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Title:
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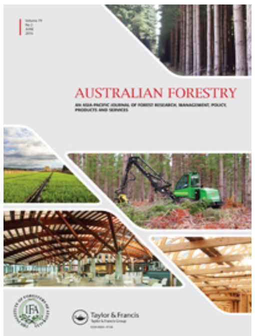
Date:
2016-04-02

Citation:
Keenan, R. J. & Nitschke, C. (2016). Forest management options for adaptation to climate change: a case study of tall, wet eucalypt forests in Victoria’s Central Highlands region. Australian Forestry, 79 (2), pp.96-107. https://doi.org/10.1080/00049158.2015.1130095.

Persistent Link:
https://hdl.handle.net/11343/113696



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Australian Forestry

ISSN: 0004-9158 (Print) 2325-6087 (Online) Journal homepage: http://www.tandfonline.com/loi/tfor20

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To cite this article: Rodney J. Keenan & Craig Nitschke (2016) Forest management options for adaptation to climate change: a case study of tall, wet eucalypt forests in Victoria's Central Highlands region, Australian Forestry, 79:2, 96-107, DOI: 10.1080/00049158.2015.1130095

To link to this article: http://dx.doi.org/10.1080/00049158.2015.1130095

AUSTRALIAN FORESTRY, 2016
VOL. 79, NO. 2, 96–107
http://dx.doi.org/10.1080/00049158.2015.1130095

Forest management options for adaptation to climate change: a case study of tall, wet eucalypt forests in Victoria's Central Highlands region

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ABSTRACT

Australia has a highly diverse and variable climate and its forests are well-adapted to climatic variation. However, human-induced changes in climate could exceed historical ranges of variability 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 but there has been little analysis of potential management options for Australian native forests. The paper analyses potential management options for the tall, wet eucalypt forests in Victoria's Central Highlands. This region has already experienced a strong drying and warming trend and a high incidence of severe bushfires over the last 15 years. Future changes are likely to include rising CO_2, increasing temperatures and an overall decrease and changing seasonal patterns in rainfall. This is likely to result in higher fire danger weather conditions, changes in phenology of flowering, seeding and germination and shifts in forest composition and productivity. A range of different management options were considered and analysed in terms of current practice, costs and implementation feasibility. Many management actions identified to support adaptation to climate change were assessed as currently being implemented as part of sustainable forest management arrangements. Options that are not generally currently implemented include developing gene management programs and off-site gene banks, *ex-situ* conservation and increasing cooperation in species management, increasing stand and regional species diversity, identification and deployment of more drought- or disturbance-tolerant species or genotypes, planning to reduce disease losses through monitoring and sanitation harvests, managing stand structure to reduce impacts on water availability and implementing silvicultural techniques to promote stand vigour, as practised elsewhere in Australia. The likelihood of more intense rainfall events will require changes to infrastructure, such as forest road design and construction specifications. Implementing adaptation will require new approaches to forest management, potentially involving significant human intervention, new ecological, environmental and social research, new modes of communication with the public, new policies and revised regulations and management prescriptions.

ARTICLE HISTORY
Received 22 January 2015
Accepted 11 November 2015

KEYWORDS
Forests; climate; impact; adaptation; management; change

Introduction

Climate change presents new challenges for forest managers that may require future forest management that is very different to that of the past (Nitschke and Innes 2008; Innes 2009; Keenan 2012, 2015). The tall, wet forests of south-eastern Australia are valued by society for a wide range of benefits and services that are potentially at risk in a changing climate. These forests have been exposed to a high degree of historical climate variability largely driven by conditions in the three oceans surrounding the Australian continent, in particular the El Niño – Southern Oscillation (ENSO) in the Pacific, the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM) in the Southern Ocean (CSIRO and BOM 2012). The region is characterised by high inter-annual and inter-decadal variability in rainfall and the occurrence of extreme episodic events such as droughts and floods, periodic high temperatures, very hot dry northerly winds and associated wildfires that are important in many ecosystem processes. Recent events include the worst drought on instrumental record subsequently broken by Australia's wettest two-year period on record (CSIRO and BOM 2012). These changes are at least partly attributable to increased atmospheric greenhouse gas concentrations. Australia has experienced an increase in average temperature of 0.7°C since the 1950s and projections indicate a further 0.8–2.8°C increase by 2050 (CSIRO and BOM 2012), accompanied by continued below-average late autumn and winter rainfall (Fiddes and Pezza 2015) and potentially increased extent and intensity of drought, punctuated by more infrequent but intense rainfall events particularly in summer months associated with extreme La Niña events (Cai *et al*. 2015; Fiddes *et al*. 2015).

Potential impacts of climate change on forest ecosystems can be either direct or indirect and operate over shorter or longer time cycles (Keenan 2015). Evidence for the effects of a changing climate on trees and forests can come from different sources, including paleo-climatic, phytological, phenological or physiological studies; current observation; and bioclimatic or physiological modelling (Hughes 2011). Although the restricted geographical ranges of many eucalypt species suggest that they might have narrow climatic amplitudes (Hughes *et al*. 1996), evidence from plantings of these species around the world suggests that many have the capacity to adapt to a wider range of climatic conditions than their limited natural ranges suggest (Booth 2013). Paleo-climatic evidence indicates that all tree species or species groups in Australia today persisted through the last glacial–interglacial transition 20 000 to 12 000 years ago,

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generally through expansion from small, multiple, localised refugia (see, for example, Nevill *et al*. 2010). However, habitat loss or modification over 200 years of European settlement mean that these refugia may no longer be present in current landscapes due to land clearing or changed fire regimes, increasing future extinction risks (Steffen *et al*. 2009). Recent evidence also indicates changes to flowering and phenology in eucalypt and other native species in response to climate change (Beaumont *et al*. 2015; Rawal *et al*. 2015a, 2015b).

