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Projecting canopy cover change in Tasmanian eucalypt forests using dynamically downscaled regional climate models

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Abstract Loss of forest cover is a likely consequence of climate change in many parts of the world. To test the vulnerability of eucalypt forests in Australia's island state of Tasmania, we modelled tree canopy cover in the period 2070–2099 under a high-emission scenario using the current climate–canopy cover relationship in conjunction with output from a dynamically downscaled regional climate model. The current climate–canopy cover relationship was quantified using Random Forest modelling, and the future climate projections were provided by three dynamically downscaled general circulation model (GCM) simulations. Three GCMs were used to show a range of projections for the selected scenario. We also explored the sensitivity of key endemic and non-endemic Tasmanian eucalypts to climate change. All GCMs suggested that canopy cover should remain stable (proportional cover change <10 %) across ∼70 % of the Tasmanian eucalypt forests. However, there were geographic areas where all models projected a decline in canopy cover due to increased summer temperatures and lower precipitation, and in addition, all models projected an increase in canopy cover in the coldest part of the state. The model projections differed substantially for other areas. Tasmanian endemic species appear vulnerable to climate change, but species that also occur on the mainland are likely to be less affected. Given these changes, restoration and carbon sequestration plantings must consider the species and provenances most suitable for future, rather than present, climates.

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Introduction

The loss of tree cover has had a greater effect on the functioning of the Earth system than any other change in land surface (Sterling and Ducharne 2008), because woody vegetation provides ecosystem services including carbon storage as well as important habitats for biodiversity. Changes in temperature and precipitation regimes are likely to affect woody vegetation structure, species composition, habitat quality, productivity, and carbon storage (Iverson and Prasad 2002; Broadmeadow et al. 2005; Littell et al. 2010; Good and Caylor 2011; Heubes et al. 2011; Becknell et al. 2012; Fauset et al. 2012; Matías and Jump 2012; Murphy and Bowman 2012). Projections of how woody

canopy cover may respond under scenarios of climate change at a landscape scale are poorly resolved, as they are based on gross outputs of dynamic global vegetation models (DGVMs) or extrapolations from historical trends typically discerned from permanent plots or sequences of aerial photography (Fensham and Fairfax 2003; Phillips et al. 2008; Sitch et al. 2008). These approaches suggest disparate trajectories in canopy cover of woody vegetation; for instance, tropical rainforest is vulnerable to cover loss because of reduced precipitation, thermal stress, and increased fire activity; yet, shrub encroachment is evident in many areas (Eldridge et al. 2011), and woody cover in some tropical savannas has increased (Mitchard et al. 2009; Bowman et al. 2010). To effectively predict future climate-related trends in tree cover requires projections from general circulation models (GCMs). For topographically diverse regions with a range of projected climate responses across a small area, such as the island of Tasmania, there is additional benefit from examining climate projections at a finer spatial resolution, generated using a technique known as downscaling (Grose et al. 2010).

Here, we investigate how canopy cover of Tasmanian temperate eucalypt forests is likely to change under a scenario of high greenhouse gas emissions and marked global warming [the A2 scenario from the IPCC Special Report on Emissions Scenarios (SRES) of Nakićenović and Swart (2000)]. We do this by building a predictive model of canopy cover in eucalypt forests in southeastern Australia and then applying this to Tasmania using global climate change data downscaled to a high spatial resolution. This approach is based on the assumption that it is possible to predict with reasonable accuracy the amount of tree canopy cover in natural ecosystems using climate data. While many studies have used such relationships to predict broadscale changes in vegetation distribution and canopy cover in relation to the outputs of GCMs [e.g., in tropical (Hoffmann et al. 2002; Calef et al. 2005) and boreal (Heubes et al. 2011; Tchebakova et al. 2011) regions], there are few regionally detailed projections, reflecting the coarse spatial scale of observed datasets, GCMs, and analysis techniques.

Eucalypts (*Eucalyptus*, *Corymbia*, and *Angophora* species) are unique in being a single lineage that dominates most of the woody vegetation on the Australian continent. Eucalypt forests and woodlands constitute 79 % of Australia's forest areas and cover 116 million ha (Bureau of Rural Sciences 2008a) in all but the driest parts of the continent. The island of Tasmania is floristically similar to southwestern Victoria, on the Australian mainland (Gill et al. 1985), which is unsurprising, given the two have been periodically connected at times of low sea level during the Quaternary (Lambeck and Chappell 2001). Eucalyptus-dominated vegetation forms a structural continuum of varying height and canopy density in response to variation in climate, soils, and topographic

position (Bureau of Rural Sciences 2008b). It is therefore possible to derive a relationship between canopy cover and climate that is common to Tasmania and the southeastern mainland of Australia, even though Tasmania is further from the equator, and cooler and wetter than most of mainland Australia (see Supplementary Material).

Tasmania is a topographically complex island, resulting in a climate with high spatial heterogeneity. Because of the predominance of westerly airstreams, there is a steep rainfall gradient with high year-round precipitation on the mountainous west coast, a drier temperate climate on the less mountainous east coast, and a rain shadow in the Midlands, a north–south valley in the center of the island. Here, in uncleared areas, there are dry eucalypt sclerophyll forest and eucalypt savanna. By contrast, at the wetter end of Tasmania's climatic spectrum is found the world's tallest angiosperm, *Eucalyptus regnans*, in the most carbon-dense forests on earth (Keith et al. 2009).

Tasmania's future climates are projected to become more like those presently experienced in mainland Australia due to rising temperatures, as well as changes to wind patterns and rainfall caused by a poleward migration of the subtropical high-pressure systems and westerly storm tracks (Cai et al. 2003; Yin 2005). Dynamically downscaled climate projections, with marked regional detail, have recently become available for Tasmania (Corney et al. 2010). This, combined with the existence of similar *Eucalyptus*-dominated vegetation in warmer and drier climates in mainland Australia (Gill et al. 1985), invites spatially detailed modelling of vegetation cover for Tasmania under various climate change projections.

In this study, we address three specific questions in relation to the effects on eucalypt forests of the changes in climate expected during this century under the A2 scenario and three GCMs:

1. Will there be substantial changes in the canopy cover of Tasmania's eucalypt forests?
2. Which areas are consistently predicted (by two or three of the three selected GCMs) to increase or decrease in their canopy cover?
3. Are the current eucalypt species likely to tolerate the projected changes in climate, or will translocation and importation of species from mainland Australia be required to maintain eucalypt canopy cover in Tasmania?

Methods

Estimating current canopy cover

In order to generate a climate envelope that accommodates the potential future climate of Tasmania, in constructing

our canopy cover–climate model, we used the eucalypt forest domain of the entire southeast Australian region, which includes areas that are hotter and drier (Appendix 1), and with sparser tree cover, than currently exists in Tasmania. Our calibration domain was defined as areas of native vegetation with >20 % tree cover ("forest" sensu Bradshaw, 2012) where the tree layer is dominated by eucalypt species, in New South Wales, Victoria, the Australian Capital Territory, and Tasmania. The integrated vegetation cover dataset (Thackway et al. 2004) was used to remove all areas not representing native forest, such as cropland, grassland and plantations, built-up areas, and water. The National Vegetation Inventory System 3.0 (Executive Steering Committee for Australian Vegetation Information 2003) was used to remove all non-eucalypt vegetation types. Tree canopy cover data (i.e., the percentage of sky light in a plane orthogonal to the ground which is intercepted by trees) at 500-m resolution were then extracted for the remaining grid cells from the MODIS

Continuous Vegetation Fields dataset (Hansen et al. 2006). We validated these data against the measurements of eucalypt cover in southern Tasmania (Prior et al. 2013). The final dataset comprised 1,041,030 grid cells representing forest, of which 99,668 were from Tasmania (Fig. 1).

Modelling canopy cover versus climate

Current climate surfaces, representing the mean values of the period 1921–1995 for temperature and rainfall and the period 1970–1995 for evaporation, were generated at 1-km resolution in ANUCLIM version 6.1 (Hutchinson and Xu 2011). Topographic variables were calculated from the NASA SRTM (Rabus et al. 2003) global dataset at a 90-m resolution. The potential explanatory variables used in our modelling are listed in Table 1.

