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# **Climate change and South Australia's plantations: impacts, risks and options for adaptation**

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## INTRODUCTION

Forest management systems are based on an assumption that past climate is a good predictor of future events. Projected climate changes and a trend towards increasing frequency of extreme climatic events (Nicholls 2008; Steffen 2009; Whetton 2007) suggest that within the timeframe of current rotations in Australia (~10 – 40 years) that this assumption may not hold and that the possible effects of climate change on plantation productivity should be explored and the adequacy of existing management tested.

South Australia holds about one tenth of Australia's plantations. South Australia's plantation estate falls within the Mediterranean woodland biome, which experiences warm climates, characterised by a high moisture index in winter and a low moisture index in summer. This results in a highly seasonal pattern of growth. One of the key factors limiting the survival and productivity of these plantations is soil water availability. The general drying trend projected by many climate models for South Australia (<http://www.csiro.au/ozclim>), combined with increasing frequency of droughts and heatwaves (Battaglia et al. 2009) makes these plantations vulnerable, not only to the direct effects of climate change, but also to the indirect effects such as potential changes in frequency and severity of pest and weed outbreaks.

The three main plantation regions in South Australia - Green Triangle, Mt Lofty/Kangaroo Island and Mid North (Figure 1) – experience different climates, soils and landforms. This is reflected in the management practices used in each region. The three regions are likely to vary in their vulnerability to changing climate, and in the capacity of adaptation to mitigate future risks. Future management responses may differ in across regions in the future.

This report provides a summary of how climate change might affect plantation regions in South Australia. It recommends changes in management options to reduce vulnerability to climate change and impacts on plantation productivity.

Sequentially, the following questions are addressed:

- How is climate expected to change in South Australia over the next 20 – 60 years, and how might these changes be expected to affect forest productivity?
- Where in the plantation estate might increases or decreases in productivity occur?
- How might risks from drought, pests and extreme weather conditions change, and how will this interact with productivity?
- What is the uncertainty around forecast changes?
- How can adapting plantation management help to maintain or promote productivity into the future?

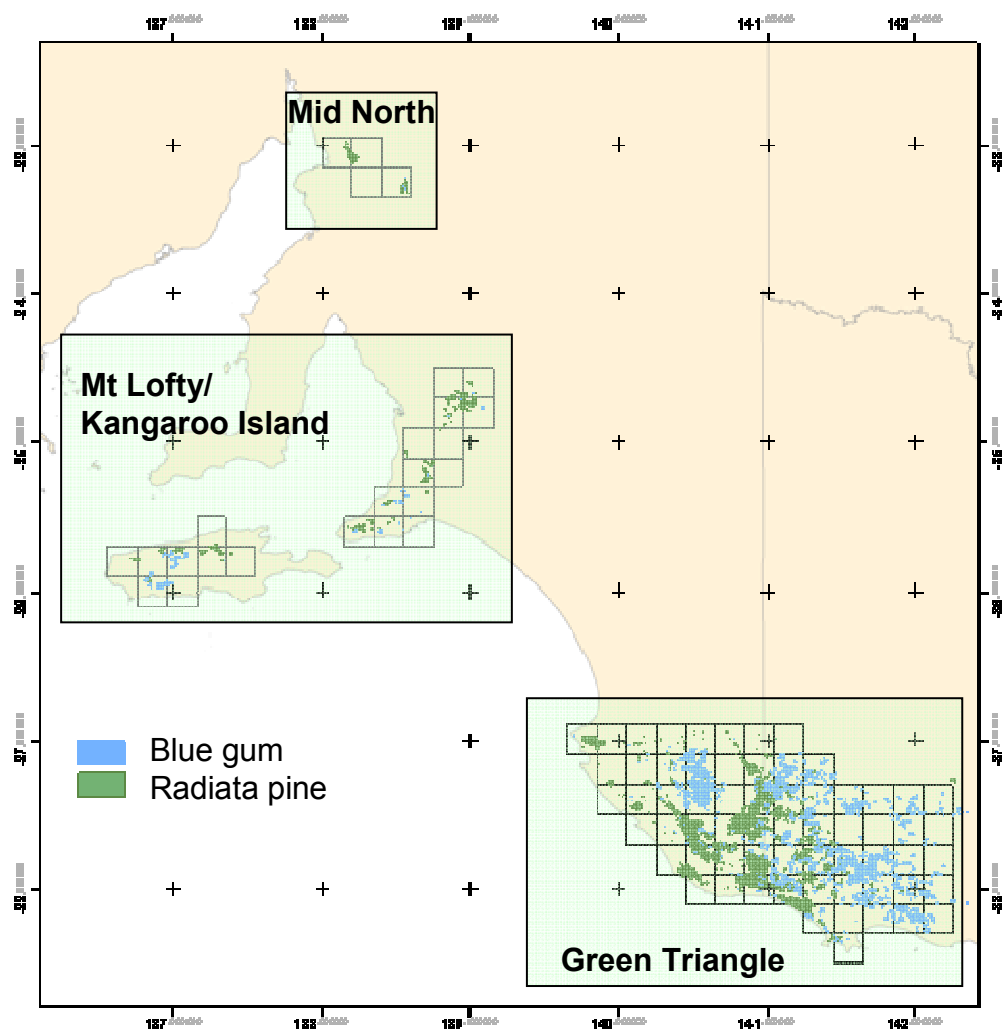


Figure 1. Location of the three main plantation regions in South Australia.



## CLIMATE CHANGE PROJECTIONS FOR SOUTH AUSTRALIA

### Summary

- While climate models project slightly different outcomes for South Australia for the future, they all project a general warming and drying trend for the plantation regions
- For example, using the CSIRO Mk3.5 model, an increase in mean maximum temperatures of 0 – 2 °C is projected for all seasons for South Australia's plantation regions by 2030. Mean minimum temperatures are projected to rise by 0 – 1 °C, and rainfall is projected to decrease by 0 - 10 mm in summer, autumn and spring, and by 20 – 60 mm in winter
- By 2070, mean maximum and minimum temperatures are projected to have risen by 1 – 3 °C in all seasons. Mean annual rainfall is projected to decrease by 20 – 80 mm, with the greatest reductions in winter

## HISTORICAL TRENDS IN CLIMATE

Nicholls ( 2008) and Steffen ( 2009) provide summaries of historical trends in Australia's climate. They point to an increase in mean annual temperature since 1910; an increase in days with maximum temperatures more than 35 °C; a decline in annual rainfall; and an increase in the number of intense weather events.

In South Australia, although there is regional variability, mean maximum temperatures in the main plantation regions have increased by between 0.4 and 0.8 °C over the last 40 years, and mean minimum temperatures have increased by 0.2 – 0.4 °C (Figure 2). The number of very hot days has also increased over this time, by around 6 days. Mean annual rainfall, in contrast, has declined by between 20 – 80 mm over the 40 year period.

## CLIMATE MODELS AND SRES

The complexity of processes governing past climate trends can not be extrapolated to forecast future conditions (Whetton 2007). Hence future climatic conditions are estimated using global climate models (GCMs) and emission scenarios (SRES- Special Report on Emissions Scenarios <http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf>). There are many such models, that assume different future scenarios for human socio-economic development and patterns of greenhouse gas emissions (IPCC 2007). Each model represents a plausible future climate, but the varying assumptions made in each result in different forecasts from different models. For example the Hadley Mk2 model projects a hotter, drier Australia, whereas the CSIRO Mk3 model projects a more moderate, less dry future.

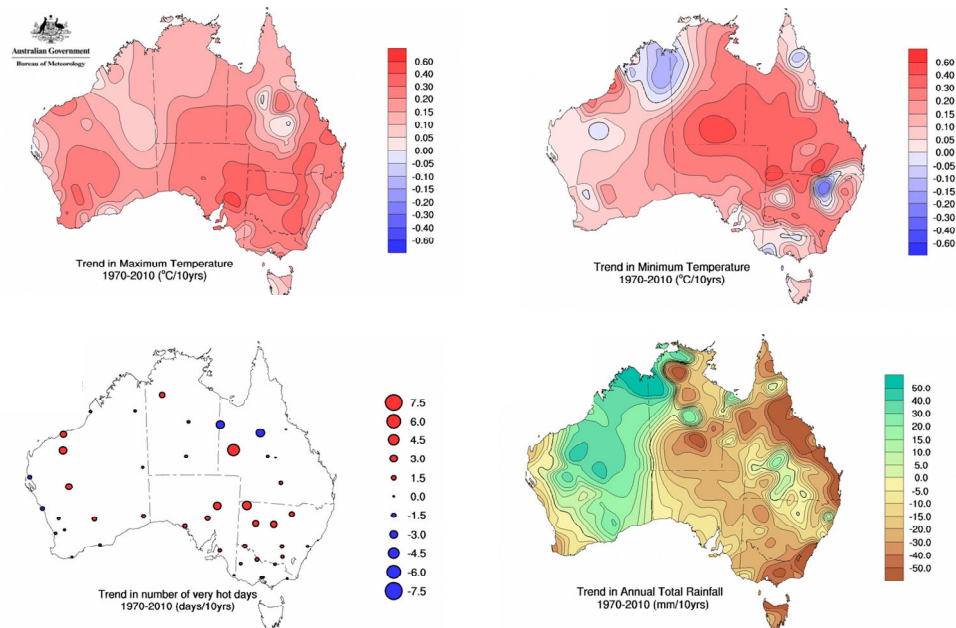


Figure 2. Historical trends in mean maximum and minimum temperature, and the number of extreme hot days in Australia. From the Bureau of Meteorology <http://www.bom.gov.au/cgi-bin/climate/change>).

The GCMs and SRES are used to project an averaged climate for some date in the future, which is then compared to averaged historical climate data. They provide a snapshot of the future, which gives indications of the possible outcomes of incremental climate change.

## UNCERTAINTY ASSOCIATED WITH CLIMATE PROJECTIONS

There are uncertainties associated with climate change projections. They are related to:

- Uncertainty in future levels of greenhouse gas emissions. While there is agreement that greenhouse gases in the atmosphere will increase, we do not know how quickly or to what level emissions will increase
- Uncertainty associated with the GCM used. Not all GCMs agree. This is related to assumptions about how much global temperatures will change for a given change in greenhouse gases
- Uncertainty about how GCM results will reflect regional or local climate

Despite the uncertainty, there are likely trends in climate in Australia (Nicholls 2008; Steffen 2009; Whetton 2007) (Table 1 on page 16), including:

- An increase in mean annual temperatures of between 0.4 and 2 °C by 2030 and between 1 and 6 °C by 2070, with high confidence in a general warming trend, and lower confidence in seasonal patterns of warming
- An increased frequency and intensity of heatwaves (moderate confidence)
- A trend towards warmer night-time temperatures and reduced frost frequency and intensity (moderate confidence)
- Possibly more frequent El Niño events resulting in an increased frequency and severity of both drought and heavy rain events

- Reductions in mean annual rainfall in southern Australia, but with low to moderate confidence in how much and where precipitation may change
- An increase in storm events, including severe wind, catastrophic bushfire danger days and cyclones (moderate confidence)

Of particular relevance to the existing and potential South Australian plantation estate will be changes in mean annual temperatures and heatwaves, increasing frequency of droughts, and changes in rainfall amount and seasonality.

## PROJECTED CHANGES IN CLIMATE FOR SOUTH AUSTRALIAN PLANTATION REGIONS

A range of climate models project an increase in maximum and minimum temperatures and a decrease in rainfall for the main plantation regions in South Australia over the course of this century (<http://www.csiro.au/ozclim>) (Figure 3, Figure 4). The extent of changes projected does, however, vary between climate models. This is illustrated in Figure 5, which shows the outputs of two climate models recognised to simulate well key elements of climate relevant to Australia (Crimp et al. 2010). The two models are the Miroc HiRes and the CSIRO Mk3.5. The CSIRO model, for instance, projects a greater reduction in rainfall than the Miroc model, as illustrated for winter rainfall in Figure 5.

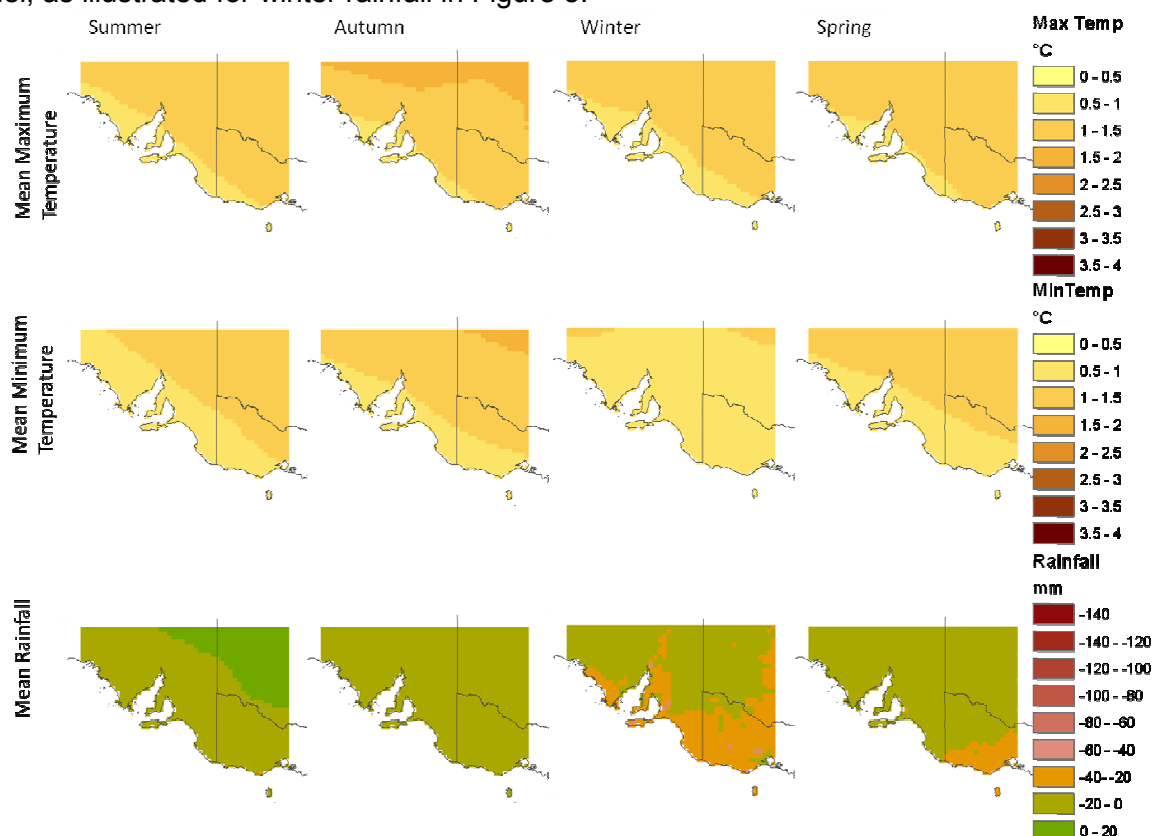


Figure 3. Projected seasonal changes in mean maximum and minimum temperatures and mean rainfall for 2030. The CSIRO Mk 3.5 model was used, with SRES scenario A1B and a moderate warming rate. Data was obtained from Ozclim (<http://www.csiro.au/ozclim>)

Figure 3 and Figure 4 provide one scenario for South Australia's climate in 2030 and 2070, generated using the CSIRO Mk3.5 model with an A1B (medium CO<sub>2</sub> emissions peaking around 2030) SRES scenario and the assumption of a moderate rate of global warming. They project increases in mean maximum temperature by 2030 of 0 – 1 °C in each season for the Green Triangle and Mt Lofty/Kangaroo Island regions, up to 1 – 2 °C increases in the Mid North. Mean minimum temperatures are projected to rise by 0 – 1 °C, with the greatest increase in autumn. Rainfall is projected to decrease by 0 – 40 mm in summer, autumn and spring, and by 20 – 140 mm in winter.

By 2070, mean maximum and minimum temperatures are projected to have risen by 1 – 3 °C (Figure 4) in all seasons. Mean rainfall is projected to decrease by 20 – 140 mm per season, with the greatest reductions in winter.

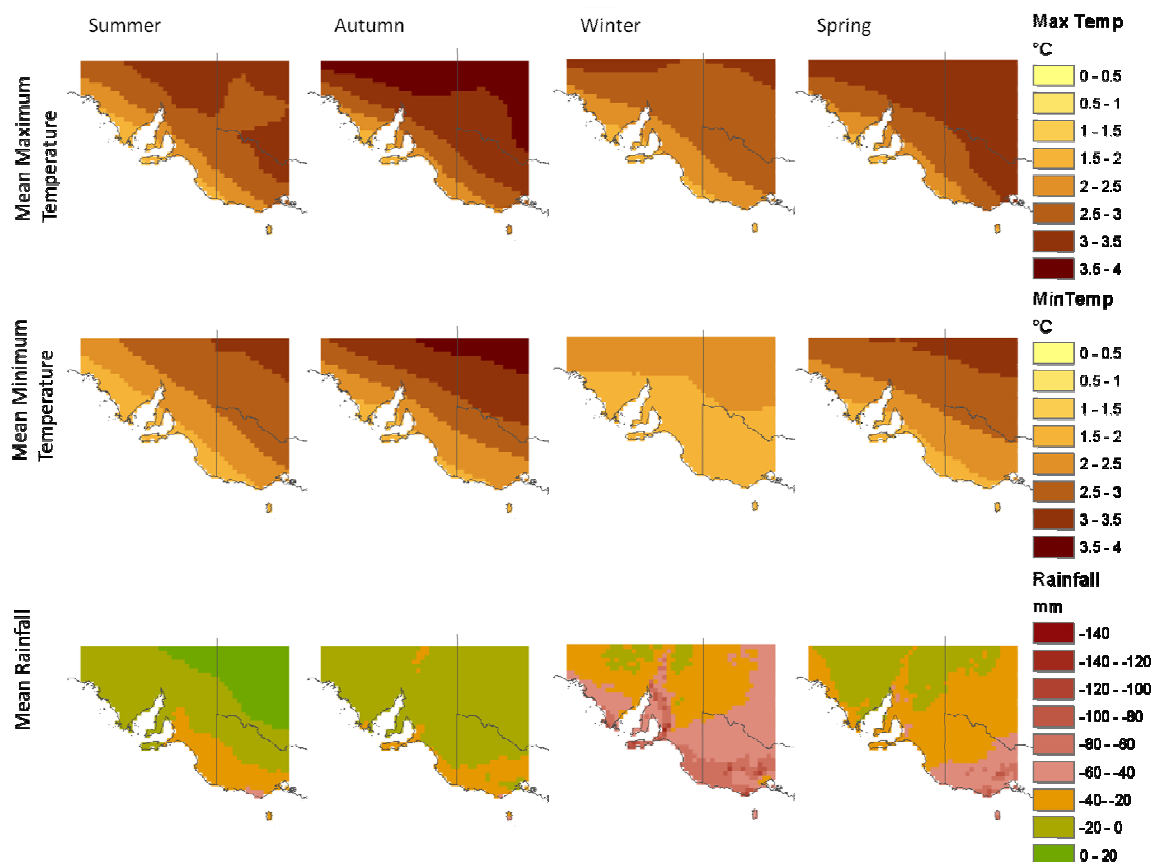


Figure 4. Projected seasonal changes in mean maximum and minimum temperatures and mean rainfall for 2070. The CSIRO Mk 3.5 model was used, with SRES scenario A1B and a moderate warming rate. Data was obtained from Ozclim (<http://www.csiro.au/ozclim>)