While there is a range of analytical tools available for assessing the impacts of climate change on native forest species, many factors and interactions must be taken into account to provide robust assessments of species sensitivity to climate change (Booth *et al*. 2015). For example, many of the impacts of a changing future climate on forests are likely to be felt through changing disturbance regimes. In this region, changes in the abundance of species (Rawal *et al*. 2015a) or distribution of ecosystems 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). Effects of climate change on fire regimes can vary between regions. For example, Bradstock *et al*. (2014) found a significant divergence in response (in terms of area burnt) to recent changes in climate in different regions of south-eastern Australia. Long periods of fire exclusion and suppression have also increased fuel loads in different forest types and these have led to increasing fire intensity and more challenges for controlling fires under severe conditions (Williams 2004, 2013).

In future, increased temperature 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). In south-eastern Australia, frequencies of days with very high or extreme FFDI ratings are likely to increase by 4–25 % by 2020 and 15–70 % by 2050 and there is likely to be higher fire-weather risk in spring, summer and autumn that will shift periods suitable for prescribed burning toward winter (Hennessy *et al*. 2005). Somewhat counter-intuitively, in a global analysis of Mediterranean ecosystems, Batllori *et al*. (2013) suggested that warmer and drier conditions may decrease the probability of intense fires in some areas but warmer and wetter conditions may cause them to increase due to the interaction between climate and fuel loads.

Biotic factors may be more important than direct climate effects on tree populations in a changing climate. Insects and diseases have much shorter generation length and are able to adapt to new climatic conditions more rapidly than trees (Regniere 2009). Currently limited knowledge on pest and host responses in eucalypts exists to predict with any reliability the 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 affected less in future (Regniere 2009). The interaction of pests, diseases and fire will also be important (Loehman *et al*. 2011) as will the interaction of pests, heat and drought (Matusick *et al*. 2013). For example Kirschbaum *et al*. (2007) found a drought-induced attack by *Cardiaspina* spp. insects on *E. delegatensis* led to significant tree mortality and reduction in net primary production.

Much of the scientific literature related to climate impacts and adaptation in forests is still heavily focused on assessing potential impacts or the vulnerability of individual species, with less analysis of adaptation options (Keenan 2015). Adaptation options can be anticipatory or reactive, and either planned or autonomous (Prowse and Scott 2008). They can aim to build resistance to change (for example, 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). 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).

Forest managers have often implicitly assumed that historical climate variability is incorporated in empirically derived growth models and into silviculture and management prescriptions. Current management practices are therefore considered more or less adapted to the present climate. ‘Fine tuning’ current management may be sufficient to meet objectives with small changes in climate but in the longer term it is likely that incremental change will be insufficient to avoid significant consequences from changing climate conditions. Adaptation will require deliberate, conscious and explicit policy, regulatory or management responses (Schipper 2007) to facilitate the transformational change required to adapt to a very different climatic future (Stafford Smith *et al*. 2011; Rickards 2013). In native forest management, incremental responses might include adjustment to silvicultural systems—such as more partial harvesting or thinning. Transformative options might include large-scale changes in species composition, planning for production of very different product types or moving to a different mix of products and services.

Designing adaptation options for forest management also needs to consider other environmental and social changes. Increasing population is increasing the demand for forest products, technology is changing the types of forest products and the way they are processed and used, and expanding urban areas are increasing the interface between urban populations and forests in high-fire-risk regions, resulting in greater impacts of wildfire on human populations, infrastructure and assets (Williams 2004).

The values and benefits provided by the forest ecosystems of the Central Highlands Region (CHR) of Victoria are potentially at risk of climate change but there has been little analysis of the management approaches for reducing risk. The aim of this paper is to explore the potential impacts, vulnerabilities and adaptation options for the forests in this region. We adopted a ‘structured decision making’ approach (Ogden and Innes 2009), which involves (i) consideration of the long-term management objectives for the forest, (ii) determining the vulnerability of forest ecosystems, economies and associated human communities, (iii) developing alternative management options for adaptation and (iv) evaluating these options against objectives. Implementing these options needs to be considered as part of an adaptive management approach involving monitoring effectiveness and modifying practices in the light of results. The options development and evaluation process presented here is relatively rudimentary and this study demonstrates a potential approach rather than a definitive and extensive analysis of management options, which should necessarily be undertaken in close consultation with forest managers and other stakeholders.

Methods

Case study area

The Central Highlands Region (CHR) in Victoria contains about 626 000 ha of public land under various management tenures: state forests comprise 62% of the area (including the timber production zone, 33%), national parks and reserves 30% and other public land 7% (DNRE 1998). The forests in this region have a long history of human use and disturbance, initially by indigenous peoples, whose impact on forests was primarily through the use of fire, and later by European settlers, through conversion to agriculture and timber harvesting, grazing native forests and removal of indigenous people and their burning practices. Provision of water and recreation were important values as the forests were brought under active state management in the early 1900s. Timber production became more intensive during the second half of the 20th century, with extensive harvesting of native forests for timber and development of associated industries to use residual wood in papermaking or woodchip exports. More recently, biodiversity conservation and recreation have become the dominant forms of land use with about 70% of the land base under some form of conservation tenure and management prescriptions providing for the protection of threatened species and habitat for the remaining area.

