage	New products with co-benefits	Requires urgent attention
Subtropical moist forest	Qld NSW	Moderate	Drought Fire	Good growth potential New products	Requires attention
Temperate moist forest	Tas Vict NSW	Low - Moderate	Drought stress Exotic species	Increased growth New industries	Merits attention
Temperate subhumid woodland	NSW	Moderate	Increased management costs (fire, invasive species) Decreased productivity of *Pinus radiata* in the south	New timber and non-timber products Increased growth	Requires attention

Agro-ecological zone	States	Vulnerability	Adverse implications	Potential to benefit	Comparative assessment
Tropical rainforest	Qld	Moderate. Risk of damage from extreme events, increased weed management issues	Increase management costs	Stable growth year round	Requires attention
Tropical Savanna	Qld	High at tree establishment stage	Increased cost of establishment	Increased productivity	Low, few plantations in this area but high for industries planning to start-up in this region
Tropical forest and woodland	WA NT Qld	Moderate (dependant on species)	Poor performance of some traditional species Increase damage costs due to storms	New species/timber products	Requires attention

Part E: The way forward

Overview

With an assessment of vulnerability for Australia's forests completed and presented in this report, we identify some actions that might take the management of Australia's forests forward into an adaptive future under climate change:

- There is some scope for incremental adjustment of existing policy in order to adopt climate change adaptation goals and actions for Australia's forests and the ways these frameworks might be adapted are considered. More severe or extreme climate change might require the introduction of more novel or innovative governance structures that might incorporate a principle of climate change adaptation and consider new categories of land use such as carbon conservation areas or climate change adaptation areas.
- Increased future resources are expected to include a national capacity to oversee adaptation among forest managers, the adoption of financial mechanisms to encourage cost-benefit analysis of actions, increased knowledge, expertise, and people-power.
- There is a need for new research to be targeted at improved modelling frameworks, improved understanding of plant distributions, understanding how elevated CO_2 and water availability interact; and further social research. In addition to new knowledge, it is essential that effective transfer of knowledge is carried out through engagement activities.

The key impacts of climate change on Australia's forests are likely to be:

- changes to the nature of Australia's forests,
- new stresses and worsening of existing stressors, and
- the overlap of mitigation and adaptation efforts.

Those forests with the greatest vulnerability will be those with existing stresses, those with the highest exposure to extreme events, existing plantations in long rotations and reserves with limited or poor management.

Key policy directions for an adaptive future in managing Australia's forests were identified:

- Create a vision of the future adapted forest
- Recognise the role of forests in mitigation
- Invest in decision-making tools and research
- Coordinate efforts at the national level
- Promote co-benefits of forests
- Audit impacts and respond when needed
- Understand and respond to community concerns

10 Future strategies, tools, resources and policies

Future strategies, tools, resources and policies: Key findings

- There are existing management institutions and tools that can be taken forward in managing Australia's forests under climate change. These can be categorised under three headings:

    1. **Adaptation of existing institutions and policy instruments** Existing instruments could be incrementally adjusted to incorporate principles of adaptation to climate change for managing forests. Changes might include adjustment assistance for changing industries in regional areas, extension of existing research programmes, expansion of voluntary certification schemes to include climate change adaptation, resuming or reallocating property rights to change the use of land and expansion of the Regional Forest Agreements framework to coordinate a national response.

    2. **Conservation reserve system** Adaptation may require the expansion of the existing conservation network or changing function to include offering refugia and connectivity within the landscape.

    3. **Land management practices** Many existing practices could be readily adapted to changing climates and are already being used in this way in some instances.

- As the severity of climate change increases, new or novel governance structures will almost certainly be required. We provide an example of a new legal model that includes the development of a new statement of principle and the creation of new categories of forest resource management (productive forests, natural values conservation areas, climate change adaptation areas, and carbon conservation areas). While such a model would require significant development and testing, it offers a discussion point for further work.

- New adaptation pathways and efforts will require considerable resourcing. These might include:

    - Oversight and coordination by a national body.

    - Financial mechanisms (such as a market for carbon) to stimulate the effective cost benefit analysis of adaptation actions and stimulation of new industries.

    - Expertise and people-power to improve knowledge transfer, communication, and ensure the requisite skill base.

    - Meeting information demands that will include basic scientific knowledge and improved modelling tools supported by a clear and targeted research programme. Important research threads include improved modelling, a better understanding of the drivers of plant distributions, the interaction of atmospheric CO_2 and water, and improved qualitative social research.

    - Increased technology transfer and capacity building will be essential to ensure engagement and action by the range of landholders and managers.

10.1 Adaptation of existing institutions, policy instruments and practices

The management of forests in Australia has a long history and land managers have considerable knowledge and experience attached to that. It is worth considering the lessons learnt from existing management that can be taken forward into the future.

Forest resources are managed currently in Australia in response to a range of principles, standards and rules that reflect the growing international adoption of principles of ecologically sustainable management. While the patchwork of policy and legislative instruments reflect historical structures and priorities, they also reflect the evolution of these international principles. Principles for managing the impacts of climate change might likewise devolve from international priorities. However, international conventions have primarily focused on mitigation rather than adaptation (e.g. the Kyoto Agreement) and we have seen historically, that the development and adoption of international conventions or principles is a lengthy process.

Currently the law in Australia does not directly address climate change mitigation or adaptation. Efforts to adapt to climate change, however, could be accommodated through incremental adjustments to existing policy arrangements. In the case of forest resources, this would mean largely using existing institutions and policy instruments to respond to symptoms or impacts as needed. Given the limits to knowledge, uncertainty of predictions and gradual change in climate, some degree of incrementalism is inevitable, however, a more proactive approach would include a general change in policy direction achieved through a series of planned steps. Such an approach will require actions across all levels of government from federal to local.

Ways that existing policy frameworks and institutions might be adapted for governance of forests under climate change might include:

- ***Structural adjustment assistance*** – If plantation or tourism industries decline in a region, retraining schemes or new business and community grants may be employed. While there is unlikely to be an immediate case to do so in response to climate change, it may add impetus to other changes, e.g. reduced logging in native forests. This would be expected to be highly targeted and time constrained.

- ***Catalysis*** – Extension of existing research and extension programmes by government and NGOs could provide information that would encourage and enable land managers to adapt. Examples would include research on species characteristics and ranges, invasive species modelling, economic modelling and extension activities.

- ***Certification*** – Existing voluntary arrangements such as the Australian Forest Certification Scheme (AFCS) and the Forest Stewardship Council scheme, could be expanded to include adaptation measures.

- ***Resuming and allocating property rights*** – The most direct approach here would be the purchase of land by governments in order to manage them for particular outcomes such as the creation of biolinks (corridors), to increase or buffer conservation areas or carbon storage. Acquisition of other property rights, such as the right to conduct agricultural activities may also be considered, so as to induce private contributions to adaptation. Models such as the Tasmanian Forest Conservation fund and the Commonwealth’s Environmental Stewardship Program could be used. In these cases the purchase of property rights requires refraining from certain activities and would be supplemented by a management agreement (e.g. additional planting, weed control, fire management).

- ***National coordination*** – There is merit in considering a national coordinating arrangement. An existing framework, the Regional Forest Agreements (RFAs) could be adapted to this end as it is already based on overall coordination and embed regional planning based on relatively sophisticated socio-economic and biophysical analyses to inform decision-making and prioritisation. The Ministerial Council on Forestry, Fisheries and Aquaculture, might also be a candidate for this role and could oversee the revision and possible expansion of the RFAs and consider where necessary the case for particular cross-border arrangements.

However, adaptation to climate change is for the most part permissive rather than mandatory under the present framework. As impacts are, or become, more extensive and pervasive, then greater policy and legislation "innovation" may be required.

Conservation reserve system Areas of natural forests will be extremely vulnerable under climate change. The existing conservation reserve system has formed the core of protecting and managing forests and will continue to do so into the future. Adaptation will require expansion and protection of the network. Under climate change, however, the function of reserves may change to become more dynamic as part of an increasingly connected landscape (Steffen et al., 2009) reflecting new principles of design of the reserve network.

From the perspective of climate change, the system will need to offer refugia and migration pathways, with design principles taking into account changes in geographic range and pathways to new locations (Dunlop and Brown, 2008). The existing reserve design principles of CAR (comprehensive, adequate and representative) should be extended to include refugia and adaptation.

Land management practices Our review of adaptation options has demonstrated that many existing land practices might be adapted to changing climates. For example, knowledge of weed control and prediction of expansion will be equally relevant under climate change as under existing conditions. Continuing to build on existing knowledge and skills will be important to adaptation. This might include principles of species selection, silviculture practices to minimise drought risk and efforts to reduce other stressors (e.g. weeds, pests, disease, land clearing, fire). However many of these practices will need to be expanded and adapted to novel climate conditions. This will rely on new information, improved predictions and substantial financial investment.

10.2 Building innovative governance structures

The legal arrangements currently in place in Australia may enable but almost certainly do not require climate change issues to be addressed. If however it is decided that arrangements should be put into place to ensure that the causes and effects of climate change are taken into account in managing forest resources or perhaps even to constitute the most important factor in the sustainable management of forest resources, then a new or novel legal model could be required.

The current system of land ownership and management is based on the evolution of Australia's legal framework. This includes controls under the Common Law and a Torrens title system. It provides for forested land to be either freehold land, leasehold land and state or crown land. Management principles can be made for leasehold lands as a condition of that lease, while for freehold land they must come through land-use planning or legislation. State lands are generally managed through policy and legislation. The dominant paradigm has historically been development of land for agriculture. Society as a whole is re-evaluating the relative value it places on ecosystem services (e.g. carbon, water biodiversity) and this has been reflected in the adoption of ecologically sustainable development principles internationally. On state land this has been played out in the rise of national parks over the last 40 years – with the legal framework evolving to accommodate this change (e.g. national parks legislation). Evolving governance frameworks to include elements necessary to allow climate change adaptation, may call for a new legal model that reconfigures the system of land ownership and controls over land use.

There are five elements which would be necessary to underpin such a model.

1. *A statement of the values and principles driving, guiding and informing the system.* Presently this is the well-recognised concept of sustainable development which includes the principle of intergenerational equity, the principle of intragenerational equity, the precautionary principle,

and the principle of integrated management. Under the proposed framework these principles need to be extended to include in relation to climate change:

- the principle of greenhouse gas reduction,
- the principle of greenhouse gas absorption, and
- the principle of adaption to climate change.

These principles would need to be elaborated and explained so that they can be translated into reality much more easily in particular sets of circumstances.

2. *Determination and classification of the best uses of the relevant land and forest resources*. The best use of land in the public interest is determined in accordance with its natural features, its characteristics and its capabilities.

3. *Creation of four classes of best forest resources management*. Under this model, each area of identifiable forest resource would be placed in one of these classes. This might include:

   - productive forests,
   - natural values conservation areas,
   - climate change adaptation areas, and
   - carbon conservation areas.

Climate change adaptation areas and carbon conservation areas are novel concepts. A climate change adaption area could be an area of forest resources which are particularly susceptible to the identified impacts of climate change: for example, drought, flood, sensitive biodiversity. Alternatively, these might be areas expected to be important under future climates with shifting distributions or a migration corridors or stepping stones for the same reason. Fundamentally, a climate change adaptation area would be managed so as to reduce as far as possible the identified impacts on it or associated species of climate change. A carbon conservations area is an area that has been identified as a particularly valuable carbon sink. Activities inconsistent with the values of the area as a carbon sink would be prohibited.

4. *An obligation to manage forest resources in these classified areas in accordance with declared management plans, management rules, and silviculture plans.* Detailed management plans and silviculture plans would be formulated and implemented for these areas. The rights and the obligations in these plans would be enforceable through the legal system in the normal way. In other words they comprise rights protectable by and obligations enforceable by the judicial system.

5. *Imposition of an obligation on decision makers in relation to proposed development and those proposing developments to consider specifically the impact of changes to the climate system on the proposed development.* Proposals for development of land in locations outside classification areas could well involve proposals which are likely to be impacted upon by climate change. In other words a proposed development in a climate change adaptation area will be refused permission if it is inconsistent with the plan for the area. However if the proposed development is not in a classified area, then the normal decision making procedures, either authorising or undertaking the proposed development, will be required to consider the impact of changes to the climate system on the proposed development.

In affect what is contemplated is a revision of current land-use planning procedure and legislation with long-term planning based upon clear and established principles and leading to a classification system that is adapted to changing climates. It is supported by detailed management arrangements for each forest class.

It should be noted that this model is untested and would require significant development and testing, but if forest resources are to be managed in a way that helps to reduce the release of greenhouse gas emissions, provides for the absorption of greenhouse gases that have been released, and enables the uses of land and of forest resources to adapt to the impact of changes to the climate system, then novel systems may be required.

10.3 Future resources needed to support adaptation

We have thus far outlined new strategies, tools, policies and legislative frameworks that may be employed to meet the challenge of climate change on Australia's forests. These adaptation pathways will require considerable resources both in terms of people, financing and information. In this section we identify some of the necessary resources identified by the FVA.

10.3.1 Oversight and coordination

Forest management in Australia cuts across a range of policy and legislative domains. It will be essential that national bodies overseeing forest and natural resource industries and policies, such as ministerial councils, incorporate climate change impacts on forests into their briefs, to deal with cross-border coordination. State agencies will also be crucial in undertaking or coordinating relevant research, providing advice on adaptation strategies, managing conservation areas and in designing and running stewardship programs that incorporate consideration of climate change. As discussed earlier there is a case for formalising a national coordinating arrangement.

10.3.2 Financial mechanisms

Mitigation efforts have a critical role in offsetting some of the socio-economic and biophysical impacts of climate change – in other words, incidental adaptation. Putting a price on carbon or providing subsidies for tree-planting activities (including private off-set schemes) is likely to be central to policy efforts to reduce carbon emissions in Australia. A number of co-benefits of this expansion can be considered and might include offset of other socio-economic impacts of climate change (renewed vigour in marginal industry), help improve profitability in marginal areas and increased non-use benefits such as habitat, water quality and micro-climatic benefits (see Box 15).

When sequestration of carbon acquires a market value, then this is likely to stimulate reforestation of lands formerly used for agricultural and pastoral purposes. This expansion, however, will be influenced by:

- National obligations under international emission reduction targets.
- Competition from alternative land uses.
- Transaction costs.
- Concerns about the consistency of government policy into the future.
- Preference for other sequestration options (e.g. geo-sequestration, alternative energy, increased efficiency).
- Treatment of forests in carbon emissions calculations.

