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ARTICLE

Climate change and Australian production forests: impacts and adaptation

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ABSTRACT
Australia has a highly diverse and variable climate and its forests evolved under a relatively high level of climatic variation. However, human-induced changes in climate are likely to exceed historical ranges of variability and rates of change, and have effects on forests well beyond the experience of forest managers. These conditions will require implementation of management practices appropriate to a changing climate. This paper provides an overview of the potential changes in climate in key forest-growing regions; current knowledge of the impacts of climate change on Australian forests, forest industries and forest-dependent communities; adaptation options; and approaches to potential climate change challenges. Developments in understanding are considered, and information gaps, research needs and policy changes required to support adaptation are discussed. In order to adapt well to a rapidly changing climate, forest managers will need to better understand how global climate change will impact on the local environment where their resources, assets and people are located, and consider their key vulnerabilities and how climate might affect their wider supply chains, inputs, customers and competitors. Improved monitoring can provide clear signals of change. New tools are required that integrate climate scenarios into organisational and business planning. Industry leaders will need to encourage experimentation, adopt greater flexibility in raw material supply sources, in species and genetic selection, and in plantation and native forest management practices, and have strategies in place to adapt quickly during periods of rapid change.

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Introduction

The forest sector encompasses forest-growing; forest-related natural resource management; the production, marketing and use of non-wood forest products and services; forest-contact industries (such as ecotourism and national park management); and wood harvesting, processing, manufacture, marketing and use (MPIGA 2013). The forest and wood products sector makes an important contribution to Australia's national economy. Financial turnover in this industry sector was $19 billion in 2005–2006. There has been strong growth in log harvest and wood product output in recent years. Non-wood forest products, such as honey and oils, also make considerable contributions to the Australian economy. Services provided by forests, such as carbon sequestration, regulation of water flow and maintenance of water quality are also highly valued by society. Total direct employment in forest-based industries was estimated to be 83 400 FTEs (full-time equivalent employees) and total national employment in businesses dependent on growing and using wood was estimated to be 120 000 FTEs, with significant employment in rural regional areas (MPIG 2013).

Australian forest ecosystems may be particularly vulnerable to climate change. A quarter of Australia's eucalypt species occur over a range of annual mean temperature of less than 1°C, and half of all native species occur over temperature ranges of less than 3°C (Hughes et al. 1996). With temperature changes to the end of the century potentially exceeding these ranges (depending on the outcomes of global greenhouse gas emissions objectives), the most suitable growing conditions for half of Australia's eucalypt species could potentially be outside the geographic range that they occupy today, although there is considerable evidence that many species can tolerate conditions somewhat different from those experienced within their natural distributions (Booth et al. 2015). There is also relatively limited understanding of the interactions between the different aspects of climate change and their effects on forests, forest ecosystem processes and forest-dependent industries and communities. This paper aims to provide an overview of the potential changes in climate in key forest-growing regions; current knowledge of the impacts of climate change on Australian forests, forest industries and forest-dependent communities; adaptation options and approaches; and information gaps and research needs.

Australian forest resources

Australia has 125 M ha of forest (16% of the land area), comprising 123 M ha of native forests, 2.02 M ha of industrial plantations, and 0.15 M ha of other forests (MPIG 2013). Native forests are dominated by eucalypts (92 M ha) and acacia forests (9.8 M ha). An estimated 81.9 M ha (66.8%) of native forest is under private management on freehold or long-term leasehold land and a portion of this is under the ownership or management of Indigenous communities. An estimated 21.5 M ha of Australia's native forest (17.5%) is in formal nature conservation reserves and 39 M ha (32%) is designated as protected for biodiversity conservation. An estimated 36.6 M ha of native forest was both available and suitable for commercial wood production in 2010–2011, comprising 7.5 M ha of multiple-use public

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forests and 29.1 M ha of leasehold and private forests (MPIG 2013). Average sawlog harvest yields from multiple-use public native forests declined by 47% between 1992–1996 and 2006–2011. This was a consequence of increased forest reservation, increased restrictions on harvesting in codes of forest practice, revised estimates of forest growth and yield, and the impacts of broad-scale wildfires (MPIG 2013).

There has been a major loss of forest area since European settlement due to the conversion of forest for agricultural land uses and urban development. More recently, forest area has fluctuated. Forests continue to be converted through human activities. Forest cover changes are also driven by natural dynamics associated with cycles of drought and regrowth during wetter periods and with fire loss and recover. In the 2000s there was an estimated net loss of forest area from 2005–2010 of 1.4 M ha, involving a decrease of 1.8 M ha in 2005–2008 due to fires and drought, followed by an increase of 0.4 M ha in 2009–2010 due to forest recovery from these disturbances (MPIG 2013).