Elevation ranges from 75 to 1600 m above sea level and annual rainfall ranges between 600 and 2000 mm and mean annual temperature between 5.4 and 14.2°C. The region comprises 10 major ecosystems, known as ecological vegetation classes (EVCs), primarily dominated by eucalypts (*Eucalyptus* spp.): (1) Heathy Dry Forest, (2) Shrubby Dry Forest, (3) Lowland Forest, (4) Herb-Rich Foothill, (5) Damp Forest, (6) Wet Forest, (7) Montane Wet Forest, (8) Montane Damp Forest, (9) Cool Temperate Rainforest and (10) Subalpine Woodland (DNRE 1998).

In the ash forests available for timber production, the traditional method of silviculture has been to clearfell, burn and sow, in which all or most (>95%) merchantable trees are felled, the site is burnt to prepare a seed bed and eucalypt seed is sown from the air to facilitate regeneration. There has been testing of alternative silvicultural approaches (Florence 1996; Lindenmayer 2009; Ryan 2013). These are now being implemented more widely, with retention harvesting on 50% of all ash sites being adopted as part of the response strategy for conservation of Leadbeater's possum (LPAG 2014).

Fire has been a dominant disturbance agent in the region. The historical fire regime in the region was characterised by infrequent severe wildfires occurring in late summer. In the wet forest types regeneration following fire is almost entirely through seedling establishment. Fires stimulate seedfall from burnt mature trees and clear the understorey and litter to provide for germination and establishment. Wildfires often kill the overstorey trees and when the interval between stand-replacing disturbances is less than 20–30 years, stands of obligate-seeder-dominated species (e.g. *E. regnans* and *E. delegatensis*) can be replaced by other species, particularly wattle (*Acacia* spp.). The area burned in the South Eastern Highland and Australian Alps bioregions has increased since 1975 due to decline in rainfall in the former and an increase in maximum temperature in the latter (Bradstock *et al*. 2014). About 50% of the 8.6 million ha of forest area burned between 1962 and 2014 across Victoria has occurred since 2003 (Fairman *et al*. 2015). Over 2.6 million ha of forest (including 189 000 ha of ash forest) was killed or severely damaged by three major bushfires in 2003, 2006–07 and 2009 (Fagg *et al*. 2013). Following the 2013 wildfires in the Australian Alps bioregion an estimated 45 000 ha of forest dominated by obligate seeders and over 300 000 ha of resprouter-dominated forests were burned twice within a 10-year period (Fairman *et al*. 2015). Though there was a high level of natural regeneration of eucalypts following the 2003 and 2009 fires, supplementary seeding across all tenures ensured eucalypt regeneration following the 2006–07 'Great Divide' fires and again following the 2013 'Harrietville' fires (Fagg *et al*. 2013; Bassett *et al*. 2015). Taylor *et al*. (2014) found that fire severity was higher in 7–36 year old stands than in stands younger or older than this in an *E. regnans* forest burnt in the February 2009 fires.

Following the catastrophic fires of 2009, the Victorian Government implemented measures to increase the extent of hazard reduction burning to reduce fuel loads and fire intensity. In the CHR region, the practice occurs in the drier mixed eucalypt species forests to reduce fuel loads in the areas adjacent to ash-dominated moist forests or closed forests where planned burning is largely excluded (DEPI 2014a).

For the public forests in the CHR, management goals are broadly defined as meeting conservation commitments, to provide recreation opportunities and clean water to local, regional and metropolitan communities, to meet sustainable yield timber production requirements and sawlog and pulpwood licence commitments for local sawmills and pulpmills and to provide employment and economic benefits (DNRE 1998). Public forests are governed through a comprehensive legal and regulatory framework (Hickey and Citroen 2007) guided by the Montreal Process Criteria and Indicators of Sustainable Forest Management under the *Sustainable Forest and Timber Act 2004*.

Climate change impacts

There have been few studies of the potential impacts of climate change on forests in the region (Mackey *et al*. 2002). More recently, Mok *et al*. (2012) used a mechanistic model incorporating germination processes to evaluate establishment probabilities of five key eucalypt species, *E. pauciflora, E. delegatensis, E. regnans, E. nitens* and *E. obliqua*, under a range of future climate scenarios. Their study provided estimates of changes to regeneration potential at landscape and site levels that were used to determine climate thresholds beyond which there might be significant shifts in vegetation composition.

With changing fire regimes potentially important in driving vegetation change in the region, we assessed the potential impact of climate change on future fire risk across the CHR, following the methods of Nitschke and Innes (2013). Assessment was based on the following 11 weather station locations: Coldstream (37.72°S; 145.41°E; 83 m), Noojee (37.90°S; 145.97°E; 275 m), Tanjil Bren (37.80°S; 146.20°E; 838 m), Mount Baw Baw (37.84°S; 146.27°E; 1561 m), Healsville (37.68°S; 145.53°E; 131 m), Mount St Leonard (37.57°S; 145.50°E; 595 m), Alexandra (37.19°S; 145.71°E; 221 m), Lake Eildon (37.23°S; 145.91°E; 230 m), Eildon Fire Tower (37.21°S; 145.84°E; 637 m), Rubicon (37.34°S; 145.85°E; 838 m) and Woods Point (37.57°S; 146.25°E; 680 m). Using the climate scenarios from Mok *et al.* (2012), changes in Fire Weather Index were used to assess the effect on frequency of forest age classes for representative forest types at the Tanjil Bren (37.80°S; 146.20°E; 838 m); Rubicon (37.34°S; 145.85°E; 838 m) and Mount St Leonard (37.57°S; 145.50°E; 595 m) weather stations.