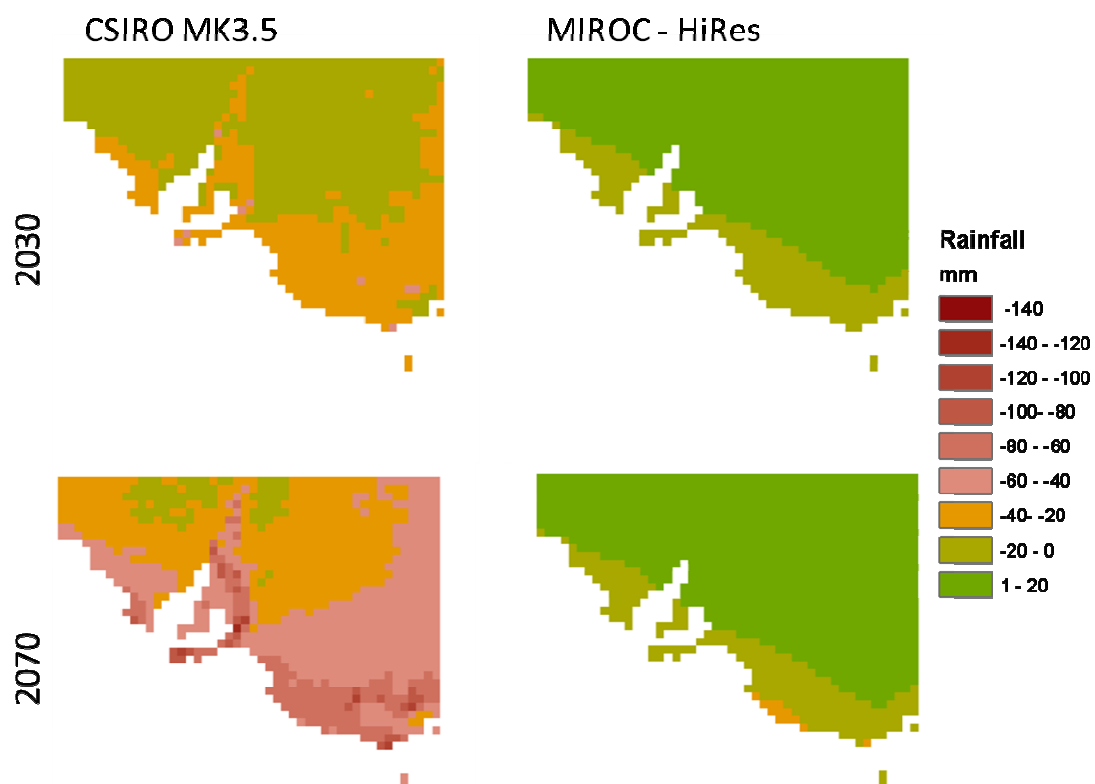


Figure 5. Projected change in future winter rainfall from present, using the CSIRO Mk3.5 and the Miroc-HiRes climate models (A1B SRES scenario, moderate rate of warming). Data was obtained from Ozclim (<http://www.csiro.au/ozclim>)

## SUMMARY OF IMPACTS OF CLIMATE CHANGE ON PLANTATION PRODUCTIVITY

### ESTABLISHMENT AND GROWTH

#### Summary

- Increases in mean temperatures are unlikely to affect the distribution of Blue gum or Radiata pine during the first half of the century, and may promote productivity provided mortality does not increase. Temperature and water stress may influence distribution later in the century
- The main impacts of high temperature events will be on growth and survival. Even short term heatwaves with temperatures above 40 °C can cause tissue damage and mortality
- While both Blue gum and Radiata pine can acclimate to drought, productivity declines as water limitation increases, through reductions in both growth rate and the length of the growing season
- While frost frequency is likely to decline, a reduction in frost hardening associated with warmer night-time temperatures and increasing atmospheric CO<sub>2</sub> concentrations means that damage from unseasonal frosts may become more of an issue in the future
- Although evidence is sparse, elevated CO<sub>2</sub> may increase crown size and density, and decrease wood density and coarse root biomass, making trees more susceptible to wind damage
- Increasing atmospheric CO<sub>2</sub> concentrations may promote plantation productivity, but this is only likely to occur when growth is not limited by water and nutrient supply
- Modelling suggests that decreasing rainfall in the latter half of the century will significantly reduce productivity particularly in the northern parts of the softwood estate.

In an initial study of the impacts of climate change on plantation productivity, Battaglia et al. (2009) found, for a range of scenarios of climate, CO<sub>2</sub> emissions, photosynthetic responses to elevated CO<sub>2</sub>, site fertility and soil depth, a broad range of productivity responses from a positive to a negative effect. Their study highlighted the extreme uncertainty associated with predicting productivity under changing climates, and the large between-site variation in responses that can be anticipated. Subsequent analysis has indicated the additional importance of considering tree drought death.

At least four aspects of climate are of importance to plantation forestry: temperature, rainfall, wind, and changes in atmospheric CO<sub>2</sub> concentrations. A summary of their effects on plantation productivity and wood properties is given below. These

variables can also influence flowering and reproduction, but these effects are not covered in this discussion.

**Changes to mean temperature:** Temperature can strongly affect carbon uptake and losses in plants, and temperatures outside the optimum range for plant performance can result in decreased production (Battaglia et al. 2009). Plants can acclimate to gradual temperature changes, and this combined with the broad temperature ranges of Radiata pine and Blue gum mean that it is unlikely that the gradual changes in mean annual temperatures projected for the first half of the century will limit the distribution of these species. For example, most Radiata pine plantations span mean annual temperatures of 10 – 18 °C (Booth and Jovanovic 2005), meaning mean annual temperature would need to rise by more than 2 °C before most commercial Radiata pine regions would become unsuitable for this species (Booth and Jovanovic 2005). An analysis by Booth and Jovanovic (2005) suggested that, in South Australia, there would be little change in the temperature suitability for Radiata pine by 2030, but by 2070 mean annual temperature may restrict the suitability of sites at the margins of the three plantation regions.

Within the climatically suitable regions for Radiata pine and Blue gum, warmer temperatures particularly in winter may promote growth through increases in the length of the growing season (Ayres and Lombardero 2000; Booth et al. 2010) and higher rates of photosynthesis (Hyvonen et al. 2007), and may advance the timing of the spring growth flush. Indirect changes in soil nutrient cycling processes may be a contributor to these effects (Battaglia et al. 2009; Kirschbaum 2004).

**Changes in high and low temperature events:** Irrespective of changes in mean annual temperatures, increases in the frequency and severity of high temperature weather events to which plants have no time to acclimate have a strong influence on species survival and growth, particularly if combined with soil water limitations (Allen et al. 2009; Ögren 1994). Species such as Blue gum can be damaged or killed by short term exposure to temperatures between 40 – 50 °C, and by longer-term exposure to temperatures as low as 35 – 40 °C (Macfarlane 1998). High temperatures combined with drought have been implicated in mortality of both Blue gum and Radiata pine plantations (Butcher 1976; Ögren and Evans 1992). Evapotranspiration is an important mechanism by which trees cool their leaves. In Blue gum for example evapotranspiration can cool leaves by around 5 °C compared to air temperature (Macfarlane 1998). Once stomata close, in response to loss of cell turgor associated with increasing vapour pressure deficits that occur at higher air temperatures, leaf temperatures rise rapidly resulting in tissue damage and death. In Blue gum, leaf temperatures 4 °C higher than the air temperature were measured in trees where stomata were nearly closed (Macfarlane 1998). At leaf temperatures more than 30 °C, little photosynthesis occurred.

Frost currently restricts the distribution of plantation species such as Blue gum at the coldest ends of their range, although this is less of an issue in South Australia. Increases in night-time temperatures and reduced frost frequency will increase the potential distribution of these species. However, phenological changes may increase the risk of damage from unseasonal frosts for which trees have not acclimated. There is evidence of reduced frost hardening with warmer temperatures (Woldendorp et al. 2008), and that increasing atmospheric CO<sub>2</sub> may increase frost sensitivity in eucalypts (Barker et al. 2005).

**Changes in the timing and amount of rainfall:** Water is the major limitation of forest production globally (Pittock et al. 2001). This was reinforced locally by

Battaglia et al. (2009) who predicted that productivity of Australian plantations under future climates would be strongly influenced by water availability. Species such as Blue gum are well adapted to short periods of water stress but are vulnerable to longer-term drought events (White et al. 2009). This species acclimates to moderate water stress by reducing photosynthesis (Pinkard et al. 2011; White et al. 2009), changing patterns of biomass allocation and reducing stem growth (Pinkard et al. 2011). More severe water stress can result in premature leaf senescence and xylem embolism (Dutkowski 1995; White et al. 2009), that can then result in tree mortality (Dutkowski 1995).

Radiata pine responds to water stress by reducing photosynthesis and stomatal conductance (Thompson and Wheeler 1992). Generally, pines shed older needles (Raison et al. 1992a) and reduces needle size and biomass (Raison et al. 1992b) in response to drought, which results in slower rates of growth than occur when water is non-limiting (Benson et al. 1992). A study in NSW demonstrated that drought not only affects growth rate, but also the length of the growing season, with well-watered trees maintaining growth throughout winter unlike drought-affected trees where growth was curtailed (Benson et al. 1992).

Species such as Blue gum can tolerate variable rainfall, but generally with reduced growth rates (White et al. 2009).

**Changes in wind speed.** Strong wind events can result in extensive damage in plantations, including stem breakage and uprooting (Wood et al. 2008). Plantations are particularly vulnerable to wind damage following thinning (Wood et al. 2008). As well as direct damage, there can be indirect effects such as damage to surrounding trees and pest incursions associated with that damage.

Windthrow is a function of wind speed, crown mass and density, and stem and rooting properties. Elevated CO<sub>2</sub> studies suggest that forests of the future may have larger crowns, greater leaf mass and reduced coarse root biomass than now (Ainsworth and Long 2005; Long et al. 2004), as well as lower-density wood (Yazaki et al. 2005). These sorts of changes may increase plantation vulnerability to wind damage. There is little understanding of how windspeeds may change in the future, particularly at the local scale.

**Changes to the concentration of CO<sub>2</sub> in the atmosphere:** A major and irrefutable aspect of global climatic change is that atmospheric CO<sub>2</sub> concentrations are increasing at a rate exceeding 2 ppm per year, and inevitably will continue to increase at least well into the next few decades (Steffen 2009). Results of elevated CO<sub>2</sub> studies suggest that many species respond to higher CO<sub>2</sub> concentrations by increasing photosynthetic rates (Ainsworth and Long 2005; Ainsworth and Rogers 2007). In Radiata pine, for example, when water and nutrients are not limiting, a doubling of CO<sub>2</sub> concentration can result in a 30 – 50% increase in photosynthetic rates (Greenep et al. 2003; Tissue et al. 2001; Turnbull et al. 1998). Similar increases were observed in well-watered and fertilised *Eucalyptus saligna* (Ghannoum et al. 2010). This response has the potential to increase productivity. However, there is strong evidence that this photosynthetic response is much reduced or non-existent when resources such as water and nutrients are limiting (Norby et al. 1999; Oren et al. 2001), which suggests that in many parts of Australia growth may not be promoted by rising CO<sub>2</sub> (Battaglia et al. 2009). Battaglia et al. (2009) suggest that the environments most likely to benefit from elevated CO<sub>2</sub> in Australia are high productivity, cooler moister sites.



Patterns of biomass allocation can be affected by rising CO<sub>2</sub> (Ainsworth and Long 2005; Hyvonen et al. 2007), with increasing allocation to leaves and fine roots (Norby et al. 2002) and little increase in allocation to stem (Ainsworth and Long 2005). Hence increases in photosynthesis may not translate to increased stemwood production.

While photosynthesis may rise with elevated CO<sub>2</sub>, stomatal conductance often declines, resulting in an increase in leaf-level water-use efficiency (Long et al. 2004). This has been touted as an advantage to trees growing in water-limited environments. However this will only be the case if trees do not respond to elevated CO<sub>2</sub> by increasing canopy size (Ainsworth and Long 2005), in which case whole tree water use may be similar to, or greater than, that of trees growing under ambient CO<sub>2</sub>.

## WOOD PRODUCTS

### Summary

- Changes in climate that influence growth rates are likely to influence wood properties such as basic density, microfibril angle and kraft pulp yield.
- Although data are scarce, they suggest that basic density may decline as temperature increases when water is non-limiting. Basic density of Blue gum and Radiata pine increases with water stress
- Seasonality of rainfall may be as important as total rainfall, because of the consequences for earlywood/latewood proportions
- Increasing stem sway has been linked to increased microfibril angle, which means that greater wind speeds may influence this wood trait

One of the most commonly-measured wood properties is density, because it is related to timber stiffness, strength, and pulp and paper productivity (Downes et al. 2009; Wimmer et al. 2002). Microfibril angle (MFA) is also a common measure, because of its relationship to wood strength and stiffness (Drew et al. 2009). These properties vary within and between trees, and between sites, and at least some of this variation has been attributed to environmental conditions. Variation in wood properties from pith to bark is a function of changing environmental and physiological conditions (Downes et al. 2009), meaning that there is a general relationship between growth rate and wood properties, albeit with wide variation (Downes et al. 2009). For example, basic density commonly decreases and MFA increase as growth rate increases (Drew et al. 2009), but the relationships are not always strong (Downes et al. 1997). Tree age and seasonality of growth can be more influential on wood properties than environmental variation (Lindstrom et al. 1998). For example, juvenile wood generally has a lower basic density and higher MFA than mature wood (Downes et al. 2009), and earlywood has a lower basic density and higher MFA than latewood (Drew et al. 2009; Watt et al. 2005). This sort of variation makes it difficult to tease apart the influences of environmental variability on wood properties. At least some of the variation observed in the literature relates to the scale of assessment. Downes et al. (2009) noted that examining patterns of wood property variation both within and between growth rings can provide insights into the drivers of wood variability that are difficult to determine from coarser-scale studies. The following summarises the possible responses of wood properties to climate change.

**Changes to mean temperature:** Drew et al. (2009) found that, under conditions of high soil water availability, Blue gum basic density declined as temperature increased. MFA of Blue gum and Shining gum was not affected by temperature (Drew et al. 2009; Wimmer et al. 2008).

**Changes in the timing and amount of rainfall:** Wood basic density increases in Blue gum and Radiata pine as soil water availability decreases (Downes et al. 2009; Watt et al. 2005). In Radiata pine plantations in New Zealand, changes in the seasonality of water availability were found to affect basic density via changes in earlywood/latewood proportions (Watt et al. 2005) through its effect on when in the season growth occurred. The effect of rainfall on MFA is less consistent. While Drew et al. (2009) found that MFA of Blue gum decreased with water stress, Wimmer et al. (2002) measured an increase in MFA of Shining gum (*E. nitens*) in unirrigated compared to irrigated plots. Water stress was found to decrease MFA of Radiata pine (Watt et al. 2005).

Kraft pulp yield of Blue gum may increase at higher rainfall, higher productivity sites (Downes et al. 1997), and fibre length may decrease (Wimmer et al. 2008).

**Changes in wind speed.** A small number of studies have demonstrated that wind can influence MFA (Watt et al. 2005; Wimmer et al. 2002). Tree sway has been shown to increase MFA (Nicholls 1982). In Shining gum, wind was the only climatic variable shown to have a positive influence on MFA (Wimmer et al. 2002). Watt et al. (2005) hypothesised that removal of the sheltering effect of woody weeds in Radiata pine plantations in New Zealand may have contributed to an increase in MFA through more exposure.

**Changes to the concentration of CO<sub>2</sub> in the atmosphere:** There have been limited studies of the possible effects of elevated CO<sub>2</sub> concentrations on wood properties (eg. Kilpelainen et al. 2007; Kilpelainen et al. 2003; Qiao et al. 2008; Yazaki et al. 2005). There seems to be wide variation in wood density responses to increased CO<sub>2</sub> (Yazaki et al. 2005), and little understanding of how MFA may change. Vessel diameters were reported to increase in *Populus* spp. (Luo et al. 2005), and tracheid wall thickness increased in Scotts pine (*Pinus sylvestris*) (Kilpelainen et al. 2003).