Preliminary modelling used generalized linear modelling (GLM), multi-model inference, and model selection

Fig. 1 Tree canopy cover for the eucalypt domain in southeastern Australia, derived from the MODIS continuous vegetation field product. *White areas* indicate non-eucalypt systems and were not considered in our analysis
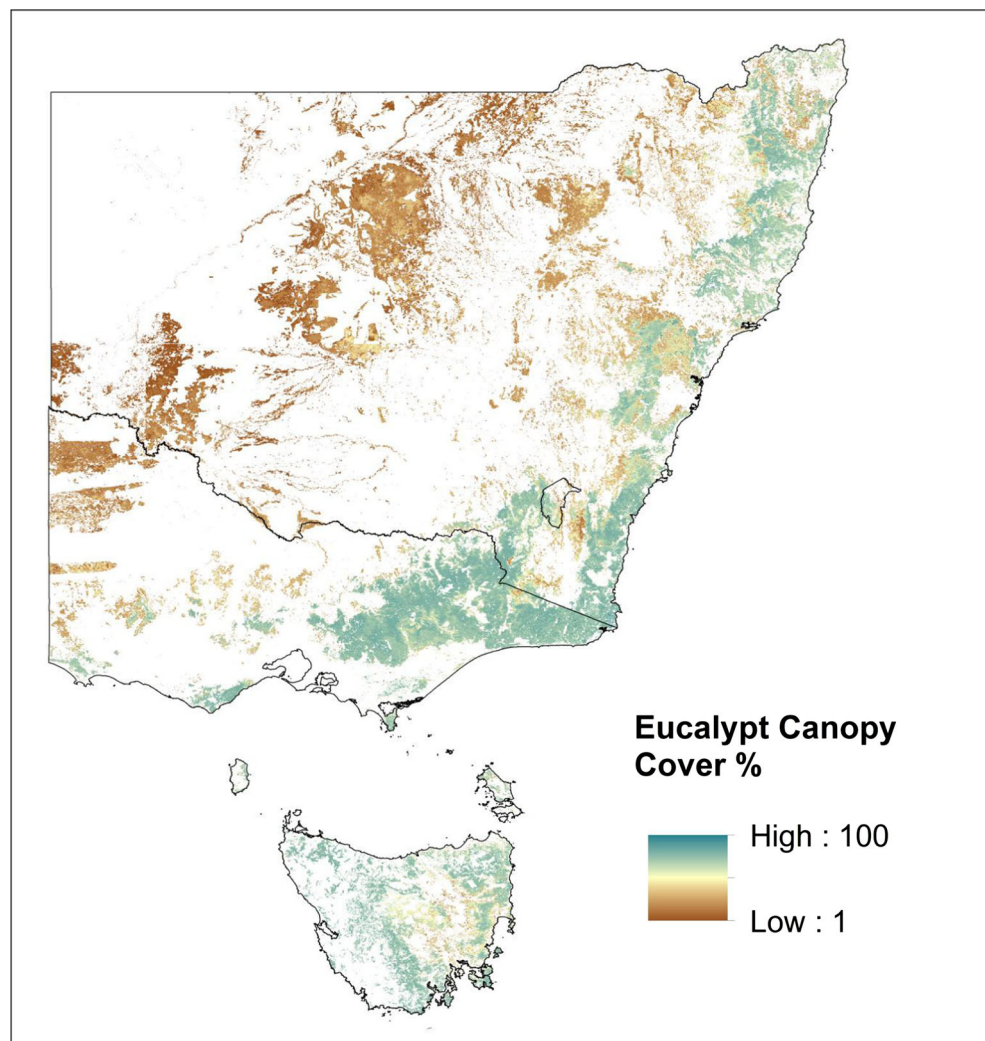
Table 1 List of potential explanatory variables used in modelling of canopy cover

Variable name	Description
Climate variables	
Rain_Yr	**Mean annual precipitation (mm)**
Rain_Jan	Mean January precipitation (mm)
Rain_Jul	Mean July precipitation (mm)
MAT	Mean annual temperature (°C)
D_Range	Mean diurnal range (°C)
bio_4	Monthly temperature coefficient of variation
bio_15	Monthly precipitation coefficient of variation
bop_18	Precipitation of warmest month
MaxT_Jan	**Mean maximum January temperature (°C)**
MinT_Jul	Mean minimum July temperature (°C)
Topographic variables	
Ele	Elevation (m)
Slope	**Slope (°)**
Water balance variables	
Evap_Yr	Mean annual pan evaporation (mm)
Evap_Jan	Mean January pan evaporation (mm)
Evap_Jul	Mean July pan evaporation (mm)
WB_Yr	**Annual Water Balance (Rain_Yr–Evap_Yr) (mm)**
WB_Jan	January Water Balance (Rain_Jan–Evap_Jan) (mm)
WB_Jul	July Water Balance (Rain_Jul–Evap_Jul) (mm)

Note that January is mid-summer and July is mid-winter in the southern hemisphere. Variables receiving most support by AIC-based model selection and used in the final Random Forest model are indicated in bold

using the Akaike information criterion (AIC), which balances model fit with parsimony (Burnham and Anderson 2002) to select a limited, biologically relevant suite of variables to explain canopy cover of eucalypt forest in southeastern Australia: mean annual precipitation, mean maximum January temperature, slope and annual water balance (Mean Annual Precipitation − Annual Pan Evaporation) (Table 1, Appendix 2). Pairwise linear regressions between these variables indicated a strong correlation between mean annual precipitation and annual water balance, but a scatterplot indicated that the relationship was quite nonlinear, so both variables were retained. To develop a canopy cover model based on the present climate, and thereby project future cover under three climate change scenarios, we used Random Forest modelling, which can cope with the potentially strong nonlinear and interacting effects of the selected variables. Random Forest modelling is an ensemble classifier, which generates many classification or regression trees based on bootstrapped samples of the data and aggregates their results (Liaw and Wiener 2002). It is robust against overfitting and has only

two parameters (the number of variables in the random subset at each node and the number of trees in the forest), and is usually not very sensitive to their values. By allowing nonlinear responses, Random Forest modelling can also provide a better fit to the data. Random Forest modelling was performed using the "randomForest" package version 4.6-6 in R (Liaw and Wiener 2002) using the four variables from the combined GLM, 500 trees, and one variable per split, on a random subset of 40,000 grid cells to ensure computational efficiency.

Future climate and canopy cover

Future climate projections were based on output from three Conformal Cubic Atmospheric Model (CCAM) dynamically downscaled GCMs (see below) run under the SRES A2 emission scenario. This scenario assumes continuously increasing global population and regionally oriented economic development and represents the highest emission scenario for which a full set of model outputs are available. It is expected that there would be a climate response that is similar in nature but smaller in magnitude under a lower-emission scenario. The three GCMs were (1) CSIRO-Mk3.5, (2) MIROC3.2(medres), and (3) UKMO-HadCM3. These models were chosen for their ability to model current southeast Australian climate means and variability, and to represent the spread of the available model results; this is particularly important when projecting annual precipitation. MIROC3.2(medres) projects an increase in rainfall over southeast Australia greater than the mean of all models considered in the CMIP3 archive, while CSIRO-Mk3.5 projects a greater rainfall decline than most models, and UKMO-HadCM3 shows a moderate decline in mean annual rainfall similar to the mean of all models. The three models together therefore provide a good spread of potential climate projections for the broad southeast Australian region. However, all three models are similar to all CMIP3 models in placing Tasmania near a borderline between increasing rainfall at higher latitudes and decreasing rainfall in southern mainland Australia (Christensen et al. 2007). The exact position of this boundary will determine the specific rainfall change projected for Tasmania, and this is influenced by the downscaling process.

The output of the three GCMs was dynamically downscaled using the regional climate model Conformal Cubic Atmospheric Model (CCAM) of McGregor and Dix (2008) to a final spatial resolution of 0.1 degrees (approximately 10–14 km) grid. Details of the specific modelling methods are found in Corney et al. (2010). Dynamically downscaled regional climate models capture the climate processes that act at the regional scale, rather than assuming a statistical relationship between large-scale patterns of climate elements and local climate, or simply interpolating coarse-

scale model output to the local scale. They can potentially capture the regional variation in response to a warming climate, which is especially relevant to Tasmania, given its complex topography, effect of coastlines, and diversity of regional climate influences. Dynamically downscaled models can also simulate extremes more realistically than the GCMs (White et al. 2013). Each of the three downscaled climate projections showed a variety of climate response changes across Tasmania, especially in seasonal rainfall, with the details varying among the GCMs, as described by Grose et al. (2010). For example, MIROC3.2 (medres) projected a rainfall decline in southern Tasmania, UKMO-HadCM3 projected a rainfall increase in most areas, and CSIRO-Mk3.5 projected a mixture of small increases and decreases in a pattern similar to the model average (Grose et al. 2010).