Potential adaptation options

In a global analysis of adaptation in forest management, Innes (2009) identified 155 potential adaptation options. These were grouped into the Montreal Process criteria that are used for assessing sustainable forest management in Victoria. In this study, reflecting the management objectives for the region, we focused on options to conserve forest biodiversity (Criterion 1), Maintenance of productive capacity of forest ecosystems (Criterion 2), Maintenance of forest ecosystem health (Criterion 3), conservation and maintenance of soil and water resources (Criterion 4) and socio-economic benefits (Criterion 6), considering only strategic options. Where a management option could address a number of criteria, it was listed in the criterion where it was considered to provide the greatest benefit.

Options were tabulated and ranked against three criteria: relevance to this region, current practice and operational feasibility. Current practice was rated as currently implemented (yes or no). Feasibility was rated as high, medium or low based on ecological or economic feasibility of the practice. An action was rated high feasibility if the authors considered that current scientific knowledge to implement the practice was adequate and it could be done at little additional cost. If one of these conditions was not satisfied (either more research is required or there were considerable costs involved, either for direct implementation or loss of timber production or other revenue generation) then it was rated as medium. If both conditions were not satisfied feasibility was rated as low.

Results

Climate change impacts

Results from the work of Mok *et al.* (2012) indicated that climate change is likely to affect regeneration potential of forest tree species. There are potential increases and decreases in regeneration potential depending on the species and the EVC, indicating that some species will increase in abundance in some vegetation classes, whilst other forest types will become unsuitable for the regeneration of those species. In general, the dry forest EVCs were most affected and the wet forests were least affected. Species with cool temperature seed dormancy mechanisms, like *E. pauciflora* and *E. delegatensis*, are likely to be at higher risk than those that do not have such requirements for regeneration. Landscape- and site-level analysis revealed heterogeneity in species response at different scales. Analysis of key thresholds indicated that a temperature increase of 2.6°C and 15% decline in precipitation (conditions predicted for 2050) may result in local-level shifts in vegetation, with considerable declines in regeneration potential for *E. delegatensis, E. pauciflora* and *E. nitens*. A mean temperature increase of 4.3°C and 22% decline in precipitation (conditions under the high end of emissions scenarios for 2080) was a threshold for large spatial, landscape-scale shifts in species regeneration niches across the study region.

Analysis of fire weather indicated a significant shift towards more frequent high- to extreme-fire weather by 2080 under the high emission scenario (Fig. 1). If the fire-return interval drops from 100 years to 50 years, the proportion of wet eucalypt forests in the region in older age classes would drop significantly (Fig. 2).

Forest management adaption options

Ninety-five of 135 management options were identified in the analysis as being relevant to the region and applicable to native forest management. Twenty-one options were aimed at conserving biodiversity of forest ecosystem, 16 options for maintaining productivity capacity, 15 for health and vitality, 8 for protecting soil and water values, 19 for maintaining economic benefits from forests, 7 focused on maintaining socio-economic benefits and 9 for maintaining forest contributions to the global carbon cycle. Fifty-five of these 95 management options could be considered current practice. Of the 40 that are not currently implemented, 22 could be

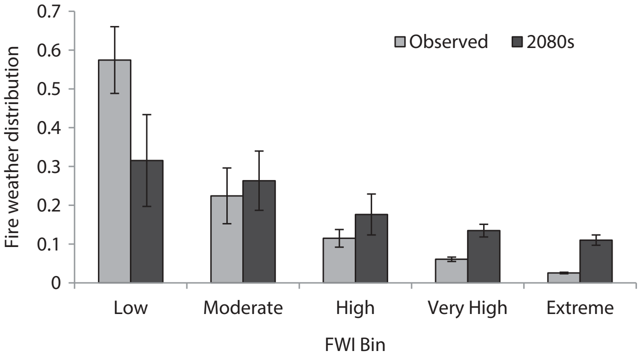

Figure 1. Distribution of daily fire weather observations classified into Fire Weather Index (FWI) classes for the Central Highlands Region of Victoria. Error bars represent the standard error of the proportion.

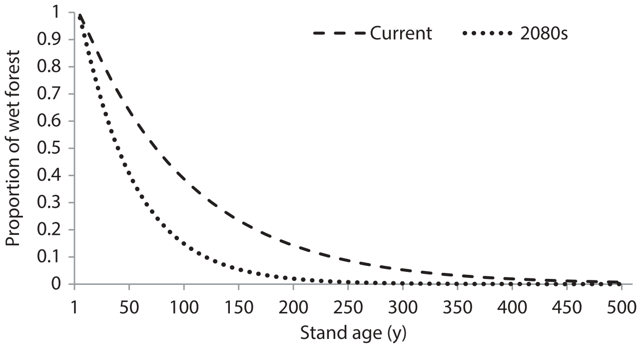

Figure 2. Potential impact of climate change on the distribution of stand ages in wet eucalypt forests in the Central Highlands region of Victoria due to a change in the fire return interval.

relatively easily implemented based on current research at low cost. There were three options that needed significant research, more analysis, major expenditure and are unlikely to be implemented unless there is major public education or other changes in policy settings. Examples of different options are presented in Table 1. These are outlined further in this section.