Production forestry is dominated by a limited number of mainly large companies or government agency producers and processors, with some products, such as sawn or finished timber, mostly consumed domestically while others, such as woodchips, are mostly exported. Industrial plantations comprise 1.03 M ha of softwood and 0.98 M ha of hardwood species and these supply about 80% of wood to industry. Ownership of trees in the industrial plantation estate changed significantly between 2005 and 2011. Of the total industrial plantation estate, the area proportion where the trees are government-owned decreased from 35% in 2006 to 24% in 2011, while the proportion where the trees are privately owned increased from 65% to 76% (MPIG 2013). There has been little expansion of softwood plantations for more than 20 years and little new planting of hardwoods since the demise of forestry Managed Investment Scheme companies in the late 2000s. Considerable areas of hardwood plantation are being harvested but not replanted and instead converted back to agriculture (AFPA 2016).

Forestry sector sales and service income declined in the period between 2010 and 2014 but is now growing strongly, increasing by from $20.1 billion to $22.2 billion (11%) between 2013–2014 and 2014–2015 (ABARES 2016). In the financial year 2015–2016, logs harvested exceeded 30 M m^3 for the first time, representing a 10% increase from the 2014–2015 log harvest. The gross value of log production also reached a record high in 2015–2016, exceeding $2.3 billion, an increase of 12% from 2014–2015, due to growth in plantation log harvests and higher log prices (ABARES 2017).

Australia is a net importer of wood and wood products in dollar terms, although exports are increasing at a faster rate than imports with increases in the volume and value of woodchip and roundwood exports. Export woodchips (mostly hardwood) were valued at $1.1 billion and roundwood (mostly softwood) valued at $0.44 billion in 2015–2016. Nearly all roundwood and the majority of woodchips are exported to China, although Japan, a long-term importer of Australian woodchips, still receives a considerable proportion. Other products exported are paper, paperboard and recovered paper to China, New Zealand and a number of other countries. The value of imports also increased in 2015–2016, primarily due to growth in paper and paperboard, miscellaneous forest products, paper manufactures and wood-based panels. Despite the increased value of exports, the trade deficit in wood products increased slightly from $1.93 billion in 2010–2011 to $2.4 billion in 2015–2016 (ABARES 2016).

Climate change in Australia

Production forestry occurs mostly in south-east Queensland and southern Australia. These forests have been exposed to a high degree of historical climate variability (Hughes et al. 1996) with extreme episodic events, such as droughts and floods, and periodic high temperatures. In the south-east and south-west, very hot dry northerly winds and associated wildfires have important impacts on forest resources. The latest data (CSIRO & BOM 2016) show that Australia's mean surface air temperature has warmed by around 1°C since 1910 and the duration, frequency and intensity of extreme heat events have increased across large parts of Australia. Since the 1970s there has been an increase in extreme fire weather and a longer fire season. May–July rainfall has reduced by around 19% since 1970 in the south-west of Australia, and there has been a decline of around 11% in rainfall in the April–October growing season in the continental south-east since the mid-1990s. Rainfall has increased across parts of northern Australia since the 1970s. In plantation regions, the highest temperatures ever recorded for North West Tasmania, Green Triangle, Central Tablelands and Murray Valley have all occurred in the last ten years (mostly in 2009), and key plantation growing areas have experienced their worst or near-worst droughts on record in the last decade, and their highest or near-highest extreme forest fire danger index (GHD 2011).

These changes are at least partly attributable to increased atmospheric greenhouse gas concentrations. Projections indicate a strengthening of these trends (CSIRO & BOM 2016), including continued declines in late autumn and winter rainfall in the south (Fiddes & Pezza 2015) and shifts in rainfall patterns with increased summer rainfall events, greater rainfall intensity and increased localised flooding. Increased temperatures and extended droughts are likely to increase the number of days with high fire danger and increase the frequency and/or intensity of wildfires, although this will depend on fuel loads, future wind patterns and topography (Clarke et al. 2013). Regional variation in climate projections is important in planning for, and managing, the future impacts of climate change (CSIRO 2017).

While current and near-term future warming and other climate shifts are locked into the climate system from past greenhouse gas emissions, the extent of longer term changes will depend on efforts to reduce greenhouse gas emissions. Under the 2015 Paris Agreement, almost all signatories to the UN Framework Convention on Climate Change agreed to adopt aggregate emission pathways consistent with holding the increase in the global average temperature to well below 2°C above pre-industrial levels, and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels (UNFCCC 2015). However, current national commitments to reduce greenhouse gas emissions are well below those required to reach these levels.

Forest vulnerability to climate change

Vulnerability of forest ecosystems to climate change is a function of exposure, sensitivity and adaptive capacity. The exposure of forests will depend on future levels of greenhouse gas emissions, and the effects of greenhouse gases on the global climate system and how these are expressed at a local level. There is considerable uncertainty in all these aspects of climate change (Wilby & Dessai 2010) and uncertainty in how species and ecosystems will respond (Herr et al. 2016). The information presented in the previous section indicates the kind of changes to which forests will be exposed.