Mean climatic change grids were calculated from each CCAM output for the future period 2070–2099 relative to a baseline period of 1961–1990. Change grids calculated included mean daily T_{max} (°C), mean daily T_{min} (°C), proportional change in rainfall (%), and proportional change in potential evaporation (%) for each month and annual means. The change grids were applied to the ANUCLIM surfaces of mean current climate to calculate future climate surfaces at the same resolution as the input data. Changes were applied as an addition for temperature, and as a multiplication for rainfall and potential evaporation.

The future climate surfaces generated using downscaled climate projections from the three GCMs were then fed into the Random Forest model to generate corresponding projections of future canopy cover for Tasmanian eucalypt forests. Mean canopy cover change was calculated as the change in percent canopy cover in each climatic grid cell. The output from each of the three models was examined to quantify the area of existing eucalypt forest likely to experience a "substantial" increase or decrease in canopy cover. A "substantial" change in canopy cover was defined as a proportional change in canopy cover of >10 %, e.g., a change from 30 to 26 % canopy cover) between the estimated current forest and the three future projections. Thus, canopy cover was defined as "Decreasing" (>10 % decrease), Stable (between −10 and 10 %), or "Increasing" (>10 % increase). We identified areas that were consistently projected to show substantial increase or decrease in canopy cover, which we considered to be those where at least two of the three models agreed in their predictions. Significant deviations from the mean projections for all GCMs were determined using the *ImageDiff* function of the "SDMTools" package version 1.1-13 in R (VanDerWal et al. 2012), which determines the significance of the pairwise differences relative to the mean and variance of all differences between the two input datasets.

The mean projected percentage change in *Eucalyptus* canopy cover for each Tasmanian Interim Biogeographic Regionalization for Australia region (Environmental Australia 2000) was calculated for each model, as well as the total area subject to substantial projected change under each model across Tasmania.

Species distributions

There are 29 *Eucalyptus* species in Tasmania, of which 16 are endemic (Wiltshire and Potts 2007). To determine the projected change in climate suitability for Tasmanian eucalypts, and cover the expected range of species responses, we selected one example each of an endemic and a non-endemic species with (1) a widespread distribution in Tasmania; (2) a narrow, high-altitude distribution in Tasmania; and (3) a narrow, low-altitude distribution in Tasmania. For each of these six species, we extracted distribution records from the Atlas of Living Australia (http://www.ala.org.au) and the corresponding January maximum temperature and mean annual rainfall for all locations (including mainland locations) using ANUCLIM version 6.1 (Hutchinson and Xu 2011). These current climate envelopes were then compared with the projected climate envelope for all of Tasmania in 2070–2099, to show the likely change in area with a suitable climate for that species.

Results

Current and future climate envelope

Our analysis shows that *Eucalyptus* forest currently occupies 33,340 km^2 of Tasmania, spanning a range of mean annual precipitation (MAP) from 537 to 2,866 mm and mean maximum January temperature from 15.5 to 23.2 °C (Table 2). Including the data from Victoria and NSW extended the range of MAP down to 257 mm, and mean maximum January temperature up to 36.1 °C (Table 2), thereby including the hottest, driest, and all but the very wettest future climates projected for Tasmanian eucalypt forests in this analysis.

The three CCAM simulations agreed closely in their temperature projections, but differed substantially for precipitation and water balance (Table 2). The simulation using CSIRO-Mk3.5 as input projected only small changes in mean annual precipitation and annual water balance, the simulation using UKMO-HadCM3 projected generally increased rainfall and a wider spread of water availability, while the simulation using MIROC3.2(medres) projected less rainfall and lower water availability over most of southern Tasmania (Table 2). Each of these future climates

Table 2 Ranges of current climate attributes in *Eucalyptus* forests in SE Australia (used for the Random Forest model) and Tasmania, and the future projections for Tasmania in 2085 under the three general circulation models (CSIRO Mk3.5, UKMO-Had CM3, MIROC 3.2 Medres)

	Current climate		Future projections for Tasmania		
	SE Australia	Tasmania	CSIRO Mk3.5	UKMO-Had CM3	MIROC 3.2 Medres
MAP (mm)	257–1,619	537–2,866	529–2,858	626–3,153	494–2,782
January maximum temperature (°C)	19.9–36.1	15.5–23.2	18.8–26.5	18.7–26.3	18.6–26.3
Annual WB (mm)	−1,466 to 908	−314 to 2,188	−479 to 2,064	−352 to 2,312	−472 to 2,013

Areal extent of change

	Km²	%	Km²	%	Km²	%
Area with substantial decline	8,342	25	1,405	4	6,544	20
Area with stable cover	23,170	69	24,729	74	25,218	75
Area with substantial increase	1,931	6	7,235	22	1,676	5

Using data from SE Australia expands the environmental envelope to cover most of the climates projected for Tasmania for the period 2070–2099. The lower half of the table shows the absolute (km²) and relative (%) areas with substantial (>10 %) projected decline or increase in cover associated with the change in climate projected under the three general circulation models. Slope is not shown because it was the same for all models

is seen as an equally plausible climate response given the A2 forcings, but not representative of all possible climate responses.

Current canopy cover

The Random Forest model, which included the terms MAP, January mean maximum temperature, annual water balance, and slope, explained 80.2 % of variance in actual canopy cover. This is a substantial improvement on the generalized linear model fit of 71 % (Appendix 2), reflecting the nonlinear relationships among the variables. Partial dependence plots of variables reveal the existence of thresholds and other nonlinear relationships between the selected environmental variables and canopy cover (Fig. 2). Canopy cover increases steeply between about 500 and 1,000 mm of precipitation and then levels off, and it declines above a mean maximum January temperature of 25 °C. There is an additional very strong decline in canopy cover where the water balance falls below zero (i.e., annual rainfall drops below pan evaporation). The effect of slope is comparatively subtle, with only a slight increase in canopy cover as slope increases from 0° to about 20°, and negligible change with steeper slopes.

There was good spatial agreement between the Random Forest model projections and satellite measurements of existing canopy cover for Tasmania (Appendix 3), although with some overprediction around the boundary of the agricultural Midlands region. This can be attributed to the extensive clearing and grazing by introduced animals in these areas, reducing the satellite-detected canopy cover below the climatically expected cover. Although the satellite-derived tree cover data provided only a snapshot of cover, we believe that the effects of fire and forestry have had little effect on the model prediction given the widespread but moderate level of occurrence of both fire and tree clearance across southern Australia, and the large number of sample points used, with non-native vegetation excluded.