Box 15 A case study of co-benefits the Wet tropics bio-carbon aggregation project. Source: Dr Noel Preece

A carbon sequestration project in the Wet Tropics of Queensland is linking landholders with carbon credit markets. The Wet Tropics Biocarbon Sequestration and Abatement Project, creates carbon credits based on the integrated, regional natural resource management activities of hundreds of landholders. These NRM activities are aimed at reduction and removal of greenhouse gasses and conservation of biodiversity, and building the resilience of the World Heritage Wet Tropics rainforests and the World Heritage Great Barrier Reef.

The project has developed a modular approach to carbon sequestration and abatement methodologies: incorporating carbon pools and land uses immediately where robust information and methodologies are available. This approach provides a framework for other pools and land uses as they become available. The forest-based methodologies of calculating carbon, for instance, are robust and globally accepted. Internationally accepted methodologies for calculating nitrous oxides emission reductions from reduced fertilizer use are also developed, but some relatively minor information gaps remain to be filled for inclusion in the project. Once this information becomes available the methodology to reduce nitrous oxides, will result in real reductions in nitrous oxides immediately, and significant reduction of fertilizer entering the Great Barrier Reef and other sensitive ecosystems. In contrast, soil carbon response to grazing land management still requires both methodological development and additional information collection. In this way, the initiative also provides an active adaptive management framework – a context for applied research that has immediate uptake and economic benefit.

The project is linked with research into better methods of restoration, through the Thiaki ARC Linkage project http://www.biome5.com.au/page/thiaki.html. One of the Thiaki project's main aims is to reduce the costs of reforestation from tens of thousands of dollars to less than $8000 per hectare.

Plantations of native species hold both biodiversity and carbon sequestration value (Photo: Noel Preece © 2009).

10.3.3 Information demands from stakeholders

In general, stakeholders interviewed as part of the FVA project, acknowledged the fragmented or disconnected nature of existing knowledge needed to support climate adaptation. Improved information sharing, knowledge brokering, extension and collaboration were called for. Specific needs included:

- Improved resourcing of knowledge transfer.
- Improved access to predictions of distribution and redistribution of species.
- Improved communication between organisations and basic extension.

Specific information gaps considered necessary by stakeholders included more modelled information and experimental information for land management as follows.

1. Information needs from modelling – One of the most consistent views expressed was that the modelled predictions of climate change impacts need to be scaled down to a regional level and that at the current scale, modelling was not at a sufficient resolution to help manage their forests into the future. It was also suggested by stakeholders that there needed to be narratives about what predicted climate changes might mean at the local level.

Some of the specific types of information sought from models to assist with developing adaptation options varied depending on the types of forests being discussed and to a lesser extent, the region in which the forest existed. For example, those working with plantations highlighted the need for detailed rainfall predictions at an appropriate resolution as a priority, along with temperature predictions as these two variables are critical for tree establishment. Other regions listed frost as important, and soil and catchment models were noted for the northern tropics. In addition, modelling for mixed plantations rather than monocultures was viewed as being important for adaptation. In contrast, while surveyed individuals managing native forests also expressed the need for models to be downscaled to the regional and local level, they also highlighted the need for models that would assist with vulnerability assessment.

2. Experimental scientific knowledge – Those researching and managing both native and plantation forests identified a range of specific information requirements that would assist them in planning adaptations.

Specific identified knowledge needs identified include:

- Trialling restoration or translocation programs to determine management for natural adaptation by plant species.
- Improved understanding of carbon fixing above and below ground under specific management treatments.
- Improved understanding water use efficiency by plants under elevated carbon dioxide.
- More focus on studying mixed species plantations – understanding near neighbour effects, interspecies competition.
- Greater understanding of climate change impacts on weeds including control strategies.
- Understanding the interplay of factors that could be contributing to shifts in dominant vegetation type.
- Information about where to collect seeds from to ensure optimal growth of plants under changed climatic conditions.

10.3.4 Information gaps from the literature review

The survey of stakeholders identified information needs considered important to land management by forest managers. The review of the literature on impacts of climate change on Australia's forests highlighted that the evidence that we do have is very piecemeal. In particular, the assessment has identified several areas in which strategic research could be conducted to improve the assessment of vulnerability and support decision-making and planning for an adaptive future for Australia's forests.

Modelling framework Although there have been a number of excellent studies using a range of experimental and modelling techniques, there has been no overall attempt to integrate different types of studies. In addition, there are very stark contrasts between the overall results of different modelling techniques in determining the vulnerability of tree species to changes in climate.

There is a need for a coherent framework to draw together disjunct strands of research. A quantitative, modelling framework such as a dynamic vegetation model, specifically developed for Australian conditions, would be a major step towards addressing this need. Such a model would act as a framework to draw together and compare existing data; to develop hypotheses for further experimental testing; and to allow informed prediction of future vegetation shifts.

Australia urgently needs to invest in strategic research to:

1. Develop a credible dynamic vegetation model that is applicable to Australian ecosystems. Given the many processes and counterbalancing responses, there is an urgent need for a credible attempt to model physiological responses in order to say how these effects will combine to affect plant ecosystems, and in particular plant distributions.

2. Develop adequate national datasets for ground-truthing such of a model.

3. Expand ecophysiological models to include an appropriate synthesis of CO_2 experiments, simulated mortality and include indirect effects of climate change (e.g. changes in pest distribution, host-pest dynamics, and changes in fire frequency and severity).

Plant distribution As highlighted in Section 4.2, understanding the change in distribution of organisms currently relies on existing distributions of organisms to establish climate tolerance. As we have discussed, factors other than climate may determine these distributions and climate tolerance might be better assessed through experimental methods. A clear and compelling research need is to integrate manipulative experimentation and bioclimatic modelling approaches. Although bioclimatic studies are only indicative of vulnerability, there do not appear to be any studies where species identified as vulnerable have been followed up with manipulative experiments testing the climate sensitivity of the species. Work of this type is clearly needed. Thus, targeted manipulative experiments and observational studies directly addressing the climatic sensitivity identified by bioclimatic modelling are needed. Equally important is the need to improve our understanding of the influence of species-species interactions on the distribution of organisms.

Carbon and water use A longstanding question is whether forest water use will be decreased at high CO_2, or whether leaf area will increase to compensate, resulting in higher productivity but no change in water use. Previous experiments have failed to resolve this question and it urgently needs to be addressed if we are to be able to predict water resources in Australia. Further large-scale research into interactions between increased carbon and water availability is a high priority for predicting dynamics of water use in Australian forests.

Temperature impacts on growth Temperature impacts on growth and the tolerance of individual species to increasing temperatures is fundamental to predicting future climate distributions. While there is some small scale evidence, the need for increased field-scale data collection is paramount.

Drought tolerance and drought mortality will be important in determining the impact of decreased rainfall on forest systems. Targeted monitoring systems could improve our understanding of when drought death is likely to occur.

Monitoring for a cause and effect While many of the information needs identified in this assessment call for improved monitoring it will be crucial to optimise monitoring given the scale of the problem, the time-frames of impacts and the potential cost of inaction. Monitoring programmes need to be carefully designed and structured to identify cause and effect to improve and adapt management plans.

Social research There is limited qualitative research into social impacts and responses under climate change in the forest sector of Australia exists (Cockfield et al., 2010). Considerable more information is required. More information on community attitudes with respect to fire and forests and priced sequestration is required. Other areas of social research include investigating the optimal mix of regulation, incentives and virtual commons to manage landscapes, reviewing the impact of current forestry impacts on communities and examining the dependence of Indigenous communities on non-wood forest products.

Developing and testing new policy and legal frameworks As described earlier, novel policy or legal frameworks may be required as climate change impacts worsen.

10.3.5 Knowledge transfer and capacity building

Given the dispersion of control over land, there will need to be engagement with a range of landholders and using different policy frameworks and instruments, especially in relation to the creation of biolinks (Mansergh et al., 2008) that will allow species movement and adaptation. Possible links will cross a range of tenures and land uses and so strategies will include:

- *Engagement through market-based approaches*. This approach recognises the problems with compulsory acquisitions and the potential benefits of engaging will conservation providers (Stoneham et al., 2003).

- *Engagement of Indigenous land managers.* Indigenous land managers hold four percent of land as Indigenous Protected Areas (Department of the Environment Water Heritage and the Arts, 2009) as well as other land under different forms of title, so they could be engaged in adaptation activities, especially in rangeland areas.

- *Public sector land management and acquisition.* Governments are a major land holder in Australia, with more than nine percent of terrestrial land area under reserves (Department of the Environment Water Heritage and the Arts, 2009), Second, there are already natural resources management (NRM) programs aimed at acquiring specific environmental assets and so the relevant agencies would have the experience to acquire areas identified as needed for forest adaptation.

11 Key messages and policy directions

An overarching theme throughout this assessment has been that climate change impacts on forests cannot be considered in isolation. Existing stressors (e.g. fire, weeds, fragmentation) and socio-economic factors (e.g. markets, regional populations) are likely to intersect with climate change impacts on forests and associated problems compounded by them.

11.1 Key impacts

Forests will change Our review of the literature has shown that while there is considerable uncertainty surrounding the precise nature of the change it is highly likely that forests will change in a number of critical ways:

1. *Rates of growth could change*. This could either be positive growth as a result of increased carbon dioxide availability in the atmosphere, warmer temperatures or water availability; or decrease as a result of unfavourable environmental conditions.

2. *Species composition could change.* This seems inevitable regardless of the uncertainty of impacts. Changes in species composition are likely to come from changes in interspecies interactions and shifts in species distributions.

3. *The areas that forest types occupy could change.* There are several reasons we expect forests to “shift”. First will be the change of species composition as conditions favour different species, second will be changes in the interactions between species (e.g. pollination, herbivory, predation), and third will be the impact of catastrophic extreme events (e.g. fire, storms).

Climate change impacts will be compounded by and will compound other stressors This is probably one of the most critical concerns for Australia’s forest, regardless of whether they are managed for production or conservation. Existing stressors – invasive species, disease, habitat fragmentation – already demand considerable resources from land managers. In addition, socio-economic stressors (e.g. carbon markets, changing demographic, changing land demands) will also interact with the physical stresses of climate change.

Mitigation and adaptation overlap Adaptation activities, if carefully designed can act as adaptation actions, and vice versa. An example of this would be the planting of corridors to connect forest reserves (an adaptation action) that could also provide carbon offset benefits.

11.2 Adaptive capacity of Australia’s forests

The level of adaptive capacity will impact on the vulnerability and resilience of Australia’s forests. The capacity to adapt varies across regions and among communities and across time. In considering the adaptive capacity of Australia’s forest, we have identified several factors that are likely to be increase adaptive capacity:

- Existing experience and expertise in managing forested landscapes including climate variability has built adaptive capacity in these sectors.

- Some considerable areas of conservation and reserves.

- Strong economic and social drivers.

- Experience of adapting to change in forest industries. This is particularly the case in plantations which have undergone some review and adjustment in response to both policy and market drivers.

- Well developed biosecurity procedures to minimise the risk of pests and disease from other countries.

- Extensive scientific and technical capabilities exist in Australia.

There are also a number of factors that will weaken adaptive capacity and these include:

- The size of Australia presents a number of challenges. It has diluted the considerable scientific effort across a large number of species and diverse set of regions.

- Existing stressors are already challenging land managers and require considerable investment to reduce the impacts.

- Market failures (e.g. collapse of managed investment schemes).

- The speed of adoption of adaptation measures. Adoption of new technologies can take several years, with major infrastructure taking several decades.

Several other factors that can impact on adaptive capacity include: inclusion of Indigenous knowledge, understanding of natural disturbance regimes (e.g. fire) under climate change, diversification in industries, demographic of the community servicing forest industries, capacity to share or disseminate knowledge, and education and training.

The adaptive capacity of natural systems is limited by: rates of evolutionary processes; organism’s or species tolerance thresholds; habitat loss, contraction and fragmentation; and vulnerability to extreme events. Further, the adaptive capacity of natural forest systems will be lower in areas that already experiencing significant stress (e.g. Mediterranean Woodlands region). There is a belief that those forests with highest diversity, will cope the best with some of the impacts of climate change. However, they also have some of the greatest risk of extinctions due to the refugial or cool climate aspects of their fauna and flora (e.g. Tropical Rainforest region) or the high stress levels already existing in those regions (e.g. Mediterranean Woodlands region).

11.3 Greatest vulnerability

In general, areas with the greatest vulnerability will be those with:

- high exposure to extreme events;

- forests/species at the edge of their climate tolerance;

- existing plantations with long time periods until harvest (i.e. where planting has occurred based on historic climate conditions rather than future climates);

- land that is already stressed (e.g. diminished biodiversity, salt incursions, high rate of disease or pests, high fire frequency/intensity); and/or

- reserve systems with inadequate or poor management and monitoring.

In examining regional vulnerability of forests we noted the uneven spread of vulnerability and risk among regions, with some expected to fare better than others. While several regions had high vulnerability, the Mediterranean Woodlands was identified as being extremely vulnerable to climate change. This was largely because of existing stressors.

11.4 Recommended actions for policy direction

1. Create a vision of the future adapted forest

Forest management needs a clear management goal for adaptation under climate change.
One of the crucial areas of policy need is a clear management goal for adaptation under climate change. In essence, what is the desired outcome of management? In recent years this has been a principle of ecologically sustainable development. Australia has used the condition, composition and biogeography of forests pre-European settlement as its benchmark for conservation. Given that one of the key outcomes of climate change will be changes in forest, this ideal is not likely to remain useful. There will therefore need to be some definition of what the features of a sustainable and desirable forest under climate change in a particular region might be. For example, this might be the preservation of particular species, the maintenance of a certain level of species richness or a level of ecosystem function (e.g. ensuring water quality or availability in a catchment). If innovative policy or legal frameworks are required, this will be an essential first step in defining these.

2. Recognise the role of forests in mitigation

Implement mitigation policies to recognise the role of forests in carbon management.
Putting a price on carbon or providing subsidies for tree-planting activities (including private offset schemes) is likely to be central to policy efforts to reduce carbon emissions in Australia. A number of co-benefits of such policies can be considered and might include offsetting of other socio-economic impacts of climate change such as renewed vigour in marginal industry, reforestation of lands formerly used for agricultural and pastoral purposes, improving the profitability of marginal areas and increased non-use benefits around habitat, water quality and micro-climate.

3. Invest in decision-making tools and research

In order for governments to make informed decisions about the best adaptation tools they will require effective decision-making tools.
One of the greatest obstacles for planners, policy-makers and land managers developing adaptation frameworks and actions for Australia’s forest is the uncertainty that is associated with climate change projections. But the risk of not acting has the potential to be more damaging than acting on the best available evidence. In order to plan and make decisions, well-developed tools for risk analysis and decision making under uncertainty are a crucial resource.