Sensitivity of forests to climate change

Sensitivity to climate change will vary with individual organisms, species, plant and animal communities, and forest ecosystems. Changes in climate will also induce indirect effects, such as exposure to fire, introduced species, and diseases that will impact on forests (Boulter 2012; Keenan 2015). Direct effects include increased atmospheric CO_2, rising temperatures, changes in rainfall and changes in fire regimes. Increased atmospheric CO_2 may increase productivity through increased water-use efficiency and could increase drought tolerance. However, it is likely that water and nutrient availability will limit productivity increases, particularly when combined with higher temperatures (Franks et al. 2013). The effect of rising temperature will depend on whether the current temperature range of a species is above or below its optimal temperature, and its capacity to acclimatise. Eucalypt species may generally be located close to their temperature optima and rising temperatures may result in an overall decline in growth (Bowman et al. 2014). Reduced frosts may impact on capacity to regenerate in those species requiring cold temperature-induced dormancy for germination (Mok et al. 2012), but as the number of frost days diminishes this may allow other, less cold-tolerant species to occupy sites that were previously not suitable. The impact of changing rainfall patterns will depend on the duration of longer periods of below-average rainfall, the drought tolerance of individual species, and the capacity of species and ecosystems to respond and take up increased available water where rainfall increases.

Changes in climate conditions will alter phenological processes, such as flowering, fruiting (Beaumont et al. 2015; Rawal et al. 2015a, 2015b) and seed set, and other important life-cycle events, such as germination and early growth. These effects will flow on to species interactions and ecosystem functions. Changes in species abundance (Rawal et al. 2015a) or distribution may be mediated through changes in fire regimes (Enright et al. 2015; Fairman et al. 2015), and conditions may cross major tipping points and drive significant change in ecosystem composition and functioning (Adams 2013). In a study of future fuel load and fire weather using projections from a range of climate models and emission scenarios, Clarke et al. (2013) projected that the amount of mean annual fine litter is projected to increase under future climate change by 1.2 to 1.7 t ha^{-1} in temperate areas and 0.7 to 1.1 t ha^{-1} in subtropical areas, with the largest increases in fuel load and fire weather projected to occur in spring. Changes in annual cumulative Forest Fire Danger Index ratings varied from 57 to 550 in temperate areas, to −231 to 907 in subtropical areas. These results suggest that there is high uncertainty in future fire weather conditions.

Limited knowledge on pest and host responses in eucalypts restricts the reliability of assessment of future impact of insects and diseases on native eucalypt forests (Booth et al. 2015). However, if insects move more rapidly to a new environment while tree species lag, some parts of the tree distribution may be impacted less in future (Regniere 2009).

Species range shifts are most likely to be southerly or to higher elevations. For some species this may represent an expansion of range, for others a reduction (Boulter 2012). Native forest communities are likely to experience local extinctions and the introduction of new species and higher potential for introduced species (including diseases, weeds and pests with expanded ranges) that are likely to result in changes to forest structure and disruption of biotic processes.

The capacity of native forests to adapt to climate change will be constrained by rates of evolutionary change, contractions of suitable habitat, limited capacity to migrate due to habitat fragmentation and limited dispersal capacity of many species, and increased likelihood of extreme events that will test recovery capacity (Boulter 2012).

In general, the forests requiring changing management are those with the greatest sensitivity to and most exposed to existing stresses such as storms, repeated fires or heavy grazing, and those with the highest exposure to extreme events (Table 1).

The forests of the Brigalow Belt and the Mediterranean Woodlands, have highly fragmented and limited remaining distributions. From a conservation perspective, these were identified as being at greatest risk among the forest vegetation types in Australia. The Cold Forest and Grasslands region and the Subtropical Moist Forests region have unique biodiversity, cool-climate-dependent species and remnant or limited distributions and are also vulnerable to climate change.

Over 80% of Australian wood supply to industry now comes from forest plantations. Plantations in the Mediterranean Woodlands region (SW Western Australia, Green Triangle and the Murray Valley plantation regions) are considered most vulnerable (Boulter 2012). Battaglia et al. (2009) found that, without a significant benefit to production from higher levels of atmospheric CO_2, growth in these regions will decrease. This will be significant, particularly with the impacts of increased hot and dry days—either directly through damage or death, or indirectly through pest attack. On the other hand, in higher latitude regions with more consistent rainfall, productivity may increase, particularly if plantation species are able to maintain increased net photosynthetic rates under elevated CO_2. These impacts may be exacerbated by potential increases in the impacts of insect pests and diseases under climate change (Pinkard et al. 2010). Other examples of potentially sensitive forests include recently established plantations intended to be managed over long rotations, particularly on marginally dry sites in the south (Boulter 2012).