Projections of future canopy cover

The three GCMs give a similar projection of the change in overall canopy cover in Tasmanian eucalypt forests for 2070–2099, but showed important differences in the spatial pattern of projected change (Fig. 3). All models suggest that canopy cover should remain fairly stable across most (69–75 %) of its range in Tasmania. However, all three models showed decline in canopy cover in the Eastern Tiers, due to the expected decreases in mean annual precipitation and increases in mean maximum January temperature in this region (Figs. 3, 4). Conversely, all models showed an increase in canopy cover in the central highlands as a result of projected increases in temperature in this coolest part of the state. The models diverge considerably in other regions (Fig. 5): two show substantial tree cover decline in 20–25 % of the current area and an increase in 5–6 %, while the remaining model, CCAM - UKMO-HadCM3, projects the converse: a substantial increase in canopy cover in 22 % of the current area and a decrease in 4 % (Table 2). Specifically, the CCAM-CSIRO-Mk3.5 GCM projections showed the greatest area of decline, concentrated on the southern Midlands, Eastern Tiers, and northeast coast, with some increased canopy

Fig. 2 Partial dependence of canopy cover (%) on slope, January maximum temperature, mean annual precipitation (MAP), and water balance, based on the Random Forest model. The tick marks on the *x*-axis indicate deciles of the model training data. The partial dependence function indicates how canopy cover responds to changes in the particular variable after accounting for the average effects of all other variables in the model (Liaw and Wiener 2002). The range shown in these *plots* indicates the relative strengths of the different predictor variables
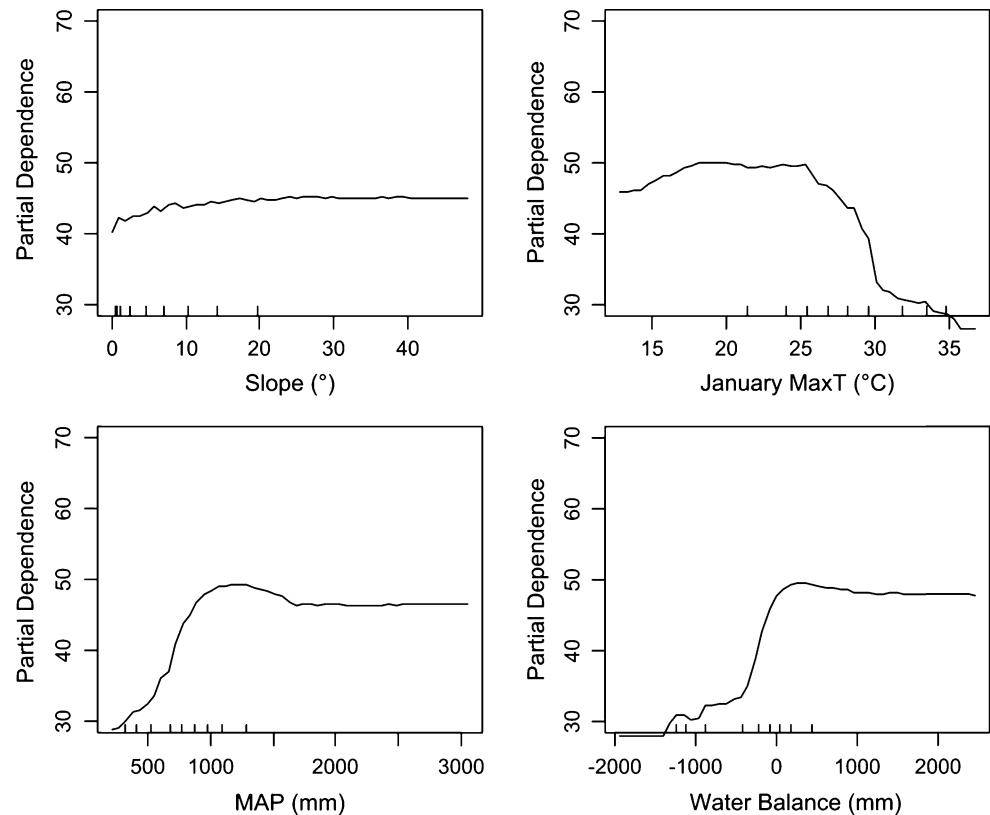
cover in the central highlands. The CCAM-MI-ROC3.2(medres) GCM projection showed a similar area of decline around the Midlands and Eastern Tiers and increase in the central highlands, but stable canopy cover on the northeast coast, while for CCAM-UKMO-HadCM3, the model distinct in projecting increased precipitation on the east coast showed a relatively small area of decline in the Eastern Tiers and increased canopy cover for much of the rest of the Midlands and central Tasmania. Projected mean change in canopy cover for defined Interim Biogeographic Regionalization for Australia 5.1 regions (Environment Australia 2000) regions (Table 3, Fig. S6) shows most consistent decline in the Tasmanian Northern Midlands and Tasmanian southeast regions, although again the higher-rainfall CCAM-UKMO-HadCM3 projects increase in these areas. Canopy cover of areas of tall eucalypt forest is projected to be relatively unaffected by climate.

Species distributions

There was considerable overlap between the current climate envelope and Tasmania's future climate for the three non-endemic species (Fig. 6). However, much of the climate envelope of the endemic species falls outside that projected for Tasmania in 2070–2099. Only a few populations of the subalpine species *E. vernicosa* currently

occur in a climate as warm as projected for Tasmania in 2070–2099, and the current, very narrow range of *E. morrisbyi* is slightly cooler and drier than any area of Tasmania will be in future under the A2 emission scenario (Fig. 6). Even the widespread endemic *E. amygdalina* is not currently found in areas as warm as most of Tasmania is expected to be in 2070–2099.

Discussion

Projected changes in canopy cover in Tasmania's eucalypt forest

Our study shows that the climate across most of Tasmania will continue to be suitable for eucalypts over the next seven or more decades under the A2 emissions scenario with marked climate changes, but that climate change is likely to alter the distributional patterns of tree canopy cover in Tasmania's eucalypt forests. These changes are influenced by the island's complex topography and climate, and their details vary according to the GCM used. Our analysis is admittedly broad-bush, and it is possible that shifts in climate variables not included in our model, for instance, changes to seasonal patterns of extreme temperatures and precipitation, might alter eucalypt tree cover in