Table 1. Summary of historical trends in Australia, possible future climate changes, confidence in those changes, and possible consequences of the changes for plantation forestry.

| Climate factor*                  | Historical trends  | Confidence in climate scenarios*  | Impact of factor on forestry  |
|----------------------------------|--|---|---|
| Warmer mean annual temperatures  | Increased by almost 1 °C since 1910.                                   | <p>High confidence in general warming</p> <p>Lower confidence in seasonal patterns of warming</p> <p>Lower confidence in degree of warming for days versus nights</p> | <p><i>1. Establishment and growth</i><br/>Changes in seasonality of growth and increases in length of growing season (Ainsworth and Long 2005; Hennessy et al. 2007)</p> <p>Potential for increased pest damage if pest phenology changes alongside tree phenology (Ayres and Lombardero 2000)</p> <p>Increased potential distribution of species currently restricted by mean minimum temperatures (eg Blue gum) (Booth et al. 2010)</p> <p>Increased transpiration and greater evaporation from soil that may result in increased water stress (Hyvonen et al. 2007)</p> <p>Increased rates of photosynthesis, and acclimation to higher temperatures, that may increase growth rates (Long et al. 1996)</p> <p><i>2. Wood properties</i><br/>Reduced wood basic density (Drew et al. 2009)</p> |
| Increased frequency of heatwaves | Over last 50 years an increase in the number of very hot days (>35 °C) | Moderate confidence of general increase in frequency and intensity of heatwaves   | <p><i>1. Establishment and growth</i><br/>Reduced window of suitable conditions for planting, with consequent potential for increased post-establishment mortality (Huth et al. 2008)</p> <p>Greater soil evaporation leading to increased plant water stress</p> <p>Reduced capacity to cool leaves through evapotranspiration following stomatal closure, with resultant tissue damage and death (Macfarlane 1998)</p>  |
| Changing patterns of frost       | Warmer night-time temperatures   | Moderate confidence   | <p><i>1. Establishment and growth</i><br/>Reduced acclimation to cold temperatures, resulting in more damage during unseasonal frost</p>  |

| Climate factor*                       | Historical trends                                      | Confidence in climate scenarios*                 | Impact of factor on forestry  |
|---------------------------------------|--|--|---|
|                                       |  |  | events (Woldendorp et al. 2008)   |
| Reduced mean annual rainfall          | Regionally variable                                    | Low to medium confidence in rainfall projections | <p><i>1. Establishment and growth</i><br/>Reduced leaf area index resulting in decreased growth rates (Benson et al. 1992; White et al. 2009)</p> <p>Hydraulic failure resulting in tissue damage and potentially tree mortality (White et al. 2009)</p> <p>Potential for higher post-establishment mortality (Huth et al. 2008)</p> <p>Increased susceptibility to some pests e.g. stem borers and bark beetles (Pook and Forrester 1984; Wardlaw and Bashford 2007)</p> <p><i>2. Wood properties</i><br/>Increase in wood basic density (Downes et al. 2009; Watt et al. 2005)</p> <p>Possible decreases in microfibril angle (but variation shown between species) (Downes et al. 2009; Wimmer et al. 2002)</p> <p>Reduced kraft pulp yield (Wimmer et al. 2008)</p> |
| Increased rainfall variability        | Regionally variable                                    | Low to medium confidence in rainfall projections | <p><i>1. Establishment and growth</i><br/>Potentially slower growth rates in Blue gum (White et al. 2009)</p> <p><i>2. Wood properties</i><br/>The proportion of earlywood to latewood may change, depending on whether rainfall occurs early or late in the growing season, with implications for basic density and MFA (Downes et al. 1997; Watt et al. 2005)</p>   |
| Increased storm events                | Increase in the number of very intense weather systems | Medium confidence                                | <p><i>1. Establishment and growth</i><br/>Increased risk of windthrow and stem breakage (Wood et al. 2008)</p> <p>Storm damage to trees may increase risk of pest damage (Wood et al. 2008)</p>   |
| Increased atmospheric CO <sub>2</sub> | Increasing   | Very high confidence                             | <p><i>1. Establishment and growth</i><br/>Increased growth where water</p>  |

| Climate factor* | Historical trends | Confidence in climate scenarios* | Impact of factor on forestry   |
|-----------------|-------------------|----------------------------------|--|
| concentrations  |                   |                                  | <p>and nutrients are non-limiting, but likely to be restricted to young, actively-growing stands (Körner 2006; Norby et al. 2002; Oren et al. 2001)</p> <p>Increased allocation of biomass below-ground meaning increased growth may not result in improved yield, although capacity for carbon sequestration may increase (Ainsworth and Long 2005)</p> <p>Greater leaf-level water-use efficiency that may reduce drought effects if whole-tree water use does not increase (Hyvonen et al. 2007)</p> <p><i>2. Wood properties</i><br/> Little is known about the likely effects of elevated CO<sub>2</sub> on wood properties</p> |

\*Possible future changes in climate, confidence around those changes occurring, and historical trends in climate, are summarised from Nicholls (2008); Steffen (2009).

## IMPACT ON PLANTATION PRODUCTIVITY IN SOUTH AUSTRALIA UNDER A CHANGING CLIMATE

### Summary

- Modelling predicts that Radiata pine productivity in 2030 in the Green Triangle and the Mt Lofty regions will remain the same or increase slightly at the coast. Productivity predictions in Mid North are highly sensitive to the choice of future climate - growth is predicted to stay the same or decrease under the drier future. Under the wetter future growth is predicted to stay the same or increase slightly.
- By 2070, productivity of Radiata pine is predicted to decrease slightly in the Green Triangle and Mt Lofty/Kangaroo Island regions. Productivity in the Mid North region is predicted to decrease sharply, by more than 20%
- Rainfall is the primary driver of changes in Radiata pine productivity, although temperature also plays a role in the Mid North region with the combination of a 20% decline in rainfall and a 3 °C increase in temperature predicted to reduce volume by 25%. Volume response to changing temperature in the Green Triangle is relatively small (thinning reduced the water stress under higher VPD)
- Blue gum is sensitive to changes in both rainfall and temperature (through increased water use under higher VPD), and the interaction of a 20% decrease in rainfall and a 3 °C increase in temperature is predicted to reduce volume by around 25% compared to current climatic conditions. In contrast a 15% increase in rainfall is predicted to increase volume by around 10%

### Predicted changes in productivity across the SA softwood estate

To assess regional changes in Radiata pine productivity under future climates, a detailed modelling exercise was undertaken. A summary of the methodology is provided below, a more detailed description can be found in Battaglia et al. 2009. Predictions of future productivity are highly dependent on the types of futures we look at (choice of global climate model) and the model inputs (soil fertility, response to elevated CO<sub>2</sub> and the type of weather input). To understand how decisions around data inputs can influence the outcomes (productivity and drought risk), we selected a range of data inputs. We used two potential future climates, the CSIRO MK3.5 (a relatively dry future) and the MIROC High resolution (small decreases in rainfall compared to current with increases in temperature). These models are broadly representative of the range of potential futures in South Australia. To ensure we captured the daily variation and extremes in climate, historical daily data from SILO (<http://www.longpaddock.qld.gov.au/silo/>) were modified using the monthly averages from the future climate projections for two time periods; 2030 and 2070. Given the uncertainties around how the main plantation species will respond under elevated atmospheric CO<sub>2</sub>, we chose two potential photosynthetic responses. The first model incorporates an increase in water use efficiency but no increase in photosynthesis in response to increasing atmospheric CO<sub>2</sub> (no increase in photosynthesis model). The second model includes both an increase in water use efficiency and an increase in photosynthesis in response to increasing atmospheric CO<sub>2</sub> but one that is capped to the average increases seen in experimental work (the acclimation of photosynthesis model). The responsiveness of trees to elevated CO<sub>2</sub> is dependant on the levels of available nutrients and water, and where these are limiting, trees may not have the

resources to respond to increased levels of atmospheric CO<sub>2</sub>. We used three levels of fertility, a low, medium and high for each of the three regions (Green Triangle, Mt Lofty and the Mid North). The silviculture used was a standard regime with initial planting at 1333sph, 4 thinnings and clearfall at age 40. For each combination of current and future climate, photosynthetic model and soil, we used 20 planting dates to capture the intra and inter decadal variation. Overall, 64,000 scenarios were run.

The results are presented as percentage change from current production rather than absolute volumes. Actual volume at harvest is driven partially by silviculture and in this project we are attempting to understand the variation in production due to climate. Percentage change allows for simple comparison. However, results need to be treated carefully, as a ten percent change in growth where production is naturally low is not the same as a 10 percent change where production is high. For simplicity, the average of the 20 planting dates and the three soil types are presented. All outputs from the modelling can be obtained from CSIRO (contact authors).

Growth predictions under the CSIRO MK3.5 GCM are broadly similar for the two photosynthetic models (Figure 6). Growth in the Green Triangle and the Mt Lofty region for 2030 is projected to remain the same or increase slightly at the coast and generally stay the same or decrease further inland. By 2070, growth is expected to decrease slightly over most regions. The Mid North region is expected to decrease sharply by more than 20% at 2070 (Figure 6)

Changes in production under the MIROC-H GCM are relatively small for all three regions (+/-10%). Growth predictions are broadly the same as current growth for 2030 where there is no change in photosynthesis and slightly more positive where there are increases in photosynthesis. By 2070, this difference between photosynthetic models disappears as water becomes too limiting for trees to utilise the additional CO<sub>2</sub> (Figure 6).

These assessments do not take into account the potential effects of events such as droughts or pest epidemics, and should be considered as best case scenarios. There is also uncertainty around how trees will respond to elevated atmospheric CO<sub>2</sub> concentrations. The modelling also does not capture the interaction of factors, such as the coincidence of drought and pest outbreak.

### **Sensitivity of productivity to rainfall and temperature**

We undertook sensitivity analysis to better understand the role of temperature and rainfall on productivity of Radiata pine and Blue gum (Figure 7), to help identify the sorts of climatic conditions under which productivity may increase or decrease in the future. Rainfall was varied between +20% and -20% of current, and temperature was altered to increase by between 0 and 3 °C. For each species, a standard silviculture was used: for Blue gum a pulp wood regime with no thinning, for Radiata pine, a standard sawlog regime with 3 thinnings. In general, Blue gum was more sensitive to changes in rainfall and particularly temperature (through increased water use under higher VPDs), than Radiata pine. There was regional variation in responses, highlighting the need for site and local assessment of the impacts of changing rainfall and temperature patterns on productivity.

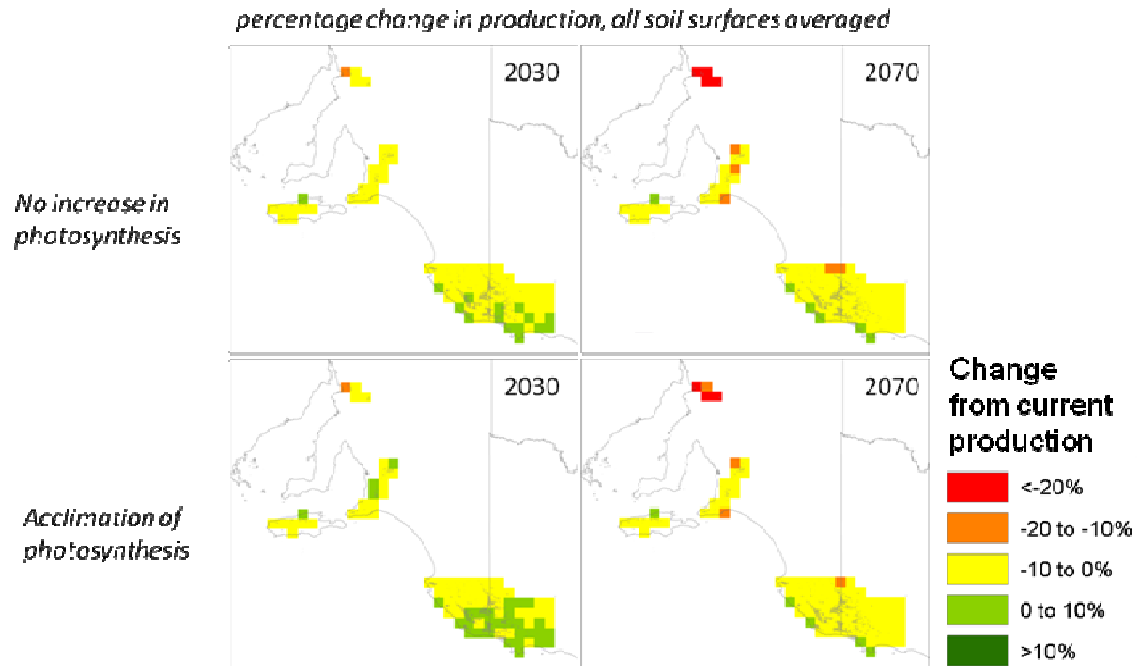
Radiata pine in the Mid North estate was predicted to increase productivity by up to 10% with a 20% increase in rainfall, highlighting the water-limited nature of plantations in this region. However if temperature also increased by 3 °C, any growth benefits from the additional rainfall disappeared. A 20% decrease in rainfall

was predicted to result in a 15% decrease in volume, or as much as a 25% decrease if temperature also increased to 3 °C. In contrast, there was only a small growth response for Radiata pine in the Green Triangle when rainfall was increased by 20%. A 20% decrease in rainfall was predicted to reduce volume by around 15%. There was little effect of temperature. The silviculture used for Radiata Pine (3 thinnings) reduced the water stress, limiting the effects of higher vapour pressure deficit under elevated temperatures.

Blue gum was more sensitive to change in rainfall and particularly temperature than Radiata pine (Figure 7). A 15% increase in rainfall was predicted to increase volume by 10%, whereas a 20% decline in rainfall reduced volume by around 15%. If the lower rainfall was combined with a 3 °C rise in temperature, volume was predicted to decrease by around 25% compared to current.



## CSIRO Mk3.5



## MIROC-H

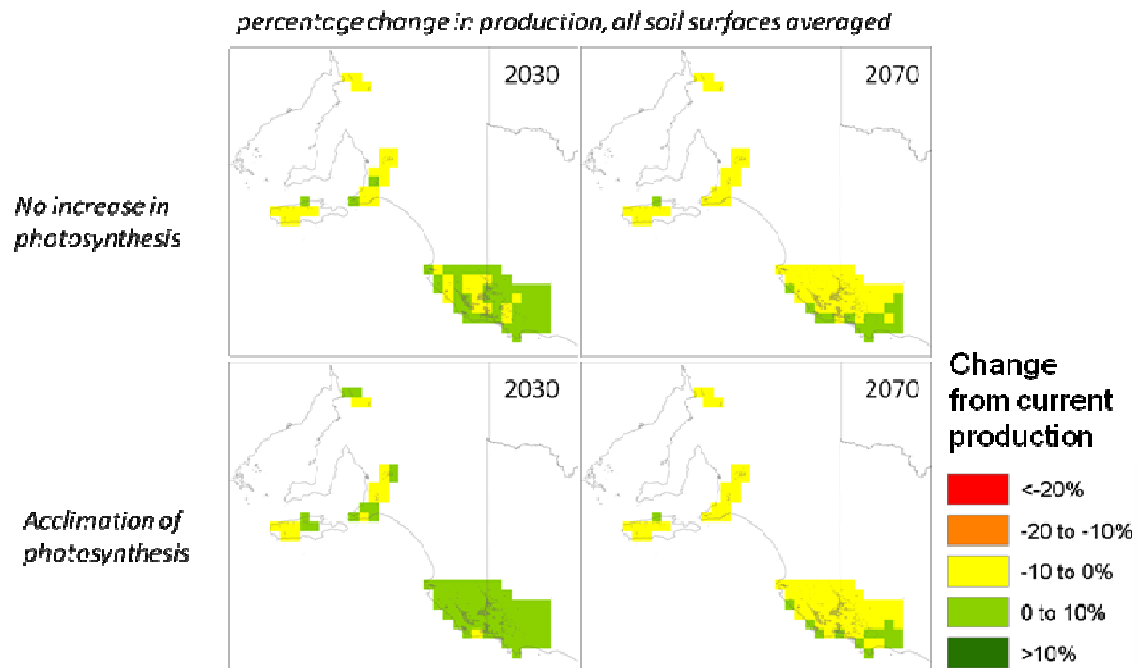


Figure 6. Predicted changes in Radiata pine volume under the CSIRO MK3.5 GCM and MIROC-H for the Green Triangle, Mt Lofty and Mid North regions.

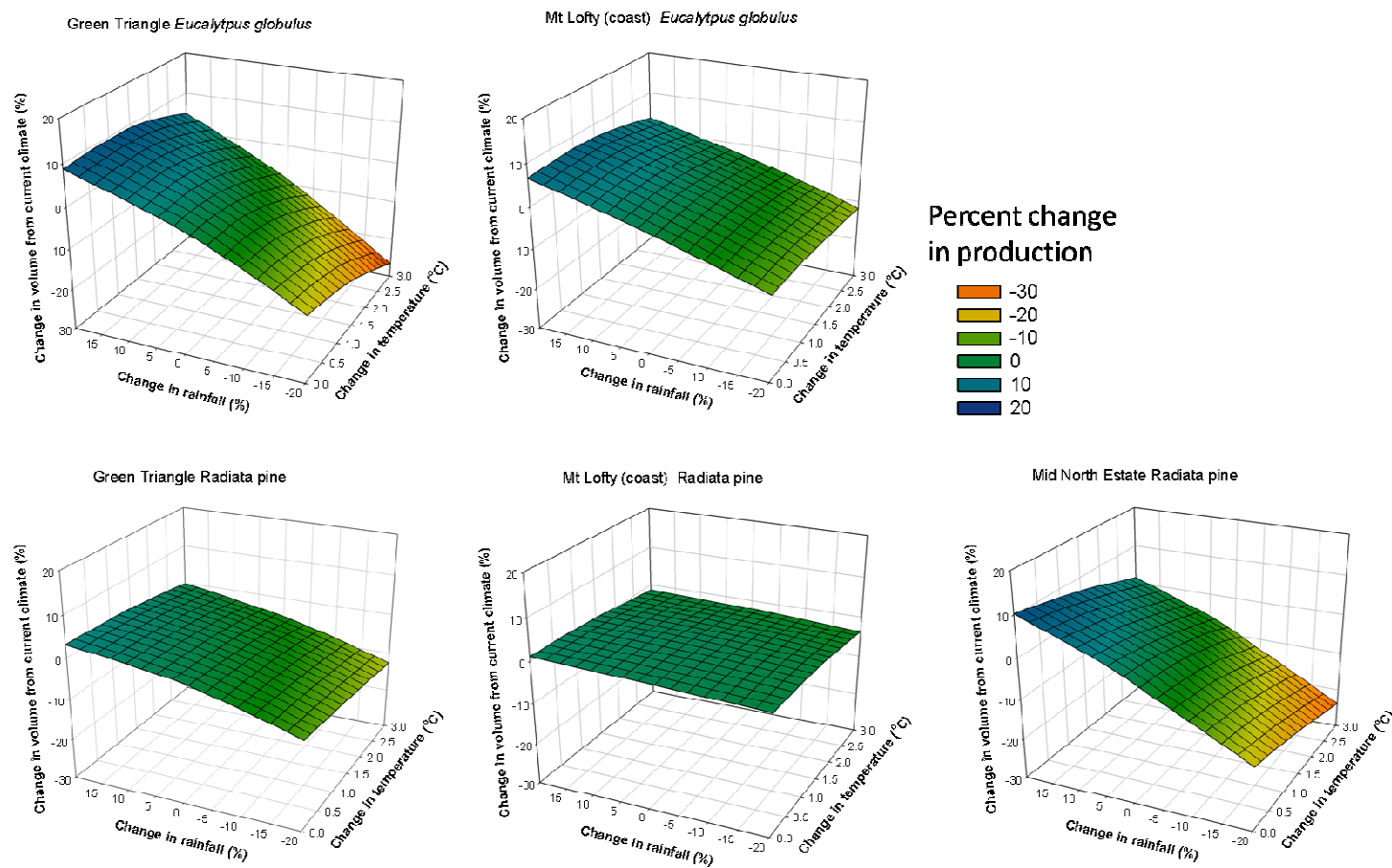


Figure 7. Sensitivity of volume of Blue gum (*Eucalyptus globulus*) and Radiata pine (*Pinus radiata*) to changes in rainfall and temperature (expressed in terms of % change in volume from current climate), for the Mid-North, Mount Lofty/Kangaroo Island and Green Triangle regions. Blue gum was not modelled for the Mid North region.