In a study of fire risk in plantation areas (GHD 2011), reductions in annual rainfall are predicted to be significantly more likely than increases in annual rainfall in most plantation regions. In combination with increased temperature and evaporation, with reduced seasonal rainfall in winter and/or spring, this will result in earlier starts to the fire season. Key regions (the Green Triangle, Murray Valley, Central Tablelands and south-east Queensland) are projected to

Table 1. Forest regions in Australia, potential climate changes, and impacts on forests

Forest region	Future climatic changes	Impacts on forests
Tropical regions	Increased atmospheric CO_2 Increased temperature Increased storm and cyclone intensity Increased dry-season fire risks Increased flooding Coastal inundation	Potential increased forest productivity on sites with better soils More introduced species (both weed and tropical native species) Loss of animal and plant biodiversity at higher elevations New species, storm and increased fire risks affecting ecosystem functioning
Temperate sub-humid woodlands	Increased atmospheric CO_2 Increased temperature Changes in rainfall pattern Decreased frost Increased fire risks	Potential increased forest productivity on sites with better soils Changes in species distribution Exacerbation of forest degradation with continued threats such as land clearing, weed invasions or feral animals
Subtropical moist forests	Increased atmospheric CO_2 Increased temperature Changes in rainfall pattern in the south, with longer dry season and more extended drought	Potential increased forest productivity on sites with better soils Drought, fire and weed potential will increase Loss or change of character of high-value biodiversity sites
Temperate moist forests	Increased atmospheric CO_2 Increased temperature Changes in rainfall pattern in the south, with longer dry season and more extended drought	On sites with lower rainfall, reduced rain and increased year-to-year variability could reduce growth. Fewer frosts could impact on regeneration of some species but allow establishment of less cold-tolerant species.
Cold forests at higher altitudes	Increased atmospheric CO_2 Increased temperature Changes in rainfall pattern in the south, with longer dry season and more extended drought	Increased plant water stress in summer High risk of loss of high-altitude species with reduced snow cover Altered distributions of other species
Mediterranean woodlands	Increased atmospheric CO_2 Increased temperature Changes in rainfall pattern with longer dry season and more extended drought More rain in summer storms More frosts Increased fire risks, although fuel loads may be reduced	Likely reduced growth At a local scale, warmer temperatures, higher CO_2 and the availability of groundwater may advantage some species Increased drought mortality

Sources: Boulter (2012), Mok et al. (2012)

experience a significant increase in the occurrence of Very High to Extreme bushfire danger days, which are strongly correlated historically with large plantation fire loss events. Tasmania is projected to experience minor changes in this risk factor.

Sensitivity of people and communities in rural and regional Australia

People and communities that are dependent on forests and forest resources are also vulnerable to climate change. While there is a high degree of exposure to changing climate, there is generally considerable capacity to adapt in Australian society (Garnaut 2008). Australia has a diverse and well-developed economy, extensive scientific knowledge, disaster mitigation and management arrangements, capacity to practise sustainable forest management, and tight biosecurity procedures. However, the adaptive capacity within communities where the local economy is highly dependent on forests is less well understood.

There are two broad approaches to understanding adaptive capacity: through 'top-down' studies and 'bottom-up' approaches (Engle 2011). Top-down approaches seek to measure the level of adaptive capacity using secondary statistical data about a suite of factors considered to influence or reflect adaptive capacity, for example demographic information such as age distribution, or economic factors such as income distribution or dependence on single crops that are sensitive to climate or market fluctuations (Nelson, Kokic, Crimp, Martin, et al. 2010; Nelson, Kokic, Crimp, Meinke, et al. 2010). Those applying bottom-up approaches adopt more sociologically oriented investigations of the complex array of factors that affect the perceived and actual capacity of different stakeholders to adapt to diverse pressures (Head et al. 2011; Leith 2011). While considerable research has been published about components of and contributors to adaptive capacity, very little research has examined the adaptive capacity of Australia's primary industry sector, and there has been little analysis of adaptive capacity in the forestry sector (ABARES 2011). Thus, while adaptive capacity remains an important factor for climate change adaptation policy and other decision-making, there remain fundamental knowledge requirements for the concept to be applied effectively and with confidence to different primary industry sectors (Barlow et al. 2013).

In a study of the potential impacts of climate change on forests and forestry (ABARES 2011), it was concluded that projected declines in log supply associated with reduced plantation productivity may result in reduced investment in harvesting, haulage and log-processing capacity and could lead to reductions in the value of production and levels of employment. Communities with a greater dependence on plantation forests in Mediterranean or subtropical regions are potentially most vulnerable due the projected decrease in wood flow from these forests compared to native forests. Seventeen of 73 communities assessed across the six forest regions exhibit high to very high vulnerability, even in the absence of climate change. Communities with a greater dependence on employment in the growing, managing and harvesting of native forests and plantations are potentially more vulnerable than those dependent on processing industries, as the latter may get wood from other sources—although this is likely to increase their cost of supply. Climate change is also just one form of rapid change affecting these communities and industries. Market changes, import competition, demographic and political change have all placed considerable demands on forest-dependent communities in the last 20–30 years.