Fig. 3 Present canopy cover in eucalyptus-dominated vegetation in Tasmania (*top*) and projected cover for the period 2070–2099 under three GCM scenarios (*left-hand panels*). Areas shown in *white* are non-eucalypt systems and were not considered in our analysis. The *right-hand panels* show areas with a substantial change in tree canopy cover for each scenario (defined as a relative change of >10 % of the existing cover, e.g., from 30 to 26 % cover = decrease). The *top-right panel* shows rainfall isohyets, high elevation areas, and regions mentioned in the text for Tasmania
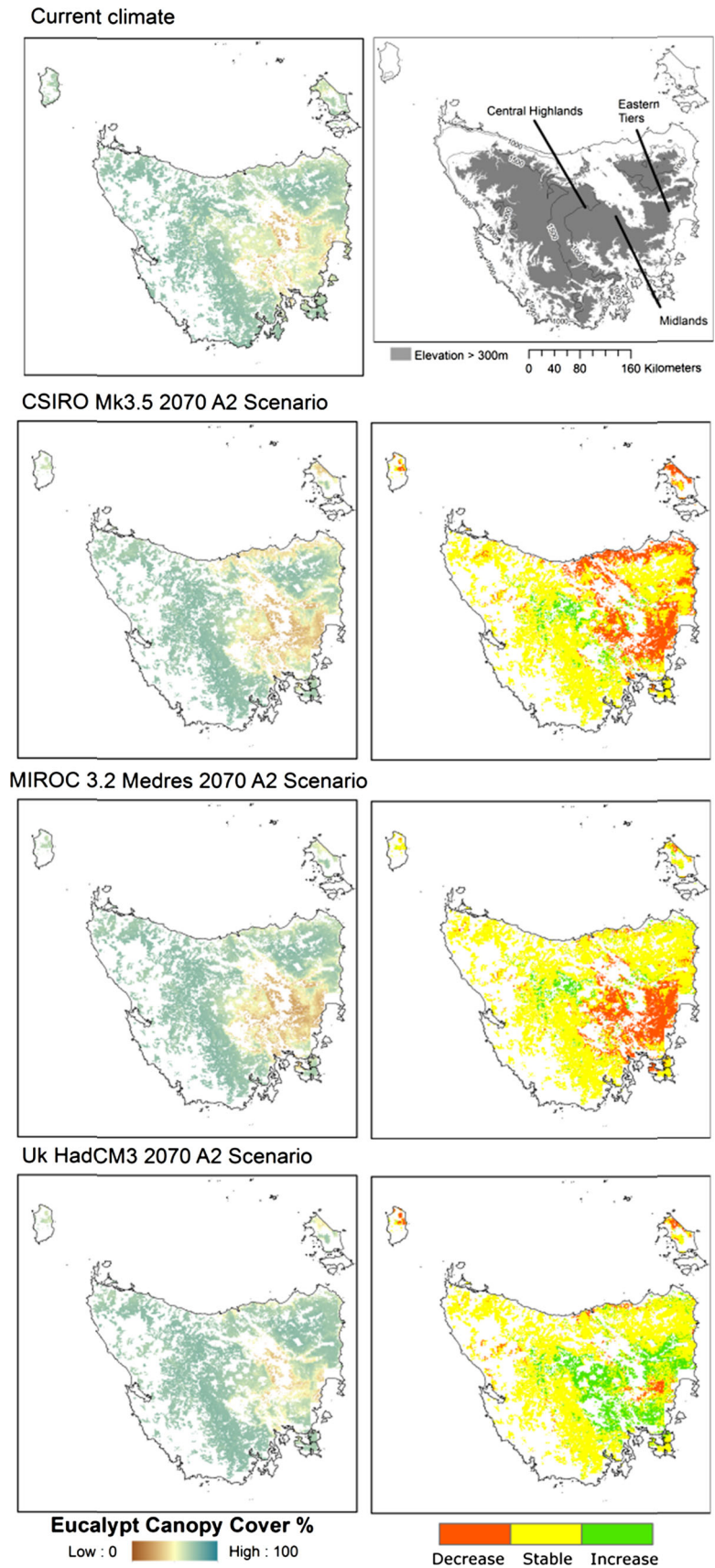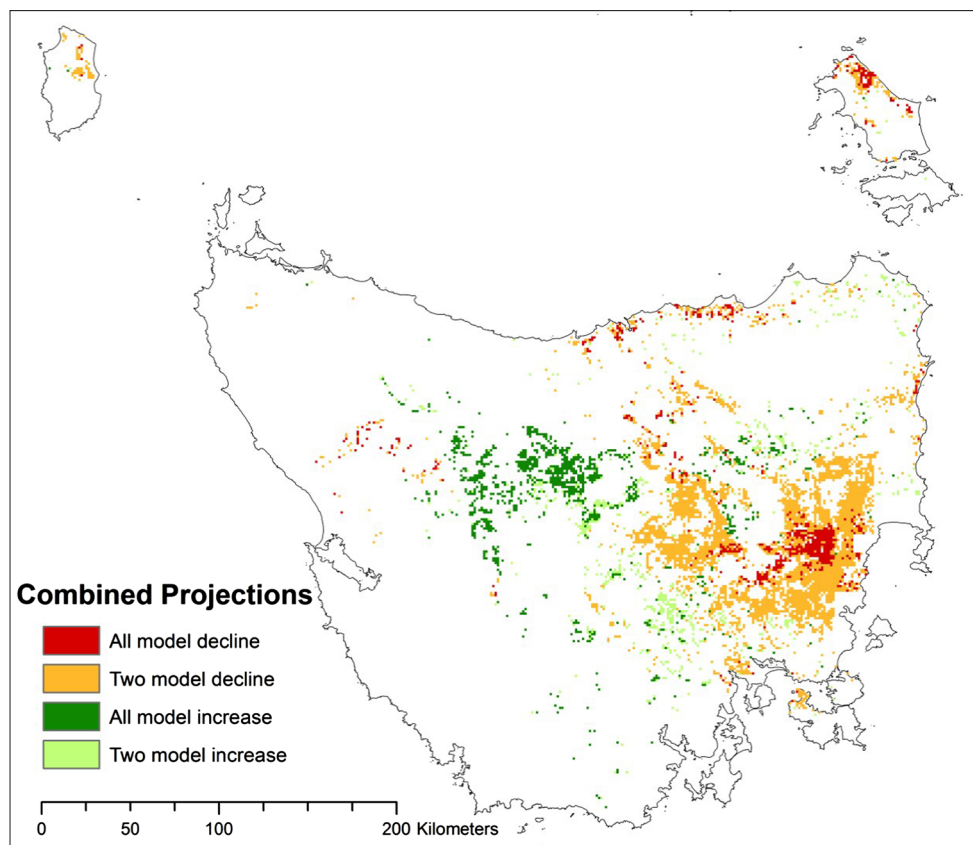
Fig. 4 Map showing areas of agreement in projected canopy cover in Tasmania in 2070–2099, based on the projections of the three downscaled GCMs

specific areas. Such complexities are difficult to capture in prognostic analyses using projected climates; hence, we chose to use a suite of climate variables selected because they were biologically meaningfully and readily available from climate models outputs. However, we believe the inclusion of the July and January monthly temperature extreme values helped to take into account this putative effect (Appendix 4).

Two of the three GCMs we used suggest that conditions will become hotter and, on average, drier, leading to a net loss of canopy cover in the state's eucalypt forests. All GCMs indicate this canopy cover loss will be centered on the Midlands, the driest part of the state. There is also a smaller area, focused on the Central Plateau, where canopy cover may potentially increase as temperatures warm from the current sub-optimal ones.

The analysis indicates that the low-lying regions of the east and northeast have the largest potential for decline in eucalypt cover. This region is in the lower range of mean annual rainfall for Tasmania (generally 600–1,000 mm), with mean annual potential evaporation at ∼1,000 mm, creating a mean water balance of approximately 0 to −400 mm. The tree cover model shows eucalypt cover has high sensitivity to rainfall in the range 500–1,000 mm and water balance between 0 and −500 mm, so the projected change in tree cover in this region is driven mainly by the projected change in mean annual rainfall and water availability. There is a spread of projections in rainfall for this region in the three models examined, with two showing a decline and one showing an increase, and also an increase in rainfall indicated in this region by the other three CCAM simulations not considered (Grose et al. 2010). There is also a high degree of uncertainty when examining projected rainfall changes at this highly regional scale. Therefore, rather than giving a single central projection of eucalypt cover in this region under a warming climate, we highlight the sensitivity of cover to water balance in this region and indicate that there is a range of possible projections, including a plausible scenario where eucalypt cover declines by >10 % based on the changes to mean conditions alone. GCM selection is therefore crucial, and interpretation of projections based on any individual GCM should acknowledge this source of uncertainty. However, there are other factors to consider not covered by changes to the mean.

Lower tree canopy cover and biomass may result from one or a combination of lower recruitment rates, increased mortality and slower growth. Tree recruitment is likely to be particularly vulnerable to the direct and indirect effects of climate change because woody seedlings are sensitive to drought, climate variability, fire, and herbivory (Brown and Wu 2005; North et al. 2005; Ibanez et al. 2007; Lloret et al.
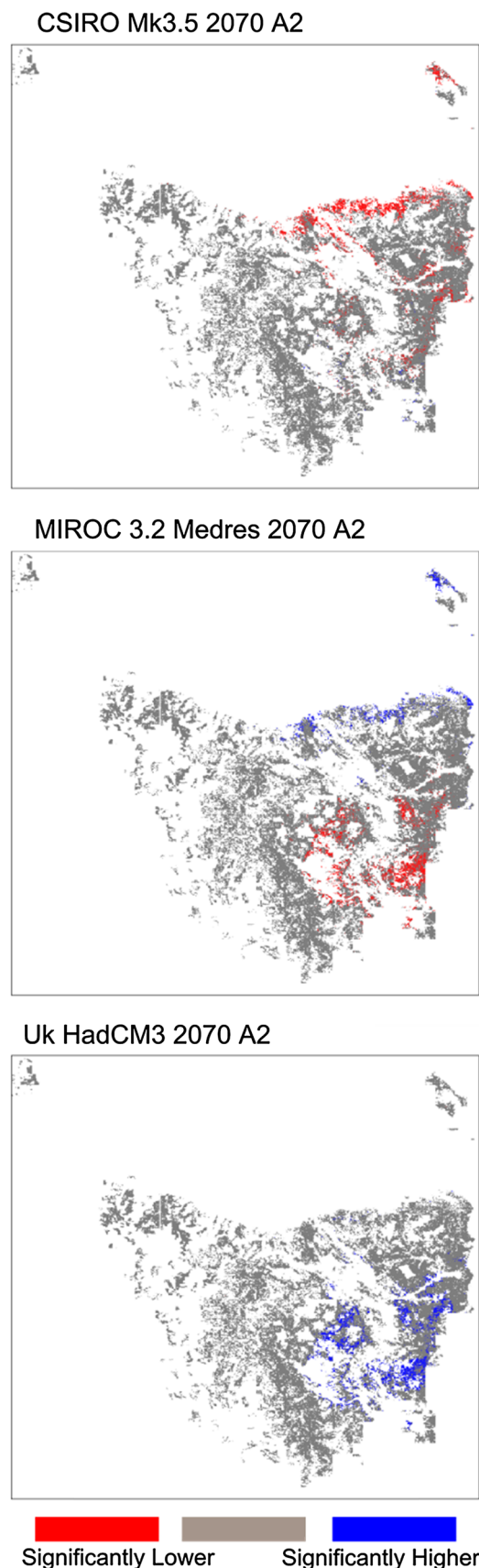
CSIRO Mk3.5 2070 A2