## SUMMARY OF RISKS TO PLANTATIONS IN SOUTH AUSTRALIA

### Summary

- Warmer mean temperatures particularly in winter are anticipated to favour many insect pests of plantation forests, which could result in a longer period of insect activity, more generations per year and increased damage. This may be counteracted by a reduced quality of food source and resultant reductions in insect fecundity and survival. Changes in host defence mechanisms may also influence levels of damage
- Diseases often require high relative humidity to promote infection and spore production and the distribution of some leaf diseases may decrease if rainfall declines
- Drought conditions favour many stem borers and bark beetles, and an increase in borer or bark beetle activity may occur if plantations become more water stressed
- Increasing temperatures may affect weed composition as C<sub>4</sub> weeds will be advantaged over C<sub>3</sub> weeds with warming and drying
- The efficacy of herbicides may change as a consequence of changing temperature and elevated CO<sub>2</sub>. The changes are likely to vary between chemicals, and may be positive or negative for weed control
- Increasing drought events, particularly when combined with heatwaves, may result in a rise in plantation mortality and reduced growth rates. Modelling suggests the risk of drought death will significantly increase in the northern regions of the plantation estate with an increase of around 5 high risk days per year by 2070
- Fire risk is likely to increase in the future, associated with an increase in weather conditions favourable to fire (including catastrophic fire risk days), increased drying of fuel, and changes in the dynamics of litter build-up and decomposition

While the last section focused on the primary drivers of possible changes in productivity and wood products, this section discusses the threats to plantations that may have a secondary effect on productivity and products. The changes in temperature, rainfall, wind speeds and atmospheric CO<sub>2</sub> concentrations projected for Australia may result in increased risk from drought, pests, weeds and fire. These are discussed in the following.

## RISK FROM PESTS

**Changes in host vigour:** Pest risk is a function of the vigour of the host, the capacity of the host to defend itself, and the distribution, abundance and activity of the pest. The sorts of impacts of climate change on plantation productivity described previously suggest that in many locations host vigour may decline in response to climate change. Pinkard et al. (2008), for example, predicted in a modelling exercise that a given level of pest damage, such as 50% defoliation, would have a

greater impact in the future than it would have today, for both Blue gum and Radiata pine, although a large variation between sites is expected. Greatest impacts were predicted at lower fertility sites or where water was limiting growth of the host.

**Changes in defence:** Plants rely on physical barriers and chemical defence mechanisms to reduce their vulnerability to insects and disease. A reduction in specific leaf area, the ratio of leaf area:dry mass, can result in a thicker or more dense leaf, which can enhance defence responses to leaf diseases (Smith et al. 2006), and can reduce damage from leaf chewing insects (Steinbauer 2001). Specific leaf area has been found to decrease in response to elevated CO<sub>2</sub> (Ayres et al. 2004) and water stress (Geiger and Thomas 2002), which may therefore reduce pest damage to trees.

Reductions in foliar nitrogen concentrations have been observed experimentally at higher atmospheric CO<sub>2</sub> concentrations (Ayres and Lombardero 2000), and are likely to affect the palatability of foliage for pests (Harrington et al. 2001). Such changes can result in compensatory feeding by the insect and higher crop damage, but have also been found to reduce survival and fecundity of the insects (Lawler et al. 1997). However, reductions in foliar nitrogen concentrations, and the resultant increase in carbon:nitrogen ratio, may also occur under elevated CO<sub>2</sub> (Ayres and Lombardero 2000; Hunter 2001), which can also result in an increase in carbon-rich defence chemicals that may reduce insect damage (Ayres et al. 2004).

Moderate water deficits have been shown to increase secondary metabolites in foliage, whereas extreme deficits decrease concentrations of these compounds (Ayres and Lombardero 2000). Similar decreases in concentrations of defence compounds have been observed in stems of drought-affected trees (Kainulainen et al. 1998), as well as increased concentrations of compounds that favour fungal development, such as glucose (Desprez-Loustau et al. 2006). Such reductions in defence chemicals may make trees more susceptible to stem pests such as stem borers and bark beetles (Old and Stone 2005). Increased entry points to the stem via bark and cambial cracks may also play a role in increasing susceptibility to these pest species (Pook and Forrester 1984).

**Changes in pest abundance and activity:** Temperature is the primary driver of development and abundance of herbivorous insects (Ayres and Lombardero 2000). As mean temperatures rise, many pest insect species are expected to respond by increasing their number of generations per year and the duration of feeding over the growing season. Any increases in the length of plantation growing season in response to warmer mean annual temperatures are likely to exacerbate this. There may also be reduced winter mortality of insects and diseases with warmer winter temperatures and fewer extreme cold temperatures, resulting in a more rapid build up of populations during the period of active host growth (Ayres and Lombardero 2000).

Changes in temperature, rainfall, soil moisture and relative humidity, as well as variability in these factors, all influence fungal spore release and infection processes (Chakraborty et al. 2008). For any diseases where cool winter temperatures restrict development, increases in disease survival during those periods because of increasing mean annual temperatures may result in more rapid disease development at the start of the host growing season (Ayres et al. 2004).

Elevated CO<sub>2</sub> has been found to stimulate disease growth rates, aggressiveness and fecundity (Chakraborty et al. 2008). Herbivores that disrupt phloem or xylem have

shown increased development and reproduction under elevated CO<sub>2</sub> (Whittaker 2001).

**Changes in pest distribution:** Temperature is a major determinant of insect range (Sutherst 2003), while relative humidity also plays a role in determining the range of many diseases. Increasing winter temperatures are expected to facilitate range expansions of pests to higher altitudes and latitudes. Of more relevance to the South Australian plantation estate may be the role of heatwaves in limiting species' ranges (Burdon et al. 2006). Temperatures above a species upper threshold will reduce pest survival and capacity to reproduce.

## Pest risk in South Australia

The pests of most commercial importance in South Australian Radiata pine plantations are the pine aphid (*Essigella californica*), Ips bark beetle (*Ips grandicollis*) and Sirex wasp (*Sirex noctilio*) (Table 2). Pests of Blue gum plantation include Mycosphaerella leaf disease, and leaf chewers such as *Paropsisterna* spp, *Uraba lugens*, *Gonpiterus scutellatus* and *Mnesampela privata*. The pine aphid causes needle chlorosis and premature needle senescence and is a widespread pest that can cause large reductions in volume (May 2004; Wharton and Kriticos 2004). A biological control agent has recently been deployed in an attempt to control this pest. Ips bark beetle and Sirex wasp are also widespread in South Australian plantations, although monitoring programs, plantation hygiene and biological control programs have helped to control outbreaks (Morgan 1989), and there has not been a *Sirex* outbreak since 1987. These pests cause reductions in productivity and (potentially) increase tree mortality. Leaf pests of Blue gum plantations can also have significant effects on plantation productivity (Carnegie and Ades 2002; Pinkard et al. 2006b; Rapley et al. 2009; Wardlaw 2001), although outbreaks tend to be localised rather than widespread.

**Changes in climatic factors:** All of the pest species found in South Australia's plantations are expected to respond favourably to warmer temperatures (Table 2) (Old and Stone 2005). Of the Radiata pine pests, *Sirex* and *Ips* are expected to be favoured by drier conditions (Old and Stone 2005; Pook and Forrester 1984). Pine aphid is likely to respond predominantly to temperature, with rainfall affecting host recovery from damage rather than the pest directly (Wharton and Kriticos 2004).

Leaf chewer pests of Blue gum plantations are likely to be favoured by warmer temperatures (Old and Stone 2005), as is Mycosphaerella leaf disease (Park 1988). Wetter conditions that promote host vigour and production of young foliage will also benefit these pest species, and in contrast drier conditions that reduce host vigour may be less favourable (Ohmart and Edwards 1991; Park 1988). Drier conditions and lower relative humidity are likely to reduce the climatic suitability for Mycosphaerella leaf disease, because high relative humidity is important for sporulation and infection (Park 1988).

**Changes in distribution:** Species niche models can be used to provide indications of how the distribution and abundance of insects and diseases might change under future climates (Sutherst 2003). The bioclimatic niche model CLIMEX provides an index of climatic suitability for species, and has been used to examine the effects of climate change on some pest species of Australia's plantations (Pinkard et al. 2008).

Figure 8 shows the projected climatic suitability of three pests of South Australia's plantations under current and future climatic conditions. The models used to develop these maps provided good fits to historical distributional data for these species (Pinkard et al. 2008), and are a useful means of exploring how climatic suitability might change in the future. The figure suggests that while for each pest species a southwards contraction of distribution is projected, the climate will remain suitable for the pests in the main plantation regions in South Australia.

Table 2. Current pest status of a range of plantation pest species of South Australia, and anticipated responses to climate change. H indicates the pest is currently of high importance; M indicates moderate importance and L indicates low damage. A '+' indicates an anticipated benefit to pest distribution and activity; a '-' indicates an anticipated negative effect to pest distribution and activity, based on our understanding of pest phenology and lifecycle requirements (source: Old and Stone 2005; Pinkard et al. 2008). Note: this is not an exhaustive list of pests of South Australian plantations. Rather it focuses on species for which there is some understanding of likely responses to changing climate. The table provides a general indication of how pests might respond to changing climate, rather than how they might respond specifically in South Australia.

| Common name                 | Species                      | Current pest status in SA* | Temp increase of 2-5 °C | Wetter | Drier |
|-----------------------------|------------------------------|----------------------------|-------------------------|--------|-------|
| <b>Insects</b>              |                              |                            |                         |        |       |
| Pine aphid                  | <i>Essigella californica</i> | M                          | +                       | +      | +     |
| Ips bark beetle             | <i>Ips grandicollis</i>      | M                          | +                       | -      | +     |
| Sirex wasp                  | <i>Sirex noctilio</i>        | M                          | +                       | -      | +     |
| Autumn gum moth             | <i>Mnesampela privata</i>    | L-M                        | +                       | +      | -     |
| Leaf skeletoniser           | <i>Uraba lugens</i>          | L-M                        | +                       | +      | -     |
| Eucalypt beetle             | <i>Paropsisterna</i> spp     | M                          | +                       | +      | -     |
| Eucalypt weevil             | <i>Gonipterus</i> spp        | L-M                        | +                       | +      | -     |
| <b>Diseases</b>             |                              |                            |                         |        |       |
| Mycosphaerella leaf disease | <i>Teratosphaeria</i> spp    | L-M                        | +                       | +      | -     |

\*based on expert opinion from Forestry SA

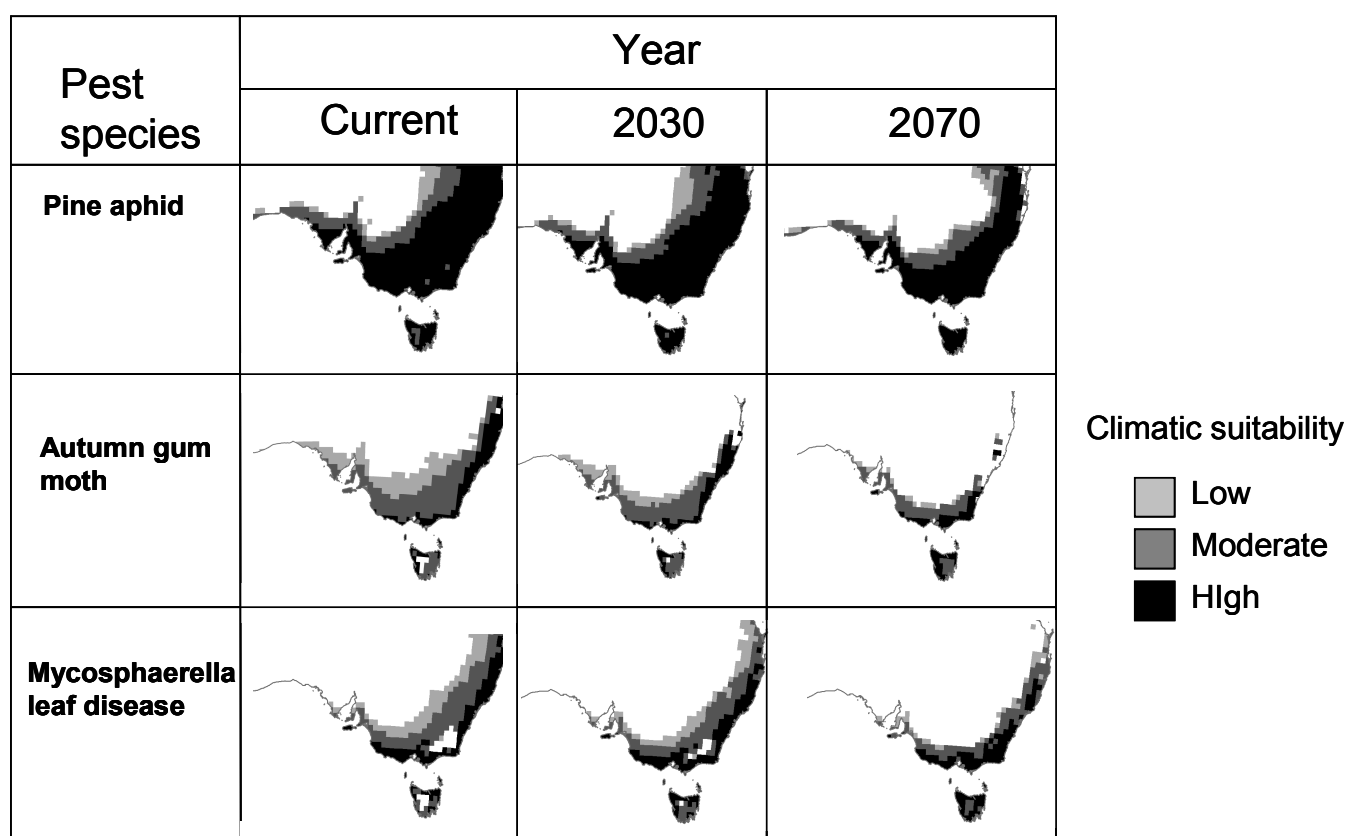


Figure 8. Projected climatic suitability for three plantation pest species, Pine aphid, Autumn gum moth and Mycosphaerella leaf disease, for current climatic conditions and for 2030 and 2070. The projections for 2030 and 2070 were done using the Echam GCM and an A2 emissions scenario (moderately high emissions throughout the 21<sup>st</sup> century). From Pinkard et al. 2008.

Table 3. An indication of how the distribution of four pests of South Australia's plantation forests might change in the future; and the climatic suitability for the pest within that distribution. Data were derived from CLIMEX projections of climatic suitability under current and future climates (Carnegie et al. 2006; Pinkard et al. 2008). Two GCMs were used in the analysis (Hadley Mk 2 and Echam, A2 emissions scenario). L indicates low climatic suitability; M indicates moderate climatic suitability for growth and survival; H indicates the climate is highly suitable for the species.

| Pest species                | Year | Potential distribution                      | Climatic suitability within distribution range |                 |                  |
|-----------------------------|------|---|--|-----------------|------------------|
|                             |      |   | Green Triangle                                 | Mt Lofty region | Mid-North region |
| Pine aphid                  | Now  | Widespread                                  | H  | H               | M                |
|                             | 2030 | No change                                   | Increasing                                     | Increasing      | Increasing       |
|                             | 2070 | No change                                   | increasing                                     | increasing      | increasing       |
| Sirex                       | Now  | Widespread                                  | H  | H               | H                |
|                             | 2030 | No change (Hadley) or smaller (Echam)^      | No change                                      | No change       | No change        |
|                             | 2070 | No change (Hadley) or much smaller (Echam)^ | No change                                      | No change       | No change        |
| Mycosphaerella leaf disease | Now  | GT and Mt Lofty                             | H  | M               | M                |
|                             | 2030 | No change                                   | Decreasing                                     | Decreasing      | Decreasing       |
|                             | 2070 | Smaller                                     | Decreasing                                     | Decreasing      | Decreasing       |
| Autumn gum moth             | Now  | GT and Mt Lofty                             | M  | M               | L                |
|                             | 2030 | Smaller                                     | No change                                      | No change       | No change        |
|                             | 2070 | No change (Hadley) or smaller (Echam)^      | No change                                      | No change       | No change        |

^ indicates differences between climate models in projections

\* Climatic suitability refers to climatic suitability within the projected distribution; hence a pest may have a projected smaller distribution but with highly suitable climatic conditions within that reduced distribution.



This is further explored in Table 3, which summarises the outputs from four CLIMEX models (Carnegie et al. 2006; Pinkard et al. 2010a; Pinkard et al. 2008) in terms of possible changes in the distribution of the pests associated with climatic changes, and climatic suitability for those pests within the range, using both the Hadley Mk 2 and ECHAM GCM's and assuming an A2 emissions scenario. The distribution of pine aphid is projected to remain unchanged in South Australia over the next 50 years. The distribution of Sirex wood wasp, Mycosphaerella leaf disease and Autumn gum moth are projected to decrease as populations are unable to persist in regions with less favourable climate.

Within these distributions, the climatic suitability for pine aphid is projected to increase over the century, which suggests that outbreaks may become more frequent and severe. The climatic suitability for Mycosphaerella leaf disease is projected to decrease as a result of a drier climate, meaning that epidemics of this species may become less prevalent. Climatic suitability for Sirex and Autumn gum moth are not projected to change.

There has been no modelling of the effects of climate change on the distribution of biological control agents used with pine aphid and Sirex wood wasp. It is unknown if changes in the distribution and abundance of the biological control agents will influence the realised distribution of the plantation pest species.

## RISK FROM WEEDS

Numerous experiments have demonstrated that effective weed control increases seedling survival and growth (Cellier and Stephens 1980). The likely effects of climate change on weed impacts result from changes in weed vigour, abundance, distribution and the efficacy of weed control methods.

**Changes in weed vigour:** While growth of all plants is affected by environmental conditions, many weed species can thrive with water and nutrient limitations, making them strong competitors for resources in less vigorous plantations. While most tree species are  $C_3$  plants, weed species use either the  $C_3$  or  $C_4$  photosynthetic pathway. The  $C_4$  pathway provides advantages under water-limited conditions, and  $C_4$  plants can grow faster while using less water than  $C_3$  plants (Hall and Rao 1992). In contrast,  $C_3$  plants are expected to be more vigorous than  $C_4$  plants in response to elevated  $CO_2$ , as the  $C_3$  pathway is optimised under such conditions (Hattersly 1983). There is some evidence that  $C_4$  weeds may be favoured over  $C_3$  weeds with both increased temperatures and  $CO_2$  concentrations. A field study found that  $C_4$  grasses fared better than their  $C_3$  counterparts under such conditions because of reduced seed production and germination rates in the  $C_3$  species (Williams et al 2007). While there is great uncertainty about the ways that future climate will influence weed vigour, these sorts of results suggest that there may be changes in weed composition in the future, as species better adapted to changed environmental conditions are favoured.

**Changes in weed abundance and distribution:** Invasive species are expected to be highly responsive to changing climate (Kriticos et al. 2010). Traits that promote invasiveness also predispose them to rapid response to climate change (Kriticos et al. 2003). As the climate changes, the geographic range of many weed species are expected to change, with range expansions to higher latitudes and elevations as

rising temperatures shift cold range boundaries. In South Australia, a southerly shift for many temperate and Mediterranean weed species is likely to lead to a decrease in their geographic range (Kriticos et al. 2010).