The interactions between people, economic change and climate impacts on natural resources are also important. For example, in their study of bushfire risks and climate change GHD (2011) identified three regions (Murray Valley, Green Triangle and south-west Western Australia) where rural population decline will present problems for recruitment of industry staff and volunteer bushfire brigades. This may be further exacerbated if climate change reduces the economic viability of family farm enterprises. The proximity of the plantations to large urban population growth centres in the Central Tablelands (NSW) and south-east Queensland means that they are likely to be adjacent to more 'tree-change' subdivision and absentee owners. These factors will increase woody and grassy vegetation cover and fire ignition potential and make hazard reduction more difficult, all increasing fire management challenges. Declining profitability in the plantation sector might lead to reduced expenditure on protection (e.g. for fire trail and fire break maintenance, hazard reduction works, silvicultural works, and firefighting workforce and equipment) and therefore declining fire suppression capacity.

Adaptation options

How might forest managers adapt to climate change? In broad terms, adaptation options can be anticipatory or reactive, and either planned or autonomous (Prowse & Scott 2008). They can aim to build resistance to change (e.g. to protect rare, high-value species in a specific location, or a plantation forest that is close to rotation age), or to promote resilience to enable forests to respond to future change while maintaining or providing for the recovery of important ecological processes (Millar et al. 2007).

Boulter (2012) suggests that adaptation strategies will be different for different stakeholders, such as:

- production forest growers and managers
- farmers and landowners growing trees for timber production, shelter or amenity values
- organisations growing trees for non-production purposes such as carbon sequestration, biodiversity or water quality
- wood product processors and those in the forest products value chain
- communities that depend on forest resources for their livelihoods and wellbeing.

For forest managers and landowners, adaptation actions in forest management can be grouped into broader land management options, site-specific silvicultural practices, building social and community skills, and policy and planning options (Table 2).

Rickards et al. (2012) note a shift from prescriptive adaptation options to identifying management principles from which locally specific options can be generated. These options include factors contributing to system resilience, such as redundancy, flexibility and cross-scale awareness. Adaptation currently practiced in primary industries often reflects what is considered currently to be good risk-management practice (Stokes & Howden 2010; Keenan & Nitschke 2016). This approach is likely to be effective under moderate climate change (Dovers 2009) but could limit planning for transformational changes (Smith et al. 2011) or the provision of pathways for adaptation options under more extreme levels of climate change as these emerge in future (Howden et al. 2007; Barnett et al. 2014; Wise et al. 2014). Adaptation planning needs to shift from simply projecting impacts to evaluating adaptation options. Primary industry and natural resource management research and development have generated valuable outputs but these need to be integrated and communicated to support institutional capacity for long-term strategic planning (Barlow et al. 2013). Limits and barriers to adaptation in Australia's forests include the physical limits of key species to future change, knowledge gaps, existing market requirements and social perceptions (Boulter 2012).

Knowledge needs

In Australia, despite some recent improvement in the information base for plantation forest managers (Stephens et al. 2012), the knowledge base on impacts and analysis of adaptation requirements for native forests is relatively poor (Wood et al. 2011). In terms of scientific knowledge, there are relatively few recent publications concerned with adaptive capacity in the production forestry sector (Barlow et al. 2013). This section provides a brief review of identified knowledge needs and how well they have been satisfied by recent research investments.

The Federal Government invested \$3.6 M in research aimed to develop information that would allow the commercial forest sector, forest planners and managers, and forestry-dependent communities to better adapt to climate change (Department of Agriculture and Water 2017). This included projects on:

- potential effects of climate change on forest and forestry
- an Australian Forest Productivity and Merchantability Database
- forestry adaptation and sequestration alliance
- amplified climate change plantation bushfire risk
- genetic resources moving with climate change
- climate adaptation strategies to manage drought risk and mortality in existing and new plantation forest in Australia
- the Hawkesbury Forest Experiment: providing the missing information for decision-support systems to manage forests under rising CO_2 and global warming
- forest biosecurity and preparedness for climate change
- prioritising uncertainties in resource flow dynamics for Australian timber industries.

This investment is relatively modest compared to other primary industry sectors and it is not clear that the results of these projects have been widely communicated to the intended users.

