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Changing Climate Suitability for Dominant Eucalyptus Species May Affect Future Fuel Loads and Flammability in Tasmania

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Abstract: Fire management is becoming increasingly relevant in our changing climate as fire frequency and intensity increases both on a global scale and locally in Tasmania. The distribution of fuel across the landscape has significant impacts on fire regimes, influencing connectivity and flammability of fuel load. Remote sensing techniques are often used to assess current fuel loads, but projections of future fuel distributions are necessary for longer term planning of fire management. *Eucalyptus* species are an important, dominant component of many Tasmanian forests, influencing fuel load and flammability. We modelled the current and future climate suitability for two *Eucalyptus* species (*E. delegatensis* and *E. obliqua*), using a suite of species distribution models (SDMs) and global climate models (GCMs) for mid (2041–2060) and end of century (2061–2080) time periods. The implications these changes may have for the distribution of these important fuel species in the future are discussed. All GCMs projected notable changes in potential distribution, with both species contracting substantially in some areas and *E. obliqua* also exhibiting considerable expansions in the west of Tasmania. On average, suitability for *E. delegatensis* expanded by 5% $\pm$ 1.8% (1658 km^2), contracted by 67% $\pm$ 22.7% (24,591 km^2) and remained unchanged in 26% $\pm$ 7.8% (8783 km^2) by the end of the century. For *E. obliqua* suitability expanded by a much greater 17% $\pm$ 6.3% (24,398 km^2), contracted by slightly less at 55% $\pm$ 16.8% (81,098 km^2) and remained unchanged in 45% $\pm$ 16.8% (63,474 km^2) by the end of the century. These changes in climate suitability have the potential to cause changes in the composition and structure of Tasmania's forests, impacting fuel loads. However, the two species exhibited different responses, reflecting their current distributions and suggesting that generalisations regarding species' responses to changing climates are not appropriate, even where the species are closely related. These results suggest that future fuel loads and flammability at the landscape scale may change, requiring longitudinal, flexible and adaptive future fire management. Assessing the specific effects of distributional changes and the mechanisms driving different responses to climate change are highlighted as further research opportunities.

Keywords: fire; management; climate change; species distribution models; SDM

1. Introduction

Fire management, the planning, prevention and fighting of fires, is becoming increasingly relevant in our changing climate as fire frequency and intensity increases on a global scale [1]. In recent history shifts have been observed in bushfire occurrence [2,3] as illustrated by the two extreme bushfire events in Tasmania in 2016 and 2019. The 2016 Tasmanian bushfires affected 126,800 ha across the state and triggered a bushfire and climate change research project which concluded that the Tasmanian Wilderness World Heritage Area (TWWHA) will face increased bushfire risk due to climate change [4]. In 2019, bushfires in Tasmania again burned vast areas (210,311 hectares) [5]. An increased frequency of fire is expected to continue as climate change accelerates [6], including at a local scale with predictions for broad increases to fire danger in Tasmania from 1961 to 2100 [7]. This highlights the need for well-informed, forward planning fire management.

The earth's climate is changing and this has a direct impact on fire regimes [8], but it also affects which areas are suitable for species to live in [9–11]. Species distributions determine what fuel is available at a site, with fuel type and load having significant impacts on the extent, intensity, frequency and seasonality of fire [12]. This is in line with findings that individual species traits impact fire characteristics [13]. The continuity of fuel is also determined by species distributions, and influences a fire's extent, intensity, burning pattern, severity and duration [12]. Additionally, vegetation type has been shown to have significant impacts on the response of fire to warming climates in the southeast of Australia, with increases in fire frequency more likely for wetter, coastal temperate forests [3].

Species distributions are commonly studied using species distribution models (SDMs). SDMs are a collection of algorithms designed to analyse species occurrence data alongside environmental variables (e.g., climate and soils) to model the potential distribution of a species based on environmental suitability [14]. SDMs are becoming an increasingly useful tool in environmental research and are commonly and successfully used to define areas of conservation significance [15]. Using data from global climate models (GCMs), species distribution models can model potential future distributions under different emissions scenarios [14]. This allows for the analysis of possible contractions, expansions and shifts in species distribution. Such changes in species distribution affect the location of fuel which is highly relevant to fire regimes, with fuel being one of the three key components affecting fire activity [16].

Assessing the current state of fuel loads and distributions is useful for informing fire management practices [17], and is currently often achieved using remote sensing techniques [18]. While these techniques are highly useful and becoming more advanced [18], they are limited to assessing current fuel loads and distributions. Because climate change is a key driver of increasing fire risk, these static models of fuel loads may not be adequate for informing fire management under future conditions. While they are useful for short term purposes, techniques of assessing fuel loads with capabilities of future projection are required for the formulation of effective long-term fire management plans. Species distribution modelling is one possible method for assessing the state of both current and future fuel load distributions and may be a valuable compliment to preexisting fuel assessment methods.

Eucalyptus species are highly flammable [19,20] and dominant in many Australian forests [21], making them an important determinant of fuel loads and a suitable subject for studying fuel and fire management using SDMs. Eucalyptus species have been shown to shift in their distribution under a suite of projected future climates [22], with significantly less cover in the hottest, driest geographic areas, and significantly more in currently cooler regions. This is in line with evidence that Eucalypts are facing increasing climate stress [23]. In a study of 830 Eucalyptus species across Australia, it was shown that within the next few decades, entire populations of many Eucalypt species may be exposed to climatic conditions outside their range of tolerance [24]. Several studies have noted the importance of considering adaptability and dispersal when analysing projected changes in species distributions [25,26]. This has been reported to be particularly relevant to Eucalyptus species [26].