**Weed control:** There is a strong reliance in Australia on herbicides to control weeds in plantations, although herbicide use is restricted primarily to young plantations. There is little understanding of how climate change might affect the chemicals used by the forestry sector. Studies with agricultural chemicals have shown that changes in climate can influence herbicide efficacy, although there are indications that this is chemical and weed-specific. For example, the efficacy and uptake of glyphosate by quackgrass (*Elytrigia repens*) was found to decline in response to elevated CO<sub>2</sub> concentration (Ziska et al. 2004; Ziska and Teasdale 2000). Warmer temperatures increase the activity of some herbicides such as flumetsulam, metosulam and clodinafop-propargyl used in agricultural systems (Madafiglio et al. 2000; Medd et al. 2001). Madafiglio et al. (2000) found that at low soil temperatures a higher rate of these herbicides was required for weed control, due to limitations on the uptake and translocation of the herbicide. These sorts of responses suggest that the effects of climate change on the efficacy of herbicides used to control weeds in forestry requires further research.

Elevated atmospheric CO<sub>2</sub> concentrations may affect herbicide efficacy in other ways. For example, herbicide uptake may be reduced if weed transpiration rates decline (Ziska et al. 2004), and changes in the ratio of root:shoot may affect chemical uptake and translocation rates.

Mechanical weed control is used in some situations in conjunction with chemical control. Mechanical control is most effective when weed species are stressed, and thus in South Australia it is generally undertaken in summer. Warming and drying of the environment may increase the window available for mechanical weed control.

## Weed risk in South Australia

Loss of productivity in South Australian plantations from weed competition has been well documented (Richardson 2010). The main weed species of South Australia's plantations, and the regions in which they occur, are listed in Table 4. There have been few studies of the likely effects of climate change on these species.

Kriticos et al. (2010), in a report on the consequences of climate change for invasive plants in South Australia, concluded that reductions in rainfall projected for the moderate rainfall regions of South Australia, would reduce the climatic suitability of many weed species. However, in more southerly regions climatic suitability may increase in response to climate warming. This highlights the need for more specific studies for the key forestry weed species.

Table 4. List of common weed species of pine and eucalypt plantations in South Australia. GT indicates Green Triangle; MLR indicates Mount Lofty Ranges and Kangaroo Island; MN indicates the Mid North region.

| Species                           | Common name       | Weed type        | C <sub>3</sub> or C <sub>4</sub> | Comments  | Regions where problematic |
|-----------------------------------|-------------------|------------------|----------------------------------|---|---------------------------|
| <i>Pteridium esculentum</i>       | Bracken fern      | Woody perennial  | C <sub>3</sub>                   | The highest impact woody weed in SA plantations | GT                        |
| <i>Conzya Canadensis</i>          | Canadian fleabane | Broadleaf annual | C <sub>3</sub>                   | A weed of 2R sites, prolific                    | GT, MLR                   |
| <i>Holcus</i> spp                 | Fog grass         | Perennial grass  | C <sub>3</sub>                   | Prolific  | GT, MLR, MN               |
| <i>Phalaris aquatica</i>          | Phalaris          | Perennial grass  | C <sub>4</sub>                   | High impact but limited distribution            | GT, MLR, MN               |
| <i>Cynodon dactylon</i>           | Couch grass       | Perennial grass  | C <sub>4</sub>                   | High impact but limited distribution            | GT, MLR, MN               |
| <i>Hypochoeris radicata</i>       | Flatweed          | Perennial herb   | C <sub>3</sub>                   | Common  | GT                        |
| <i>Acetosella vulgaris</i>        | Sorrel            | Perennial herb   | C <sub>3</sub>                   | Common  | GT                        |
| <i>Acacia longifolia</i>          | Coastal wattle    | Woody perennial  | C <sub>3</sub>                   | Significant problem in coastal areas            | GT, MLR                   |
| <i>Genista monspessulana</i>      | Montpellier broom | Woody perennial  | C <sub>3</sub>                   | Significant problem                             | MLR                       |
| <i>Ulex europaeus</i>             | Gorse             | Woody perennial  | C <sub>3</sub>                   | Significant problem                             | MLR                       |
| <i>Rubus fruticosus</i> aggregate | Blackberry        | Woody perennial  | C <sub>3</sub>                   | Common  | GT, MLR                   |
| <i>Onopordum</i> spp.             | Thistles          | Annual           | C <sub>3</sub>                   | Common  | MN                        |

## RISK FROM DROUGHT

The area affected by drought in Australia has been increasing in many regions since the 1970s (Nicholls 2008), and there is a high likelihood that this trend will continue. Both a decrease in rainfall and changes in the seasonality of precipitation are projected for much of Australia (Hennessy et al. 2007). Combined with the increasing mean annual temperatures that are projected (Steffen 2009), this is likely to result in reduced available soil water in many parts of Australia, at least in some seasons, and increased risk from drought.

As early as the 1960's in Western Australia drought deaths were documented in *P. radiata* and *P. pinaster* plantations (Butcher 1976). These occurred primarily at sites with shallower than usual soils, at around the time of canopy closure, and were not restricted to any particular size class. Drought mortality has also been observed in pine plantations in other Australian states, although direct drought effects have often been confounded by other factors. For example, in South Australia mortality has been observed in the drier regions, particularly on shallower soils, but it is difficult to separate direct drought effects from the secondary effects of drought, such as damage from *Sirex noctilio* and *Ips grandicollis*, (Morgan 1989).

Drought mortality in eucalypt plantations is a relatively new phenomenon, reflecting both changes in rainfall patterns and amounts and expansion of the plantation estate into increasingly drier environments. However drought mortality has been observed from cooler, wetter climates such as Tasmania through to warmer drier climates such as south west Western Australia.

Impacts of drought on plantation productivity may be exacerbated by warmer temperatures and heat stress. A number of mortality events in forests have been linked to drought stress combined with a period of hot weather (Groom et al. 2004). The projected increases in drought conditions and heatwaves suggest that there will be an increased risk of mortality in Australia's plantations under future climatic conditions. Figure 9 gives an indication of how the average number of hot, dry days may change between now and 2030 (Battaglia et al. 2009).

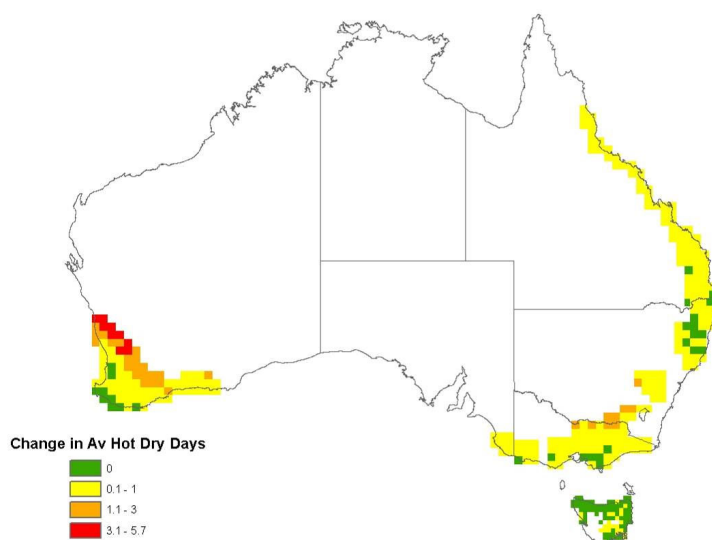


Figure 9. Change in the average number of hot dry days per year between current and 2030 climate projections. Hot dry days are defined as having temperatures greater than 35 °C combined with pre-dawn water potentials equal to or less than -3.2MPa. Non-coloured areas indicate areas for which no data are available. From Battaglia et al. (2009).

## Drought risk in South Australia

As part of the modelling project to understand potential changes in productivity in the previous section, an analysis looking at potential changes in the risk of drought death for Radiata pine was undertaken. High risk days where tree mortality is possible were defined as maximum daytime temperatures greater than 35 °C combined with pre-dawn water potentials equal to or less than -2.2MPa.

For the Green Triangle, the number of high risk days remained similar to current levels on the coast and a small increase over the remainder of the region for both future climates and photosynthetic models (Figure 10). For the Mt Lofty region, coastal areas also remained broadly similar (or with a small increase) to current levels. The northern part of the Mt Lofty region is predicted to have significant increases in high risk days under the CSIRO MK3.5 GCM (Figure 10). The Mid North region is predicted to have significant increases in high risk days under both future climates, with up to 5 additional days a year under the CSIRO MK3.5 GCM (Figure 10). Assumptions about how trees respond to photosynthetically to elevated CO<sub>2</sub> concentrations were projected to have little impact on the number of high risk days, with only a slight increase in risk days projected for the Mid North Region in 2070 where acclimation of photosynthesis to CO<sub>2</sub> was assumed compared with no increase in photosynthesis.

## RISK FROM FIRE

Fire risk is a function of factors such as weather, ignition source and fuel load, terrain and land management practices. These factors may be influenced by climate change. In the following we focus on three issues of most relevance to plantation forests.

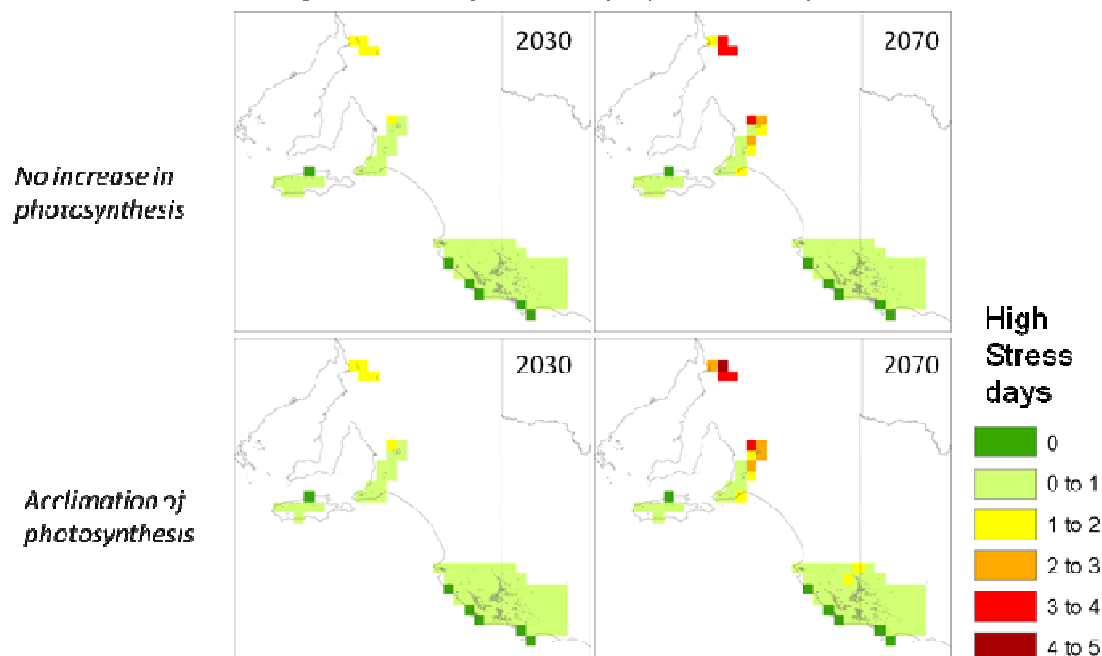
**Fire weather:** Reduced rainfall, warmer temperatures and increased incidence of high temperature events are projected to increase forest fire weather risk over much of Australia (Booth 2008; Hennessy et al. 2005; Nicholls and Lucas 2007; Pitman et al. 2007). Hennessy et al. (2005) predicted an increase in fire weather risk at a range of locations in south eastern Australia, including the average number of days with a high or extreme forest fire danger rating. The increase ranged from 4 – 25% by 2020 and 15 – 70% by 2050, with the increases generally being largest at inland sites. A conclusion of this study was that the window available for prescribed burning may shift and narrow, with more prescribed burning in winter (Hennessy et al. 2005).

**Fuel load:** There is a strong relationship between plantation growth rate and the amount of litter and debris produced, whereby faster-growing stands produce more litter (Paul and Polglase 2004). The increases in leaf C:N ratio that have been observed in a number of species in response to elevated atmospheric CO<sub>2</sub> concentrations (Ayres and Lombardero 2000; Lawler et al. 1997) may influence litter decomposition rates. While decomposition of both leaf litter and woody debris is faster at warmer temperatures provided there is adequate moisture (Hyvonen et al. 2007; Mackensen et al. 2003), increased C:N ratios have been shown to decrease litter decomposition rates (Hyvonen et al. 2007). This may further exacerbate fuel build-up.

Higher temperatures, reduced rainfall and increased vapour pressure deficit are likely to result in drier fuel (Hennessy et al. 2005; Matthews et al. 2009). Matthews et al.

## CSIRO Mk3.5

*Change in the average number of high stress days per year*



## MIROC-H

*Change in the average number of high stress days per year*

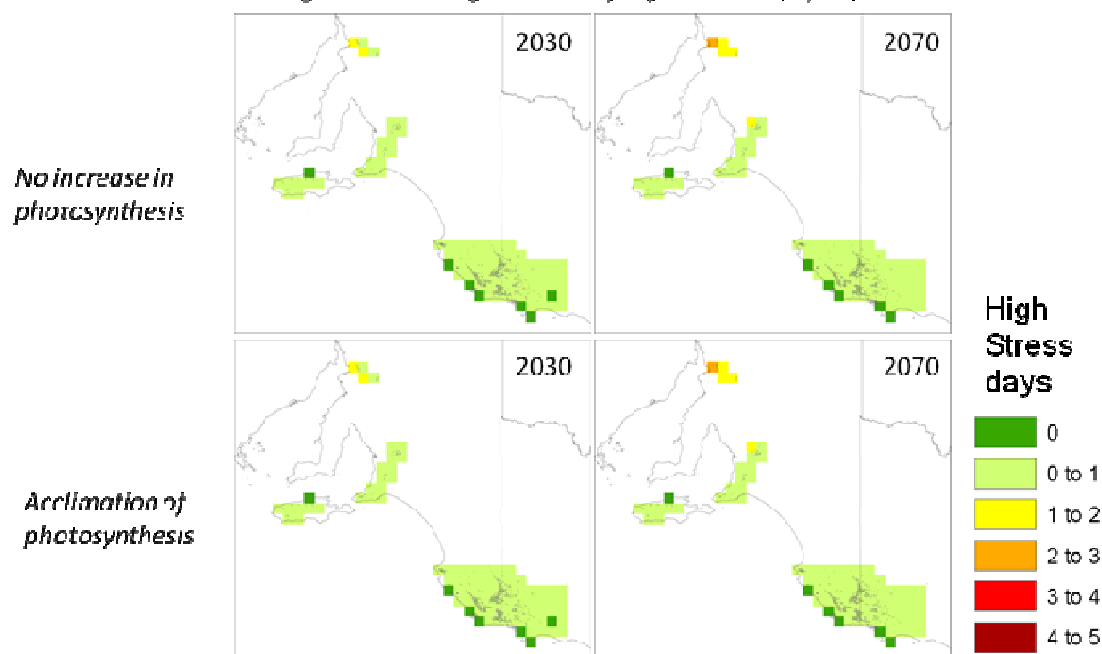


Figure 10. Change in the number of high risk days in the Green Triangle, Mt Lofty and the Mid North regions under two future climates, and assuming either no increase in photosynthesis in response to elevated atmospheric CO<sub>2</sub> concentration, or an acclimation of photosynthesis to elevated CO<sub>2</sub>.

(2009) suggested that this, combined with an increase in the number of days of high fire danger, may increase the length and severity of the fire season and reduce the window for prescribed burning.

Plantations with high risk of fire damage will be those that are older (ie with a greater build-up of debris) (Pinkard et al. 2010b), with a woody weed understorey (Geddes 2006), and where thinning debris is present, although young plantations are also highly vulnerable. Second rotation plantations where debris is left on-site will also be at risk. While fuel reduction burning has been used in some instances to reduce fuel loads in plantations (eg Forestry Plantations Queensland 2009), damage to trees in the stand can occur, and there is no evidence that fire risk is reduced in plantations by this action. There is also evidence that reducing debris on-site may have negative effects on nutrient cycling processes, with consequences for site fertility management and productivity (Nambiar 1984).

**Ignition source:** Projected increases in frequency of thunderstorms in some regions may result in increased natural ignition (Steffen 2009).

## **ADAPTATION TO MANAGE RISK AND IMPACTS**

### **WHAT IS ADAPTATION?**

Adaptation to climate change is defined as ‘the adjustment of management in response to real or anticipated climate change, which moderates harm or exploits beneficial opportunities’ (Innes et al. 2009). Adaptation aims to reduce the vulnerability of a system to possible changes in climate. While Australia’s natural systems have a limited capacity to adapt to climate change (Hennessy et al. 2007), plantation forests are considered to have a high capacity for adaptation of management and a large potential benefit from adaptation (Hennessy et al. 2007). This adaptive capacity is a function not only of biophysical traits but also factors such as a strong economy, well-developed research capabilities and management skills. (Wilson and Turton 2010).

Adaptation can be either reactive or planned (Easterling et al. 2007; Seppala et al. 2009). Reactive adaptation generally involves *ad hoc* responses to events as they occur. This is commonly how the forest sector has responded to unfavourable climatic episodes (Roberts et al. 2009), and is a reasonable response to infrequent events. Planned adaptation, in contrast, involves changing policy and operational procedures to account for our understanding of how climatic conditions might change, the risk that this presents to our forests, and the uncertainty around possible future conditions (Easterling et al. 2007). This approach offers many advantages under conditions of rapid change where reactive adaptation is less likely to be effective.

Implicit in planned adaptation is recognising that we do not have complete knowledge of how our forests will respond to changing climate, or of spatial and temporal changes likely to occur in our climate (Spittlehouse 2005). Acknowledging this uncertainty, and building it in to management systems, is an important element of planned adaptation (Seppala et al. 2009). In order to deal with this uncertainty, ongoing evaluation of what did or did not work is important (Spittlehouse and Stewart 2003). The development of tools to assist in decision-making and enable comparisons of approaches and scenario generation is also an important element (Seppala et al. 2009). These tools should include the capacity for cost-benefit analysis, so that various strategies can be compared with each other and with a ‘do nothing’ approach. It is also important to recognise that adaptation will not work in all situations, and a realistic appraisal of where, and under what circumstances, adaptation may be effective is a necessary element of adaptation.

### **WHAT ADAPTATION STRATEGIES ARE AVAILABLE TO FOREST MANAGERS?**

When responding to relatively small climatic changes, adaptation focused around silviculture may be sufficient to manage risk and impact. Silviculture has been



effective in response to past climatic events such as drought. Silvicultural practices in Australian plantations are based on a long history of experimentation (O'Hehir and Nambiar 2010), and the principles are well-understood, although how to best apply this knowledge to managing the effects of climate change may require further development. Process-based productivity models can assist in this, by enabling managers to compare a range of management scenarios to determine where and when changing silviculture may be beneficial.

As climatic changes become more pronounced, or in areas more marginal for forestry where small changes in climate may have a larger impact, significant alterations in management may be required. Selecting more resilient species or genotypes, and implementing different establishment techniques, are examples of such changes. These sorts of responses are likely to be more costly than altering silviculture, and will require significant development before they could be deployed in the field.