Adaptation options for conserving forest biodiversity

Options considered current practice to provide for forest biodiversity conservation under a changing climate included minimising habitat fragmentation and maintaining connectivity, protecting representative forest types and protecting remaining primary forests in conservation reserves, identifying and protecting climate refugia through landscape analysis, fire protection and controlling invasive species. Increasing the size of reserves or allowing more dynamic reserve boundaries may provide some further conservation protection in a changing climate. This is happening in part of the region under plans to protect Leadbeater's possum (LPAG 2014). However, land tenure arrangements need to give consideration to the potential requirements for more active intervention to achieve desired management goals.

Management options for forest biodiversity conservation that are not generally being implemented and needing investment, either in new knowledge or investment of funds to make them happen, include developing gene management programs and off-site gene banks and assisted translocation of species at risk. In some cases, measures might include protecting highly threatened or rare species in ex-situ situations, as is being done with orchid species in Western Australia (Swarts and Dixon 2009). This will require a greater focus on managing across land tenures and increasing regional cooperation in species management for biodiversity conservation.

Adaptation options for maintaining productive capacity of forest ecosystems

Forest management options to maintain productive capacity under a changing climate identified by Innes (2009) and that are currently being implemented in the region include ensuring effective regeneration following harvesting and disturbance, maintaining seed banks (in soil, on trees or ex-situ) and salvage harvesting of fire-killed timber. Regeneration following harvesting and disturbance has not always been successful and there is a considerable area that is not fully stocked with eucalypts (VAGO 2013).

Management options that are not yet implemented for maintaining forest productivity include identification and deployment of more drought- or disturbance-tolerant species or genotypes. This will require selection, testing and breeding programs. More broadly, adaptation will require design and establishment of long-term, multi-species and seedlot trials to test genotypes across a diverse array of climatic and latitudinal environments. *In situ* monitoring of reproduction and regeneration should be strengthened to identify areas where facilitated migration and or translocations of populations from drier to wetter/warmer to cooler environments should occur to eventually provide a source of pre-adapted alleles into populations of concern through gene flow as suggested by Aitken *et al*. (2008). For important species, population response curves to climate should be

Table 1. Management options for adaptation to climate change for forests in the Central Highlands Region of Victoria. Options selected from those identified in the study of Innes (2009). Options considered relevant to the region and currently being implemented or could be implemented with limited investment.

Montreal Process criteria	Adaptation options currently being implemented	Adaptation options needing limited investment
Biodiversity conservation	Minimise habitat fragmentation and maintain connectivity Protect representative forest types in reserves Increase reserve size Protect primary forests Protect climate refugia More dynamic reserve boundaries More structural complexity to increase habitat value Identify and protect functional groups and keystone species	Protect highly threatened or rare species ex-situ Develop a gene management program and off-site gene banks Increase regional cooperation in species management
Productive capacity	Ensure effective regeneration Maintain seed banks (in soil, trees or ex-situ) Investigate alternatives to clearfelling Reduce disease losses through sanitation harvests Salvage harvesting	Thinning to reduce water stress Use more drought- or disturbance-tolerant species or genotypes Silvicultural techniques to promote stand vigour Implement alternatives to clearfelling
Forest health	Manage fire risks Increase prescribed burning Monitor and manage pests and disease Landscape-level targets for age-class	Reducing losses due to insects and diseases through sanitation harvests Implement silvicultural techniques to promote stand vigour
Soil and water	Implement and maintain stream buffers Maintain/decommission roads to minimise sediment run-off Minimise soil disturbance during harvest	Change road design and construction specifications to anticipate changing climatic conditions Thinning to reduce impacts on water availability
Socio-economic benefits	Diversify local and regional economies	Include climate risk management in planning Consider alternative supply arrangements in the case of short-term logistical disruption or longer-term loss of production Anticipate and plan for changes in wood properties or species Increase awareness and enhance dialogue with stakeholders on climate adaptation Integrate local community knowledge of past and current changes into management plans

developed and used to select appropriate provenances for reforestation and tree growth monitored for longer-term suitability (Aitken *et al*. 2008).

Transferring genotypes to new regions will require revision of rules governing the movement of seed stocks from one area to another and examining options for modifying seed transfer limits and systems (Potter and Hargrove 2012). For example, the government of British Columbia, Canada is implementing modified seed transfer guidelines for *Larix occidentalis* following the research by Rehfeldt and Jaquish (2010).

Alternative silvicultural practices to clearfelling that increase stand structural diversity and capacity for natural regeneration are being investigated (Ryan 2013) and more widely adopted as part of mammal conservation strategies. More research is needed to explore the benefits of retention harvesting and thinning for increasing forest resilience, regeneration and productive capacity.

Adaptation options to maintain forest health

Adaptation options that are generally underway that focus on maintaining forest health include managing fire risks, increasing prescribed burning, monitoring and managing of forest pests and diseases, and setting appropriate landscape-level targets for forest age-class distributions.