In the primary industries sectors more broadly, there has been considerable research on incremental or adjustment-level adaptation, but less about systems-level and

Table 2. Examples of adaptation options in forest management

Adaptation options	Activities
Land management options	• Increased investment in monitoring of forest condition and functioning • Early detection and management of insect pests, diseases and invasive species • Improved selection of land with appropriate growing conditions for timber production under current and future conditions • Trialing new species and genetic varieties • Changing timing and frequency of planned fire to reduce fuel loads; introducing more fire-tolerant tree species • Managing fire risks through monitoring and reducing fuel loads, reducing ignition sources and maintaining access and response capacity
Site-level silvicultural practices	• Nursery regimes to increase drought- and frost-hardiness • Delayed establishment to increase water recharge • Increasing species and genetic diversity in forest stands • Identifying species and genetic varieties that are more suitable for tolerating longer droughts or increased storm events • Increased weed control • Reduced planting densities and earlier or more intensive thinning to reduce water demands • Relaxing seed zone rules in native forests for aerial seeding or replanting, to allow more seed exchange • Using more measures to conserve water and prevent soil erosion in areas likely to experience higher-intensity rainfall events
Social and community actions	• Enhancing community awareness of climate change impacts and variability • Building partnerships for regional cooperation with other natural resource management bodies • Creating a greater capacity to pool limited resources • Making more use of indigenous or local knowledge in forest management
Facilitators of adaptation at planning and policy levels	• Mechanisms for integrated assessment that facilitate interaction and planning between government agencies and related industry sectors such as agriculture, transport and construction • Increased flexibility in decision-making based on improved understanding of the impacts of different climate-related events such as floods, intense storms or extreme temperatures on forests, infrastructure and production assets

Sources: Boulter (2012); Pinkard et al. (2015)

transformational adaptation, or about how decision makers could understand the relative costs and benefits of these different options. Analysis of the potential benefits, costs and risks of incremental versus systems change or transformational changes needs to be integrated into management processes (Pinkard et al. 2015). Timing is also critical—deciding when to change, and what climate signals drive that decision, are critical issues for agriculture, forest and aquaculture managers (Barlow et al. 2013).

Integration of climate projections into planning tools

A number of tools currently in use by forest managers can be used to assess adaptation options, including software for modelling and analysis of specific silviculture practices, but these will need to be modified to consider new species or planting configurations, and the incorporation of risk assessment and management tools (Coles & Scott 2009). Improvements are required in climate projections (Hochman et al. 2013) and the integration of these projections in planning tools.

Improved understanding of vulnerability in forest ecosystems

While there is improved general evidence of the vulnerability of native and plantation forest ecosystems to climate change and factors limiting species distributions (such as extreme climatic events or other correlated factors such as the incidence of fire), more detailed studies are required to identify species or ecological communities at greatest risk and appropriate risk management options to minimise the potential adverse effects of climatic changes.

Understanding long-term patterns of growth in response to changes in temperature and rainfall has been considered an important component of our knowledge of ecosystem responses to climate change. There has been a long history of observation of forest growth in a range of different forest types across Australia. Analysis of these data have provided important insights into historical growth responses that can be a guide to future responses (Bowman et al. 2014). Potential risks from climate change in major production forest regions are now increasingly understood, with improved capacity to translate regional-level predictions to forest-stand management responses (Battaglia et al. 2009; Pinkard et al. 2010, 2015).

Investment in natural resource management planning has provided risk and vulnerability assessments of the impact of climate change on forest growth, regeneration and mortality. There is a need to translate these assessments into impacts on timber supply, carbon sequestration, vegetation composition, wildlife populations, soil processes, hydrology and water yield, and include assessment of changing fire frequency and intensity on forest ecosystems.

There has been significant improvement in understanding of how increased atmospheric CO_2 might impact on the forest growth through Free Air Carbon Dioxide Enrichment (FACE) studies (Crous et al. 2013; Quentin et al. 2015; Duursma et al. 2016; Ellsworth et al. 2017) and more broadly (Franks et al. 2013). The evidence suggests that nutrients (particularly phosphorus) may limit capacity of eucalypts to take advantage of higher levels of CO_2 through increased growth. Further research is required to integrate this scientific knowledge for the forest sector (Ainsworth 2016).

While there has been considerable discussion of possibilities of translocation of species to assist adaptation, in Australia and elsewhere (Spittlehouse 2005; Corlett & Westcott 2013), the appropriate situations in which to implement assisted migration of species to new habitats that may become suitable under changed climatic conditions are still poorly understood (Doley 2010; Weeks et al. 2011).

Effective monitoring to determine risk occurrence

There has been some improvement in capacity to monitor and assess forest condition in some parts of Australia (Haywood, Mellor, et al. 2016), although monitoring of other potential risks in some regions, such as mapping of the spread of myrtle rust (*Puccinia psidii*), has ceased as a result of funding cuts and staff losses. National investment and improved coordination across states and research organisations are supporting capacity to detect emergence of key risks such as declining tree health, insect pests or disease outbreaks, reduced water availability and changing fire regimes (TERN 2017).

Improved monitoring can facilitate the implementation of alternative management options to address key risks. Remote sensing tools will play an increasingly important role in adaptive management, and significantly reduce the costs of forest monitoring. Remote sensing can be used to assess land cover change, temperature, soil moisture and physiological responses, changes in pest, disease and fire impacts, drought stress and mortality, and wildlife habitat conditions (McDermid et al. 2009; Stone et al. 2012; Yang et al. 2013; Haywood, Verbesselt, et al. 2016). However, a combination of ground plot information and remote sensing will be most effective in detecting shifts in species distribution (Fei et al. 2017). Hydrological monitoring can be used to analyse the interaction of alternative forest management options, including timber harvesting and the use of prescribed fire, and impacts of climate change on water yield and quality.