Transformational change occurs when forestry in its current form is no longer a viable land use. A move to new forest products (eg biosequestration), or to non-forest products, may be the most appropriate course of action. The effects of this type of change are unlikely to be restricted to the forest industry, but may be felt within the communities that support that industry, forest processors and end users. In the core *E. globulus* and *P. radiata* growing regions of Australia, transformational change is unlikely to be required in the foreseeable future, because the levels of climatic change that are projected are well within the levels that can be tolerated by these species (Booth et al. 2010 ).

It is important to recognise that climate change is but one consideration out of many when determining plantation management strategies, and a 'do nothing' approach may be the most sensible option when weighed up against competing demands. Providing plantation managers with tools to compare the outcomes of different management strategies on productivity, wood flow and financial return is an important element of adaptation.

## **ADAPTATION IN SOUTH AUSTRALIA'S PLANTATIONS**

Despite a drying climate, productivity of plantations in southern Australia has been increasing over the last 100 years, due to improvements in silvicultural practices and genotypes (O'Hehir and Nambiar 2010) (Figure 11). This suggests that there is good scope to modify the impacts of climate change on productivity into the future via management. As climate change progresses, risks to plantations will increase and understanding the trade-offs between risk and productivity will become increasingly important, with strategies that promote high productivity perhaps resulting in an altered risk profile. It will not be the smaller shifts in productivity that affect the viability of forest enterprises but the frequency and severity of damaging events.

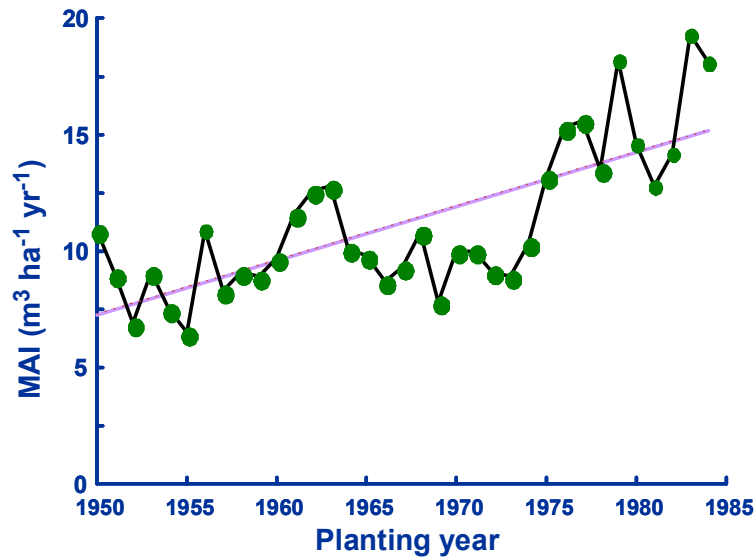


Figure 11. Trends in mean annual increment of Radiata pine plantations in South-Eastern Australia over a 35 year period. MAI was measured at age 11 across many sites, soil types and planting years. From Lieshout et al. 1996.

How trees respond to changing climate will depend on local factors such as nutrition and soil depth, as well as climatic characteristics such as temperature, rainfall and atmospheric CO<sub>2</sub> concentration. This means that climate change impacts on production may vary considerably between sites and regions, requiring an increased emphasis on site-specific management in order to manage productivity and risk (Battaglia et al. 2009).

We have insufficient knowledge to make informed decisions about the usefulness of many of the adaptation strategies available to us. Until this situation improves, models will be the most important tool to assist in decision making through assessment of risk and impact, defining the potentially most effective adaptation strategies for specific sites, as long as they enable forest managers to undertake cost-benefit analyses to determine whether adaptation presents economic advantages over a 'do nothing' approach.

In the following, some suggestions of site-level adaptation strategies are presented. While specific management strategies may seem to offer benefits in managing risk and impact from climate change, each needs to be considered in the context of broader management implications and undesirable feedbacks. These are discussed where relevant.

## Establishment

Promoting early survival and growth through establishment practices can be critical to longer-term productivity and resilience of plantations to climatic variability. Possible adaptation strategies to promote establishment under changing climate are listed in Table 5. They revolve around reducing water loss from seedlings, increasing resilience of seedlings, and promoting early growth.

**Site preparation techniques:** Fallowing prior to planting is already practiced in some low rainfall sites in Australia, with the objective of improving seedling survival and early growth by improving soil water stores. Fallowing can have longer-term benefits, particularly in second-rotation sites where it has been found that incomplete soil water recharge between rotations can contribute to declining productivity of the second rotation *E. globulus* plantations (Mendham et al. 2011).

We used a process-based model (Battaglia et al. 2004) to examine the consequences of fallowing for 12 months prior to planting on final stand volume of a first-rotation Blue gum plantation. There was a predicted benefit of fallowing on plantation productivity irrespective of the soil water content at planting. At low initial soil water content, when drought is presumed to have coincided with the fallow period, the benefit predicted from fallowing was related to a slight increase in nutrient availability rather than increased soil water content. When fallowing resulted in full recharge of the soil profile, productivity was greater than it would have been without the fallow period.

Response to fallowing is equally about nutrition as about soil water, as illustrated in Figure 12. Hence at a low fertility site such as in Figure 12, fertilising at the start of the fallowing combined with mineralisation during the fallow period was predicted to increase final volume even when the soil profile was not fully recharged. This response will be different if weeds are not controlled during the fallow period.

The length of fallow time required to recharge the soil profile, and the degree of recharge that occurs, will vary between sites, meaning that this method may not be appropriate for all sites. Site-specific analyses should be performed using models.

Fallowing has been linked to increasing weed control problems (Forestry SA, pers comm.) that may also influence the practicality of the method as a response to changing climate. Much of the recharge benefit of fallowing will be lost if weed cover establishes rapidly and intercepts and transpires rainfall.

In South Australia spot cultivation has been found to increase survival of Radiata pine seedlings compared to soil mounding on well drained soils in dry environments (Forestry SA. 2008). Growth was not affected.

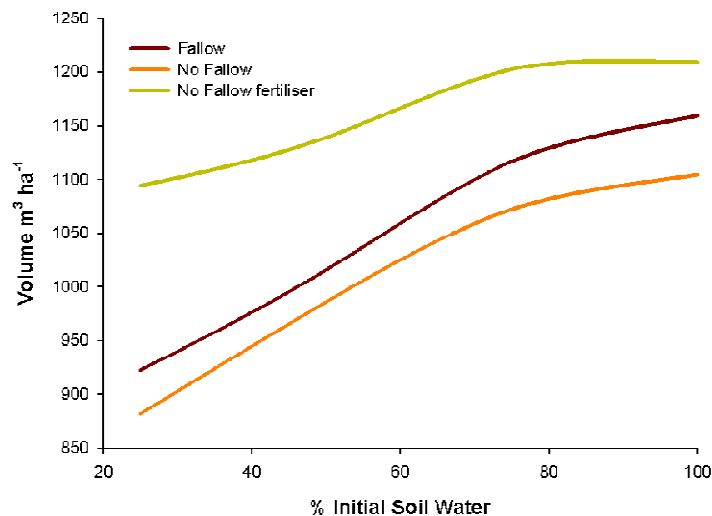


Figure 12. Relationship between final volume/ha of Radiata Pine over 37 years with different soil water content at planting.

**Nursery management practices to promote resilience:** Drought hardening in the nursery has been shown to enhance the survival of eucalypt species (Guarnaschelli et al. 2003; Thomas 2009). When water is withheld or reduced for a proportion of days per week prior to leaving the nursery, the seedlings can experience reduced water stress when planted, and can recover from transplant shock more rapidly than non-hardened seedlings (Thomas 2009).

Seedling type can influence rates of survival at planting. For example, in South Australia open-rooted seedlings have been found to have dramatically reduced survival compared to containerised seedlings or cuttings when planted outside the optimal planting time under dry conditions (Forestry SA. 2010b).

**Transport and planting practices to reduce transpiration:** Anti-transpirant sprays may be an effective way of reducing water loss both during transport and immediately following planting, as well as providing protection from pests and ultraviolet light. There is little literature available to indicate whether these products are ultimately effective at reducing mortality. Hydrogel applied to the root plug in the nursery was found to reduce post-planting mortality in *E. pilularis* and *Corymbia citriodora* var *variegata* (Thomas 2008), although Terrasorb applied to the roots of *P. radiata* seedlings prior to planting reduced stocking 12 months after planting, by 200 stems per hectare (Forestry SA 2006). Polypropylene tree shelters were found to reduce mortality of *Quercus suber* in Tunisia (Chaar et al. 2008), presumably by reducing transpiration but also possibly by protecting seedlings from browsing damage. Antitranspirant sprays are currently used in some plantations in Australia to reduce frost damage, and tree shelters are sometimes used to control browsing in locations with high browsing pressure where more conventional methods are not available (P. Adams, Forestry Tasmania, pers comm.).

Understanding the optimal window for planting will promote seedling survival. In South Australia the optimal period is June-July (Forestry SA. 2010b), although this may change in the future depending on the rate of winter drying that is experienced. While

planting in May had little effect on the comparative survival of open-rooted and containerised plants, planting in September resulted in a dramatic decline in the survival of open-rooted cuttings. Huth et al. (2008) used a minimum stored soil moisture of 90 mm to identify optimal planting times for *Eucalyptus melliodora* and *E. populnea*, based on an understanding of the physiological requirements of the species.

**Site management to promote survival and growth:** Weed control is a critical element of site preparation that increases both survival and growth (Baker et al. 1988). In South Australia it currently targets weed species that are likely to be present during the first 6 - 12 months after planting, starting in the spring prior to planting, and extending for 2 years in higher rainfall zones and 3 years in lower rainfall zones (Forestry SA, pers comm.) or where wider spacing has been used. This strategy is well-developed and is likely to continue into the future.

Table 5. Potential impacts of climate change on plantation establishment, and possible adaptation strategies to moderate the impacts.

| Climate variable   | Impact                      | Related consequences   | Possible adaptation options   |
|--|-----------------------------|--|---|
| Reduced precipitation or changes in rainfall seasonality | Increased risk of mortality |  | <ul style="list-style-type: none"> <li>• Time planting to coincide with cool, moist conditions</li> <li>• Identify methods to reduce post-planting transpiration</li> <li>• Nursery management practices to promote resilience (eg drought hardening)</li> <li>• Transport and planting practices to reduce transpiration</li> <li>• Select genotypes more resilient to conditions</li> <li>• Site-species matching</li> <li>• Site preparation to promote soil water recharge</li> <li>• Organic matter retention</li> </ul> |
|  | Slower establishment rates  | Longer-term susceptibility to weed competition and pest damage | <ul style="list-style-type: none"> <li>• Maintain weed control for longer</li> <li>• Select genotypes more resilient to conditions</li> </ul>   |

## Growth

Some possible adaptation strategies to promote plantation growth are listed in Table 6. They include silvicultural practices, species selection and strategies for managing risk.

**Silviculture:** Silvicultural management can be used to manipulate availability of site resources such as water, nutrients and light. Initial spacing influences stem size and form as well as levels of weed competition, and generally falls within a tight range in South Australia particularly in plantations grown for solid wood products. In Western Australia some pulpwood plantations are established at 800 stems/ha to reduce mortality in dry environments, and this strategy may be appropriate in some pulp plantations in South Australia. Figure 13 (White et al. 2009) shows that reducing the

stocking of Blue gum from 1200 to 600 stems/ha increased mean annual increment over a 10 year rotation by 11%. The lower spacing reduced risk from drought. This experiment was done under weed-free conditions, and the implications of lower stand density on stem form were not assessed. However studies in Tasmania with Shining gum (Neilsen and Gerand 1999) suggest that lower initial spacing will reduce the number of stems with suitable form for solid wood production and increase the requirement for early pruning.

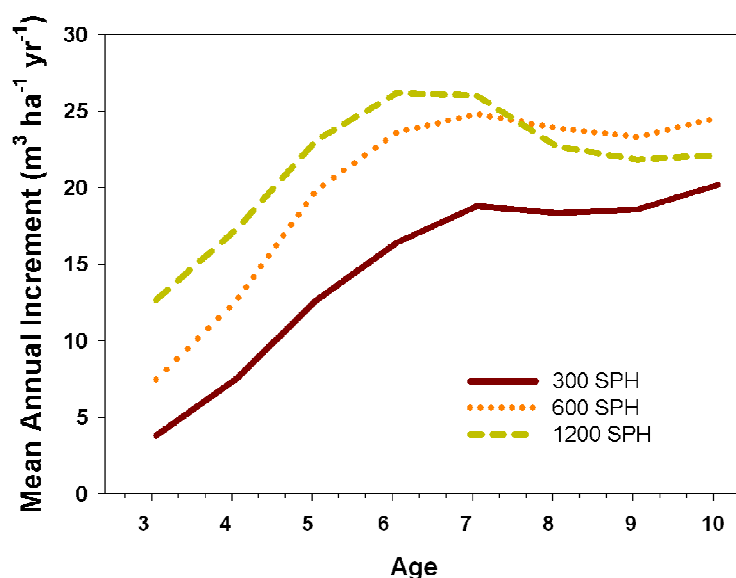


Figure 13. Effects of different initial spacing on mean annual increment in a Western Australian Blue gum plantation (White et al. 2009).

White et al. (2009) demonstrated that thinning is an effective strategy for managing water stress in Blue gum stands in Western Australia. Currently thinning is not practiced routinely in pulpwood plantations, but may offer benefits at dry sites. Radiata pine plantations in South Australia are routinely thinned to optimise stem volume, with first thinning at around 11 years of age, and subsequent thinning at 7 year intervals. Stands are reduced from an initial stocking of around 1600 stems/ha to a final stocking of around 250 stems/ha (although initial stocking is lower in drier regions). Thinning is not generally performed in pulpwood Blue gum plantations.

Until the advent of a softwood pulpwood market in Australia in the 1990's, pre-commercial thinning was commonly practiced in many Radiata pine growing regions (Neilsen and Pinkard 2002). Commercial thinning now provides an important source of within-rotation income, which generally requires a minimum volume of thinned wood to make it economically viable. This can lead to delays in thinning.

Figure 14 highlights the possible consequences of delaying thinning. We used a modelling approach to compare the impacts on productivity and risk, of delaying thinning past the prescribed age of 11 years in Radiata pine in South Australia. Overall, total volume (final standing volume plus thinning) between the delayed and on time silviculture were very similar, (within 40 m³/ha at this particular site), however delaying thinning was associated with greater risk of tree mortality in producing that volume, so actual volumes may be lower when thinning is delayed. This provides an

indication that pre-commercial or early thinning may reduce risk without significantly impacting on final volume in dry environments. Models are useful tools for examining the consequences of different thinning strategies on productivity and risk.

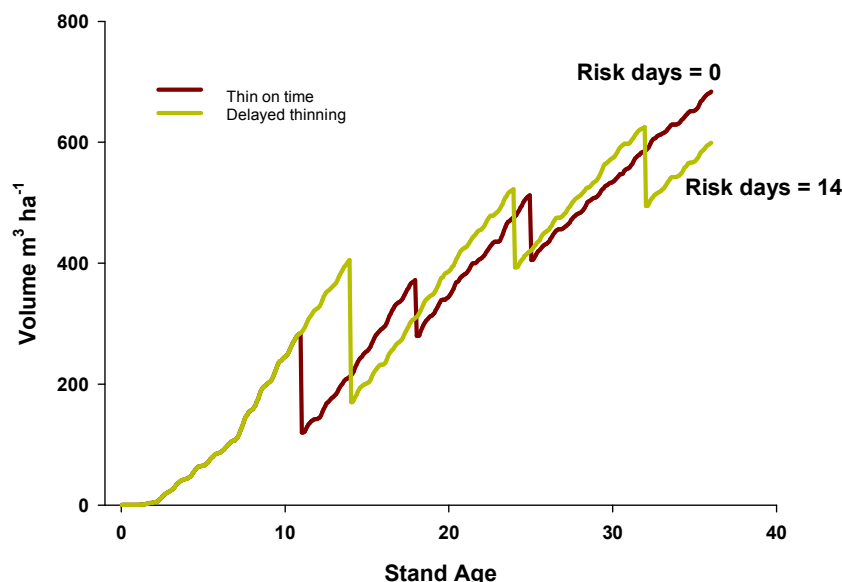


Figure 14. The impact of age of thinning on Radiata pine stand volume, simulated using a process-based model (Battaglia et al. 2004). The brown line indicates when thinning was scheduled as per the management prescription (11 years), and the green line indicates when thinning actually occurred on this experimental site. Thinning on time was predicted to produce a very similar total volume but with less risk to the plantation from water stress compared to delayed thinning. Risk days refers to the number of days at risk of drought-induced mortality.

Forestry SA (2010a) highlighted that fertiliser responses vary considerably with soil type and rainfall, and the need to carry out a detailed assessment of soils where fertilising may be beneficial. Within the limitations highlighted by Forestry SA, fertilising may play a role in the context of managing risk and impact of climate change in plantations. For example the interaction of fertilising and thinning has been used to minimise drought risk at dry sites in Western Australia (White et al. 2009), although if nutrition is not the primary factor limiting growth, then adding fertiliser will not reduce drought risk (Mendham et al. 2007). Fertilising has been shown to promote recovery following pest attack, even on sites with high fertility (Pinkard et al. 2006a; Wardlaw et al. 2005). Fertilising can however promote weed growth prior to canopy closure. This can be minimised by spot as opposed to broadcast application of fertiliser.

**New species:** New species can be selected on the basis of better adaptation to warmer and drier environments. However South Australia's forest industry (along with significant national and international markets) is based around Blue gum and Radiata pine and species substitution needs to consider many factors, including:

- Species at less risk from drought often achieve this via decreased resource use, meaning that they are slower growing than Blue gum or Radiata pine
- There is considerable difficulty matching drought tolerance traits to desirable wood properties and growth. So for example a species such as Sugar gum (*Eucalyptus cladocalyx*) which has high drought tolerance, has slower growth and different wood properties compared to Blue gum

- Wood properties of alternative species may not match current product specifications, requiring the development of alternative markets and potentially new processing methods
- Developing new species and genotypes takes time, with at least 10 years between starting assessment and deployment in the field
- Management practices required to grow new species efficiently are undeveloped and require new research

Table 6. Potential impacts of climate change on plantation growth, and possible adaptation strategies to moderate the impacts.

| Climate variable                 | Impact  | Related consequences                        | Possible adaptation options  |
|----------------------------------|---|---|--|
| Warmer mean annual temperatures  | Change in seasonality of growth   | Potential for increased pest damage         | <ul style="list-style-type: none"> <li>• Monitor for increased pest damage</li> <li>• Select genotypes more resistant to pests</li> </ul>  |
|                                  | Increased rates of photosynthesis that may increase growth rates  |   | <ul style="list-style-type: none"> <li>• Decrease stocking to manage water and nutrients</li> </ul>  |
|                                  | Increased vapour pressure deficit, transpiration and soil evaporation resulting in greater water stress |   | <ul style="list-style-type: none"> <li>• Management practices such as thinning and weed control to manage site leaf area index and water use</li> <li>• Select drought tolerant genotypes</li> </ul>   |
| Increased frequency of heatwaves | Increased mortality, particularly if combined with drought  |   | <ul style="list-style-type: none"> <li>• Promote resilience through management (eg spacing, thinning, weed control) to reduce water limitation</li> </ul>  |
|                                  | Greater soil evaporation leading to increased plant water stress  |   | <ul style="list-style-type: none"> <li>• Management practices such as thinning and weed control to manage site leaf area index and water use</li> </ul>  |
| Reduced precipitation            | Reduced leaf area index   | Reduced growth rates                        | <ul style="list-style-type: none"> <li>• Manage leaf area index through thinning, weed control and fertilising</li> <li>• Develop tools for predicting risk and identifying effective risk management options</li> <li>• Plant more drought tolerant genotypes</li> <li>• Spread risk by planting mixed provenances</li> </ul> |
|                                  |   | Site no longer suitable for current species | <ul style="list-style-type: none"> <li>• Plant alternative species</li> <li>• Choose different sites</li> </ul>  |



## Pests

Some possible adaptation strategies for managing risk and impact of pests under future climates are listed in Table 7. Strategies include risk assessment, pest monitoring to detect increases in pest activity and damage, and promoting plantation resilience to pest damage.