This study aims to model the environmental suitability of two Tasmanian Eucalyptus species (*E. delegatensis* and *E. obliqua*), under current and future climatic conditions, to assess the implications any potential changes to distribution may have on future fire activity. We focus on *E. delegatensis* and *E. obliqua* because they are dominant species in both dry and wet forests and their current distributions suggest different limiting factors. The current distribution of E.delegatensis suggests that temperature is an important determinant of this species' distribution, as it is restricted to cooler, sub-alpine areas in Tasmania and the Australian Alps [21]. In contrast, *E. obliqua*, with a broad south eastern Australian range, appears not to be limited to areas with lower temperatures, and is more moisture dependent [21]. As a result, they may exhibit contrasting changes to their future distributions, potentially enabling general rules for application to other species to be

identified. We test the null hypothesis that there will be no change in climate suitability for *E. delegatensis* or *E. obliqua* over the next century in Tasmania.

2. Method

Environmental suitability under current and future climate conditions for two Eucalyptus species (*E. delegatensis* and *E. obliqua*), was modelled using an ensemble of Species Distribution Models (SDMs) and Global Climate Models (GCMs). Areas where suitability is projected to increase, decrease or remain unchanged between the time periods are mapped and the extent of suitability for each species across Tasmania quantified.

2.1. Modelling Platform (The BCCVL)

All analyses were completed in the Biodiversity and Climate Change Virtual Laboratory (BCCVL) [27], an online modelling platform which provides integrated tools and datasets for climate change and species distribution analyses, with high powered computational and storage capacities.

2.2. Species Occurrence Data and Preparation

Species occurrence data for *E. delegatensis* [28] and *E. obliqua* [29] was imported from the Atlas of Living Australia (ALA) (https://www.ala.org.au/). The ALA is a nationwide database containing 9553 occurrence records for *E. delegatensis*, and 34,403 for *E. obliqua*. These records were cleaned to remove potentially low-quality records—those from before 1960, situated outside Australia, listed as preserved specimens or of unrecognised occurrence status and those flagged as an outlier for one or more bioclimatic layers. This data cleaning process is crucial, as it reduces discrepancies in the definition of the climatic conditions under which a species can occur caused by erroneous occurrence data [30,31]. Occurrence points arranged in rows indicative of human planting were retained in the data, as they were unlikely to be receiving maintenance and not flagged as preserved specimens. Species occurrence points nationwide, rather than a restricted Tasmanian subset, were used in the training of the models so that the full range of environmental conditions under which the species can survive and reproduce were best represented. After cleaning, 7639 records for *E. delegatensis* and 30,788 for *E. obliqua* remained. The dataset has been published for open access via Mendeley Data [32].

The current distribution of *E. obliqua* spans the coast of southeast Australia and is widely distributed in Tasmania, particularly along the north and east coasts, while *E. delegatensis* is restricted to subalpine forests in southeastern Australia and Tasmania.

2.3. Species Distribution Models

The distributions of the two Eucalyptus species under recent climatic conditions, between the years 1960–1990, were modelled using the cleaned data. Three different SDM algorithms were used to model the distributions, chosen to represent a range of algorithm types. The two algorithm types used were machine learning models and statistical models (listed in Table 1, with a description of their strengths and weaknesses). Default configurations (see Supplementary Methods S1) and generation of pseudo absences were used for each of the three models.

Table 1. Details of the three species distribution modelling algorithms used with associated descriptions, strengths and weaknesses.

Algorithm	Description	Strengths	Weaknesses
Artificial Neural Network (ANN)	A collection of models consisting of interconnected nodes arranged in three layers. Layer one is an input layer with a node for each environmental variable (EV), layer two is a hidden layer consisting of different weighted combinations of the EVs, and the third layer is an output layer representing a prediction of presence. The model learns by calculating the difference between the output layer and known occurrences and back propagating to achieve more accurate outcomes [33]	Powerful predictions; Handles large amounts of data; Can model non-linear relationships	Does not deal well with missing or outlying data; Inefficient handling of mixed data types; Long processing times
Maxent	Maximum entropy modelling finds the most uniform distribution that falls within the limits of the environments observed at known occurrence points. These limits are implemented as constraints of six types, being linear, quadratic, product, threshold, hinge and categorical [34]	Does not require absence data; Compatible with continuous and categorical variables; Considers interactions between variables; Inbuilt mechanisms to avoid overfitting	Provides suitability rather than probability of presence
Multivariate Adaptive Regression Splines (MARS)	A model that finds and partitions at appropriate points in environmental data and builds a linear regression model for each partitioned section which is then knotted together. The model has built-in pruning mechanisms to avoid overfitting, and makes no assumptions about response-predictor variable relationships (as linear regression models do) [35].	Handles many variables; Detects inter-variable interactions; Complex but fast; Handles outliers well	Overfitting; Difficult interpretation; Handles missing data poorly

The outputs from the three algorithms were combined into an ensemble mean to account for the variability associated with different SDM algorithms [36].

2.4. Climate Variables and Soil Parameters

Bioclimatic variables, derived from spatial interpolation of long-term mean monthly data, are commonly used in ecological studies and species distribution modelling. There

are 35 available bioclimatic variables, representing annual trends (e.g., mean annual temperature and precipitation), seasonal trends (e.g., annual range in temperature or precipitation) and extreme or limiting environmental factors (e.g., temperature of the coldest and warmest month, precipitation for wettest or driest quarters) [14,37].

Variable selection can affect the results of SDMs, particularly when projecting into future conditions [38], although this is less of an issue for long-lived sedentary plant species such as Eucalypts [14]. In consultation with ecologists from the Department of Primary Industries, Parks, Water and Environment (DPIPWE), bioclimatic variables were selected that were uncorrelated and expected to influence Eucalyptus distributions in Tasmania. Five variables representing seasonality in rainfall and temperature and the potential impact of extreme heat and dryness were selected: Annual Mean Temperature (B01), Maximum Temperature of Warmest Month (B05), Mean Temperature of Coldest Quarter (B11); Precipitation of the Driest Quarter (B17) and Isothermality (B03) (a measure of temperature consistency, calculated by dividing the average range in monthly temperature (B02) by the range in annual temperature (B07)) [39].