Analytical tools

Diagnostic tools and techniques are required to determine when and where to apply specific management interventions that can assist tree survival, water efficiency, pest management and other hazards. For example, assessing the impacts of climate change on forests and water resources will require calibrated and tested process-based models and other landscape-level analytical tools to explore likely changes in water use by important forest types (including plantations) in key regions. There is also a need for better understanding of forests currently under marginal water supply to assess the impact of future climate scenarios on vegetation productivity and water availability in these regions (e.g. Mitchell et al. 2014). These tools can be used to determine the impact of management responses (such as thinning and fertility management, on stand survival and growth, and evaluate alternative species that may be suitable for next-generation plantations under future climates.

Understanding forest fire risks and management responses

There has been an improvement in the understanding of fire risks and how they are projected to change under future climate scenarios. Improved climate change scenarios are supporting assessment of the extent to which climate change alters the risk of bushfires in different regions of Australia. There is ongoing debate about appropriate management options (such as fuel reduction burning) to reduce bushfire risks to forests, plantations, biodiversity and the community under changed climatic conditions (Adams 2013; Bowman et al. 2013; Burrows & McCaw 2013; King et al. 2013; Bradstock et al. 2014). Resolving these debates will require a combination of fire science, forest ecology and social research (Sharples et al. 2016).

Understanding socioeconomic impacts

Adaptation in primary industries needs to take account of a range of social, economic and environmental factors that operate at the individual, community, regional, state, national and international levels. In addition to understanding the range of potential future climate conditions, adaptation policies need to identify and define the roles and responsibilities of various actors (landholders, managers, industry and government) in responding to potential opportunities or managing future risks (Barlow et al. 2013).

There have been a few studies on the socioeconomic impacts of climate change on forests (Keating et al. 2013). Further work is required on the effects of climate change on yields of forest products, the effects on global markets, regional economic impacts, gender and indigenous dimensions, forest employment and forest access (including recreation), and the impact of changing social values of forests. There is also relatively limited information about other factors affecting the effectiveness of adaptation options, such as lost work time, costs for training, price of products and financial risks (Barlow et al. 2013).

In order to prioritise responses to climate change impacts, land managers and policy makers will need to assess the costs and benefits of adaptation actions (Boulter 2012), such as traditional industry values (timber and tourism), new industry values (carbon sequestration), and non-market values. The overall benefits of investing in adaptation may be positive. However, analyses are complicated by uncertainty about when and where the impacts will be felt, and how the costs, benefits and risks associated with climate change impacts, and related adaptation actions, will be distributed among public institutions and private actors (Hotte et al. 2016).

The processing sector will have particular risks associated with infrastructure, such as roads, bridges, power and sawmill sites and processing facilities, with the latter being significant users of natural resources (e.g. water use by pulp and paper mills). Understanding the impacts of extreme weather events on forest sector businesses, including production, storage, transport, use and export, is still poor. There is also a need to improve knowledge of the adaptive capacity in the sector, the key factors that affect adaptive capacity, and how measures to increase adaptive capacity can be communicated more widely.

Other climate change policy responses have the potential to substantially change the global supply of timber. For example, wide implementation of the REDD+ (Reduced Emissions from Deforestation and Forest Degradation) mechanism could lead to reduced harvesting. On the other hand, carbon mitigation policies may result in increased investment in new forests, with potential to increase future timber supplies, depending on the types of forests planted and their management. A key component of adapting to climate change for forest managers will be considering the impacts of global climate change policies on markets for the various products that arise from forests. Policy makers will need to understand potential synergies between the role of forests in climate change adaptation and mitigation, and avoid potential perverse outcomes.

Improved decision-making capacity

Further research is required on the information, knowledge, tools, management skills, programs and policies that are necessary for forest producers and industries to identify the range of potential climate change adaptation responses, understand their benefits and costs and the risks and opportunities associated with these responses, and measure the effectiveness of adaptation. Further research is also required on how these can be communicated to support effective adaptation.

Individual companies will need to consider the potential impacts of climate change on their staff, their supply chains and their customer base, some of which may be in locations well-removed from the company's operations (Young & Jones 2013). While there has been considerable focus on climate change mitigation in forest policy, there is little explicit reference to climate change adaptation requirements in forest policy.

Key stakeholders and decision-makers will have different roles and responsibilities in adaptation. Analysis of industry structures and leadership arrangements can lead to new strategies and management approaches to improve adaptive capacity. By giving managers a fuller understanding of the benefits and costs of adaptation options (including potential financial risks), they will be better placed to decide on the appropriateness of different options.