Management options that are not yet being implemented include reducing losses due to insects and diseases through sanitation harvests and implementing silvicultural techniques to promote stand vigour, as has been done elsewhere (Whitehead *et al*. 2004). Older regrowth *E. regnans* stands may be particularly susceptible to a combination of drought stress and disease impacts (Wardlaw 1990) and thinning may support improved resilience to disease in these forest types.

Adaptation options for maintaining soil and water resources

Current management practices that can support adaptation and that are aimed at protecting soil and water values included implementing and maintaining stream buffers (although these may reduce streamflow in low-rainfall periods), maintaining or decommissioning roads to minimise sediment run-off, minimising soil disturbance during harvest and thinning to reduce stand water use.

Managing stand structure to increase water availability is likely to be more important in future climates. As forests are an important mediator in the water supply to major cities, forest water use has been extensively studied in this region (Langford 1976; Vertessy *et al*. 2001), including thinning regrowth to increase water yield (Jayasuriya *et al*. 1993; Hawthorne *et al*. 2013). While there were observed increases in streamflow in thinned catchments under higher rainfall conditions, Hawthorne *et al*. (2013) reported that the response was lower under drought conditions and suggested that thinning may not result in a net gain in water yield over the long term if the recent trend of decreasing rainfall continues, but this will depend on the intensity of thinning.

Adaptation options for maintaining socio-economic benefits

Adaptation measures involving maintenance of social and economic benefits in the region involve diversifying local and regional economies, increasing awareness about the potential impact of climate change on fire regimes and encourage proactive actions with respect to fuels management and community protection. Economic diversification can lead to greater resilience in the community in response to changing species or product mixes and greater variability in timber supply. Diversifying forest-based tourism and recreation options can also reduce the future economic impacts of climate change. Effects of future climate regimes on fire risk are being considered in fire management planning (DEPI 2014a) and there has been investment to foster learning and innovation and to conduct research to determine when and where to implement adaptive responses in the broader Victorian setting (Victorian Government 2013).

However, economic diversification in the region is occurring as part of a general restructuring of the Australian economy to services and not as a part of strategic planning for changing risks under a future climate. While there have been some studies to assess future risks and vulnerability of ecosystems (Mackey *et al*. 2002; Mok *et al*. 2012; Burns *et al*. 2015; Rawal *et al*. 2015a, 2015c), there has not been a systematic analysis to consider impacts of climate change on forests for the broader society.

Options that are not currently being undertaken and that could be easily implemented and may support adaptation to future climatic conditions include:

- review of forest policies, forest planning, forest-management approaches and institutions to assess the ability to achieve management objectives under climate change and to encourage societal adaptation
- enhancing capacity to undertake integrated assessments of system vulnerabilities at various scales
- supporting indigenous and local community efforts to document and preserve local forest-related knowledge and practices for coping with climatic variability and associated changes in forest structure and function
- decentralisation and greater local input into decision making over resources in order to build greater linkages between the communities and industries affected by climate change and management decisions.

For industry, there will be a need to consider alternative timber supply arrangements in the case of short-term logistical disruption due to more intense floods or storms, more frequent and/or intense fire or longer-term decline in timber production and anticipating and planning for changes in wood properties or species.

Discussion

The results of this study suggest that many of the forest management options proposed in the international literature to support adaptation to climate change are being implemented for public forests in this region. A number of proposed management options however present technical, economic, social or scientific challenges. Achieving desired conservation outcomes will depend on the success of global and local actions to reduce greenhouse gas emissions and mitigate future climate change (Steffen *et al*. 2009). Preventing the loss of forest-dwelling species in Australia in future climates will present a number of challenges, particular given the high level of fragmentation in many natural ecosystems and the pressures from invasive species and predators. A number of broader measures have been proposed (Lindenmayer *et al*. 2010) including tackling pre-existing stressors on biodiversity, better preparing for the effects of major natural disturbances, significantly improving off-reserve conservation efforts including fostering appropriate connectivity, and enhancing the existing reserve system by making it more comprehensive, adequate and representative.

Legal and management responses to threatened species are largely focused at the species level but these approaches are likely to be less effective in the future. System-level analysis and regional- and landscape-level responses are likely to be more successful in the long term (Hughes 2011). Species translocation is being proposed as a conservation measure for some species (Weeks *et al*. 2011). However, in implementing *ex-situ* conservation and translocation options for species or genotypes, managers will need to consider effects on the receiving environment. There are also significant social questions about implementing translocation at larger scales (Corlett and Westcott 2013). Translocation needs to be considered in the light of the historical legacy of some disastrous introductions and species movement in Australia, where the introduction of a native species from one part of the country to another has resulted in significant effects on the local flora and fauna, for example the release of koalas into new island habitats (Low 2002).

It is unlikely that all species and ecosystems will persist under future climates. Analysis will be required to determine those with the best prospects of survival that can be the focus of future conservation efforts (Bottrill *et al*. 2008). Species 'triage' will present significant challenges for conservation policy and for communities who may wish to see continuing effort to maintain all current species and ecosystem conditions.

Proposed options to maintain productive capacity that present challenges include practising high-intensity plantation forestry, enhancing growth through the application of fertiliser and shortening timber harvesting rotations to enable species replacement with more drought- or disturbance-tolerant species. Plantation forestry is technically feasible and potentially socially desirable in this region but, under current policies, could occur only on currently cleared land and would require significant financial investment. Fertilisation of native forests has been studied in the past in other regions (La Sala 2006; Raison and Connell 1992) but not in this region, and shortening rotations is likely to be highly contentious. Thinning and selection harvesting to achieve water, wood or wildlife outcomes of older forests are also being promoted (Ryan 2013). Thinning and stand management could also reduce the severity of wildfire impacts.