4. Coordinate efforts at the highest level of government

While the impacts of climate change will differ among regions, many adaptation responses will cross regional and state borders. This will require national coordination.
Management of Australia’s forest resources under climate change will demand intensive regional effort and planning. But, in addition, national coordination will be essential. For example, an adaptation action is the development of biological links or corridors across the landscape. Such an undertaking will require national coordination to ensure the right locations are included and gaps are filled. Potential policy instruments already exist at the regional level such as the Regional Forest Agreement that might be adapted to meet this need.

5. Promote co-benefits of forests

There is scope to expand and coordinate programs to maximise the multiple benefits from forests.
The Forest Vulnerability Assessment demonstrated the contribution of Australia’s forests to multiple ecosystem services. There are already in existence a number of government funded programs for extension of the reserve system, protection of wildlife habitat on private land and planting for ecosystem services such as shade or shelter. There is considerable scope to expand and coordinate such programs for multiple benefits under climate change. For example, an agency managing a stewardship program primarily aimed at conservation could undertake to additionally negotiate and validate carbon sequestration outcomes. This allows the agency to bundle sequestration parcels and conservation lands and so reduce transaction costs.

6. Audit impacts and respond when needed

Monitoring of changes and impacts in Australia’s forests is essential, but must include inbuilt markers or trigger points at which new or changed adaptation actions should occur.

There is considerable capacity to adapt existing institutions and policy to include consideration of climate change adaptation for forests, i.e. mainstreaming climate change adaptation into decision-making for Australia’s forest resources. However, to ensure this capacity remains sufficient as climate change impacts become more severe or as the accuracy of predictions improves, it is important to have identifiable trigger-points for action or a change in policy direction. This “auditing” process should identify the point at which a need for policy changes may emerge. Likewise in natural systems, ‘auditing’ should indicate thresholds or triggers when changes in management or management interventions are needed. This approach is beyond simple monitoring, with inbuilt markers which trigger the need for changes in adaptation strategies.

7. Understand and respond to community concerns

The support and confidence of the wider community will be important for successful implementation of planned adaptations, particularly if innovative policy or legislative changes become necessary.

The support and confidence of the wider community, and especially those people in forest-based communities, will be important in supporting planned adaptations. There will need to be a two-way flow of information, one informing people, and another identifying community and stakeholder views.

8. Invest in targeted research

There are many uncertainties and research gaps that are important to address in order to improve the adaptation response of forest managers to climate change. A targeted research program is essential to support and improve the adaptation process.

While more information on impacts is important, there is an equal urgency to develop research programs that focus on developing adaptation actions. Priority areas for future research identified in this assessment are:

- To develop a credible dynamic vegetation model that is applicable to Australian ecosystems, and adequate national datasets for ground-truthing such a model.
- To increase our understanding of the factors driving changes in distribution of plants and animals.
- Large-scale research into interactions between increased carbon and changing water availability in order to predict the dynamics of water use productivity in Australian forests.
- Field-scale data on the impact of temperature on forest growth.
- An improved understanding of drought tolerance and drought mortality in trees.
- More information on community attitudes with respect to fire and forests and priced carbon sequestration.
- Determination of the optimal mix of regulation, incentives and community self-regulation to manage landscapes.
- Understanding the relationships between Indigenous communities and forests and their ecosystem services.
- Developing and testing new policy and legal frameworks.

9. Agree to prioritise actions

Governments and industry bodies need to develop and agree to the means by which actions that address the impacts of climate change on forests will be prioritised. For example, in fire management of forests should priority be given to protection of large conservation forests over lifestyle forests? In the absence of comprehensive study of all regions decision-making frameworks (discussed above) will be critical. This agreement will be best facilitated through an overarching coordinating body or mechanism as a highlighted above. Because many of the socio-economic impacts of climate change are diffuse and indirect and some are intangible, it will be difficult to decide on priority areas for governments and industry bodies to address and so agreement on indicators of change would be helpful. Cockfield et al., (2010) have reviewed some of the potential indicators and evaluation tools.

Glossary/Definitions

Acclimation – is the process by which tolerances to an environmental stress is increased and it is usually triggered by an environmental cue (Woldedorp et al., 2008).

Adaptation to climate change – is "the adjustment, in natural or human systems, in response to actual or expected climatic changes or their effects, which moderates harm or exploits beneficial opportunities" (Pittock 2003). Various types of adaptation can be distinguished, including anticipatory, autonomous and planned adaptation (http://www.global-greenhouse-warming.com/climate-mitigation-and-adaptation.html; IPCC WPII, 2007):

Adaptive capacity – is the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or cope with the consequences. Adaptive capacity of a system is its capacity to change in a way that makes it better equipped to deal with potential impacts. It is affected by the things you do to increase the coping range. The capacity to adapt varies considerably among regions, countries and socioeconomic groups and will vary over time. For society, it is related to the level of attachment and sense of place people have for a region and the activities that they undertake there. The length of residence is often an indicator of place of attachment (*pers. comm.* B. Jorgensen, La Trobe University).

Anticipatory – adaptation that takes place before the impacts of climate change are observed.

Autonomous – adaptation that does not constitute a conscious response to the impacts of climate change, but is triggered by ecological changes in natural systems and by market or welfare changes in human systems (Easterling, 1996). For example, change in time of seedling development in response to climate change in a native forest (autonomous adaptation) and assisted migration (planned adaptation).

Climate mitigation – is "an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases." (http://www.global-greenhouse-warming.com/climate-mitigation-and-adaptation.html). Forests are of critical importance in mitigation for their role in sequestering carbon dioxide from the atmosphere. They are the major terrestrial carbon sink which absorbs approximately 30% of CO_2 emissions from anthropogenic activities including the burning of fossil fuels and net deforestation (Canadell and Raupach, 2008). They are also important as carbon reservoirs, storing more than double the amount of carbon in the atmosphere (Canadell and Raupach, 2008), making their management of prime importance in adapting to and mitigating against negative effects of climate change.

El Niño – The term El Niño refers to a sequence of changes in circulations across the Pacific Ocean and Indonesian archipelago when warming is particularly strong (on average every three to eight years). El Niño events are characterised by extended drought periods that in turn lead to increased sunshine hours (due to reduced cloud) and an increase in radiative cooling at night (again due to reduced cloud cover). In contrast, the alternative cycle to El Niño, La Niña, is characterised by cooler than normal ocean temperatures across the central and eastern tropical Pacific Ocean and increased convection or cloudiness over tropical Australia and southeast Asia with an associated increased chance of rain.

Endophytic – an endosymbiont, often a bacterium or fungus, that lives within a plant for at least part of its life without causing apparent disease.

Evapotranspiration – The combined process of evaporation from the earth's surface and transpiration from vegetation.

Exposure – is the degree, duration and/or extent to which a system is likely to be in contact with a perturbation e.g. cyclones, drought, fire (Adger, 2006, Gallopin, 2006). Defined as the external side of vulnerability (Gallopin, 2006). It is influenced by a combination of the probability and magnitude of climate change.

Planned adaptation – is adaptation that is the result of deliberate policy decision, based on awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state. Planned adaptation measures are conscious policy options or response strategies, often multi-sectoral in nature, aimed at altering the adaptive capacity of agricultural systems of facilitating specific adaptations. For example deliberate crops selection and distribution strategies across different agro-ecological zones, substitution of new crops for old ones and resource substitution induced by scarcity (Easterling et al., 2007).

Sensitivity – is “the extent to which a human or natural system can absorb impacts without suffering long-term harm or other significant state change” (Adger, 2006) i.e. an internal component of vulnerability (Gallopin, 2006). It is also defined as the extent to which changes in climate will affect the system in its current form.

Vulnerability – a function of the character, magnitude and rate of climate change variation to which a system is exposed, its sensitivity and its adaptive capacity (IPCC).

Abbreviations

Abbreviation	
ABARE	Australian Bureau of Agricultural and Resource Economics
AGO	Australian Greenhouse Office
BRS	Bureau of Rural Science
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAFF	Department of Agriculture, Fisheries and Forestry
DCCEE	Department of Climate Change and Energy Efficiency
DEHA	Department of Environment, Water, Heritage and the Arts
ENSO	El Niño Southern Oscillation
ESP	Environmental Stewardship Program
FVA	Forest Vulnerability Assessment
GCM	Global climate model/General circulation model
IBRA	Interim Biogeographic Regionalisation for Australia
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
MIS	Managed Investment Scheme
MIS	Managed Investment Scheme
NCAS	National Carbon Accounting System
NCCARF	National Climate Change Adaptation Research Centre
NFI	National Forest Inventory
NFPS	National Forest Policy Statement
NIFS	National Indigenous Forestry Strategy
NRM	Natural Resource Management
NRMMC	Natural Resource Management Ministerial Council
PPFS	Pastoral Properties Future Simulator
RFA	Regional Forest Agreement
SOFR	Australia’s State of the Forests Report

Appendix 1 Forest vulnerability assessment work packages

Table A1.1 The Work Package reports delivered as part of the Forest Vulnerability Assessment (Abbreviations: JCU – James Cook University, Macquarie – Macquarie University, Murdoch – Murdoch University, QUT – Queensland University of Technology, USC – University of the Sunshine Coast, USQ – University of Southern Queensland, GU – Griffith University, NCCARF – National Climate Change Adaptation Research Facility, WP – work package).

WP	Report title	Authors and affiliations
1	Establishing the need and consultation with key stakeholders in forest policy and management under climate change. Contribution of Work Package 1 to the Forest Vulnerability Assessment (Wood et al., 2010).	Helen Wallace (USC), Kathleen Wood (USC), Anne Roiko (USC), Peter Waterman (USC)
1	The scenarios of climate change: Tools, methods, data and outputs. Supplementary Materials of Work Package 1 to the Forest Vulnerability Assessment (in Wood et al., 2010).	Richard Warrick (USC and CLIMsystems Ltd)
2	Biophysical impacts of climate change on Australia's forests. Contribution of Work Package 2 to the Forest Vulnerability Assessment (Medlyn et al., 2010).	Belinda Medlyn and Melanie Zeppel (Macquarie), Tom Lyons, Giles Hardy and Niels Brouwer (Murdoch)
3	Socio-economic implications of climate change with regard to forests and forest management. Contribution of Work Package 3 to the Forest Vulnerability Assessment (Cockfield et al., 2010).	Geoff Cockfield and Tek Maraseni (USQ), Laurie Buys and Jeffrey Sommerfeld (QUT), Clevo Wilson and Wasantha Athukorala (QUT)
4	Climate change adaptation options, tools and vulnerability. Contribution of Work Package 4 to the Forest Vulnerability Assessment (Wilson and Turton, 2010).	Steve Turton and Robyn Wilson (JCU)
5	An Assessment of the Vulnerability of Australian Forests to the Impacts of Climate Change (this report).	Sarah Boulter (GU & NCCARF), Roger Kitching (GU)
5	An Assessment of the Vulnerability of Australian Forests to the Impacts of Climate Change Supplementary Material: Forest Resources, Climate Change and the Law.	Douglas E. Fisher (QUT)

Appendix 2 Australia’s dominant native forest vegetation types

Table A2.1 Australia’s major native forest types and percentage area of each type in conservation reserves. Source: ABARE-BRS.

Forest vegetation type	Area (‘000 ha)	Percentage of forest type in conservation area	Description
Acacia	10 365	5	Acacia forests account for 7% of the total native forest area making them Australia’s second most common forest type. They predominantly form woodlands in regions where average annual rainfall is less than 750 millimetres. In wetter areas, they can form open forests, usually dominated by a single species: in Tasmania, for example, blackwood (*A. melanoxylon*) dominates extensive stands of swamp forest on poorly drained sites. Acaia forests are found in all states and the Northern Territory, with Queensland and Western Australia supporting the largest areas. Mulga (*Acacia aneura*) is the dominant species in many parts of the arid and semi-arid zone, and also occurs as an understorey species in some eucalypt forests in eastern Australia. Brigalow (*A. harpophylla*) is widespread in Queensland and northern New South Wales, forming dense forests on flat or undulating country with clay soils.
Callitris	2597	8	Callitris species are found in a wide variety of climates and are tolerant of temperatures ranging from below 0°C to more than 40°C. They mostly occur where annual rainfall is greater than 300 millimetres – including on Queensland’s Atherton Tablelands, where annual rainfall is as high as 2 000 millimetres. Some callitris forests survive, however, on annual rainfalls as low as 200 millimetres, including in a small area of desert in Western Australia. They occur on a wide range of soil types, but most commonly on nutrient-poor soils with sandy or loamy surface layers and a clay loam at depth. Callitris has mycorrhiza – mutually beneficial associations between fungi and plant roots – that enhances the plant’s uptake of nutrients, especially phosphorus, from nutrient-poor soils and gives the fungi access to carbohydrates from the tree’s roots.
Casuarina	2229	39	Casuarina forests occur as woodlands or open forests Casuarina forests occur in all states and territories of Australia. Its largest expanse occurs in a band from the semi-arid zone in South Australia through western New South Wales and into Queensland. Significant forests are also found in coastal New South Wales. Belah (*Casuarina cristata*) forests have the widest distribution, growing in habitats ranging from stony slopes to heavy clay soils. Common inland species include belah and river she-oak (*C. cunninghamiana*), which often occur in association with acacias and eucalypts. Coast she-oak (*C.*

			equisetifolia) occurs in pure stands on coastal fore-dunes in eastern Australia and, in less exposed sites, also in association with coastal banksias. Pure stands of the rock she-oak (*Allocasuarina huegeliana*) are found on granite soils and outcrops in Western Australia. Because it is more resistant than local eucalypts to drought, drooping she-oak (*A. verticillata*) forms pure stands on very dry sites in Tasmania.
Eucalypt	116 449	18	Three genera – *Eucalyptus*, *Corymbia* and *Angophora* – are usually referred to as eucalypts. Eucalypt forests are by far the most common in Australia. Eucalypt forests are found throughout Australia except in the most arid regions. For national reporting, eucalypt forests are grouped into 11 categories defined by dominant species and structure. The most important of these are the eucalypt medium woodland (38% of Australia's total forest area), eucalypt medium open forest (19%) and the eucalypt low woodland (9%). The forests of southeastern Australia contain a wider range of dominant eucalypt species than those of southwestern or northern Australia. In the southeast, the greater topographic variability results in major changes in species groupings. In southwestern and northern Australia, where the topography is less variable, a few species of eucalypts, such as woollybutt (*E. miniata*), stringybark (*E. tetrodonta*) and jarrah (*E. marginata*), dominate large areas of forest, although many other species occur in localised areas.
Mangroves	980	18	Mangroves are important and widespread coastal ecosystems in the intertidal zone of tropical, subtropical and protected temperate coastal rivers, estuaries and bays. Individual species have characteristic tidal-zone or preferred upriver estuarine locations. Mangroves can form dense, almost impenetrable stands of closed forests, often dominated by only one or two species, as well as less dense stands characterised as open forests and, to a lesser extent, woodlands. Closed mangrove forests, which comprise about 56% of the total mangrove forest estate, provide coastal protection from storm and wave action.
Melaleuca	7556	11	There are hundreds of species in the genus *Melaleuca* and many other species in closely related genera, such as *Callistemon.* About 75% of Australia's melaleuca forest occurs in Queensland, particularly on Cape York Peninsula. A further 22% is found in the northern part of the Northern Territory. Small pockets occur along the subtropical and temperate coasts of Queensland, New South Wales and Victoria, and on the fringes of rivers and coastal wetlands, including in brackish and saline areas. Extensive stands of swamp dominated by melaleucas, blackwood (*Acacia melanoxylon*) and *Leptospermum* species occur on poorly drained sites in northwestern Tasmania. The dominant species in melaleuca forests vary markedly. Northern Australian melaleuca forests are dominated by