In addition to the bioclimatic variables, the model was trained with substrate data from the dataset 'Australia, National Soil Grids (2012), 9 arcsec (~250 m) [40]. Substrate is a strong determinant of Eucalyptus distributions [21] and it has been shown that using a combination of climate and landscape predictors results in more robust distribution models [41].

2.5. Climate Data—Current and Future

Environmental suitability for each species was modelled under current climate conditions and a range of projected future climate conditions. Statistically downscaled climate data at a spatial resolution of ~1 km (30 arcsec) from the BCCVL data collection was used (the 'Australia, current and future climate' dataset [39]). Data for the period 1976–2005 represents the current period, and two future time periods were chosen to represent mid-century (2041–2060) and end of century (2061–2080). Twenty year means are typically used when modelling future distributions to encompass a range of climatic variations that occur on decadal scale [42].

2.6. Global Climate Models

The Climate Futures Tool [43] was used to select three Global Climate Models (GCMs) with the aim of best representing the spectrum of plausible futures for Tasmania. Forty-eight different climate models were sorted into categories based on changes in temperature and rainfall, with a model from each of the three most common categories chosen, which were: (i) "Very hot, very dry", which comprised 19% of the Coupled Model Intercomparison Project 5 (CMIP5) model archive (9 of 48 models); (ii) "Hot, little rainfall change", which made up 21% of the models (10 of 48), and (iii) "Hot and dry", which represented 12% of the models (6 of 48). We did not consider a "warmer and wetter" scenario, because only 3 of the 48 models fell in this category.

The models selected were ACCESS1.0, to represent a very hot and very dry future (a temperature increase of >3 °C and annual precipitation decline of 15%); MIROC5 to represent a future with relatively low warming and little change in precipitation (a temperature increase of 1.5–3 °C and −5% to 5% change in annual precipitation), and CNRM-CM5, which projects a hot and dry future (a temperature increase of 1.5–3 °C and −15% to −5% change in annual precipitation (Table 2).

Table 2. Climate models selected to represent a range of plausible futures.

Climate Model	Projection for 2100 in Relation to the CMIP5 Archive Mean
ACCESS1.0	A hot, dry future. Warming exceeds 2.5 °C across most of Australia, and >3.5 °C in central Australia. Drying is projected over most areas, with decreased annual precipitation of 15%. This model shows high skill in modelling historical climate. Maximum consensus for many regions across Australia.
MIROC5	Moderate warming and slight changes in annual precipitation, with declines in north-east Queensland and south-west Australia; Relatively low warming, wetter model, with a 1.5–3 °C temperature increase and −5% to 5% change in annual precipitation.
CNRM-CM5	Hot/wet end of range in Southern Australia. A temperature increase of 1.5–3 °C and −15% to −5% change in annual precipitation. It also has a good representation of extreme El Niño in CMIP5 evaluations [44].

2.7. Emissions Scenarios

Future climate suitability was based on the highest of the Intergovernmental Panel on Climate Change's (IPCC) four emissions scenarios (RCP 8.5), which represents a future in which carbon emissions continue on our current trajectory without mitigation [45]. This is the scenario we are currently tracking [46]. However, if global emissions were reduced, similar patterns in climate trends are projected, but at a lower magnitude [42]. A single emissions scenario is sufficient to describe the next two to three decades, a time period of relevance to operational fire management, as the scenarios do not fully diverge until after 2040–2050 [42].

3. Results

The models reflected the known distributions of both species well (Figure 1), with *E. delegatensis* currently distributed over areas of mid to high elevation across most of the state, especially inland and to the east and *E. obliqua* exhibiting a relatively wide distribution across Tasmania, concentrated along a wide section of the north coast and the southeast quadrant.

The three models provided a similar pattern of environmental suitability for both species, but there was some variation in the extent of suitable area. The Maxent model produced the most restricted area for both species (Figure 1).