**Identify pest thresholds:** Current understanding of the levels of pest damage that significantly reduce plantation productivity is limited. In both Blue gum and Radiata pine, foliage reductions greater than 50% have been found to reduce productivity (Pinkard et al. 2006a; Rapley et al. 2009; Sutton and Crowe 1975). However this is strongly linked to the age and frequency of defoliation, with later-age defoliation, and chronic defoliation, expected to have more impact than early-age or infrequent defoliation. There is some evidence from modelling studies that damage thresholds above which productivity is reduced will decline under future climates if trees become more stressed (Pinkard et al. 2008), with site attributes and changes in atmospheric CO<sub>2</sub> concentrations potentially influencing resilience. Better understanding these thresholds, and the impact of damage on productivity, will help to identify high risk sites where a greater emphasis on monitoring of pest populations and damage may be required.

**Understand population dynamics:** for many pests of plantations in Australia there is limited understanding of how the species respond to temperature, precipitation and increasing CO<sub>2</sub> concentrations. This makes it difficult to determine how pest distribution and abundance might change in the future, and harder to identify conditions conducive to serious outbreaks. Further research is required.

**Promote plantation resilience:** Silvicultural management that reduces the impacts of drought on plantation health, productivity and survival will help to promote resilience to pest attack. Measures include thinning/spacing, fertilising and genotype selection for resilience to both drought and pests.

One of the management responses to outbreaks of pine aphid, Ips bark beetle and Sirex wood wasp in South Australia involves managing debris to reduce breeding sites (*Ips*), and managing drought stress through thinning (pine aphid, *Sirex*). Harvesting operations are undertaken in winter where possible, to reduce the likelihood of pest populations building up in harvest residue (Morgan 1989). Warmer winter temperatures will increase the importance of managing harvest residue for *Ips* control.

## Weeds

Some possible adaptation strategies for managing risk and impact from weeds are listed in Table 8. Management will likely revolve around risk assessment and approaches for promoting weed control in plantations.

Table 7. Potential impacts of climate change on plantation pests, and possible adaptation strategies to moderate the impacts.

| Climate variable                         | Impact   | Related consequences                | Possible adaptation options  |
|--|--|-------------------------------------|--|
| Warmer mean annual temperatures          | Increased number of insect generations per year              | Potentially increased damage        | <ul style="list-style-type: none"> <li>• Identify damage thresholds in host species</li> <li>• Identify high risk sites using models</li> <li>• Promote recovery by fertilising, thinning</li> </ul> |
|  | Increased late-season damage                                 | Potentially increased damage        | <ul style="list-style-type: none"> <li>• Identify damage thresholds for host species</li> </ul>  |
|  | Decreased winter mortality of pests                          | More rapid pest population build-up | <ul style="list-style-type: none"> <li>• Improve or maintain plantation hygiene by weed and debris control</li> </ul>  |
|  | Increased risk from invasive pests                           |                                     | <ul style="list-style-type: none"> <li>• Profile new forest pests based on likelihood of invasion and potential damage</li> <li>• Develop tools to examine risk from invasive pests</li> </ul>       |
| Decreased precipitation                  | Greater susceptibility to some pests                         |                                     | <ul style="list-style-type: none"> <li>• Pest monitoring and control</li> <li>• Manage drought risk through spacing, thinning and weed control</li> </ul>  |
| Increased high intensity rainfall events | May favour foliar pathogens if high relative humidity occurs |                                     | <ul style="list-style-type: none"> <li>• Understand lifecycle requirements of pests to identify risk</li> <li>• Identify damage thresholds for host species</li> </ul>                               |

**Risk assessment:** All plantations in South Australia are susceptible to weed impacts. The suite or abundance of weeds at given locations may change in the future in response to climate change even though management strategies for the current suite of weeds are well-understood. It is important to recognise that monitoring will be required to identify emerging weeds of plantations. Species niche models may assist in identifying locations where conditions may be favourable for new weeds (Kriticos et al. 2010) which can be used to identify priority site types for monitoring.

**Long-term weed control:** Forestry SA has well-developed weed control strategies for the three plantation regions in South Australia (Richardson 2010), involving combinations of herbicide and soil cultivation. These are likely to continue to be appropriate weed control methods, although the suite of weeds may change in each region.

Monitoring will be required to identify emerging weeds and changing distributions of current weed species. An industry-wide approach to this will be desirable.

Table 8. Potential impacts of climate change on plantation weeds, and possible adaptation strategies to moderate the impacts.

| Climate variable               | Impact  | Related consequences                          | Possible adaptation options  |
|--------------------------------|---|---|--|
| Warmer mean annual temperature | Range shifts to higher latitudes                        |   | • Model climate change impacts on distribution and abundance of key weed species |
|                                | Increased growth rates                                  | Increased competition with plantation species | • Ongoing weed control at dry sites  |
| Decreased precipitation        | Change in suite of weeds                                |   | • Risk assessment to identify new problem weeds                                  |
|                                | Increased competition for water with plantation species |   | • Ongoing weed control at dry sites  |

## FUTURE RESEARCH

Further research and development will play an increasingly important role in defining adaptation strategies at both site and regional scales as new knowledge is generated. Areas identified as requiring further research include:

- 1 Development of modelling tools to enable managers to assess risk and impact, identify high risk sites, inform decisions about where adaptation may be required, compare the effectiveness of alternative management strategies, and identify trade-offs between risk and productivity
- 2 Research into pest and weed management should encompass:
  - a) Developing distribution models for key species where these models do not exist, for biological control agents, and for species that may be emerging threats (eg. Guava rust);
  - b) Development of new approaches to monitoring pests and weeds and their biological control agents, including remote networks that provide the advantage of broad landscape coverage;
  - c) Identifying damage thresholds and quantifying the impact of pest damage on productivity;
  - d) Determining how site and climate influence host responses to pest damage, to help identify high risk sites;
  - e) Identifying threats from invasive species and strategies for managing these threats.
- 3 Understanding how plantation species respond to increasing atmospheric CO<sub>2</sub> concentrations and its interactions with site and climate. There has been limited research in this area for Blue gum and Radiata pine. Developing the capacity for rapid screening of response to elevated CO<sub>2</sub> concentrations would contribute to identifying sites and environments under which positive responses to increasing CO<sub>2</sub> might be expected. This type of research requires specialist facilities meaning industry research groups are unlikely to be able to undertake such studies. The plantation industry has an important role in promoting the need for this research.

- 4 Identifying the processes underlying drought-induced mortality in Blue gum and Radiata pine, so that a capacity for modelling the probability of mortality events can be developed.

## REFERENCES

- Ainsworth, E.A. and S.P. Long 2005. What have we learned from 15 years of free-air CO<sub>2</sub> enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO<sub>2</sub>. *New Phytologist*. 165:351 - 372.
- Ainsworth, E.A. and A. Rogers 2007. The response of photosynthesis and stomatal conductance to rising [CO<sub>2</sub>]: mechanisms and environmental interactions. *Plant, Cell & Environment*. 30:258 - 270.
- Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears, E.H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.-H. Lim, G.B. Allard, S.W. Running, A. Semerci and N. Cobb 2009. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*. 259:660 - 684.
- Ayres, E., J. Heath, M. Possell, H.I.J. Black, G. Kersteins and R.D. Bardgett 2004. Tree physiological responses to above-ground herbivory directly modify below-ground processes of soil carbon and nitrogen cycling. *Ecology Letters*. 7:469 - 479.
- Ayres, M.P. and M.J. Lombardero 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. *The Science of the Total Environment*. 262:263 - 286.
- Baker, T.G., J.N. Cameron, P.C. Fagg and D. Matthews 1988. Effect of timing and rate of hexachlorocyclopentadiene application on weed control and early growth of *Pinus radiata* on two contrasting sites. *Australian Forestry*. 51:92 - 97.
- Barker, D.H., B.R. Loveys, J.G. Egerton, H. Gorton, W.E. Williams and M.C. Ball 2005. CO<sub>2</sub> enrichment predisposes foliage of a eucalypt to freezing injury and reduces spring growth. *Plant, Cell & Environment*. 28:1506 - 1515.
- Battaglia, M., J. Bruce, C.L. Brack and T. Baker 2009. Climate change and Australia's plantation estate: analysis of vulnerability and preliminary investigation of adaptation options. CSIRO, Hobart, Australia, p. 128.
- Battaglia, M., P.J. Sands, D. White and D. Mummery 2004. CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. *Forest Ecology and Management*. 193:251 - 282.
- Benson, M.L., B.J. Myers and J. Raison 1992. Dynamics of stem growth of *Pinus radiata* as affected by water and nitrogen supply. *Forest Ecology and Management*. 52:117 - 137.
- Booth, T.H. 2009. Climate change and the 2009 bushfires. *In* CSIRO Submissions 09/345 Ed. V.B.R. Commission. CSIRO, Canberra, p. 24.
- Booth, T.H. and T. Jovanovic 2005. Tree species selection and climate change in Australia. Australian Greenhouse Office, Canberra.
- Booth, T.H., M.U.F. Kirschbaum and M. Battaglia 2010. Forestry. *In* Climate change adaptation in Australia: Preparing agriculture, forestry and fisheries for the future Eds. C.J. Stokes and S.M. Howden. CSIRO Publishing, Canberra.
- Burdon, J.J., P.H. Thrall and A. Ericson 2006. The Current and Future Dynamics of Disease in Plant Communities. *Annual Review of Phytopathology*. 44:19-39.

- Butcher, T.B. 1976. Influence of moisture relationships on thinning practice. *Journal of Forestry Science*. 6:158 - 170.
- Carnegie, A., M. Matsuki, D.A. Hauger, B.P. Hurley, R. Ahumada, P. Klasmer, J.H. Sun and E.T. Lede 2006. Predicting the potential distribution of *Sirex noctilio*, a significant exotic pest of *Pinus* plantations. *Annals of Forest Science*. 63:119 - 128.
- Carnegie, A.J. and P.K. Ades 2002. *Mycosphaerella* leaf disease reduces growth of plantation-grown *Eucalyptus globulus*. *Australian Forestry*. 66:113 - 119.
- Cellier, K.M. and C.G. Stephens 1980. Effect of fertilizer and weed control on the early growth of plantation-grown *Pinus radiata* D. Don in Southern Australia. *Australian Forest Research*. 10:141 - 153.
- Chaar, H., T. Mechergui, A. Khouaja and H. Abid 2008. Effects of treeshelters and polyethylene mulch sheets on survival and growth of cork oak (*Quercus suber* L.) seedlings planted in northwestern Tunisia. *Forest Ecology and Management*. 256:722-731.
- Chakraborty, S., J. Lucj, G. Holloway, A. Freeman, R. Norton, K.A. Garrett, K. Percy, A. Hopkins, C. Davis and D.F. Karnosky 2008. Impacts of global change on diseases of agricultural crops and forest trees. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 3
- Crimp, S., P. Kokic, G. McKeon, I. Smith, J. Sytkus, B. Timbal and P. Whetton 2010. A review of appropriate statistical downscaling approaches to apply as part of Phase 2 of the Consistent Climate Projections project. CSIRO, Canberra, p. 26.
- Desprez-Loustau, M.L., B. Marçais, L.M. Nageleisen, D. Piou and A. Vannini 2006. Interactive effects of drought and pathogens in forest trees. *Annals of Forest Science*. 63:597 - 612.
- Downes, G.M., D.M. Drew, M. Battaglia and D. Schulze 2009. Measuring and modelling stem growth and wood formation: a review. *Dendrochronologia*. 27:147 - 157.
- Downes, G.M., I.L. Hudson, C.A. Raymond, G.H. Dean, A.J. Mitchell, L.S. Schimleck, R. Evans and A. Muneri 1997. Sampling plantation eucalypts for wood and fibre properties. CSIRO Publishing, Melbourne.
- Drew, D.M., G.M. Downes, A.P. O'Grady, J. Read and D. Worledge 2009. High resolution temporal variation in wood properties in irrigated and non-irrigated *Eucalyptus globulus*. *Annals of Forest Science*. 66
- Dutkowski, G.W. 1995. Genetic variation in drought susceptibility of *Eucalyptus globulus* ssp. *globulus* in plantations in Western Australia. In *Eucalypt plantations: improving fibre yield and quality* Eds. B.M. Potts, N.M.G. Borralho, J.B. Reid, W.N. Tibbits and C.A. Raymond. CRC for Temperate Hardwood Forestry, Hobart, Australia.
- Easterling, W.E., P.K. Aggarwal, P. Batima, K.M. Brander, L. Erda, S.M. Howden, A. Kirilenko, J. Morton, J.-F. Soussana, J. Schmidhuber and F.N. Tubiello 2007. Food, fibre and forest products. In *Climate change 2007. Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change* Eds. M.L. Parry, O.F. Canziani, J.P. Paluikof, P.J. van der Linden and C.E. Hanson. Cambridge University press, Cambridge, pp. 273 - 313.
- Forestry Plantations Queensland 2009. Profitable sustainable plantation forests.
- Forestry SA 2010a. Radiata pine young age fertiliser response prediction tool for the Green Triangle region. Forestry SA, p. 50.
- Forestry SA. 2010b. Performance comparison of containerised Vs open rooted seedlings and cuttings radiata pine planting stock. Forestry SA, p. 15.

- Forestry SA. 2008. Site preparation methods comparison study: *Pinus radiata* growth and survival after mounding or spot cultivation in a low rainfall area. Forestry SA, p. 5.
- ForestrySA 2006. Anti-Stress vs Terrasorb root dipping trial. ForestrySA internal report, 6p.
- Geddes, D. 2006. Fire behaviour in hardwood plantations. *In* Australian Forest Growers conference proceedings. Australian Forest Growers, pp. 283 - 290.
- Geiger, T. and F.M. Thomas 2002. Effects of defoliation and drought stress on biomass partitioning and water relations of *Quercus robur* and *Quercus petraea*. *Basic and Applied Ecology*. 3:171 - 181.
- Ghannoum, O., N.G. Phillips, M.A. Sears, B.A. Logan, J.D. Lewis, J.P. Conroy and D.T. Tissue 2010. Photosynthetic responses of two eucalypts to industrial-age changes in atmospheric [CO<sub>2</sub>]. *Plant, Cell & Environment*. 33:1671 - 1681.
- Greenep, H., M.H. Turnbull and D. Whitehead 2003. Responses of photosynthesis in second-generation *Pinus radiata* trees to long-term exposure to elevated carbon dioxide partial pressure. *Tree physiology*. 23:569 - 576.
- Groom, P.K., B.B. Lamont, S. Leighton and C. Burrows 2004. Heat damage in sclerophylls is influenced by their leaf properties and plant environment. *Ecoscience*. 11:94 - 101.
- Guarnaschelli, A.B., J.H. Lemcoff, P. Prystupa and S.O. Basci 2003. Responses to drought preconditioning in *Eucalyptus globulus* Labill. provenances. *Trees*. 17:501-509.
- Hall, D.O. and K.K. Rao 1992. *Photosynthesis*. Cambridge University Press, Cambridge. 122 p.
- Harrington, R., R.A. Fleming and I.P. Woiwod 2001. Climate change impacts on insect management and conservation in temperate regions: can they be predicted? *Agricultural and Forest Entomology*. 3:233 - 240.
- Hattersley, P. W. (1983) The Distribution of C3 and C4 Grasses in Australia in Relation to Climate. *Oecologia*, **57**, 113-128.
- Hennessy, K., B. Fitzharris, B.C. Bates, N. Harvey, S.M. Howden, L. Hughes, J. Salinger and R. Warrick 2007. Australian and New Zealand climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Eds. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson. Cambridge University Press, Cambridge, UK, pp. pp 507 - 540.
- Hennessy, K., C. Lucas, N. Nicholls, J. Bathols, R. Suppiah and J. Ricketts 2005. Climate change impacts on fire weather in south-east Australia. Australian Greenhouse Office, Canberra, p. 88.
- Hunter, M.D. 2001. Effects of elevated atmospheric carbon dioxide on insect-plant interactions. *Agricultural and Forest Entomology*. 3:153-159.
- Huth, N.I., P.S. Carberry, B. Cocks, S. Graham, H.M. McGinness and D.A. O'Connell 2008. Managing drought risk in eucalypt seedling establishment: An analysis using experiment and model. *Forest Ecology and Management*. 255:3307-3317.
- Hyvonen, R., G.I. Agen, S. Linder, T. Persson, M.F. Cotrufo, A. Ekblad, M. Freeman, A. Grelle, I.A. Janssens, P.G. Jarvis, S. Kellomaki, A. Lindroth, D. Ioustau, T. Lunkmark, R.J. Norby, R. Oen, K. Pilegaard, M.G. Ryan, B.D. Sigurdsson, M. Stromgren, M. van Oijen and G. Wallin 2007. The likely impact of elevated [CO<sub>2</sub>], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. *New Phytologist*. 173:463 - 480.
- Innes, J.L., L.A. Joyce, S. Kellomaki, B. Louman, A.E. Ogden, J. Parrotta and I. Thompson 2009. Management for adaptation. *In* Adaptation of forests and people