			broadleaved paperbark (*Melaleuca viridiflora*), weeping or long-leaved paperbark (*M. leucadendra*), silver paperbark (*M. argentea*), blue paperbark (*M. dealbata*) and yellow-barked paperbark (*M. nervosa*). In southern and eastern Australia, melaleuca forests are confined to permanently wet watercourses and swamps. The most common coastal species is the paperbarked tea tree (*M. quinquenervia*). In Western Australia, melaleuca forests are restricted to small pockets on specific sites, such as Preiss's paperbark (*M. preissiana*) in near-coastal swampy areas and freshwater or swamp paperbark (*M. rhaphiophylla*) along watercourses.
Rainforest	3280	55	Rainforest is a general term for a range of broad-leaved forest communities with closed canopies. Rainforest canopy species are shade-tolerant trees that are able to establish in the understorey and take advantage of canopy gaps that might open up as a result of tree falls, lightning strikes or other disturbances. Unlike many Australian forest species, rainforest canopy trees do not depend on fire for their regeneration. Rainforests account for most (77%) of Australia's closed crown cover forest. They extend across the top of northern Australia from the Kimberley to Cape York and down the east coast to the cool temperate zone in Tasmania. Rainforests occur in all states and territories except South Australia and the Australian Capital Territory. Queensland has the largest area (57% of all rainforests), followed by Tasmania (18%), New South Wales (15%) and the Northern Territory (9%).

Appendix 3 Tools: SimCLIM and the approach to scenario generation

SimCLIM is a software modelling system used to link and integrate complex arrays of data and models in order to simulate (both temporally and spatially) bio-physical impacts and socio-economic effects of climate variability and change, including extreme climatic events. SimCLIM is the generic name of the “open-framework” system developed from CLIMPACTS, an integrated modelling system developed specifically for New Zealand at the University of Waikato (Warrick, 2009), and its various “clones” (for example, the Australian version, OzCLIM; CSIRO, 2004).

The “open-framework” features of SimCLIM provide the flexibility for importing data and models in order to customise the system for specific applications – much like a GIS. There are tools to allow the user to import spatially-interpolated climatologies and other spatial data (e.g. elevation surfaces), site time-series data and patterns of climate and sea-level changes from General Circulation Models (GCMs). The geographical size is a matter of user choice (from global to local), as is the spatial resolution (subject to computational demands and data availability and quality). For the FVA project an Australian version of SimCLIM was used that contained Australia-wide observed monthly-mean values of precipitation and mean, maximum and minimum temperature derived from the 1961-1990 baseline period (source: Australian Bureau of Meteorology) and interpolated to a 0.025 lat/lon resolution, as well as spatial patterns of change for these same variables from general circulation models (GCMs).

Every SimCLIM contains a “climate scenario generator”. In using SimCLIM, there are three major areas of uncertainty in the generation of scenarios which are treated independently and for which ranges of uncertainty can be taken into account:

- The **climate sensitivity** (which determines the *magnitude* of global warming for a given change in GHG concentrations). The “climate sensitivity” refers to the responsiveness of the climate system to changes in atmospheric concentrations of greenhouse gases. Conventionally, the climate sensitivity is defined as the *equilibrium* change in global-mean temperature for a doubling of CO_2. Different GCMs produce different values for the climate sensitivity due to differences in the way in which climate feedbacks – e.g. changes in snow and ice cover, clouds – enhance or dampen the direct radiative forcing from GHGs. The SimCLIM user can select from a low, “best estimate” and high climate sensitivity, a range of uncertainty corresponding to the 90% confidence interval in accordance with that used by the IPCC Fourth Assessment Report.

- **GHG emissions** (which determine the *rate* of change of GHG concentrations and associated radiative forcing). The six key IPCC SRES marker scenarios, spanning low to high emissions, can be chosen individually in scenario generation within SimCLIM.

- **Spatial patterns of change from GCMs** (which determine the *regional differences* in changes in temperature, precipitation and other climate variables). SimCLIM has sets of results from 21 GCMs (see below), which can be used either individually or in *ensembles* (combinations of GCMs). For the latter, the user can select the “best estimate” (median value) or select a percentile range to represent the uncertainties.

The SimCLIM user interface provides considerable scope for choosing amongst emission scenarios, model sensitivity values, GCM patterns, regions, seasonal aggregations and future time horizons, and thus for examining the range of uncertainties involving future greenhouse gas emissions and scientific modelling. For the FVA project, the following specifications applied:

- Climate sensitivity: **HIGH**

- Emission Scenario: SRES A1FI (highest)

- GCM: the median value of an ensemble of equally weighted 21 GCMs

Using “pattern scaling” techniques, these three factors can be combined to generate scenarios of climate change, as described below.

METHODS

SimCLIM uses a variation of the *pattern scaling* described originally by Santer et al., (1990) to generate regional patterns of climate change for user-selected years between 1990 and 2100. In pattern-scaling, the global-mean and spatial patterns of future change are treated separated. Spatial patterns of climate change (monthly-means) from GCMs are “normalised” (i.e. expressed as changes per 1°C change in global-mean temperature) and scaled up to a projected global-mean temperature change for a given year. As stated by Kennett and Buonomo (2006), “...pattern scaling method offers a possibility of representing the whole range of uncertainties involved in future climate change projection based on various combinations of emission scenarios and GCM outputs, which makes the cross model sensitivity analyses and uncertainties examinations can be easily conducted (TGICA, 2007)”. Pattern scaling may be described as follows:

For a given climate variable *V*, its anomaly ΔV^* for a particular grid cell (*i*), month (*j*) and year or period (*y*) under an emission forcing scenario is calculated as:

$$\Delta V^*_{yij} = \Delta T_y \cdot \Delta V'_{ij} \quad (1)$$

ΔT being the annual global-mean temperature change.

For SimCLIM, the local “normalised” (i.e. the change per 1°C of global temperature change) pattern value ($\Delta V'_{ij}$) is calculated from the GCM simulation anomaly (ΔV_{yij}) using linear least squares regression, that is, the slope of the fitted linear line.

$$\Delta V'_{ij} = \frac{\sum_{y=1}^{m} \Delta T_y \cdot \Delta V_{yij}}{\sum_{y=1}^{m} (\Delta T_y)^2} \quad (2)$$

Where *m* is the number of future sample periods used, in this case a 10 year average was the period.

The anomaly ΔV^* is then used to perturb the baseline *observed* values, V_{obs}, in order to generate a “new” climate scenario for the future year.

Pattern scaling is based on two key assumptions: firstly, that a simple climate model can accurately represent the global responses of a GCM, even when the response is non-linear (Raper et al., 2001); and, secondly, that a wide range of climatic variables represented by a GCM are a linear function of the global annual mean temperature change represented by the same GCM at different spatial and/or temporal scales (Mitchell, 2003, Whetton et al., 2005).

DATA

ΔT projections contained in SimCLIM were produced by the simple climate model, MAGICC (Wigley, 2008), using emission scenarios and a set of climate model parameters (in SimCLIM, represented by the “climate sensitivity” value) which produce temperature projections consistent with those of IPCC AR4. In SimCLIM, there are thus 18 possible projections of global-mean temperature change from which to select (3 climate sensitivities X 6 emission scenarios).

The GCM data were obtained from the experiments of 21 models from research groups around the world (Table A3.1). The data were obtained from the Coupled Model Intercomparison Project 3

(CMIP3) database (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php), produced for the IPCC AR4. The models in the CMIP3 database represent the current state-of-the-art in climate modelling, with generally more sophisticated representations of physical and dynamical processes and finer spatial resolution. The CMIP3 database provides monthly mean temperature and precipitation data for all 21 models. The simulations of 20th century climate were driven by observed changes in greenhouse gases and aerosols and were used as the simulated baseline calculating change values. For the 21st century, simulations were driven by various emission scenarios; the patterns obtained for SimCLIM were driven by the SRES A1B forcing. The global patterns are generated in 0.5 degree latitude * longitude grids interpolated from the GCM's original resolution, using a bilinear interpolation method. These were further interpolated to a 0.025 grid for Australia.

Table A3.1 GCMs used in SimClim Precipitation and temperature patterns.

No.	Originating Group(s), Country	Model	SimClim name	Horizontal grid spacing(km)
1	Bjerknes Centre for Climate Research, Norway	BCCR	BCCRBCM2	~175
2	Canadian Climate Centre, Canada	CCCMA T47	CCCMA-31	~250
3	Meteo-France, France	CNRM	CNRM-CM3	~175
4	CSIRO, Australia	CSIRO-MK3.0	CSIRO-30	~175
5	CSIRO, Australia	CSIRO-MK3.5	CSIRO-35	~175
6	Geophysical Fluid Dynamics Lab, USA	GFDL 2.0	GFDLCM20	~200
7	Geophysical Fluid Dynamics Lab, USA	GFDL 2.1	GFDLCM21	~200
8	NASA/Goddard Institute for Space Studies, USA	GISS-E-H	GISS—EH	~400
9	NASA/Goddard Institute for Space Studies, USA	GISS-E-R	GISS—ER	~400
10	LASG/Institute of Atmospheric Physics, China	FGOALS	FGOALS1G	~300
11	Institute of Numerical Mathematics, Russia	INMCM	INMCM-30	~400
12	Institute Pierre Simon Laplace, France	IPSL	IPSL-CM40	~275
13	Centre for Climate Research, Japan	MIROC-H	MIROC-HI	~100
14	Centre for Climate Research, Japan	MIROC-M	MIROCMED	~250
15	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, Germany/Korea	MIUB-ECHO-G	ECHO---G	~400
15	Max Planck Institute for meteorology DKRZ, Germany	MPI-ECHAM5	MPIECH-5	~175
17	Meteorological Research Institute, Japan	MRI	MRI-232A	~250
18	National Center for Atmospheric Research, USA	NCAR-CCSM	CCSM—30	~125
19	National Center for Atmospheric Research, USA	NCAR-PCM1	NCARPCM1	~250
20	Hadley Centre, UK	HADCM3	UKHADCM3	~275
21	Hadley Centre, UK	HADGEM1	UKHADGEM	~125

Appendix 4 Climate scenarios

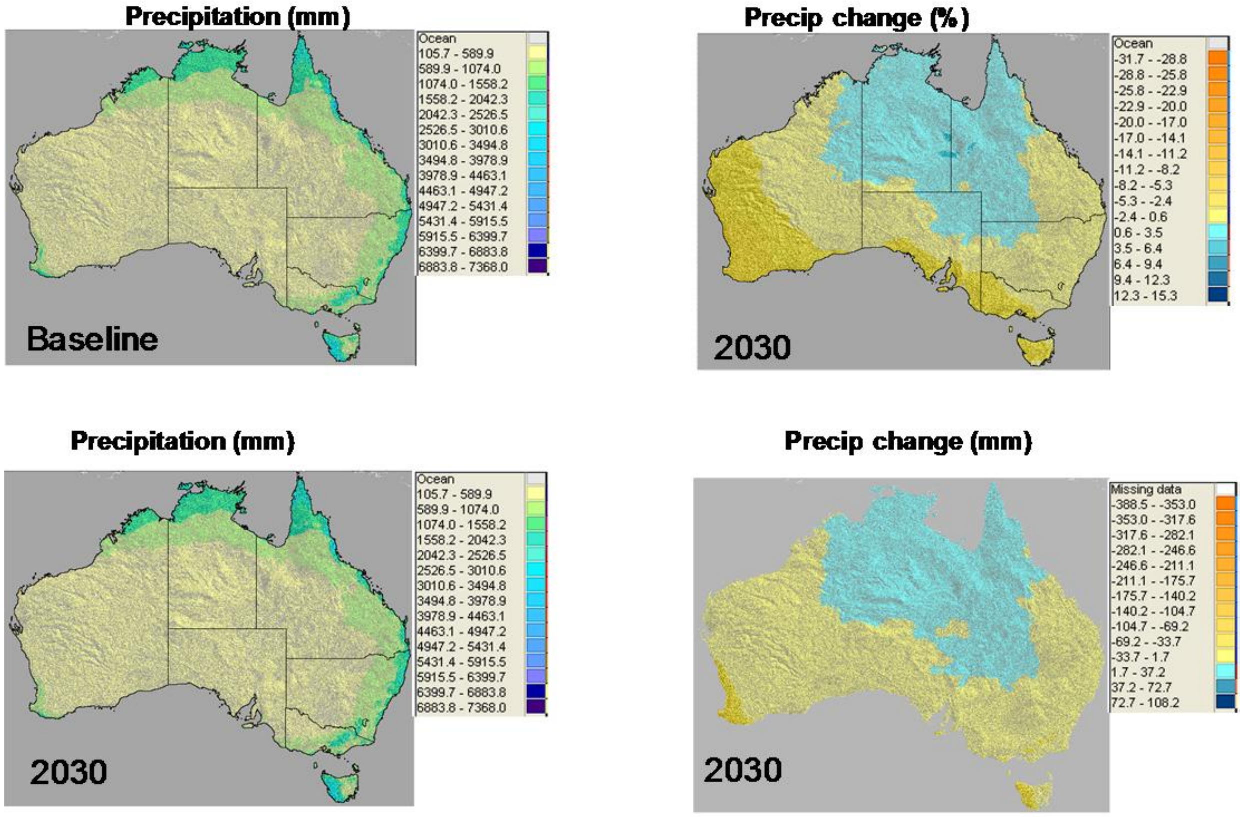


Figure A4.1 Australia: Annual mean precipitation for 2030 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2030 scenario are shown in both mm and percent change.