The projections showed that suitability for *E. delegatensis* may change notably over time, with high consensus between the three GCMs at each time period (Figure 2). The area with conditions suitable for *E. delegatensis* is projected to contract by 67% ± 22.7% (81,098 km^2) on average across the models by the end of the century (Table 3, Supplementary Table S2), contracting to the areas of highest elevation within its original distribution (Figure 2). A comparatively minimal expansion of only 5% ± 1.8% (1658) is expected to occur in the same time period (Figure 2 and Table 3). This contraction was particularly evident in the southern, eastern and northern edges of the original range of environmental suitability, with the western boundary remaining largely unchanged (Figure 2).
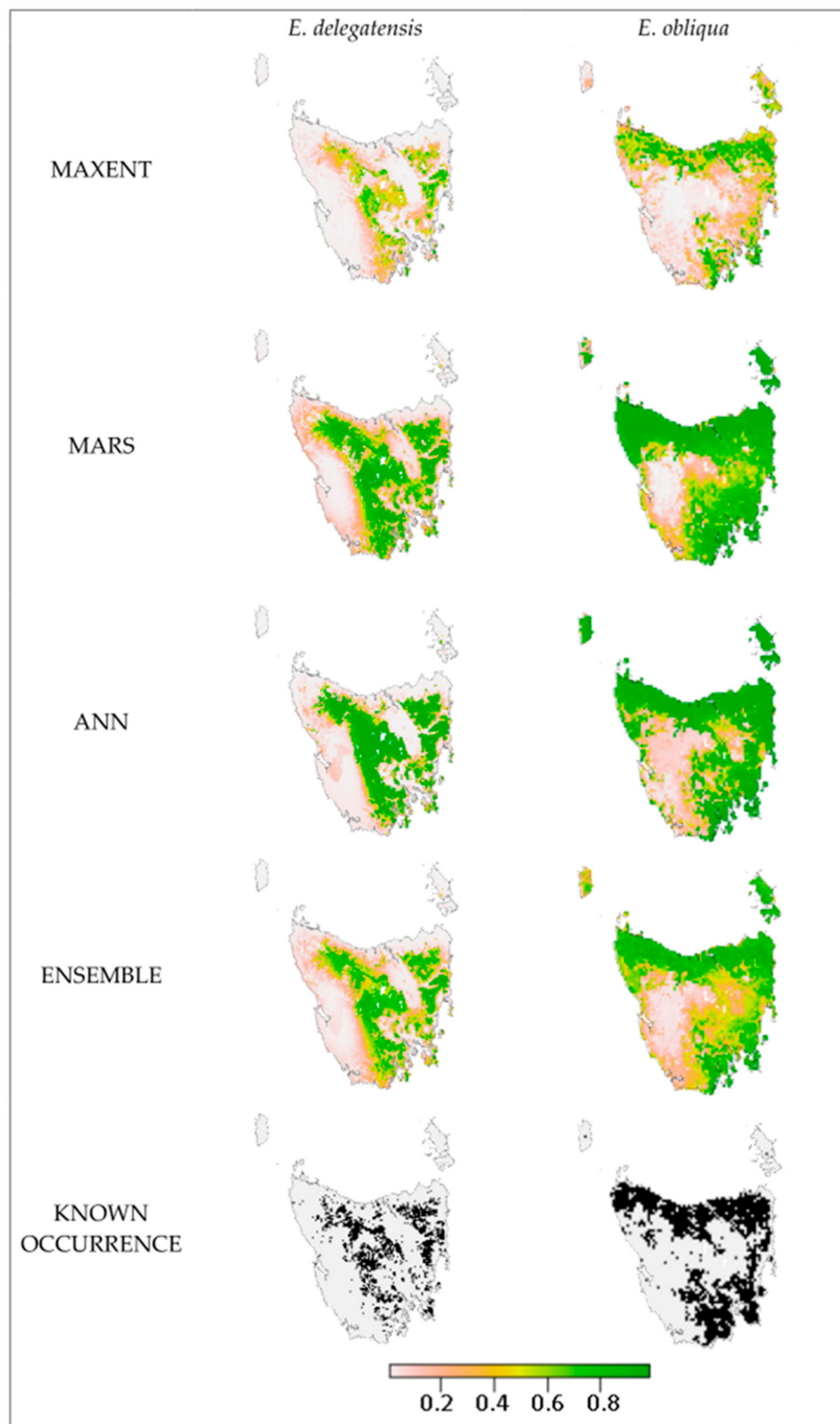
Figure 1. Environmental suitability for *E. delegatensis* and *E. obliqua* in Tasmania as modelled by SDM algorithms Maxent, multivariate adaptive regression splines (MARS) and artificial neural networks (ANN). The ensemble displays the mean of the three models. Black dots represent observed occurrence points.
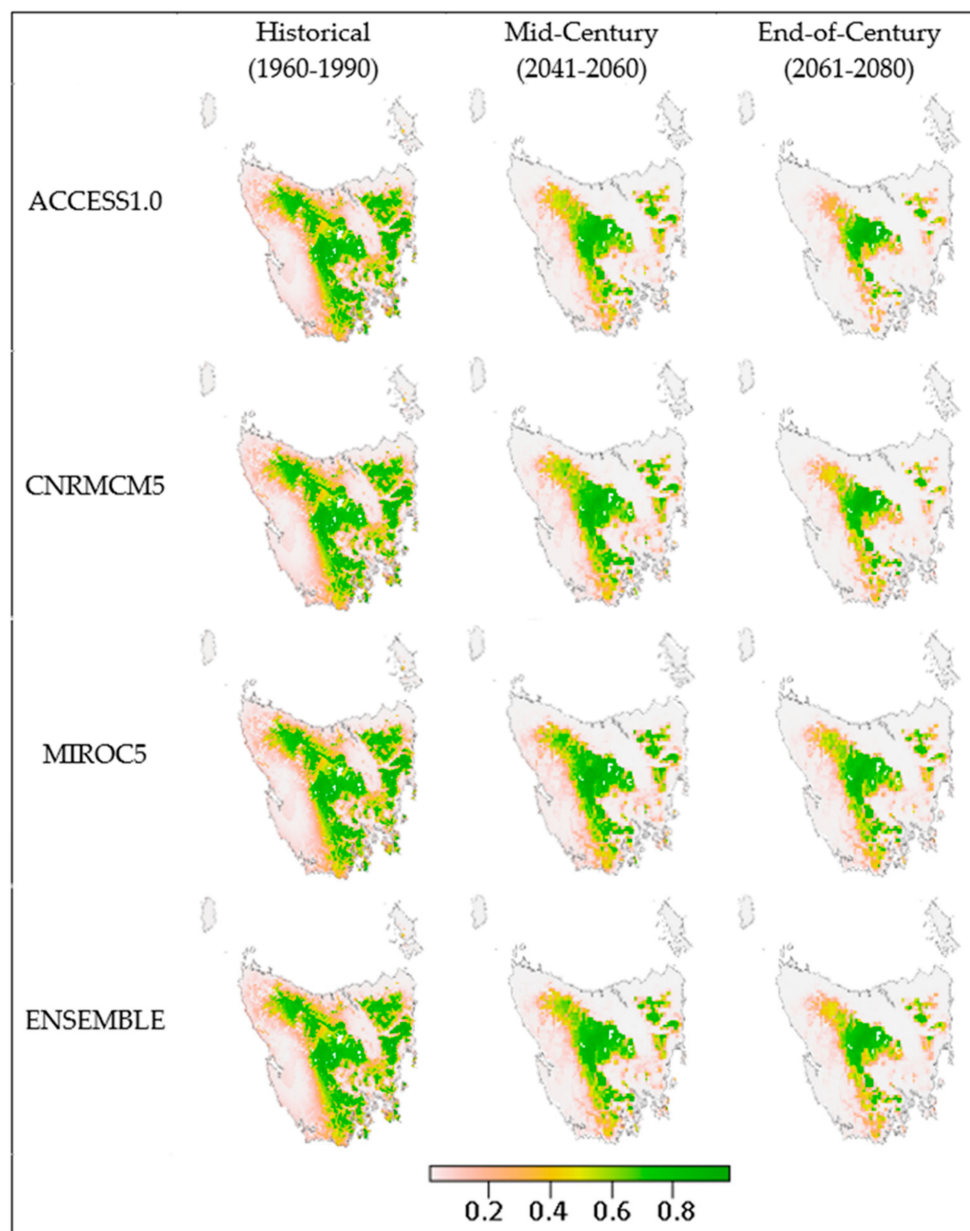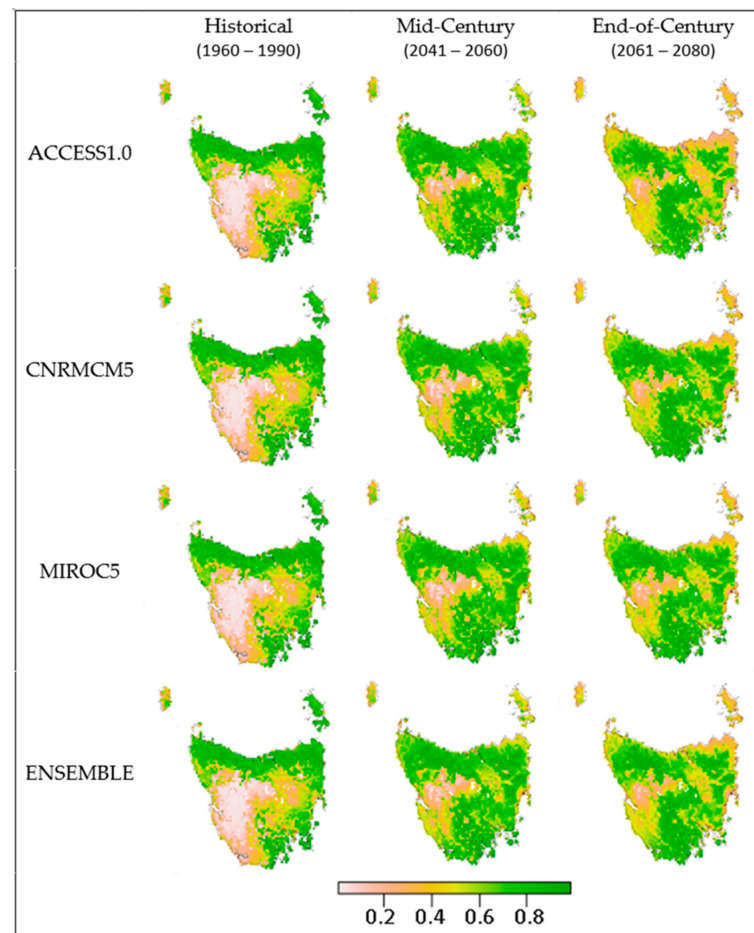
Figure 2. Environmental suitability for *E. delegatensis* in Tasmania as determined by an ensemble mean of 3 SDMs (Maxent, MARS and ANN) under historical (1960–1990) and projected future climates for mid (2041–2060) and end of century (2060–2081) according to global climate models ACCESS1.0, CNRM-CM5 and MIROC5, with ensemble mean of the 3 GCMs for each time period.