- to climate change - a global assessment Eds. S. Kellomäki, A. Buck and P. Katila. IUFRO, Helsinki, pp. 135 - 186.
- IPCC 2007. Climate change 2007: the physical science basis. Contributions of Working Group I to the fourth assessment report of the intergovernmental panel on climate change Eds. S. Solomon, D. Qin, M. Manning, Z.L. Chen, M. Marquis, K. Averyt, M.M.B. Ingmor, H.L. Miller and Z. Chen. Cambridge University Press, Cambridge, UK and New York, NY, p. 996.
- Kainulainen, P., J.K. Holopainen and T. Holopainen 1998. The influence of elevated CO<sub>2</sub> and O<sub>3</sub> concentrations on Scots pine needles: changes in starch and secondary metabolites over three exposure years. *Oecologia*. 114:455-460.
- Kilpeläinen, A., A.Z. Gerendai, K. Luostarinen, H. Peltola and S. Kellomäki 2007. Elevated temperature and CO<sub>2</sub> concentration effects on xylem anatomy of Scots pine. *Tree Physiology*. 27:1329 - 1338.
- Kilpeläinen, A., H. Peltola, A. Ryyppö, K. Sauvala, K. Laitinen and S. Kellomäki 2003. Wood properties of Scots pine (*Pinus sylvestris*) grown at elevated temperature and carbon dioxide concentration. *Tree Physiology*. 23:889 - 897.
- Kirschbaum, M.U.F. 2004. Direct and indirect climate change effects on photosynthesis and transpiration. *Plant Biology*. 6
- Kookana, R., G.K. Holz, C. Barnes, K. Bubb, R. Fremlin and B. Boardman 2010. Impact of climatic and soil conditions on environmental fate of atrazine used under plantation forestry in Australia. *Journal of Environmental Management*. 91:2649 - 2656.
- Körner, C. 2006. Plant CO<sub>2</sub> responses: an issue of definition, time and resource supply. *New Phytologist*. 172:393-411.
- Kriticos, D.J., N.D. Crossman, N. Ota and J.K. Scott 2010. Climate change and invasive plants in South Australia. CSIRO, p. 92.
- Kriticos, D.J., R.W. Sutherst, J.R. Brown, S.A. Adkins and G.F. Maywald 2003. Climate change and the potential distribution of an invasive alien plant: *Acacia nilotica* ssp. *indica* in Australia. *Journal of Applied Ecology*. 40:111 - 124.
- Lawler, I.R., W.J. Foley, I.E. Woodrow and S.J. Cork 1997. The effects of elevated CO<sub>2</sub> atmospheres on the nutritional quality of *Eucalyptus* foliage and its interaction with soil nutrient and light availability. *Oecologia*. 109:59 - 68.
- Leishout, H., P.H. Whiteman and S. Pongracic 1996. Improvement in *Pinus radiata* plantation production through breeding and silvicultural development since the 1950's. In Research Working Group N° 2 proceedings, Australian Forestry Council, Mount Gambier, Australia, 6p.
- Lindström, H., J.W. Evans and S.P. Verrill 1998. Influence of cambial age and growth conditions on microfibril angle in young Norway spruce (*Picea abies*). *Holzforschung*. 52:573 - 581.
- Long, S.P., E.A. Ainsworth, A. Rogers and D.R. Ort 2004. Rising atmospheric carbon dioxide: plants FACE the future. *Annual Review of Plant Biology*. 55:591 - 628.
- Long, S.P., C.P. Osborne and S.W. Humphries 1996. Photosynthesis, rising atmospheric carbon dioxide concentration and climate change. In *Global Change: Effects on Coniferous Forests and Grasslands* Eds. A.I. Breymeyer, D.O. Hall, J.M. Melillo and G.I. Ågren. John Wiley and Sons, Chichester, pp. 121 - 159.
- Luo, Z.-B., R. Langenfeld-Heyser, C. Calafapietra and A. Polle 2005. Influence of free air CO<sub>2</sub> enrichment (EUROFACE) and nitrogen fertilisation on the anatomy of juvenile wood of three poplar species after coppicing. *Trees*. 19:109 - 118.
- Macfarlane, C. 1998. The potential for high temperature stress of trees of *Eucalyptus globulus* in south-western Australia during summer-autumn. A report to Bunnings Treefarms Pty Ltd. The University of Western Australia, Perth, p. 30.

- Mackensen, J., J. Bauhus and E. Webber 2003. Decomposition rates of coarse woody debris - a review with particular emphasis on Australian tree species. *Australian Journal of Botany*. 51:27 - 37.
- Madafiglio, G.P., R.W. Medd, P.S. Cornish and R. Van de Ven 2000. Temperature-mediated responses of flumetsulam and metosulam on *Raphanus raphanistrum*. *Weed Research*. 40:387 - 395.
- Matthews, S., K. Nguyen and J.L. McGregor 2009. Modelling fuel moisture under climate change. *In* 18th World IMACS/MODSIM congress, Cairns, Australia.
- May, B.M. 2004. Assessment of the causality of *Essigella*-ascribed defoliation of mid-rotation radiata pine and its national impact in terms of cost of lost wood production. Forest and Wood Products Research and Development Corporation, p. 43 p.
- Medd, R.W., R. Van de Ven, D.I. Pickering and T. Nordblom 2001. Determination of environment-specific dose-response relationships for clodinafop-propargyl on *Avena* spp. *Weed Research*. 41:351 - 368.
- Mendham, D., D. White, M. Battaglia, J.F. McGrath, T.M. Short, G.N. Ogden and J. Kinal 2011. Soil water depletion and recharge during first- and early second-rotation *E. globulus* plantations with deep soil profiles. *Agricultural and Forest Meteorology*. In press
- Mendham, D., D.A. White, M. Battaglia, J. Kinal, S.N. Walker, S. Rance, J.F. McGrath and S. Abou Arra 2007. Managing the trade-off between productivity and risk in the bluegum plantations of south-western Australia. CSIRO, Canberra.
- Morgan, F.D. 1989. Forty years of *Sirex noctilio* and *Ips grandicollis* in Australia. *New Zealand Journal of Forest Science*. 19:198 - 209.
- Nambiar, E.K.S. 1984. Critical processes in forest nutrition and their importance for management. *In* Research for forest managers Eds. W. Parsons and J. J. Landsberg. CSIRO, Canberra.
- Neilsen, W.A. and A.M. Gerard 1999. Growth and branching habit of *Eucalyptus nitens* at different spacings and the effect on final crop selection. *Forest Ecology and Management*. 123:217 - 229.
- Neilsen, W.A. and E.A. Pinkard 2002. Appropriate pruning regimes for *Pinus radiata*. Forestry Tasmania Technical Report 05/2002, Hobart, Australia, p. 16 p.
- Nicholls, J.W.P. 1982. Wind action, leaning trees and compression wood in *Pinus radiata* D. Don. *Australian Forest Research*. 12:75 - 91.
- Nicholls, N. 2008. Australian climate and weather extremes: past, present and future. Department of Climate Change, Canberra, p. 26.
- Nicholls, N. and C. Lucas 2007. Interannual variations of area burnt in Tasmanian bushfires: relationships with climate and predictability. *International Journal of Wildland Fire*. 16:540 - 546.
- Norby, R.J., P.J. Hanson, E.G. O'Neill, T.J. Tschaplinski, J.F. Weltzin, R.A. Hansen, W.X. Cheng, S.D. Wullschleger, C.A. Gunderson, N.T. Edwards and D.W. Johnson 2002. Net primary productivity of a CO<sub>2</sub>-enriched deciduous forest and the implications for carbon storage. *Ecological Applications*. 12:1261-1266.
- Norby, R.J., S.D. Wullschleger, C.A. Gunderson, D.W. Johnson and R. Ceulemans 1999. Tree responses to rising CO<sub>2</sub> in field experiments: implications for the future forest. *Plant Cell and Environment*. 22:683-714.
- O'Hehir, J.F. and E.K.S. Nambiar 2010. Productivity of three successive rotations of *P. radiata* plantations in South Australia over a century. *Forest Ecology and Management*. 259:1857 - 1869.
- Ögren, E. 1994. The significance of photoinhibition for photosynthetic productivity. *In* Photoinhibition of photosynthesis Eds. N.R. Baker and J.R. Boyer. Bios Scientific Publishers, Oxford, pp. 433-447.



- Ögren, E. and J.R. Evans 1992. Photoinhibition of photosynthesis in situ in six species of *Eucalyptus*. Australian Journal of Plant Physiology. 19:223 - 232.
- Ohmart, C.P. and P.B. Edwards 1991. Insect herbivory on *Eucalyptus*. Annual Review of Entomology. 36:637 - 657.
- Old, K.M. and C. Stone 2005. Vulnerability of Australian Forest Carbon Sinks to Pests and Pathogens in a Changing Climate. Australian Greenhouse Office, Canberra, p. 52 p.
- Oren, R., D.S. Ellsworth, K.H. Johnsen, N. Phillips, B.E. Ewers, C. Maier, K.V.R. Schafer, H. McCarthy, G. Hendrey, S.G. McNulty and G.G. Katul 2001. Soil fertility limits carbon sequestration by forest ecosystems in a CO<sub>2</sub>-enriched atmosphere. Nature. 411:469-472.
- Park, R.F. 1988. Epidemiology of *Mycosphaerella nubilosa* and *M. Cryptica* on *Eucalyptus* spp. in south-eastern Australia. Transcript of the British Mycological Society. 91:261 - 266.
- Paul, K.I. and P.J. Polglase 2004. Prediction of decomposition of litter under eucalypts and pines using the FullCAM model. Forest Ecology and Management. 191:73-92.
- Pinkard, E., A. Eyles and A.P. O'Grady 2011. Are gas-exchange responses to resource limitation and defoliation linked to source:sink relationships? Plant, Cell & Environment. In press
- Pinkard, E., D.J. Kriticos, T. Wardlaw, A. Carnegie and A. Leriche 2010a. Estimating the spatio-temporal risk of disease epidemics using a bioclimatic niche model. Ecological Modelling. 221:2828 - 2838.
- Pinkard, E.A., C.C. Baillie, V. Patel, M. Battaglia, P.J. Smethurst, C. Mohammed, T. Wardlaw and C. Stone 2006a. Growth responses of *Eucalyptus globulus* Labill. to nitrogen application and severity, pattern and frequency of artificial defoliation. Forest Ecology and Management. 229:378 - 387.
- Pinkard, E.A., C.C. Baillie, V. Patel and C.L. Mohammed 2006b. Effects of fertilising with nitrogen and phosphorus on growth and crown condition of *Eucalyptus globulus* Labill. experiencing insect defoliation. Forest Ecology and Management. 231:131 - 137.
- Pinkard, E.A., M. Battaglia, D.J. Kriticos, C.L. Mohammed, T.N. Wharton, A. Leriche, J. Bruce and K. Paul 2008. Climate change and Australia's plantation estate: pest impacts on carbon stores. CSIRO, p. 155.
- Pinkard, E.A., D.J. Kriticos and K. Potter 2010b. Implications of climate change for Australia's plantation forests: weeds, insects and fungal pests. CSIRO, 28 p.
- Pitman, A.J., G.T. Narisma and J. McAneney 2007. The impact of climate change on the risk of forest and grassland fires in Australia. Climate Change. 84:383 - 401.
- Pittock, B., D. Wratt, R.E. Basher, B.C. Bates, M. Finlayson, H. Gitay and A. Woodward 2001. Australia and New Zealand. In IPCC working group II, Third assessment report Eds. J.J. MacCarty, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White. Cambridge University Press, Cambridge, UK, pp. 591 - 639.
- Pook, E.W. and R.I. Forrester 1984. Factors influencing dieback of drought-affected dry sclerophyll forest tree species. Australian Forest Research. 14:201 - 217.
- Qiao, Y.-Z., Y.-B. Zhang, K.-Y. Wang, Q. Wang and Q.-Z. Tian 2008. Growth and wood/bark properties of *Abies faxoniana* seedlings as affected by elevated CO<sub>2</sub>. Journal of Integrative Plant Biology. 50:265 - 270.
- Raison, J., P.K. Khanna, M.L. Benson, B.J. Myers, R. McMurtie and A.R.G. Lang 1992a. Dynamics of *Pinus radiata* foliage in relation to water and nitrogen stress: II. Needle loss and temporal changes in total foliage mass. Forest Ecology and Management. 52:159 - 178.

- Raison, J., B.J. Myers and M.L. Benson 1992b. Dynamics of *Pinus radiata* foliage in relation to water and nitrogen stress: I. Needle production and properties. *Forest Ecology and Management*. 52:139 - 158.
- Rapley, L.P., B.M. Potts, M. Battaglia, V.S. Patel and G.R. Allen 2009. Long-term realised and projected growth impacts caused by autumn gum moth defoliation of 2-year-old *Eucalyptus nitens* plantation trees in Tasmania, Australia. *Forest Ecology and Management*. 258:1896-1903.
- Richardson, W. 2010. Current Forestry SA best practice plantation establishment weed control in the Green Triangle Region of South Australia and Western Victoria. *In* Integrating our resources. Australian Forest Growers, Mount Gambier, South Australia.
- Roberts, G., J. Parrotta and A. Wreford 2009. Management for adaptation.
- Seppala, R., A. Buck and P. Katila 2009. Adaptation of forests and people to climate change - a global assessment report. *In* IUFRO world series volume 22 Ed. IUFRO. IUFRO, Helsinki, p. 244
- Smith, A., E. Pinkard, G. Hunter, M.J. Wingfield and C. Mohammed 2006. Anatomical variation and defence responses of juvenile *Eucalyptus nitens* leaves to *Mycosphaerella* leaf disease. *Australasian Plant Pathology*. 35:725 - 731.
- Spittlehouse, D.L. 2005. Integrating climate change adaptation into forest management. *The Forestry Chronicle*. 81:691 - 695.
- Spittlehouse, D.L. and R.B. Stewart 2003. Adaptation to climate change in forest management. *BC Journal of Ecosystems and Management*. 4
- Steffen, W. 2009. Climate change 2009. Faster change and more serious risks. Department of Climate Change, Canberra, Australia, p. 52.
- Steinbauer, M.J. 2001. Specific leaf weight as an indicator of juvenile leaf toughness in Tasmanian bluegum (*Eucalyptus globulus* ssp. *globulus*): implications for insect defoliation. *Australian Forestry*. 64:32 - 37.
- Sutherst, R.W. 2003. Prediction of species geographical ranges (Guest editorial). *Journal of Biogeography*. 30:805 - 816.
- Sutton, W.R.J. and J.B. Crowe 1975. Selective pruning of radiata pine. *New Zealand Journal of Forest Science*. 5:171 - 195.
- Thomas, D.S. 2008. Hydrogel applied to the root plug of subtropical eucalypt seedlings halves transplant death following planting. *Forest Ecology and Management*. 255:1305 - 1314.
- Thomas, D.S. 2009. Survival and growth of drought hardened *Eucalyptus pilularis* Sm. seedlings and vegetative cuttings. *New Forests*. 38:245-259.
- Thompson, W.A. and A.M. Wheeler 1992. Photosynthesis by mature needles of field-grown *Pinus radiata*. *Forest Ecology and Management*. 52:225 - 242.
- Tissue, D.T., K.L. Griffin, M.H. Turnbull and D. Whitehead 2001. Canopy position and needle age affect photosynthetic response in field-grown *Pinus radiata* after five years of exposure to elevated carbon dioxide partial pressure. *Tree Physiology*. 21:12-13
- Turnbull, M.H., D.T. Tissue, K.L. Griffin, G.N.D. Rodgers and D. Whitehead 1998. Photosynthetic acclimation to long-term exposure to elevated CO<sub>2</sub> concentration in *Pinus radiata* D. Don. is related to age of needles. *Plant, Cell & Environment*. 21:1019 - 1028.
- Wardlaw, T. 2001. *Mycosphaerella* leaf blight of *Eucalyptus globulus* in the Circular Head area. *Forestry Tasmania*, Hobart, p. 13 p.
- Wardlaw, T., E.A. Pinkard and C. Mohammed 2005. Can fertilisation with nitrogen and phosphorus lessen impacts of *Mycosphaerella* leaf blight in *Eucalyptus globulus*? *In* 15th Australasian Plant Pathology Society Conference, *Mycosphaerella* leaf

- diseases of eucalypts workshop Ed. A. Carnegie. Australasian Plant Pathology Society, Geelong, Australia, p. p 22.
- Wardlaw, T.J. and D. Bashford 2007. The effectiveness of thinning eucalypts in reducing losses from stem-boring insects and fungal rots. *In* Borers and rots in Eucalypts. Commercial management issues. IFA - WA Division, Western Australia.
- Watt, M.S., G.M. Downes, D. Whitehead, E.G. Mason, B. Richardson, J.C. Grace and J.R. Moore 2005. Wood properties of juvenile *Pinus radiata* growing in the presence and absence of competing understorey vegetation at a dryland site. *Trees*. 19
- Wharton, T.N. and D.J. Kriticos 2004. The fundamental and realized niche of the Monterey Pine aphid, *Esigella californica* (Essig) (Hemiptera: Aphididae): implications for managing softwood plantations in Australia. *Biodiversity and Distributions*. 10:253 - 262.
- Whetton, P.H. 2007. Climate change in Australia. CSIRO, Canberra.
- White, D., D.S. Crombie, J. Kinal, M. Battaglia, J.F. McGrath, D. Mendham and S.N. Walker 2009. Managing productivity and drought risk in *Eucalyptus globulus* plantations in south-western Australia. *Forest Ecology and Management*. 259:33 - 44.
- Whittaker, J.B. 2001. Insects and plants in a changing atmosphere. *Journal of Ecology*. 89:507-518.
- Williams, A.L., K. E. Wills, et al. (2007). Warming and free-air CO<sub>2</sub> enrichment alter demographics in four co-occurring grassland species. *New Phytologist*: 365-374.
- Wilson, R. and S. Turton 2010. An assessment of the vulnerability of Australian forests to the impacts of climate change. IV. Climate change adaptation options, tools and vulnerability Ed. N.C.C.A.R. Facility, p. 119.
- Wimmer, R., G.M. Downes and R. Evans 2002. Temporal variation of microfibril angle in *Eucalyptus nitens* grown in different irrigation regimes. *Tree Physiology*. 22:449 - 457.
- Wimmer, R., G.M. Downes, R. Evans and J. French 2008. Effects of site on fibre, kraft pulp and handsheet properties of *Eucalyptus globulus*. *Annals of Forest Science*. 65
- Woldendorp, G., M.J. Hill and M.C. Ball 2008. Frost in a future climate: modelling interactive effects of warmer temperatures and rising atmospheric [CO<sub>2</sub>] on the incidence and severity of frost damage in a temperate evergreen (*Eucalyptus pauciflora*). *Global Change Biology*. 14:294 - 308.
- Wood, M.J., R. Scott, P.W. Volker and D.J. Mannes 2008. Windthrow in Tasmania, Australia: monitoring, prediction and management. *Forestry*. 81:415 - 427.
- Yazaki, K., Y. Maruyama, S. Mori, T. Koike and R. Funada 2005. Effects of elevated carbon dioxide concentration on wood structure and formation in trees. *In* 6th International symposium on plant responses to air pollution and global change Eds. K. Omasa, I. Nouchi and L.J. DeKok, Tsukuba, Japan, pp. 89 - 97.
- Ziska, L.H., S. Faulkner and J. Lydon 2004. Changes in biomass and root:shoot ratio of field-grown Canadian thistle, a noxious, invasive weed, with elevated CO<sub>2</sub>: implications for control with glyphosate. *Weed Science*. 52:584 - 588.
- Ziska, L.H. and J.R. Teasdale 2000. Sustained growth and increased tolerance to glyphosate observed in a C-3 perennia weed, quackgrass (*Elytrigia repens*), grown at elevated carbon dioxide. *Australian Journal of Plant Physiology*. 27:159 - 166.