MIROC 3.2 Medres 2070 A2

Uk HadCM3 2070 A2

Significantly Lower | Significantly Higher

◀**Fig. 5** Significant pairwise differences ($p < 0.05$) in projected eucalyptus cover change for Tasmania under three GCMs, relative to the mean projected change ($p < 0.05$)

2009; Brodie et al. 2012; Kouba et al. 2012; Mok et al. 2012). Globally, there is evidence that tree mortality is increasing because of more frequent and more severe droughts and fires (van Mantgem et al. 2009; Allen et al. 2010; Michaelian et al. 2011; Williams et al. 2010), leading to reduced woody vegetation cover in many regions, especially semiarid ones (Notaro 2008). In addition to changes in average rainfall, increasing climate variability and higher evaporation rates from hotter temperatures will also reduce water availability to plants. Severe drought, which is likely to become more frequent with climate change, has been linked to substantial crown dieback and death of eucalypts in mainland Australia (Fensham et al. 2009; Brouwers et al. 2012). Drought also exacerbates the dieback and mortality of Tasmanian eucalypts induced by intensified land-use practices (McMurray 1983; Davidson et al. 2007).

The observed trends in eucalypt canopy cover in relation to climate are similar to global patterns showing a peak in forest biomass in cool maritime climates (Larjavaara and Muller-Landau 2012). The climatic trends in canopy cover were also very similar to those of eucalypt growth (Prior et al. 2011), consistent with growth rate being a major determinant of canopy cover. In warm climates, tree growth is limited more strongly by low precipitation and high temperatures than by low temperatures (Mäkinen et al.

Table 3 Projected percentage change in *Eucalyptus* cover in Tasmanian Interim Biogeographic Regionalization for Australia (IBRA) bioregions under three GCMs

| Region	CSIRO Mk3.5 %	MirocMedres 3.2 %	UK HadCM3 %
Ben Lomond	−5.8	0.2	4.3
Flinders	**−22.5**	−1.2	−0.5
King	−5.0	−2.8	−3.7
Tasmanian central highlands	2.7	1.3	**10.1**
Tasmanian northern Midlands	**−13.2**	−9.8	**13.0**
Tasmanian northern slopes	−6.3	−0.6	0.1
Tasmanian southeast	**−11.6**	**−18.2**	**11.0**
Tasmanian southern ranges	1.5	−0.4	3.1
Tasmanian west	−2.9	−2.4	−3.4
All Tasmania	−0.6	−0.4	0.5

Changes greater than 10 % are highlighted in bold
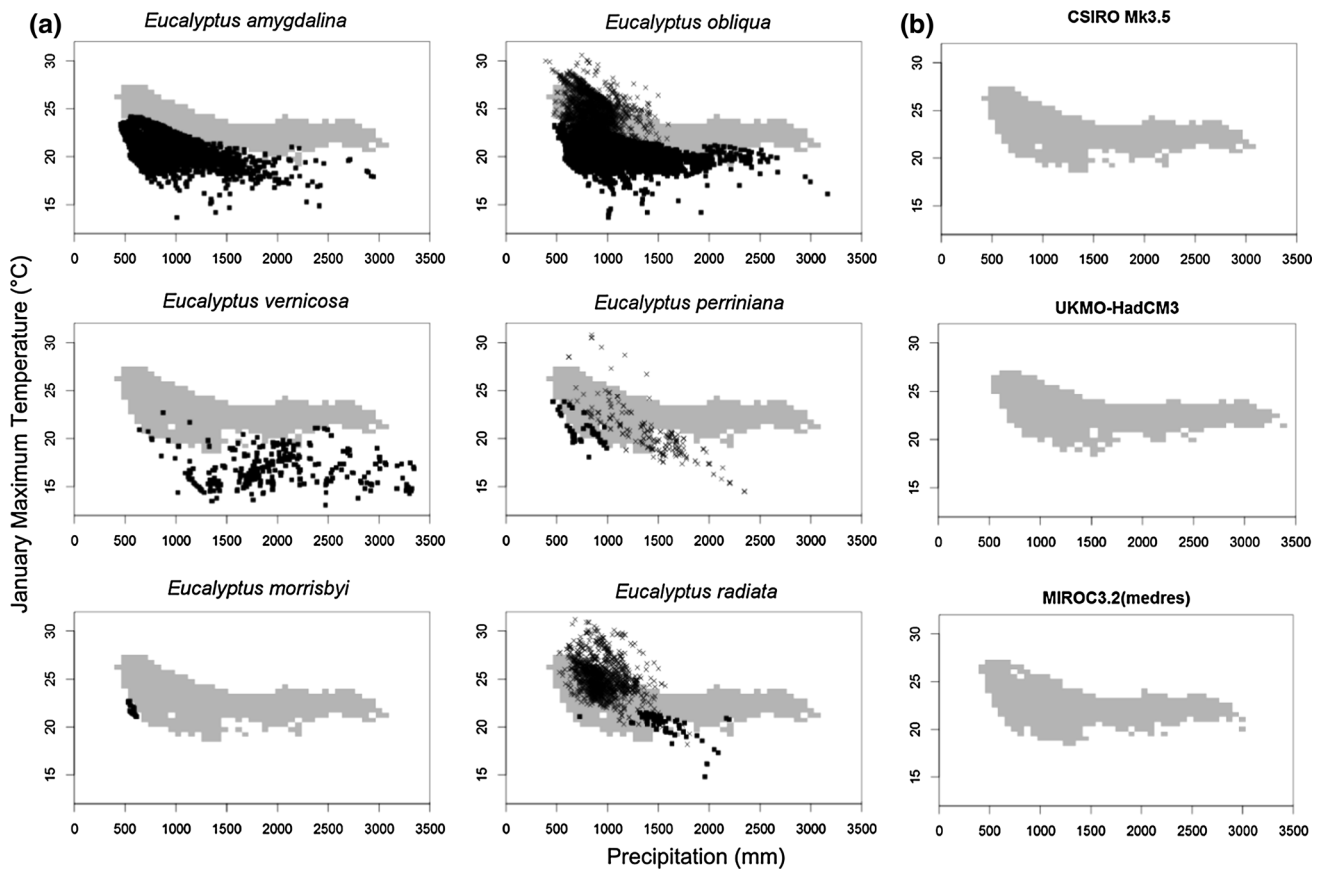
Fig. 6 a Occurrence in relation to mean annual precipitation and mean January maximum temperature of six eucalypt species, sourced from the species records in the Atlas of Living Australia (http://www.ala.org.au) and ANUCLIM. Tasmanian endemic species are shown in the *left-hand panels* and non-endemics in the *right-hand panels*. Tasmanian records are represented by *squares* and mainland records by *crosses*. The *gray area* represents the climate envelope projected for Tasmania for the period 2070–2099 under the CSIRO Mk3.5 Model. *Eucalyptus amygdalina* and *E. obliqua* are widespread, while the other species have more restricted distributions in Tasmania. **b** Climate envelope for the CSIRO Mk3.5 projections compared to the UKMO-HadCM3 and MIROC3.2 (medres) model projections

2002; Reich and Oleksyn 2008; Maxime and Hendrik 2011). Thus, as temperatures increase, growth of eucalypts is likely to slow in all but the coldest areas of Australia (Prior et al. 2011). It is unlikely that these climatically induced growth reductions will be offset by the CO_2 fertilization effect, even though water-use efficiency will probably increase (Peñuelas et al. 2011; Booth 2013).

Indeed, over the past 50 years, increased atmospheric CO_2 has consistently led to increased water-use efficiency across the planet but tree growth has generally declined, especially at lower latitudes (Silva and Anand 2013). Any direct benefits of increased atmospheric CO_2 on tree growth may have been offset by perturbations to foliar nutrient concentrations (Sherwin et al. 2013), as well as the climatically induced growth reductions discussed above.