Table 3. Change in species range for *E. delegatensis* according to the mean of 3 SDMs (Maxent, MARS and ANN) and 3 global climate models (GCMs) (ACCESS1.0, CNRM-CM5 and MIROC5) as a percentage of initial distribution and areal extent (km^2).

	2050		2070	
	km^2	**%**	**km^2**	**%**
Contraction	18,763	56 ± 7.3	24,591	67 ± 22.7
No Change	14,500	44 ± 7.3	8783	26 ± 7.8
Expansion	2097	6 ± 1.4	1658	5 ± 1.8

Similarly, the projections of environmental suitability for *E. obliqua* showed substantial contractions in some regions over time (Figure 3), resulting in an average reduction of 55% ± 16.8% (81,098 km^2) across all models by end of century (Table 4, Supplementary Table S3). These contractions were largely limited to narrow areas around the coast, concentrated in the north and northeast (Figure 3). Contrary to the changes observed in *E. delegatensis*, the areas of environmental suitability for *E. obliqua* also expanded extensively into the southwest of Tasmania with an average expansion of 17% ± 6.3% by end of century (Table 4), resulting in a shift rather than a simple reduction in the geographic range of the species.
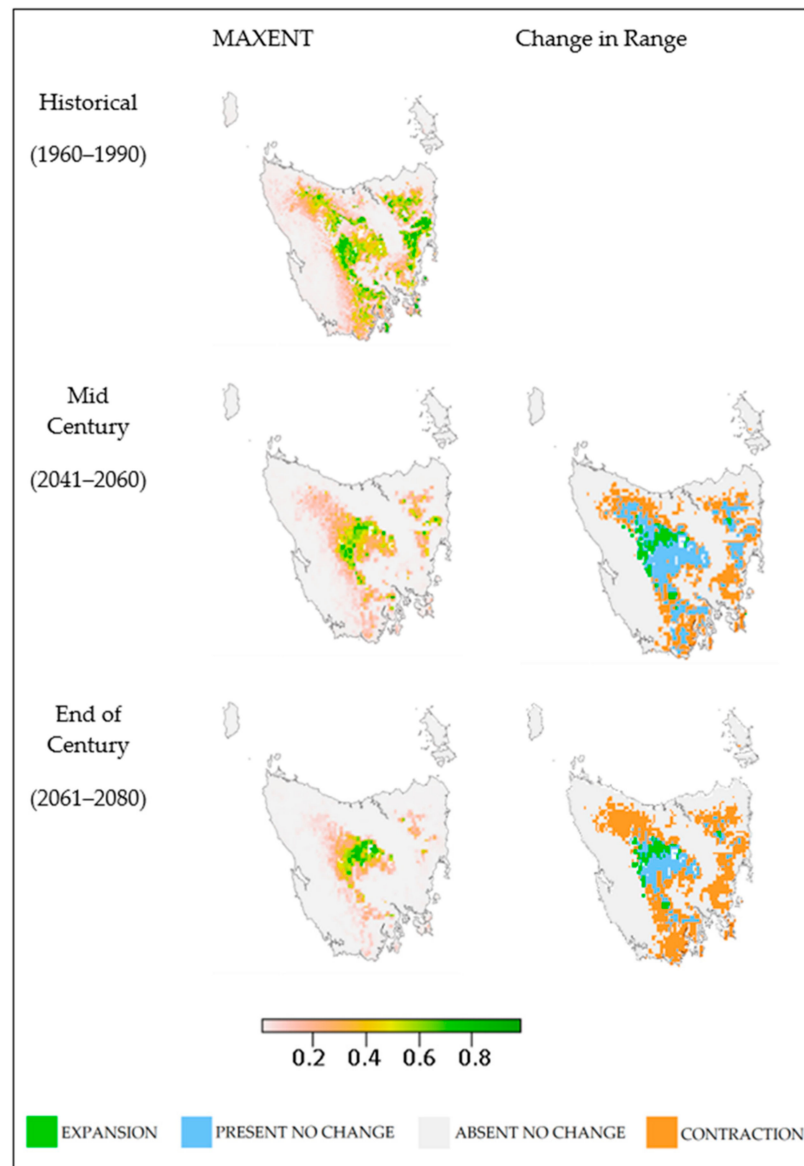