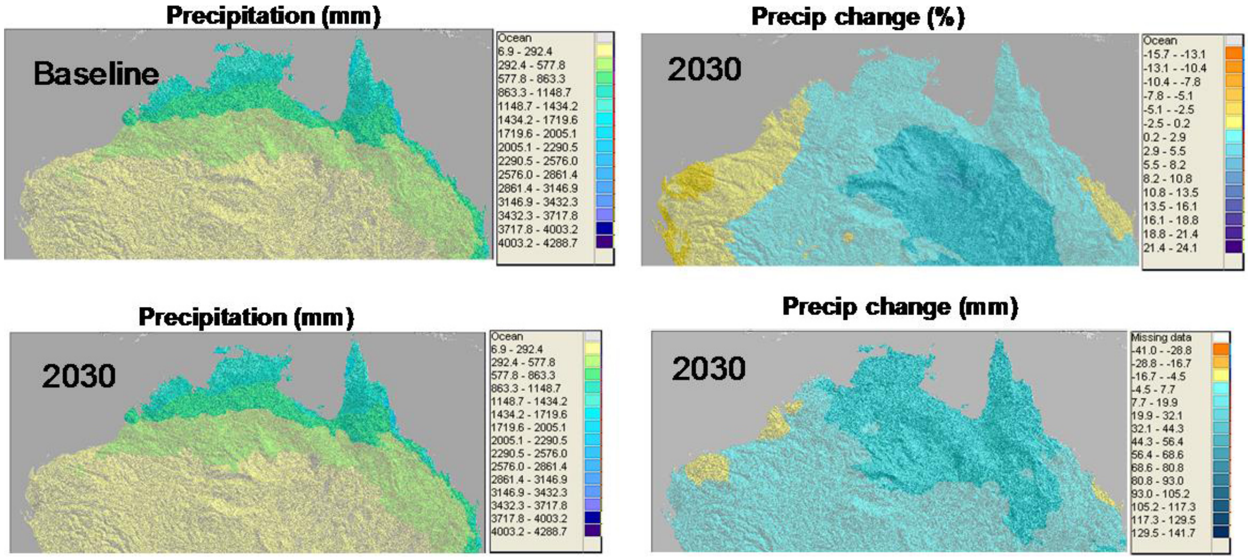


Figure A4.2 Northern Australia: Precipitation Change in Wet Season (Nov - Mar) for 2030 scenario created using high emissions, high climate sensitivity and the median of 21 GCM

Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2030 scenario is shown in both mm and percent change.

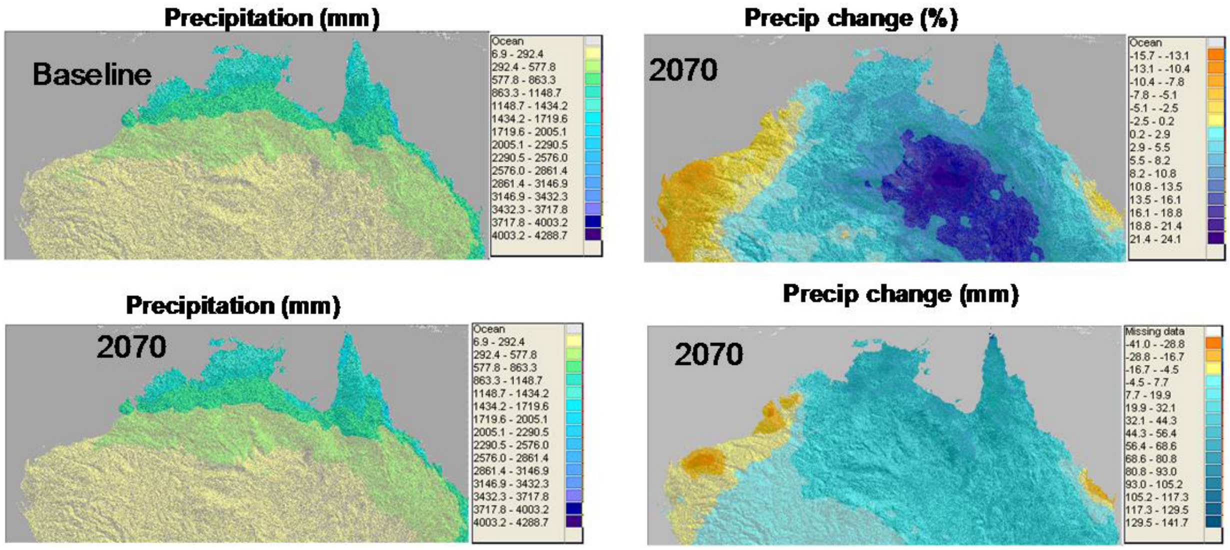


Figure 11.1 Northern Australia: Precipitation Change in Wet Season (Nov - Mar) for 2070 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2070 scenario is shown in both mm and percent change.

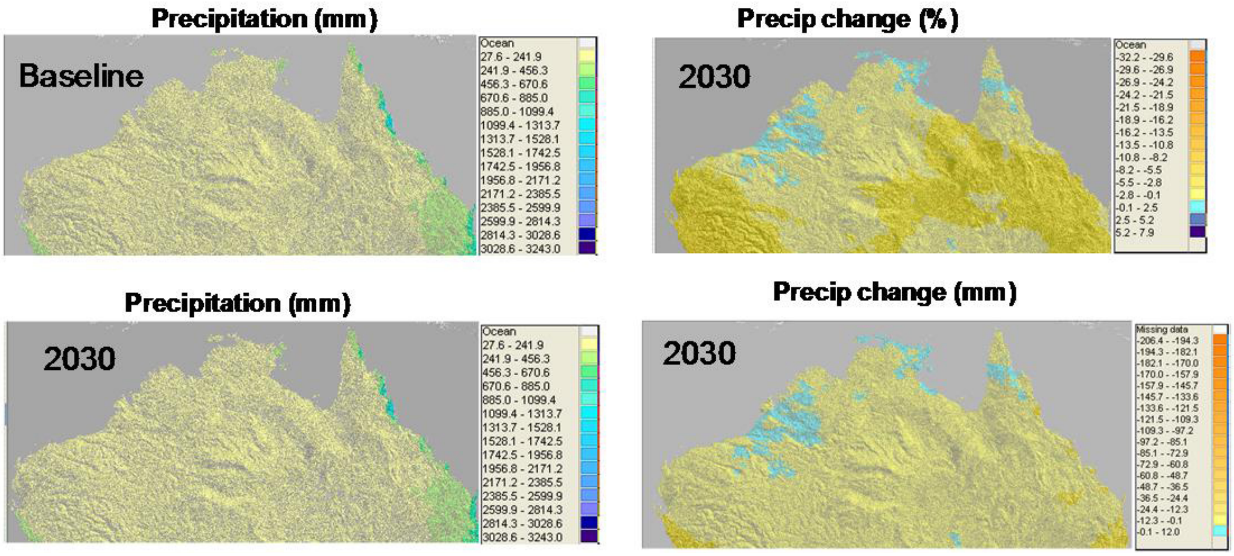


Figure A4.2 Northern Australia: Precipitation Change in Dry Season (Apr - Oct) for 2030 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2030 scenario is shown in both mm and percent change.

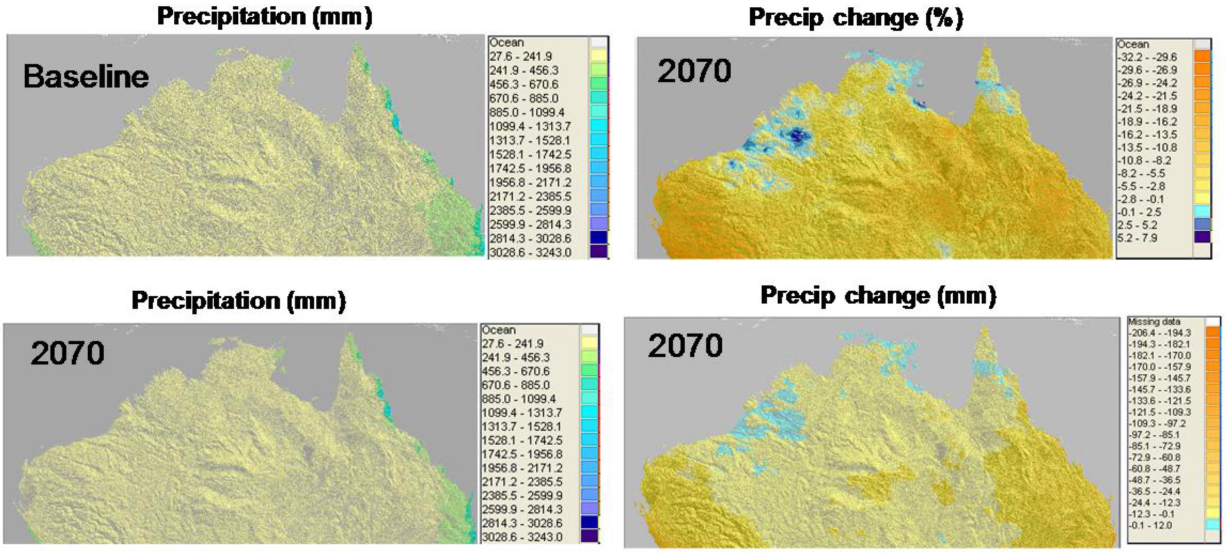


Figure 11.3 Northern Australia: Precipitation Change in Dry Season (Apr - Oct) for 2070 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2070 scenario is shown in both mm and percent change.

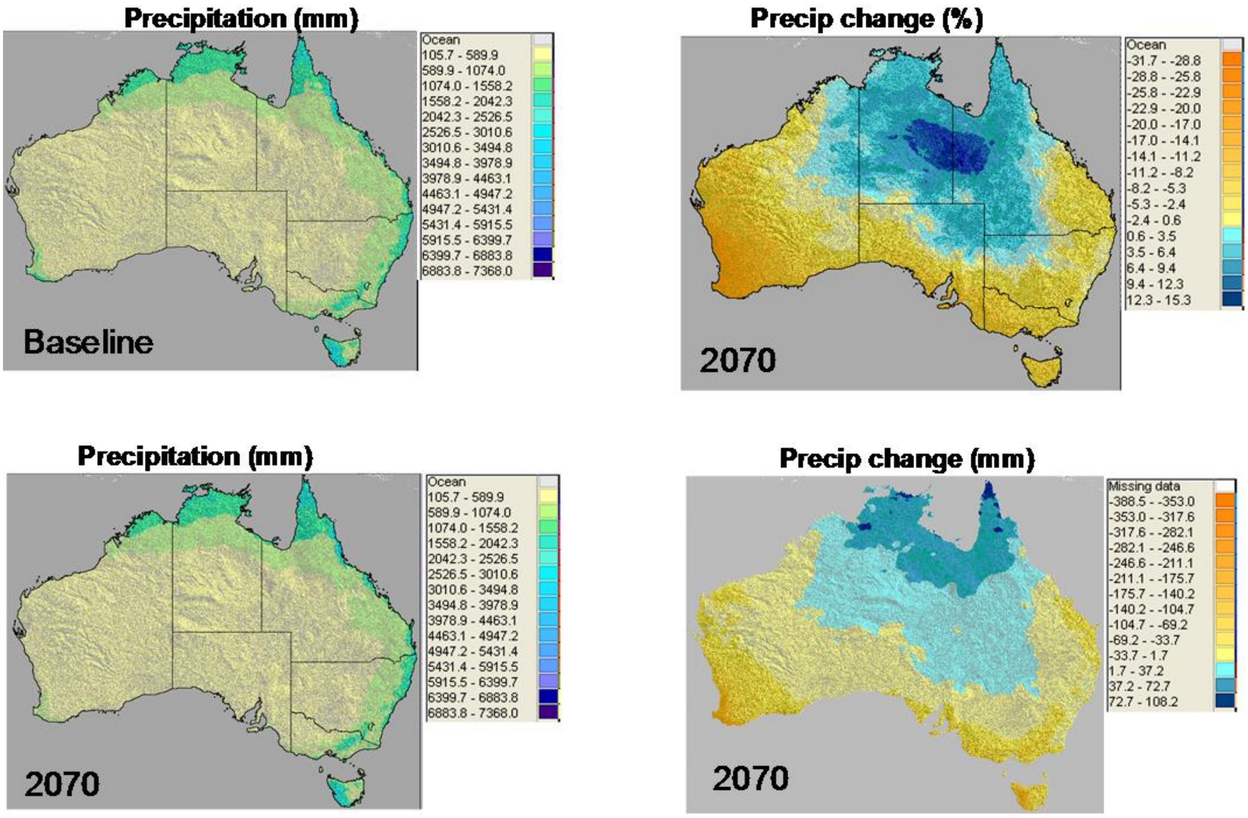


Figure A4.4 Annual mean precipitation for 2070 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2070 scenario are shown in both mm and percent change.

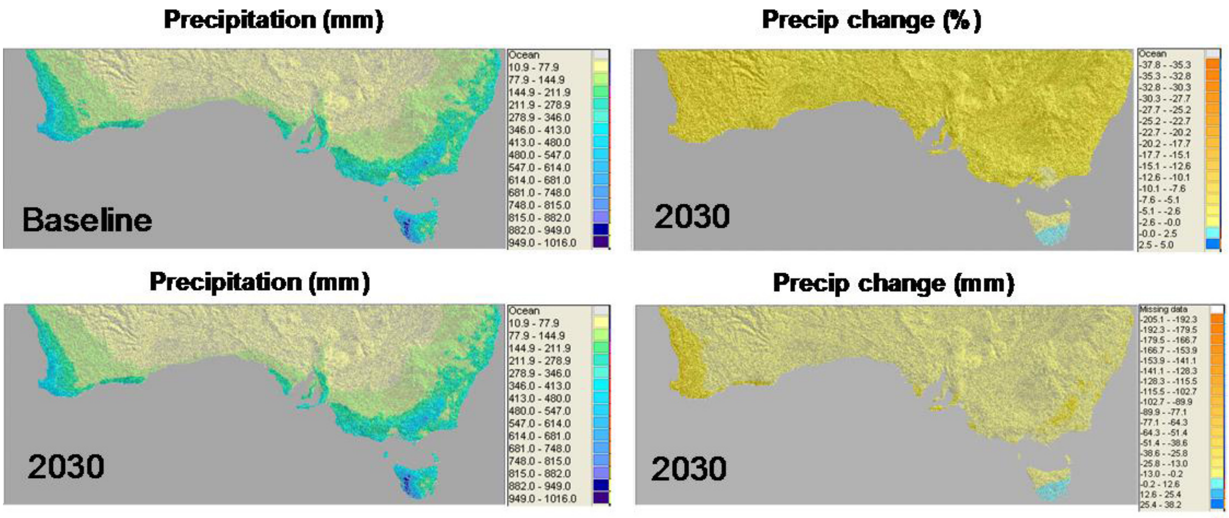


Figure A4.5 Southern Australia: Precipitation Change in Winter (Jun - Aug) for 2030 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2030 scenario is shown in both mm and percent change.