Maintaining productivity in a future climate will probably depend more on the capacity to manage seed stocks and regenerate forests with a higher frequency of disturbance. Ferguson (2009) suggested that climate presented significantly increased future risks to production and other forest values that could be mitigated through a well-equipped workforce, removal and salvage of fire-killed trees along access roads, seed collection and artificial regeneration in conservation reserves and strategic swaps of age classes between production and conservation areas. A strong rationale would be required, as converting land from conservation to production tenures may not be supported by all parts of the community.

One of the critical decisions in relation to forest management for production or conservation is a determination of where tree species may be able to exist and under what conditions (Doley 2010). The issue is not so much a technical one, as current understanding in relation to species movement and propagation is adequate for much of our planning (Doley 2010). Most plant species can grow satisfactorily beyond their natural distributions, which are often constrained more by the interaction of climate and soil on the processes of reproduction and natural establishment rather than on vegetative growth. The challenge is deciding where and when it is socially and ecologically acceptable to introduce new species.

Fire is a major threat to many forest values—timber production, recreation, water and biodiversity conservation—but fire-management options are contentious. Many are now arguing for a greater use of prescribed burning and thinning to mitigate the extent and consequences of large-scale, high intensity fires. Adams (2013) and King *et al*. (2013) suggested that reductions in fuel loads through prescribed burning under a warmer, drier climate could reduce the probability of wildfire in mesic vegetation types. On the other hand, Bowman *et al*. (2013) suggested that fire suppression may be the best management option for managing tall wet eucalypt forests under future fire regimes. Effective suppression may be required to provide for an increase in the area of forest with old-growth attributes and provide for future conservation of many mammal species (LPAG 2014). Monitoring future fuel loads will be important in determining future adaptation measures and deciding the balance of effort in a risk-based approach to fire management between fuel reduction and suppression.

Debris flows following wildfires can cause significant problems for water quality and for forest and water infrastructure. In upland eucalypt forests in the CHR, debris flows are typically triggered by extreme rainfall events (> 1:50 year events) within 12 months of a high-severity fire (Nyman *et al*. 2011). A future with more fires and more extreme rainfall events could lead to greater erosion risk, which will affect water quality. This will have implications for the design and construction of roads in order to prevent losses to erosion and highlights the need for rapid reforestation following wildfire on steep slopes to reduce the risk of landslides and debris flows. These actions will need to be carried out on areas with forest types not targeted for commercial wood utilisation. Restoring degraded or deforested areas in non-commercial upland areas following fires is technically feasible (Bassett *et al*. 2015) and will probably be socially acceptable but will require significant investment.

In a global survey, McDowell and Allen (2015) predicted that tall forests will be at greatest risk to drought-induced mortality under climate change. With lower rainfall and increased drought, tall forests may be replaced by shorter and xeric-adapted vegetation, which will have implications for timber production, habitat values and carbon storage. Reducing stand density through thinning can be an important measure for managing drought-induced tree mortality. Evidence from plantations of pine and eucalypt species indicate that thinning can reduce drought stress, increase forest health and improve resilience to disturbances. For example, Stone *et al*. (2012) identified increased mortality to drought in unthinned stands of *Pinus radiata* in New South Wales, highlighting the need to maintain stands on a site-dependent thinning schedule to prevent widespread drought-based mortality. Thinning has also been beneficial in reducing drought stress in *E. globulus* plantations in Western Australia (White *et al*. 2009).

In native forests, thinning reduced drought mortality in tall *E. camuldulensis* forests on the Murray River in south-eastern Australia (Horner *et al*. 2009). In *E. marginata* forests of south-western Australia thinning was found to reduce water stress in juveniles, but not adults, compared with unthinned stands (Qiu *et al*. 2013) while Stoneman *et al*. (1995) found that mature trees of *E. marginata* in thinned stands typically exhibited lower shoot water stress than unthinned stands, leading to higher growth efficiencies. Given that drought responses will be site and species specific, appropriate silvicultural prescriptions will be required to ensure thinning is used in appropriate stand ages and frequencies that align with drought risk and changing structural characteristics (density and height) across a diversity of forest types.

At the stand level, it has been argued that ecosystem resilience can be increased by incorporating more species diversity and structural complexity and identifying and protecting functional groups and keystone species (Noss 2001; Messier *et al*. 2015). While the concept of resilience is gaining increasing prominence in natural resource management (Walker and Salt 2012) and climate change adaptation (McEvoy *et al*. 2013), Rist and Moen (2013) argue that its contributions to date have been largely conceptual and offer more in terms of being a problem-framing approach than providing analytical or practical tools. There may also be trade-offs involved with focusing on resilience through retention of current species composition or using a more adaptation-oriented management approach to shift species composition after disturbances (Buma and Wessman 2013). There is also a need to consider other aspects of forest condition. Longer growing seasons and higher winter or spring or autumn temperatures might accelerate development of old-growth features in the short term through increased growth, senescence and mortality (Keenan and Read 2012).