Figure 3. Environmental suitability for *E. obliqua* in Tasmania as determined by an ensemble of 3 SDMs (Maxent, MARS and ANN) under historical (1960–1990) and projected future climates for mid (2041–2060) and end of century (2060–2081) according to global climate models ACCESS1.0, CNRM-CM5 and MIROC5, with ensemble mean of the three GCMs for each time period.
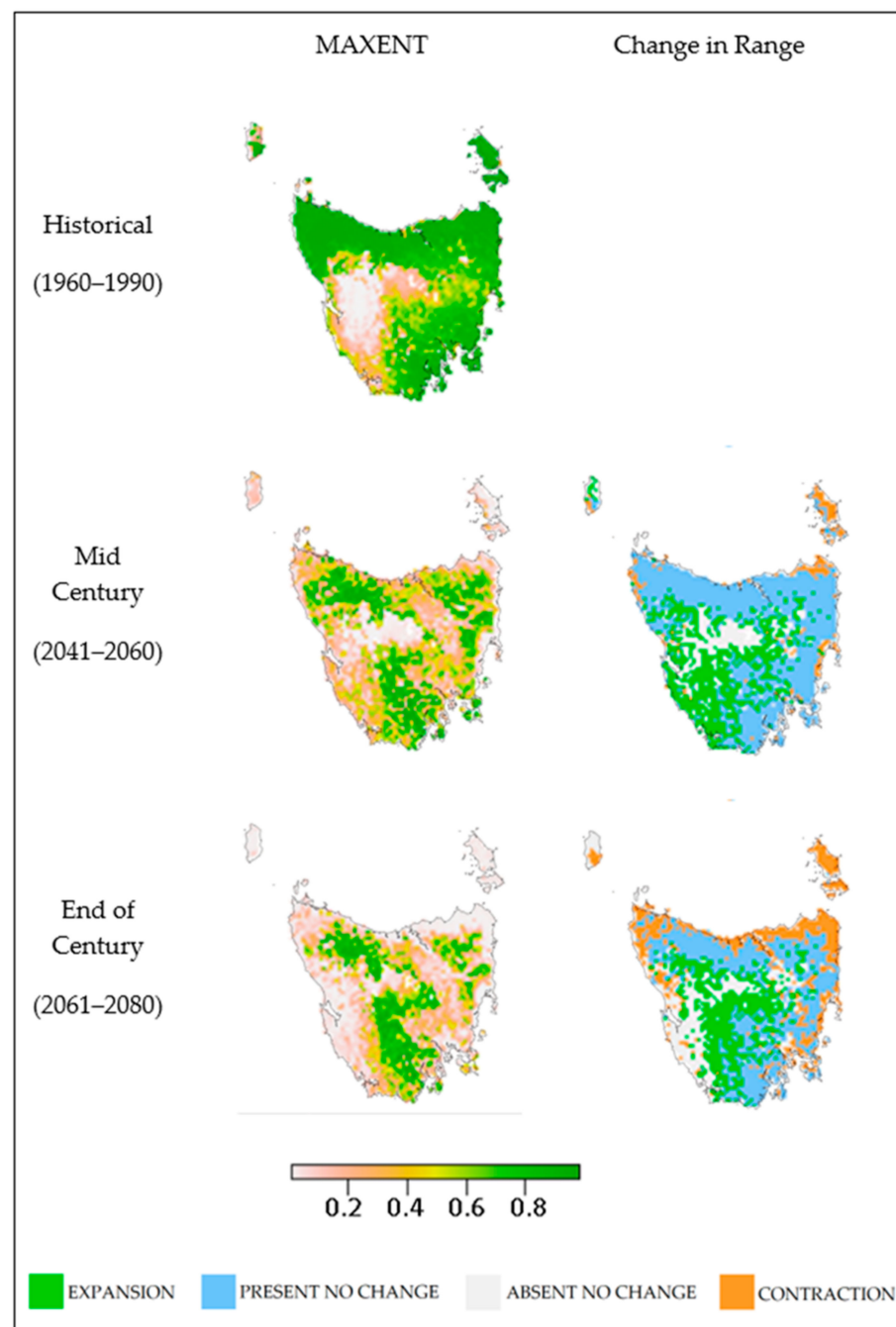
Table 4. Change in species range for *E. obliqua* according to the mean of 3 SDMs (Maxent, MARS and ANN) and 3 GCMs (ACCESS1.0, CNRM-CM5 and MIROC5) as a percentage of initial distribution and areal extent (km^2).