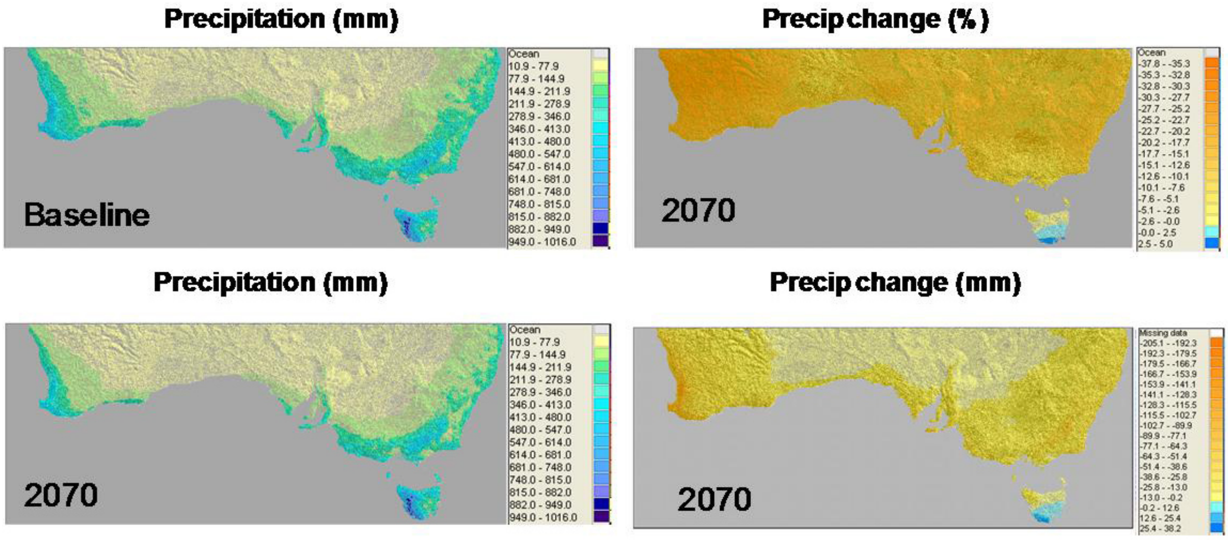


Figure A4.6 Southern Australia: Precipitation Change in Winter (Jun - Aug) for 2070 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2070 scenario is shown in both mm and percent change.

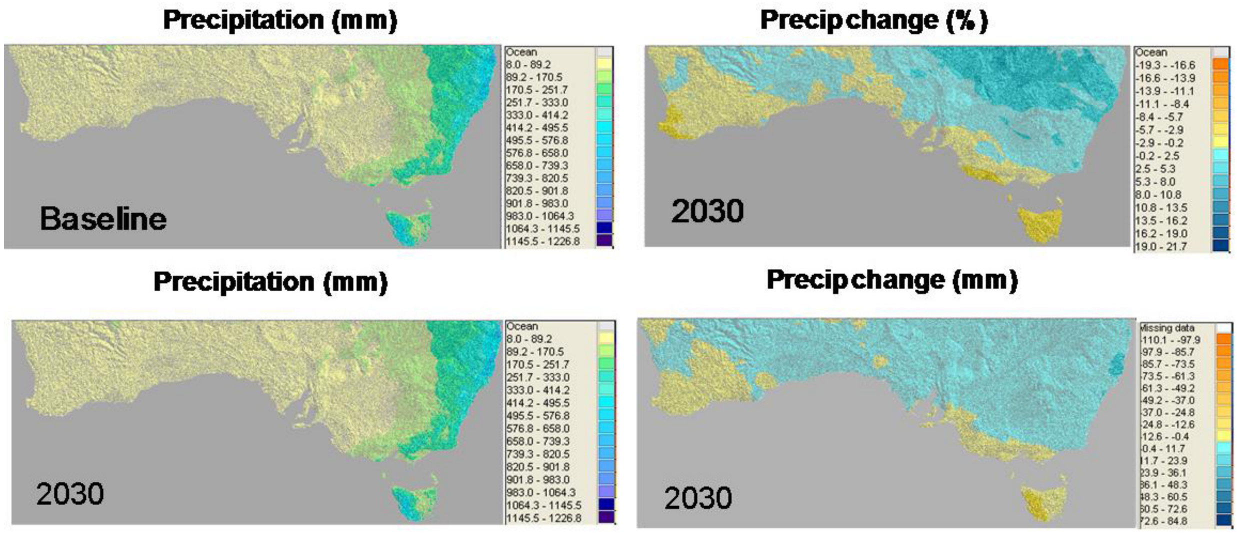


Figure A4.7 Southern Australia: Precipitation Change in Autumn (Mar - May) for 2030 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2030 scenario is shown in both mm and percent change.

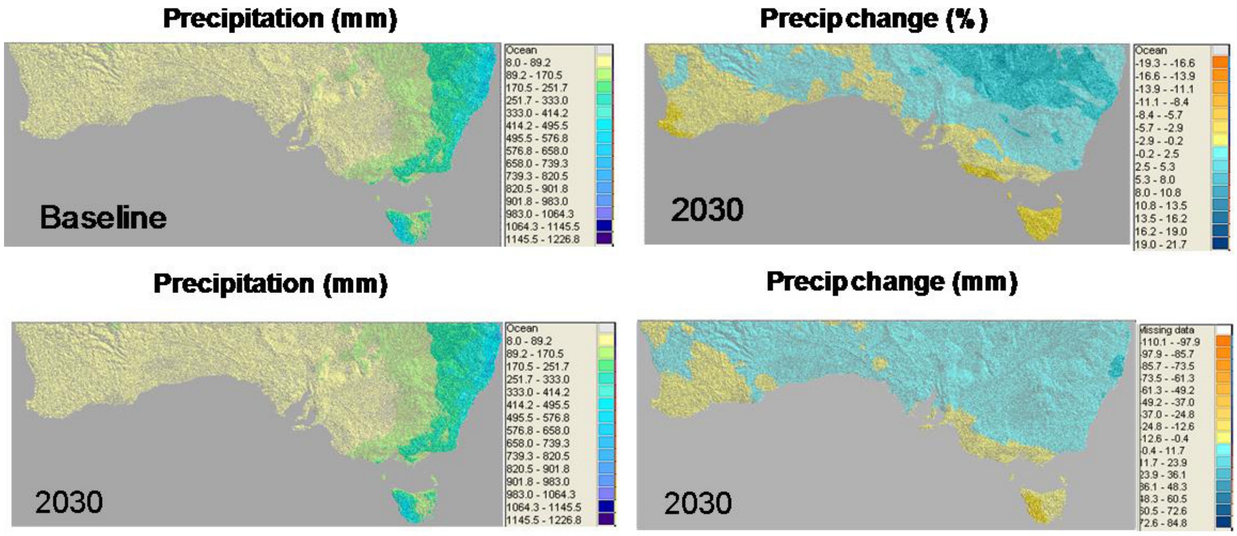


Figure A4.8 Southern Australia: Precipitation Change in Summer (Dec - Feb) for 2030 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2030 scenario is shown in both mm and percent change.

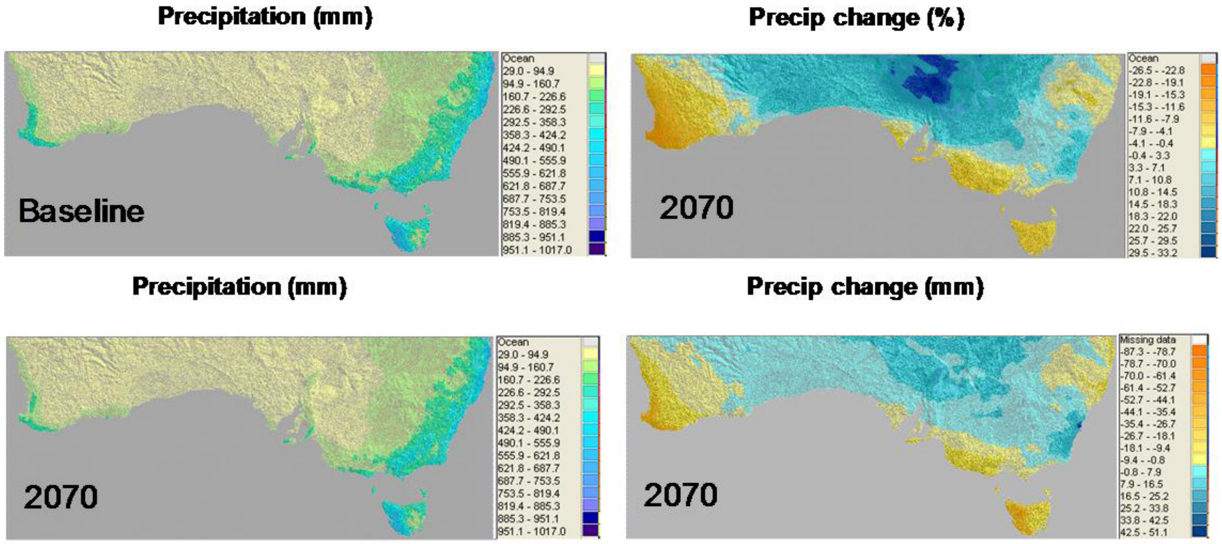


Figure A4.9 Southern Australia: Precipitation Change in Autumn (Mar - May) for 2070 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2070 scenario is shown in both mm and percent change.

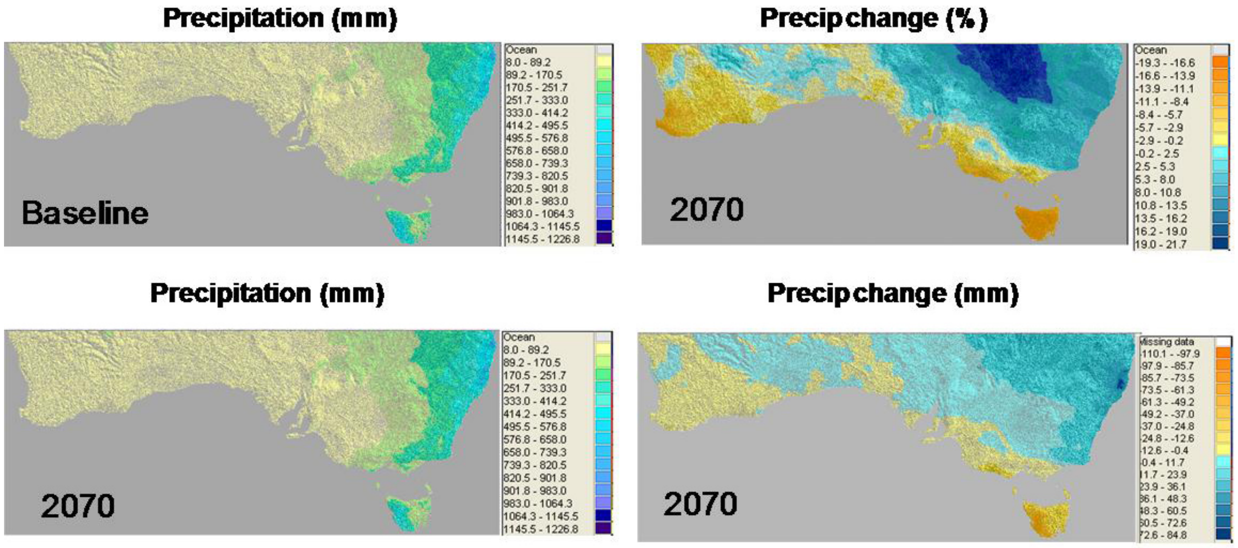


Figure A4.10 Southern Australia: Precipitation Change in Summer (Dec - Feb) for 2070 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual precipitation (based on 1961 - 1990 data) and the change in precipitation from that baseline to 2070 scenario is shown in both mm and percent change.

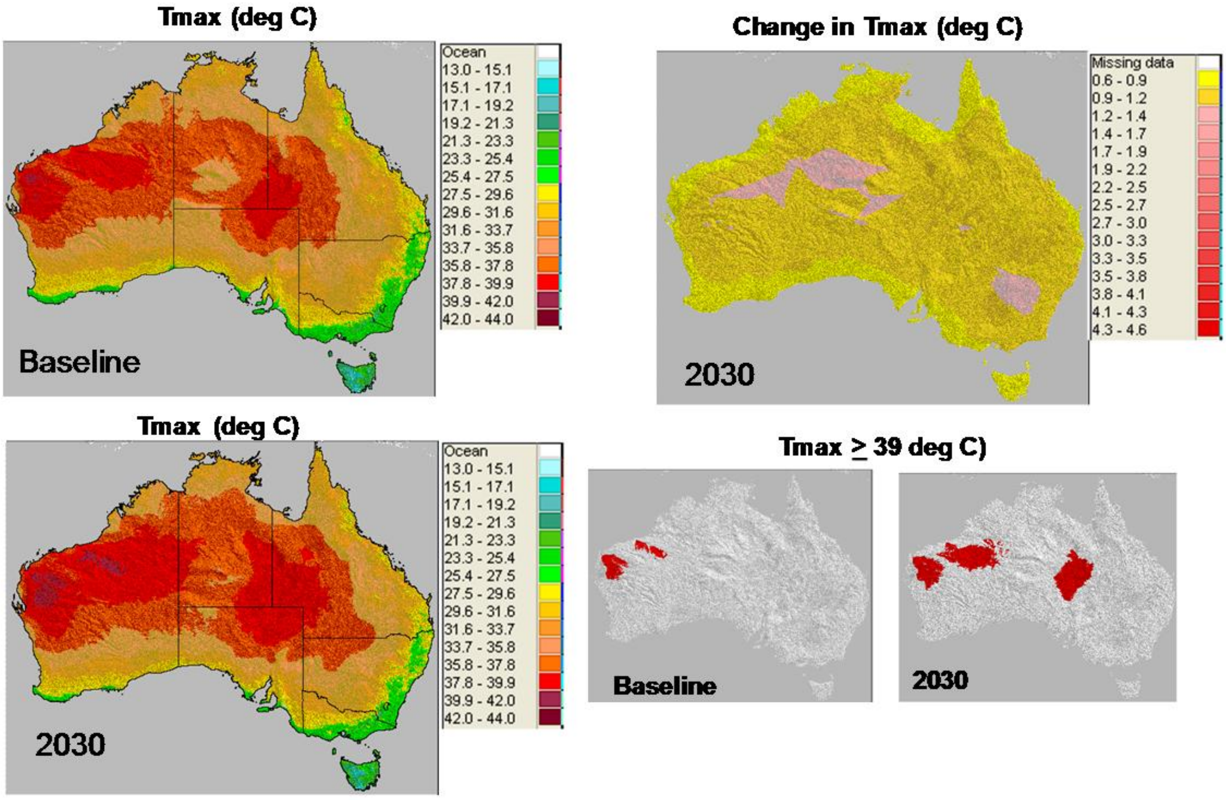


Figure A4.11 Australia: February Maximum Temperature for 2030 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual maximum temperatures for February (based on 1961 - 1990 data) and the change in temperature from that baseline to 2030 scenario is shown in both degrees Celsius and percent change.