Our modelling considered changes in mean annual precipitation, but not in the seasonal or inter-annual distribution of that rainfall. The changes in seasonal rainfall are expected to be larger than annual totals, with the west coast showing an increase in winter and a decrease in

summer rainfall, the central highlands a decrease in every season, and the northern east coast an increase in autumn and summer rainfall (Grose et al. 2010). Trees growing in areas with decreased summer rainfall will experience more intense drought stress, potentially leading to greater loss of canopy cover than suggested by our analysis. In addition, increased inter-annual climate variability may reduce vegetation cover (Notaro 2008).

On continental or global scales, while climate constrains the upper limit of forest biomass, it explains little of its variation, with realized biomass often falling below the constraint due to disturbances such as fire and herbivory (Sankaran et al. 2008; Stegen et al. 2011). The effects of fire are implicitly included in our analysis, because current tree canopy cover is modified by fire. This is based on the assumption that climate and fire regimes are in a dynamic equilibrium. However, any changes to the current fire–canopy cover relationship (for example, due to changes in rainfall seasonality) may alter future canopy cover from the values projected here. In particular, tall eucalypt species

are especially vulnerable to increased frequency and intensity of wildfire because most are obligate seeders and generally killed after fire (Tng et al. 2012).

Will species translocations be required? Responses of individual species

Our projections of canopy cover change are probably optimistic, because they are based on cover of species and provenances that are adapted to current, rather than future, climates and assume instant dispersal and establishment of trees to new regions. Our analysis effectively assumes that many existing tree species are replaced by ones better adapted to the warmer conditions. Hughes et al. (1996) stressed the fine thermal tolerance of most eucalypt species, with half of all species having a range in mean annual temperature across their distribution of less than 3 °C. Tasmania's future climates are already experienced by eucalypts on mainland Australia (Fig. 4), but may fall outside the current climate envelope of some Tasmanian endemics, which are therefore likely to be most affected by climate change. Increasing drought frequency has already been implicated in the decline of the endemic Tasmanian tree *Eucalyptus gunnii* spp. *divaricata* (Sanger et al. 2011), and other endemic species are also likely to be adversely affected by the hotter, drier summers projected for much of the state. Therefore, to achieve the future canopy cover projected by our models, compensatory range expansions by other species are required. This necessarily involves substantial lags unless anticipatory planting of non-native provenances or species is undertaken (Broadmeadow et al. 2005). Currently, there are plant trials and genetic studies to identify Tasmanian eucalypt species suitable for restoration plantings (Bailey et al. 2013). Restoration and carbon sequestration plantings need to consider the species and provenances most suitable for future, rather than present, climates (Close and Davidson 2004).

Not only do tree species vary in their climatic requirements, but also in their responses to changing climate (Linares et al. 2011). Already, increased aridity and fire frequency in eucalypt forests in southwest Western Australia have shifted species composition toward fire-resistant species and resulted in denser stands of small trees (Pekin et al. 2009). Similar changes in species composition and structure can be expected in Tasmanian forests, with concomitant changes in tree canopy cover and carbon storage.

To conclude, while eucalypt forests should persist over much of Tasmania during the coming century, climate change will modify their distribution, structure, canopy cover and biomass, and species composition. Maintaining the current high levels of canopy cover may require planting of new *Eucalyptus* species and provenances, including those currently found only on mainland Australia.

References

Allen CD, Macalady AK, Chenchouni H et al (2010) A global overview of drought and heat- induced tree mortality reveals emerging climate change risks for forests. Forest Ecol Manag 259:660–684

Bailey T, Davidson N, Potts B, Gauli A, Hovenden M, Burgess S, Duddles J (2013) Plantings for carbon, biodiversity and restoration in dry rural landscapes of Tasmania. Australian Forest Grower, Summer 2013 Edition

Becknell JM, Kucek LK, Powers JS (2012) Aboveground biomass in mature and secondary seasonally dry tropical forests: a literature review and global synthesis. Forest Ecol Manag 276:88–95

Booth TH (2013) Eucalypt plantations and climate change. Forest Ecol Manag 301:28–34

Bowman DMJS, Murphy BP, Banfai DS (2010) Has global environmental change caused monsoon rainforests to expand in the Australian monsoon tropics? Landsc Ecol 25:1247–1260

Broadmeadow MSJ, Ray D, Samuel CJA (2005) Climate change and the future for broadleaved tree species in Britain. Forestry 78:145–161

Brodie J, Post E, Watson F, Berger J (2012) Climate change intensification of herbivore impacts on tree recruitment. Proc R Soc B Biol Sci 279:1366–1370

Brouwers N, Mercer J, Lyons T, Poot P, Veneklaas E, Hardy G (2012) Climate and landscape drivers of tree decline in a Mediterranean ecoregion. Ecol Evol 3:67–79

Brown PM, Wu R (2005) Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. Ecology 86:3030–3038

Bureau of Rural Sciences (2008a) Australia's state of the forests report 2008. Department of Agriculture Fisheries and Forestry, Canberra

Bureau of Rural Sciences (2008b) Australian forest profiles. Eucalypts Department of Agriculture Fisheries and Forestry, Canberra

Burnham KP, Anderson DR (2002) Model selection and multimodel inference. A Practical Information-Theoretic Approach. Springer, New York

Cai WJ, Whetton PH, Karoly DJ (2003) The response of the Antarctic Oscillation to increasing and stabilized atmospheric CO_2. J Clim 16:1525–1538

Calef MP, McGuire AD, Epstein HE, Rupp TS, Shugart HH (2005) Analysis of vegetation distribution in Interior Alaska and sensitivity to climate change using a logistic regression approach. J Biogeogr 32:863–878

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen

Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Cambridge University Press, Cambridge

Close DC, Davidson NJ (2004) Review of rural tree decline in a changing Australian climate. Tasforests 15:1–18

Corney SP, Katzfey JJ, McGregor JL et al (2010) Climate Futures for Tasmania: climate modelling technical report. Hobart, Tasmania

Davidson NJ, Close DC, Battaglia M et al (2007) Eucalypt health and agricultural land management within bushland remnants in the Midlands of Tasmania, Australia. Biol Conserv 139:439–446

Eldridge DJ, Bowker MA, Maestre FT, Roger E, Reynolds JF, Whitford WG (2011) Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis. Ecol Lett 14:709–722

Environment Australia (2000) Revision of the Interim Biogeographic Regionalization of Australia (IBRA) and the development of version 5.1—summary report. Department of Environment and Heritage, Canberra

Executive Steering Committee for Australian Vegetation Information (2003) National Vegetation Inventory System 3.0. Canberra, ACT

Fauset S, Baker TR, Lewis SL et al (2012) Drought-induced shifts in the floristic and functional composition of tropical forests in Ghana. Ecol Lett 15:1120–1129

Fensham RJ, Fairfax RJ (2003) Assessing woody vegetation cover change in north-west Australian savanna using aerial photography. Int J Wildland Fire 12:359–367

Fensham RJ, Fairfax RJ, Ward DP (2009) Drought-induced tree death in savanna. Global Change Biol 15:380–387

Gill AM, Belbin L, Chippendale GM (1985) Phytogeography of Eucalyptus in Australia. Bureau of Flora and Fauna, Canberra

Good SP, Caylor KK (2011) Climatological determinants of woody cover in Africa. Proc Natl Acad Sci USA 108:4902–4907

Grose MR, Barnes-Keoghan I, Corney SP et al (2010) Climate futures for Tasmania: general climate impacts technical report. Hobart, Tasmania

Hansen M, DeFries R, Townshend JR, Carroll M, Dimiceli C, Sohlberg R (2006) Vegetation Continuous Fields MOD44B, 2001 Percent Tree Cover, Collection 4. University of Maryland, College Park, Maryland, 2001

Heubes J, Kuhn I, Konig K, Wittig R, Zizka G, Hahn K (2011) Modelling biome shifts and tree cover change for 2050 in West Africa. J Biogeogr 38:2248–2258

Hoffmann WA, Schroeder W, Jackson RB (2002) Positive feedbacks of fire, climate, and vegetation and the conversion of tropical savanna. Geophys Res Lett. doi:10.1029/2002GL015424

Hughes L, Cawsey EM, Westoby M (1996) Geographic and climatic range sizes of Australian eucalypts and a test of Rapoport's rule. Global Ecol Biogeogr Lett 5:128–142