	2050		2070	
	km^2	**%**	**km^2**	**%**
Contraction	59,264	40 ± 13.9	81,098	55 ± 16.8
No Change	85,342	60 ± 12.1	63,474	45 ± 16.8
Expansion	26,085	18 ± 5.1	24,398	17 ± 6.3

The extent of contraction for *E. delegatensis* as predicted by SDM Maxent and the hottest driest GCM ACCESS1.0 was projected to be 82% of the original potential distribution by the end of century, with expansions projected for only 6% (Figure 4, Supplementary Table S2). A smaller, yet still substantial, contraction in *E. obliqua* of 76% was projected as well as, in contrast to *E. delegatensis*, a substantial expansion of 12% by the end of century (Figure 5, Supplementary Table S3). This expansion in environmental suitability for *E. obliqua* was greater at mid-century with a projected expansion of 19%, but suitability was then shown to decline under conditions projected for the end of the century.

Figure 4. Environmental suitability for *E. delegatensis* in Tasmania, shown as a probability of occurrence, and change in species range projected under historical (1960–1990) and future climates for mid (2041–2060) and end of century (2060–2081), as modelled by SDM Maxent and GCM ACCESS1.0.

Figure 5. Environmental suitability for *E. obliqua* in Tasmania, shown as a probability of occurrence, and change in species range projected under historical (1960–1990) and future climates for mid (2041–2060) and end of century (2060–2081), as modelled by SDM Maxent and GCM ACCESS1.0.

An SDM response curve illustrates the relationship between an environmental variable and the probability of occurrence of a species calculated by each algorithm, allowing an assessment of the relative importance of each variable in the modelled distribution [47]. The environmental variables shown to be the strongest determinants of species occurrence for *E. delegatensis* according to the three models were Maximum Temperature of the Warmest month (<25 °C), Precipitation of the Driest Quarter (100–400 mm), pH (>4), Annual Mean Temperature (~8–12 °C) and Mean Temperature of the Coldest Quarter (>8 °C). Soil clay content was shown to have little relationship and the models displayed mixed results for Isothermality, Plant Available Water Capacity and Bulk Density (Supplementary Material Figure S1). For *E. obliqua* there was more variation between the three models, with MARS

indicating no relationship for some variables which ANN and Maxent identified as important (soil bulk density and plant available water capacity). The strongest determinants of species range for *E. obliqua* were Soil Clay Content (>3%), Precipitation of the Driest Quarter (>300/500 mm), Annual Mean Temperature (<15/12 °C), Mean Temperature of the Coldest Quarter (7–10/15 °C) and Maximum Temperature of Warmest Month (~25–30 °C). Two of the three models (ANN and Maxent) showed a suitability for Soil Bulk Densities above 0.7 Mg/M^3 and a Plant Available Water Capacity of >40% for *E. obliqua*. A minor relationship was observed for pH (Supplementary Material Figure S2).

4. Discussion

This study has demonstrated that climate suitability for *Eucalyptus* species such as *E. delegatensis* and *E. obliqua* may change substantially over time due to anthropogenic climate change. Such changes have important implications for the potential distribution of these species, and because they are widespread, dominant tree species in a range of forest types, these changes are likely to have significant impacts for future fuel load and fire danger across Tasmania.

4.1. Outcomes

All Global Climate Models (GCMs) presented notable changes in future climate suitability for both species. The patterns of contraction and expansion for the two Eucalypt species are most clearly illustrated in projections using the 'worst-case' scenario, based on the most restricted SDM (Maxent) and the hot and dry GCM (ACCESS1.0) (Figures 4 and 5), which projected drastic contractions of up to 82% for *E delegatensis* and 76% for *E. obliqua*. Suitability for the more widely distributed *E. obliqua* increased in some areas and decreased in others, contracting in coastal areas and expanding in the west of the state. In contrast, suitability for *E. delegatensis* contracted to areas of higher elevation with very little expansion. This difference demonstrates that bioclimatic changes may pose a greater risk to narrowly distributed species than their more widely distributed counterparts, which is in line with previous findings that geographic range has a significant positive impact on species survivorship [48].

The three GCMs displayed similar changes in species range over time; however, variation was observed between the models in the extent of suitability, with ACCESS1.0, the hottest and driest of the models (with warming in excess of 2.5 °C by 2100), projecting noticeably larger contractions, and MIROC5, which projects the lowest warming, suggesting smaller contractions. This is in line with previous findings of *Eucalyptus'* response to very hot dry climatic conditions [22].

4.2. Potential Ecological Impacts

Changes to climate suitability, such as those projected here for *E. delegatensis* and *E. obliqua*, have the potential to lead to shifts in distribution, with ecosystem-wide repercussions, as is already being observed in natural systems globally [49,50]. As dominant species in many forest types [21], changes in the distribution of *E. obliqua* and *E. delegatensis* are likely to have substantial and cascading effects in forests across Tasmania. In areas where climate suitability declines and the species may contract, competition will be reduced, resulting in changing dominants, either to species that may already be present or new species that are able to disperse to fill the vacated niche. Contractions may also lead to declines in species where facilitatory relationships with the eucalypts occurred. In areas where changing suitability may result in expansions (as projected for E. *obliqua* in the southwest of Tasmania), competition with resident species could lead to population declines in species which are unable to compete with the eucalypts. There is also the possibility that the eucalypts will facilitate certain species to become more prominent or expand into the area.

Research has shown that species can have non-additive effects on fire risk [19], which makes these complex changes in vegetation composition even more important to consider

when evaluating the implications that shifting eucalypt distributions could have on fire management requirements. Such changes have the potential to substantially alter the structure, litter accumulation and flammability of forests. As shifts in distribution start to occur, historical knowledge of the fire attributes of different forest types will need to be reassessed and management changed accordingly.