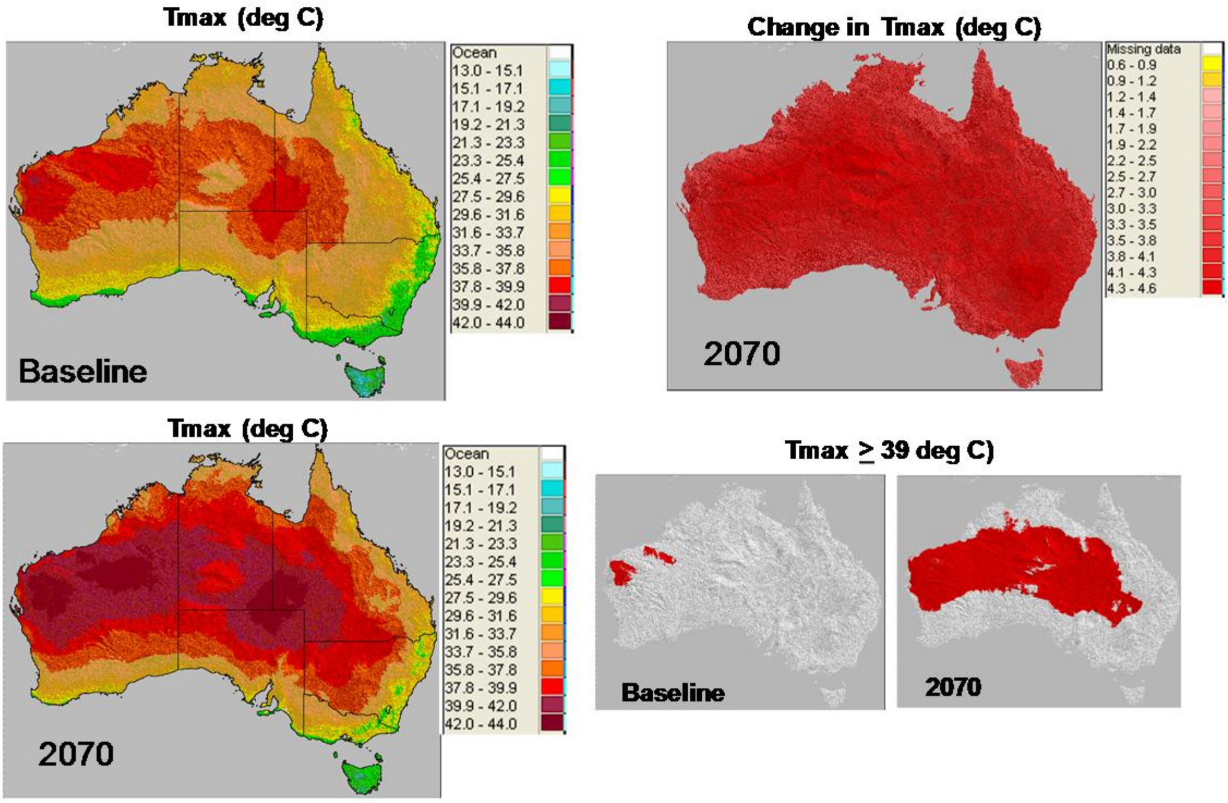


Figure A4.12 Australia: February Maximum Temperature for 2070 scenario created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual maximum temperatures for February (based on 1961 - 1990 data) and the change in temperature from that baseline to 2070 scenario is shown in both degrees Celsius and percent change.

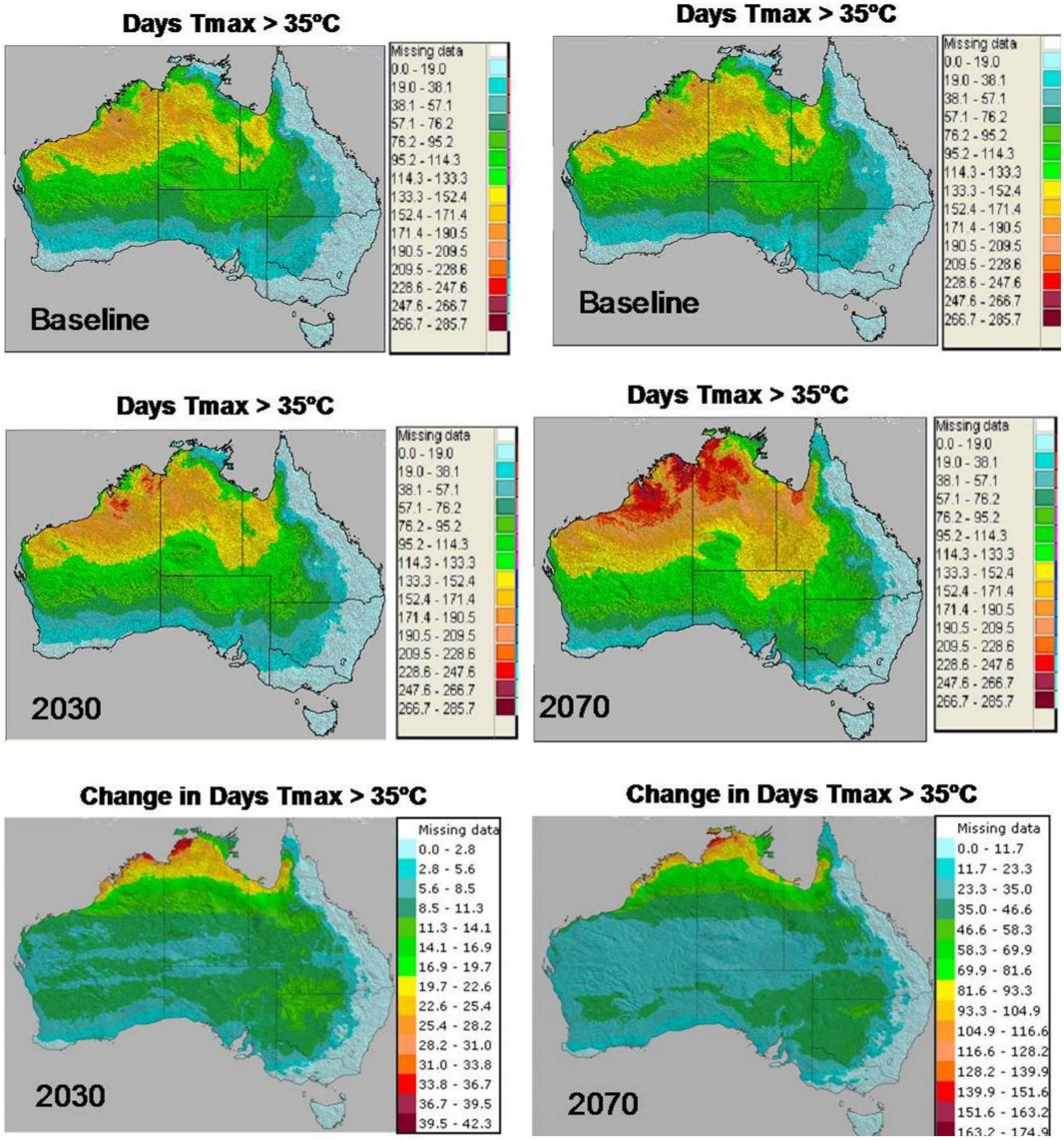


Figure A4.13 Australia: Number of days with maximum temperatures greater than 35ºC for 2030 and 2070 scenarios created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual maximum temperatures (based on 1961 - 1990 data) and the change in number of hot days (>35ºC) from that baseline to both 2030 and 2070 scenarios are shown in degrees Celsius.

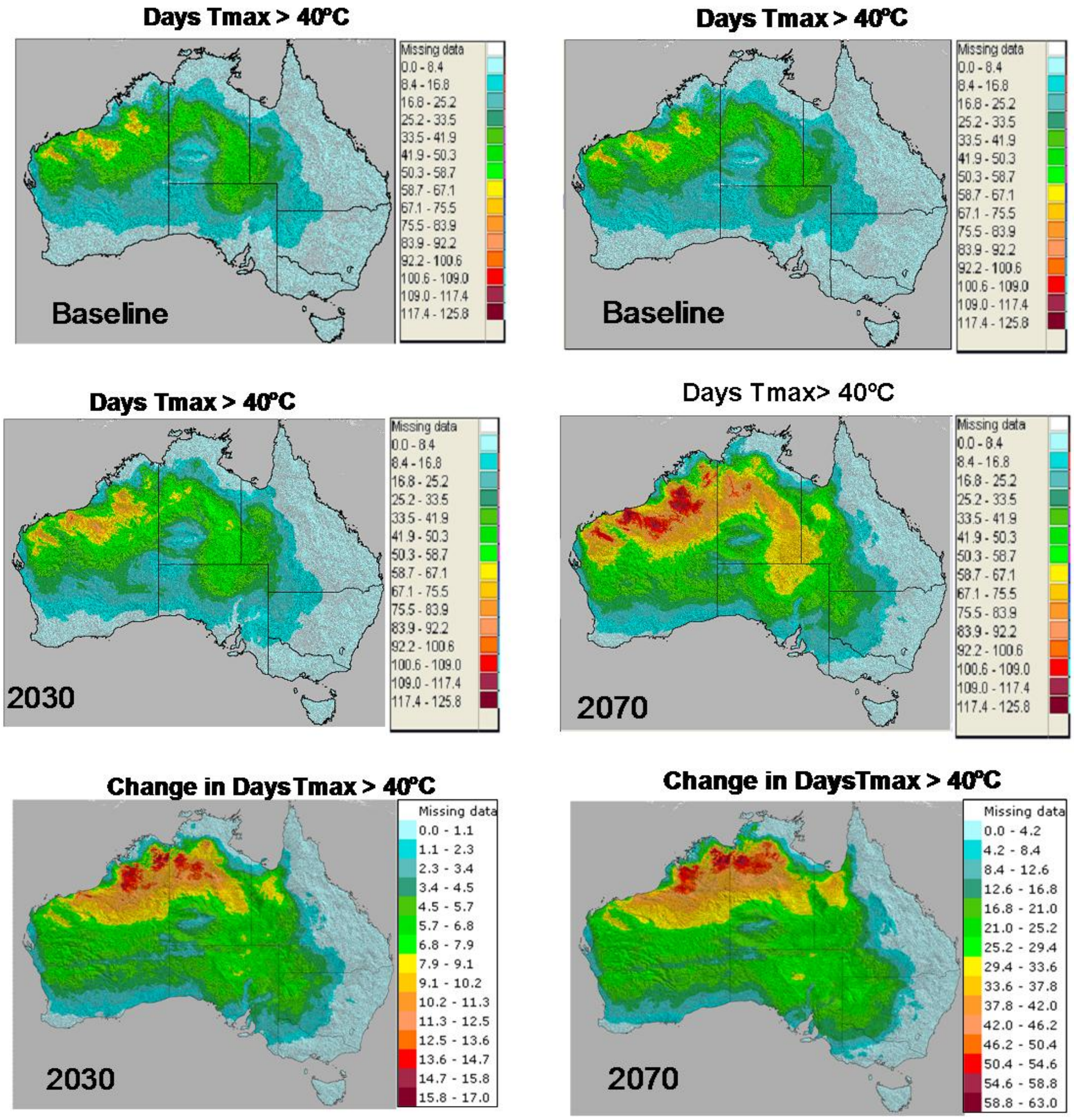


Figure A4.14 Australia: Number of days with maximum temperatures greater than 40ºC for 2030 and 2070 scenarios created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Current annual maximum temperatures (based on 1961 - 1990 data) and the change in the number of extreme hot days (>40ºC) from the baseline to both 2030 and 2070 scenarios are shown in degrees Celsius.

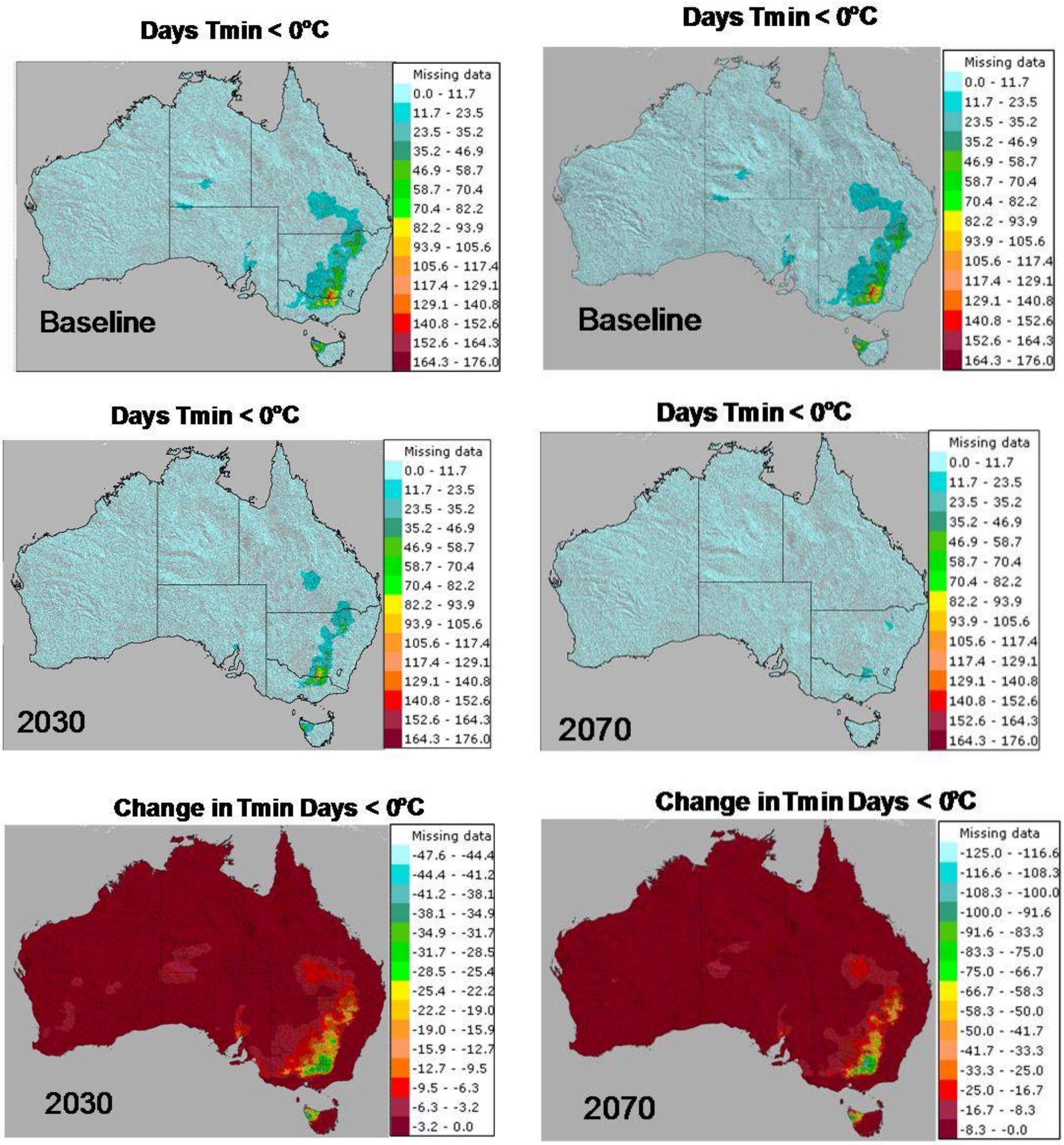


Figure A4.15 Australia: Number of days with minimum temperatures less than 0ºC for 2030 and 2070 scenarios created using high emissions, high climate sensitivity and the median of 21 GCM Ensembles. Number of days with minimum temperatures (based on 1961 - 1990 data) less than 0ºC and the change in the number of days from that baseline to both 2030 and 2070 scenarios are shown.