Maintaining the forest contribution to global carbon cycles is a key criterion of sustainable forest management and many of the adaptation options that attempt to maintain productive function and ecosystem health and reduce disturbance impacts will also support the maintenance and enhancement of forest carbon values. There have been a number of studies analysing carbon stocks in the region (Keith *et al*. 2009; Fedrigo *et al*. 2014) and a study of potential changes under alternative future management scenarios (Keith *et al*. 2014) but this did not consider the implications of climate change. More broadly, the integration of forest management for mitigation and adaptation is strongly supported (Kant and Wu 2012) but there has been little integration to date of mitigation and adaptation objectives in forest or climate policy. For example, there is little connection between policies supporting Reducing Emissions from Deforestation and Degradation (REDD+), sustainable forest management and adaptation (Long 2013).

Consideration of adaptation options depends on climate projections and analyses of the potential impact of future climate change on forest ecosystems (Harris *et al*. 2014). However, these are often based on a limited number of climate scenarios that do not include some of the key climate variables to which species or ecosystems might be sensitive or key functional or regeneration or soil requirements (for example, Burns *et al*. 2015). Incorporating these elements can provide a very different assessment of species and ecosystem vulnerability (Mok *et al*. 2012).

Broad-scale monitoring being implemented across Victorian forests will improve capacity to detect changes in ecosystem conditions (DEPI 2014b). More widespread monitoring of phenological changes (Keatley 2015) would improve early warning of changing ecosystem function. These monitoring results need to be incorporated in development of new forest management indicators to assess the effectiveness of adaptation efforts.

In general, adaptation of forest management to climate change should be considered a social learning process. It requires an understanding of how forests have responded to past and current climatic conditions to inform potential future climate impacts and planning for their consequences. It also requires consideration of the broader social, economic or other environmental changes that may have an impact on forests and communities. Effective and ongoing dialogue between researchers, policy makers and practitioners is a critical element of adaptation. There is much to be done to engage people with the need for adaptation in the forest management sector, especially where they are dealing with more pressing short-term issues associated with structural change in the Australian economy. There is underlying scepticism in regional communities in Australia about the nature and extent of climate change, or at the very least, uncertainty about the local and personal impacts of that change (Evans *et al*. 2011). To explain and predict adaptation to climate change, the combination of personal experience and beliefs must be considered (Blennow *et al*. 2012). Berkhout *et al*. (2006) found that interpreting climate signals is not easy for many types of organisations because the evidence of change is often ambiguous and the stimuli are not often experienced directly within the organisation. Many forest managers in Australia currently feel little need to change practices to adapt to climate change, given both weak policy signals and limited perceived immediate evidence of increasing climate impacts (Cockfield *et al*. 2011).

In managing forests in the future, forest managers will have to resolve significant questions with the community, including the degree of intervention and human disturbance that is acceptable in native forests to achieve management objectives. Management actions such as promoting development of old-growth features, maintaining roads for access and protection, more widespread prescribed burning or intervention to manage pests and diseases in natural systems will be required in different tenures. Managers will need improved decision-making tools (Gregory *et al*. 2012) to inform choices on site and species selection and management regimes that incorporate understanding of future climate change risks. Successful adaptation will require dissemination of knowledge of potential climate impacts and suitable adaptation measures to decision makers at both practice and policy levels (Kolström *et al*. 2011), but

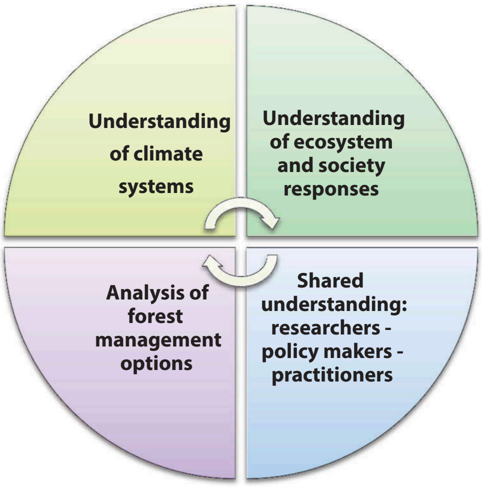

Figure 3. Components of climate-smart forest management (After Nitschke and Innes 2008)

wider implications also need to be considered. For example, the forest products industry will also need to consider adaptation options for infrastructure, roads and processing facilities to anticipate higher temperatures and potentially more intense storm events or other extreme climate events and the implications for wider changes in the economy, for supply chains, markets and for competitors both across the country and internationally (Hayman *et al*. 2012; Young and Jones 2013). Researchers will need to develop new modes of research, providing knowledge in forms that are appropriate to management decisions and suitable for use by a range of different audiences (Preston *et al*. 2015).

'Climate smart' forest management frameworks (Fig. 3) can provide an improved basis for managing forested landscapes and maintaining ecosystem health and vitality based on an understanding of landscape vulnerability to future climatic change (Keenan 2015; Nitschke and Innes 2008). In building 'learning organisations' to adapt to climate change, leaders in forest management organisations will need to support a greater diversity of inputs into decision making, avoid creating rigid organisational hierarchies that deter innovation and be inclusive, open and questioning (Joyce *et al*. 2009; Konkin and Hopkins 2009; Peterson *et al*. 2011). Managing the forests of the CHR to meet the future objectives of our society will require vision, creativity, collaboration and persistence supported by sufficient resources to test and implement new approaches to forest management in an uncertain future.

Acknowledgements

Thanks to two anonymous reviewers for their helpful contributions and to Michael Ryan for his input to the study.

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