Hutchinson MF, Xu TB (2011) ANUCLIM version 6.1 User guide. Fenner School of Environment and Society, Australian National University, Canberra

Ibanez I, Clark JS, LaDeau S, Hille Ris Lambers J (2007) Exploiting temporal variability to understand tree recruitment response to climate change. Ecol Monogr 77:163–177

Iverson LR, Prasad AM (2002) Potential redistribution of tree species habitat under five climate change scenarios in the eastern US. Forest Ecol Manag 155:205–222

Keith H, Mackey BG, Lindenmayer DB (2009) Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. Proc Natl Acad Sci USA 106:11635–11640

Kouba Y, Camarero JJ, Alados CL (2012) Roles of land-use and climate change on the establishment and regeneration dynamics of Mediterranean semi-deciduous oak forests. Forest Ecol Manag 274:143–150

Lambeck K, Chappell J (2001) Sea level change through the last glacial cycle. Science 292:679–686

Larjavaara M, Muller-Landau HC (2012) Temperature explains global variation in biomass among humid old-growth forests. Global Ecol Biogeog 21:998–1006

Liaw A, Wiener M (2002) Classification and regression by random-Forest. R News 2:18–22

Linares JC, Delgado-Huertas A, Carreira JA (2011) Climatic trends and different drought adaptive capacity and vulnerability in a mixed Abies pinsapo-Pinus halepensis forest. Clim Change 105:67–90

Littell JS, Oneil EE, McKenzie D et al (2010) Forest ecosystems, disturbance, and climatic change in Washington State, USA. Clim Change 102:129–158

Lloret F, Penuelas J, Prieto P, Llorens L, Estiarte M (2009) Plant community changes induced by experimental climate change: seedling and adult species composition. Perspect Plant Ecol 11:53–63

Mäkinen H, Nojd P, Kahle HP et al (2002) Radial growth variation of Norway spruce (Picea abies (L.) Karst.) across latitudinal and altitudinal gradients in central and northern Europe. Forest Ecol Manag 171:243–259

Matías L, Jump AS (2012) Interactions between growth, demography and biotic interactions in determining species range limits in a warming world: the case of Pinus sylvestris. Forest Ecol Manag 282:10–22

Maxime C, Hendrik D (2011) Effects of climate on diameter growth of co-occurring Fagus sylvatica and Abies alba along an altitudinal gradient. Trees 25:265–276

McGregor JL, Dix MR (2008) An updated description of the conformal-cubic atmospheric model. In: Hamilton K, Ohfuchi W (eds) High resolution numerical modelling of the atmosphere and ocean. Springer, New York, pp 51–76

McMurray SK (1983) An investigation of tree decline on Tasmanian farms. Masters, University of Tasmania

Michaelian M, Hogg EH, Hall RJ, Arsenault E (2011) Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. Global Change Biol 17:2084–2094

Mitchard ETA, Saatchi SS, Gerard FF, Lewis SL, Meir P (2009) Measuring WoodyEncroachment along a Forest-Savanna Boundary in Central Africa. Earth Interact 13:1–29

Mok H-F, Arndt SK, Nitschke CR (2012) Modelling the potential impact of climate variability and change on species regeneration potential in the temperate forests of South-Eastern Australia. Global Change Biol 18:1053–1072

Murphy BP, Bowman DJMS (2012) What controls the distribution of tropical forest and savanna? Ecol Lett 15:748–758

Nakićenović N, Swart R (2000) Special report on emissions scenarios. A special report of working group III of the intergovernmental panel on climate change. Cambridge, pp 599

North M, Hurteau M, Fiegener R, Barbour M (2005) Influence of fire and El Nino on tree recruitment varies by species in Sierran mixed conifer. Forest Sci 51:187–197

Notaro M (2008) Response of the mean global vegetation distribution to interannual climate variability. Clim Dyn 30:845–854

Pekin BK, Boer MM, Macfarlane C, Grierson PF (2009) Impacts of increased fire frequency and aridity on eucalypt forest structure, biomass and composition in southwest Australia. Forest Ecol Manag 258:2136–2142

Peñuelas J, Canadell JG, Ogaya R (2011) Increased water-use efficiency during the 20th century did not translate into enhanced tree growth. Global Ecol Biogeogr 20:597–608

Phillips OL, Lewis SL, Baker TR, Chao KJ, Higuchi N (2008) The changing Amazon forest. Philos T R Soc B 363:1819–1827

Prior LD, Williamson GJ, Bowman DMJS (2011) Using permanent forestry plots to understand the possible effects of climate change on Australia's production forest estate. Department of Agriculture, Fisheries and Forestry, Canberra

Prior LD, Sanders GJ, Bridle KL, Nichols SC, Harris R, Bowman DJMS (2013) Land clearance not dieback continues to drive tree loss in a Tasmanian rural landscape. Reg Environ Change. doi:10.1007/s10113-012-0396-0

Rabus B, Eineder M, Roth A, Bamler R (2003) The shuttle radar topography mission—a new class of digital elevation models acquired by spaceborne radar. ISPRS J Photogramm 57:241–262

Reich PB, Oleksyn J (2008) Climate warming will reduce growth and survival of Scots pine except in the far north. Ecol Lett 11:588–597

Sanger JC, Davidson NJ, O'Grady AP, Close DC (2011) Are the patterns of regeneration in the endangered *Eucalyptus gunnii* ssp. divaricata shifting in response to climate? Aust Ecol 36(6): 612–620

Sankaran M, Ratnam J, Hanan N (2008) Woody cover in African savannas: the role of resources, fire and herbivory. Global Ecol Biogeogr 17:236–245

Sherwin GL, George L, Kannangara K, Tissue DT, Ghannoum O (2013) Impact of industrial- age climate change on the relationship between water uptake and tissue nitrogen in eucalypt seedlings. Funct Plant Biol 40:201–212

Silva LCR, Anand M (2013) Probing for the influence of atmospheric CO_2 and climate change on forest ecosystems across biomes. Global Ecol Biogeogr 22:83–92

Sitch S, Huntingford C, Gedney N et al (2008) Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five dynamic global vegetation models (DGVMs). Global Change Biol 14:2015–2039

Stegen JC, Swenson NG, Enquist BJ et al (2011) Variation in above-ground forest biomass across broad climatic gradients. Global Ecol Biogeogr 20:744–754

Sterling S, Ducharne A (2008) Comprehensive data set of global land cover change for land surface model applications. Global Biogeochem Cycle. doi:10.1029/2007gb002959

Tchebakova NM, Parfenova EI, Soja AJ (2011) Climate change and climate-induced hot spots in forest shifts in central Siberia from observed data. Reg Environ Change 11:817–827

Thackway R, Donohue RJ, Smart R (2004) Integrated regional vegetation information—a compilation of vegetation types for National Action Plan and Natural Heritage Trust regions. Canberra, ACT

Tng DYP, Williamson GJ, Jordan GJ, Bowman DMJS (2012) Giant eucalypts—globally unique fire-adapted rain-forest trees? New Phytol 196:1001–1014

van Mantgem PJ, Stephenson NL, Byrne JC et al (2009) Widespread Increase of tree mortality rates in the western United States. Science 323:521–524

VanDerWal J, Falconi L, Januchowski S, Shoo L, Storlie C (2012). SDMTools: species distribution modelling tools: tools for processing data associated with species distribution modelling exercises. R package version 1.1-13. http://CRAN.R-project.org/package=SDMTools

White C, McInnes K, Cechet R, Corney S, Grose M, Holz G, Katzfey J, Bindoff N (2013) On regional dynamical downscaling for the assessment and projection of temperature and precipitation extremes across Tasmania, Australia. Clim Dyn. doi:10.1007/s00382-013-1718-8

Williams AP, Allen CD, Millar CI et al (2010) Forest responses to increasing aridity and warmth in the southwestern United States. Proc Natl Acad Sci USA 107:21289–21294

Wiltshire R, Potts B (2007) Eucaflip. Life-size guide to the eucalypts of Tasmania. University of Tasmania, Hobart

Yin JH (2005) A consistent poleward shift of storm tracks in simulations of 21st Century climate. Geophys Res Lett 32: L18701