Appendix 5 Key Stakeholders

Key interest bodies that represent the stakeholders of Australia's forests are listed below:

National

- Department of Infrastructure Energy and Resources (DIER)
- National Forests Inventory (BRS – DAFF)
- Forests Australia (DFF.)
- Bureau of Rural Sciences (BRS)
- Australian Bureau of Agricultural and Resource Economics (ABARE)
- Commonwealth Scientific and Industrial Research Organisation (CSIRO)
- Department of Agriculture, Fisheries and Forestry (DAFF)
- Department of the Environment, Water, Heritage and the Arts (DEWHA)
- National Forest Inventory (NFI)

Australian Capital Territory

- Department of Territory and Municipal Services

New South Wales

- Department of Environment, Climate Change and Water
- Forests NSW

Northern Territory

- Department of Natural Resources, Environment, the Arts and Sport

Queensland

- Department of Environment and Resource Management
- Queensland Primary Industries and Fisheries
- Forestry Plantations Queensland

South Australia

- Department of Primary Industries and Resources SA
- Department of Water, Land & Biodiversity Conservation
- Forestry SA

Tasmania

- Department of Primary Industries, Parks, Water and Environment
- Forestry Tasmania
- Private Forests Tasmania
- Tasmanian Forest Practices Authority
- Tasmanian Parks and Wildlife Service

Victoria

- Department of Primary Industries
- Department of Sustainability and Environment
- VicForests

Western Australia

- Department of Environment and Conservation
- Forest Product Commission
- Western Australia Forest Industries

Non-government Organisations

- Australian Forestry Standard
- Bushcare
- Forest Products Association
- Greenpeace
- National Association of Forest Industries
- Forest Industries Association of Tasmania
- WWF Australia
- Global Forest Watch
- Australian Plantation Products & Paper Industry Council
- Victorian Association of Forest Industries
- Western Australia Forests Alliance
- Forest and Wood Products Australia
- Australian Hardwood Network

International

- Food and Agriculture Organisation
- Forest Stewardship Council
- International Tropical Timber Organisation
- International Union of Forest Research Organisations
- Centre for International Forestry Research
- United Nations Forum on Forests
- Montreal Process
- Ministerial Conference on the Protection of Forests in Europe

Appendix 6 Key reports and documents

State	Organisation	Publications	Climate Change?
QLD	Forestry Plantations Queensland	FPQ Strategic Plan 2008-2012	Key challenges to enhancing plantation productivity: Responding to climate change and increasing extreme climatic events
NSW	Natural Resources Commission	Riverina Bioregion Regional Forest Assessment: River red gum and other woodland forests	Current health, uses and values of the forests, and how climate variability and climate change is likely to affect them
Cwth	Dep Env Water Heritage Arts	Biodiversity conservation research in a changing climate	Conserving biodiversity WRT climate change, minimise damage, identify management and research strengths and weaknesses
Cwth	Dep Env Water Heritage Arts	Australia's Biodiversity Conservation Strategy 2010 - 2020	Stopping decline in biodiversity, ensuring biodiversity is resilient to climate change, taking action over 10 yrs.
Cwth	Dep Env Water Heritage Arts	Climate change impacts on biodiversity in Australia	Recent impacts on biodiversity, climate change, what governments can do
Cwth	Dep Env Water Heritage Arts	Developing a National Biodiversity and Climate Change Action Plan	Supporting government's CC plans and identifying strategies to support biodiversity
Cwth	Dep Env Water Heritage Arts	National Biodiversity and Climate Change Action Plan 2004 - 2007	Strategies, climate change impacts, responding to change, refuges for wildlife, etc.
Cwth	Dep Env Water Heritage Arts	Parks Australia Climate Change Strategic Overview 2009 - 2014	Climate projection, threats to resilience of national parks, strategies
Cwth	Dep Env Water Heritage Arts	Parks Australia Climate Change Strategic Overview 2009 - 2014	Changes to reserve management due to climate change impacts
Cwth	Dep Climate Change	Implications of Climate Change for Australia's National Reserve System – A Preliminary Assessment	Possible future impacts of climate change on NRS, and the consequences of these impacts for the development and management of the reserve system
Cwth	Dep Climate Change	Implications of climate change for Australia's World Heritage properties: a preliminary assessment	Assess vulnerability of the World Heritage values of each World Heritage property to climate change impacts

State	Organisation	Publications	Climate Change?
NSW	Dep Env Climate Change Water	State of Environment 2009: Chapter 7: Biodiversity	Impacts of climate change on terrestrial vegetation, forests
NSW	Dep Env Climate change Water	NSW Adaptation Strategy for Climate Change Impacts on Biodiversity	Impacts of climate change, building up a reserve system, protecting forests, etc.
NSW	Dep Env Climate change Water	Great Eastern Ranges Initiative annual progress report for 2007 - 08	Connectivity of forests NSW in face of threats such as climate change
NSW	Dep Env Climate Change Water	Lower Hunter Regional Conservation Plan	Conservation plan for region, including climate change strategies
NSW	Dep Env Climate Change Water	NSW Biodiversity and Climate Change Adaptation Framework	Accepting climate change and working out how to respond, biodiversity, region ecosystems
Cwth	Dep Agric, Forestry, Fisheries	National Climate Change and Commercial Forestry Action Plan 2009 - 2012	Strategies for climate change in forestry industry
QLD	Dep Env and Resource Management	AFS Summary Audit Report September 2007	Audit of forestry business unit RW of DERM; recognises forests for reducing greenhouse emissions
QLD	Dep Env and Resource Management	The statewide landcover and trees study (SLATS) - monitoring land cover change and greenhouse gas emissions in Queensland - technical report	Mapping land clearing rates and veg cover WRT greenhouse gas emissions, with view to reduce emissions
VIC	Dep Sustainability and Environment	State of the Forests Report - 2008	State of Victoria's forests, with mention of climate change mitigation through forest services
VIC	Dep Sustainability and Environment	Potential Biological Indicators of Climate Change: evidence from phenology records of plants along the Victorian Coast 2008	Response of plants to climate change
VIC	Dep Sustainability and Environment	A Scoping Study on Impact and Adaptation Strategies for Climate Change in Victoria 2004	Scoping of impact of CC on biodiversity, and workshops required
SA	Environmental Protection Agency SA	State of Environment Report for South Australia 2008	Impacts of climate change on biodiversity – present and future
Cwth	CSIRO	Understanding forests and climate change – web project page	Science to understand impact of CC on forests to help natural resource management and forestry
TAS & Cwth	Commonwealth and Tasmanian governments	Joint Australian and Tasmanian response to Second Five Yearly Review of Progress with Implementation of the Tasmanian Regional Forest Agreement	Forest agreement identifies area of concern, and this is response to those concerns, including importance of forests and CC

State	Organisation	Publications	Climate Change?
Cwth	Institute of Foresters Australia	Forests and climate change mitigation	Short statement on strategies for using forestry to mitigate climate change
Cwth	CSIRO	Opportunities and threats to South Australia's agricultural landscapes from reforestation under a carbon market	Climate change means a proposed carbon market, land use change from agriculture to tree farming for carbon points, what that means for land and economy
TAS	Forests and Forest Industry Council of Tasmania	Climate Change Forum FWC	
TAS	Forests and Forest Industry Council of Tasmania	Global Climate Change and the Tasmanian forests sector	Effect of climate change on Tasmania's forests and forestry
TAS	Forests and Forest Industry Council of Tasmania	Climate Change Forum CSIRO	
TAS	Forests and Forest Industry Council of Tasmania	Forest Industries and climate change	Brochure, effect and mitigation of climate change on forestry
Cwth	Department Climate Change	Carbon pollution reduction scheme stakeholder consultation	Management of forest stand plantations for carbon reduction, how to define the stand, unit limits
Cwth	Department Climate Change	Climate Change in Australia Technical Report 2007	Technical Report sections – see online for section downloads
Cwth	Dep Agriculture, Fisheries and Forestry	National Climate Change and Commercial Forestry Action Plan 2009-2012	Guide action by the forestry industry to respond to climate change through adaptation and mitigation, underpinned by research and development and communication
Cwth	Dep Sustainability, Environment, Water, Population and Communities	National Framework for the Management and Monitoring of Australia's Native Vegetation and the upcoming revised version	CC outcomes sought conservation and enhancement, as appropriate, of sinks and reservoirs for all greenhouse gases not controlled by the Montreal Protocol, including biomass and forest
Cwth	Dep Climate Change and Energy Efficiency	Adapting to Climate Change in Australia: An Australian Government Position Paper	Government's vision for adapting to the impacts of climate change and proposes practical steps to realise that vision

Appendix 7 Summary of adaptive capacity

Table A7.1 Assessment of adaptive capacity of forests from ten agro-climatic zones of Australia.

Agro-climatic zones	Potential adaptations	Knowledge gaps/needs	Adaptive capacity
Tropical savanna	Selection of production species not traditionally grown, but suited to local climate for plantation/environmental planting	Species selection support Community structure Training and skills needs Impacts on Indigenous responses, diets and culture Tourist preferences and responses	Enhanced by: Indigenous management knowledge Fire management experience Strong tourist appeal Weakened by: Existing community/social issues
Tropical rainforest	Cooperatives to create economies of scale from small lots Virtual commons Targeting stewardship programs Tree growing for multiple benefits (conservation, carbon sequestration)	How to get the most environmental value out of small-scale plantings Getting smallholders to cooperate for environmental benefits	Enhanced by: Indigenous management knowledge Existing conservation framework Plantation/farm forestry experience Weakened by: Lack of policy certainty Existing disturbance recovery Existing tourism focus High spiritual, existence value
Brigalow belt woodland	Training for prospective managers R&D and extension Protection and enhancement of representative areas Targeted stewardship programs Legislative flexibility to include property plans and internal trades	Species suitability for plantings Tree spacing and management Minimum viability for remnant areas Legislation and re-growth pattern interaction	Enhanced by: Capacity to embrace new opportunities/industries (some evidence) Weakened by: Existing disturbance and species loss/vulnerability Vegetation fragmentation Traditional land use values
Tropical forest and woodland	New species selection for plantations Conversion of planting value to new industries New management regimes for fire and weeds	Species suitability for plantings Tree spacing and management Modelling species distributions for plant and animal species including interactions	Enhanced by: Large population Existing strong forestry industry Some large conservation areas Weakened by: Conflicting land-use demands

Agro-climatic zones	Potential adaptations	Knowledge gaps/needs	Adaptive capacity
Temperate sub-humid woodlands	Species or hybrid selection for plantings Fire regime management Planning for processing of timbers for expanding plantation industry Continuation of industry adjustment to plantation (move out of productive native forests) Coordination of incentives, tenure and management Regional adjustment to changing industry/reserve needs	Growth modelling Species selection & profitability How to acquire the best conservation value? Optimising ecosystem services	Enhanced by: Existing forestry industry and experience Weakened by: Limited conservation reserves Vegetation fragmentation Existing disturbance and species loss/vulnerability
Subtropical Moist Forests	Land use planning Adjustment from timber to other industries Virtual commons Species selection	Alternative areas Citizen responses to changes in forest composition How to get the most environmental value out of small-scale plantings Getting smallholders to cooperate for environmental benefits	Strengthened by: Existing forestry and conservation traditions Already adaptation to changing plantation industry (softwood to hardwood) Weakened by: Highly vulnerable ecosystem
Temperate moist forests	Regional structural adjustment Fire management strategies Coordination of incentives, tenure and management Co-benefits programs New land management capabilities	Fire management Optimising location By-product economics How to acquire the best conservation value? Forest management skills for non-farm landholders Fire protection strategies	Strengthened by: Existing forestry and conservation traditions Already adapting to changing plantation industry Opportunities for new industries (carbon, new timber species) Weakened by: Highly vulnerable ecosystem Existing fragmentation
Cold forest and grassland	Improved fire management strategies Re-branding landscapes Relocation of species?	Fire management How will change impact on tourism?	Strengthened by: Large conservation reserves Weakened by: Strong reliance on climate dependant industries
Mediterranean woodland	Adjustment from timber and crops to bio-energy and sequestration plantations Continuation of industry adjustment Protection and enhancement of representative areas Co-benefits program Regional NRM coordination	Bio-energy tree production Maximising co-benefits by location	Strengthened by: Strong forestry tradition and knowledge Weakened by: Existing degradation issues

Agro-climatic zones	Potential adaptations	Knowledge gaps/needs	Adaptive capacity
	Regional adjustment		
Arid shrubland and grassland	New industries Protection and enhancement of conservation areas	Understanding species tolerance to variability Maximise co-benefits by location	Strengthened by: Existing adaption to variability and extreme conditions Weakened by: Vulnerable human communities

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