4.3. Modelled and Realised Distributions

Species distribution modelling can indicate the potential for future changes in the distribution of species, but how changes are realised will be affected by many factors in addition to climate [26,51]. Reasons that actual distribution may not be the same as environmental suitability include expansions not being realised due to dispersal limitations, lags in response to changing environments and the influence of other species and their associated ecological interactions. Dispersal range can limit plants' capacity to expand [51,52], especially where suitable habitat is fragmented [53,54]. There can also be physical barriers to dispersal such as mountain ranges, which can substantially shape and limit the distribution of a species [55]. The ability of *E. delegatensis* and *E. obliqua* to expand into areas that become suitable in the future will also be limited by competition and interactions with other species [54,56]. From this, it is evident that it is important to consider what species are already at a site when assessing expansions in potential distribution, such as was projected for *E. obliqua* in the west of Tasmania. Another factor that may cause variations between modelled suitability and actual species distribution is a delayed response to changing bioclimatic conditions. There is expected to be a lag between changes in environmental suitability and changes in observed distribution [57], especially in tree species such as *Eucalyptus* which have relatively long lifespans [58]. This means that contractions and expansions in actual distribution may occur much later than projected changes in environmental suitability. This is especially relevant for cases such as *E. obliqua*, where projected expansions were observed to be greater at mid-century than end of century. Due to lag effects and *Eucalyptus*' slow rate of expansion, it is unlikely that the larger expansions projected at mid-century would ever be realised in the actual species distribution of *E. obliqua*.

On the other hand, the magnitude of extreme events can exceed the conditions that are projected to occur by the end of the century under the high emissions scenario (e.g., heat events with daily temperatures more than 10 °C higher than the long-term mean) [59,60], causing abrupt shifts in the composition and structure of forests decades before changes in mean climate conditions start to influence distributions. Changes to the fire regime can also lead to abrupt change, as has been seen in the *E. delegatensis* forests of the Australian Alps following repeated intense fires with insufficient time between fires for recovery [61,62]. Extreme events can reset competitive interactions, opening niches that can be filled by range-shifting species, facilitating the rapid movement of species. Such effects are increasingly being observed in natural systems in Australia and around the world [63–65].

The influence of the many ecological factors affecting species distribution which are not accounted for in species distribution models highlights the need for more complex and wholistic models. There are several different approaches to address this, such as combining landscape and climate predictor variables [41], using a multi-model framework to assess the combined impacts of climate change on the distribution of a species [66], and multi-species analysis [67]. Nevertheless, the outcomes from this study provide a good insight into changes that may occur in the future, and clearly represent shifts in single species range, from which implications and conclusions can be drawn.

4.4. Species Variation

The two *Eucalyptus* species exhibited different responses to changing climate in terms of their distributions, suggesting that generalisations regarding the response of different species to changes in climate, even when they are functionally and genetically similar, are not always appropriate. These differing responses are likely to be the due to the differing

climate conditions which limit the distribution of each species. For instance, *E. delegatensis* is restricted to subalpine areas and areas in Tasmania with average winter temperatures of less than 8 °C, whereas *E. obliqua* requires slightly warmer conditions (average winter temperatures greater than 10 °C) (Supplementary Figures S1 and S2).

4.5. Model Evaluation

The response curves for both *E. obliqua* and *E. delegatensis* indicate some degree of overfitting, where the model fits species distribution too strictly to the environments of known occurrence points, overstating noise and resulting in a failure to accurately predict occurrence [68]. This overfitting is especially evident in the Maxent algorithm, and more prevalent in *E. obliqua* than *E. delegatensis*, possibly due to increased noise resulting from the larger dataset of *E. obliqua* occurrences.

Multiple peaks in probability of occurrence were observed for some environmental variables for *E. obliqua* (annual temperature, warmest month and coldest quarter) (Supplementary Figure S2). This could possibly be explained by the existence of ecotypes, which are a sub-unit of a species resulting from a genotypical response to habitat [69] as described in [70]. This would be in agreement with previous research which has shown evidence for the existence of *E. obliqua* ecotypes [71], and could provide further explanation as to why the models projected differing responses between *E. obliqua* and *E. delegatensis*.

4.6. Implications for Fire Management

The projected shifts in environmentally suitable area for *E. delegatensis* and *E. obliqua* indicate a change in fire risk and management requirements, due to shifting fuel type and amount [12], and demonstrate the usefulness of SDMs as a complimentary tool in assessing fuel loads and informing longitudinal fire management plans. This has implications for the mapping and management of existing fuel and high fire danger areas as well as future fuel loads, which cannot be assumed to be static. Locations that may be high or low fire danger under present conditions may shift significantly over the next decades.

5. Conclusions

Species distribution modelling shows a shift in the climatic suitability for both *E. obliqua* and *E. delegatensis* over the next century, suggesting that these species may change their geographic distribution in the future. This has implications for fuel loads and flammability across the landscape, which could have a notable impact on fire management practices as the areas of greatest concern to fire management shift over time. These observations highlight the usefulness of SDMs as a complimentary tool for assessing fuel loads and informing long-term fire management plans. The two *Eucalyptus* species show contrasting responses to changing climate conditions, suggesting that generalisations regarding species' response to climate change are not always appropriate, and that climate change may pose a greater risk to narrowly distributed species than to those with wide distributions. The findings of this study highlight a need for fire management plans to be regularly updated as the climate continues to change, and for longitudinal plans to consider changing fire risk associated with vegetation change over time.

There is much that can still be learned about the impacts that changing vegetation distributions will have on fire management and how to best address these changes in management plans. There are many opportunities for further study in determining the complex ecological effects of contractions and expansions of a species, including the specific effects these will have on fire regimes. Opportunities for further study also lie in assessing what characteristics, such as breadth of original distribution, cause different species to respond to climate change differently. The responses of other fire-sensitive species to climate change is also a valid area for further research, due to this demonstration that there is unlikely to be a uniform response across even genetically similar species. This study provides an insightful initial step into the use of SDM as a tool for informing long term fire management practices and highlights a range of potential areas for further investigation.

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