Management skills to handle uncertainty and complexity will be a critical element of effective decision-making for adaptation in the forest sector. The introduction of more flexible regulations is also important. These can provide for potential shifts in species distributions, support species translocation, and allow local managers to experiment with and test new species combinations or forest management options. Certification schemes may be a useful pathway to introduce some of these concepts into forest management decisions.

Policies to support 'climate-smart' forest management frameworks (Nitschke & Innes 2008) can provide an improved basis for managing forested landscapes and maintaining ecosystem health and vitality (Nitschke & Innes 2008; Keenan 2015). Policies to adapt to climate change will increasingly need to facilitate management across tenures and across agencies. Managers will need to create 'learning organisations', gathering a greater diversity of inputs into decision-making, and avoiding creating rigid organisational hierarchies that deter innovation (Joyce et al. 2009; Konkin & Hopkins 2009; Peterson et al. 2011). Like the forest managers of the past that were tasked with implementing change in an uncertain future (Summerfield & Keenan 2017), this will require vision, creativity, collaboration and persistence. Forest policy makers will need to ensure that sufficient resources are available to test and implement new approaches to forest management, and build public support for these new approaches.

Australian forest managers are facing multiple challenges. Increased population and global wealth are driving increased demand for forest products. Plantations are supplying an increasing proportion of wood supply. However, there has been virtually no new softwood plantation establishment in Australia since the 1990s and the area of plantation hardwoods is declining (AFPA 2016). It is unclear where new investment in plantations will come from, or the geographic focus for new investment. Changing global markets are increasing competition, including from imports, and from new suppliers of wood in export markets. Technological change is driving development of new products and new ways of managing and using natural resources. Demographic trends in rural Australia will mean changes to the nature and availability of workers. Climate and other environmental changes will need to be considered in the context of this broader environment.

In considering options for adaptation to climate change, forest managers will need to (Fig. 1):

(1) better understand how global climate change will impact on the local environment where their resources, assets and people are located, and consider their key vulnerabilities
(2) better understand how change might affect their wider supply chains, inputs, customers and competitors
(3) integrate climate scenarios into organisational and business planning tools

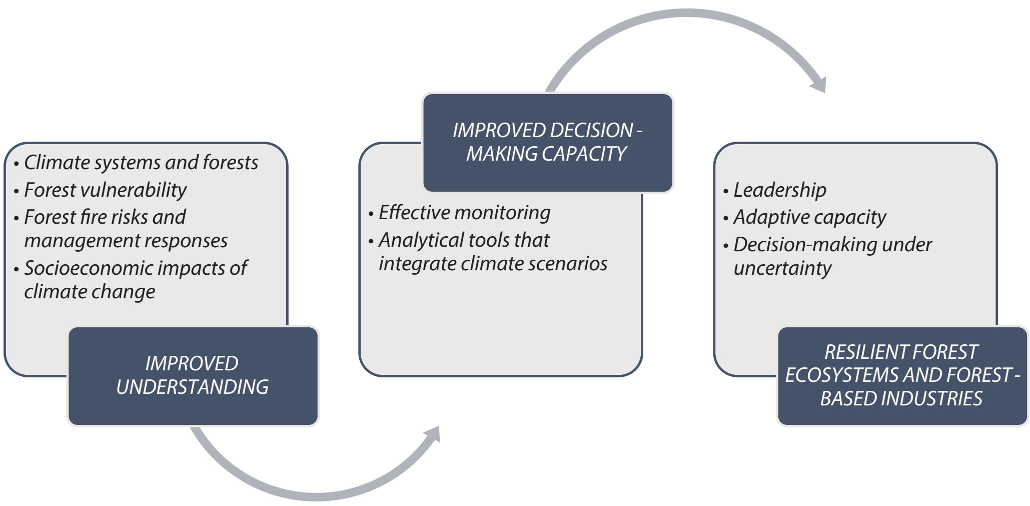

Figure 1. Knowledge needs and decision-making for adaptation to climate change

(4) encourage experimentation and flexibility in raw material supply sources, species and genetic selection, and plantation and native forest management practices
(5) be more open to signals of change, and have strategies in place to adapt quickly during periods of rapid change.

Conclusions

Forest managers will face multiple challenges in a rapidly changing climate. This analysis indicates that a range of production forest types, industries and local economies are sensitive and vulnerable to climate change. While there are broader signals in legislation and regulation, there has been relatively little policy development to support adaptation in the production forest sector. Forest management is an inherently conservative activity, and policy makers and managers are reluctant to implement rapid changes that might undermine existing industries or communities. The measures that have been introduced to date have focused on the provision of tools and information, but there is a need to facilitate wider adoption and better integration of these into current decision processes. In order to be 'adapting well' to a changing climate (sensu Tompkins et al. 2010), the forest and wood products industry needs appropriate information, tools and expertise. The interactions of adapting to climate change, and climate change mitigation through expanding forest area, increasing growth and productivity and increasing the use of wood products, should also be considered. Policy and management should aim to minimise risks and take advantage of opportunities presented by a changing climate.

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