Northward expansion of fire-adaptive vegetation in future warming

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Abstract

Fire frequency and intensity are increasing due to higher temperatures and more droughts. The distributions of fuels (vegetation in natural conditions) are also changing in response to climate change. The vegetation in cold environments such as high latitudes and high altitudes is found to move upward or northward due to global warming. However, few studies have investigated the distribution changes of fire adaptive species in warm environments. This study estimated and compared the distributions of a typical fuelwood, the *Eucalyptus globulus*, under different climate scenarios. The species distribution modeling techniques were adopted to estimate the current distributions of the *Eucalyptus globulus* and the future distributions under scenarios of both SSP245 and SSP585 in 2060. Results show that the probability of the existence of the *Eucalyptus globulus* in the Northern Hemisphere increases significantly ($p < 0.001$) under both SSP245 and SSP585, especially in North America and Europe. However, the probability in the Southern Hemisphere decreases. The distribution of the *Eucalyptus globulus* expands in the mid-latitude (40°–60° N) of the Northern Hemisphere. High carbon emissions contribute to the boost of the establishment of the *Eucalyptus globulus* in the Northern Hemisphere. These findings demonstrate that the fire adaptive species shows the tendency of shifting northward in response to climate change, highlighting the challenge of northward expansion of fires in future warming.

1. Introduction

Climate change has influenced the distributions of species and ecosystems on Earth (Pecl et al. 2017, Løkken et al. 2020). Many studies have found that vegetation and treelines in cold environments, such as high latitudes and high altitudes, are moving upward or northward due to rapid temperature increase induced by global warming (Harsch et al. 2009, Hansson et al. 2021). Harsch et al. (2009) analyzed 166 sites globally for treeline dynamics and found that treelines advanced over 52% of the sites whereas only 1% showed recession. Mekonnen et al. (2021) reviewed and summarized shrub expansion over the Arctic tundra, concluding that global warming contributed to high latitude tundra shrubification. Besides, plants in mountain regions over the mid-latitude were also found to have shifted (Kelly and Goulden 2008, Crimmins et al. 2011, Liang et al. 2018). Kelly and Goulden (2008) observed that the dominant plants in southern California rose by ~65 m along a 2314 m elevation gradient using plant cover made in 1977 and 2007. With a longer time scale and the larger study area, Crimmins et al. (2011) found that plant species in California moved downhill from 1930 to 2005. Liang et al. (2018) used 151 species over the Hengduan Mountains and modeled their distributions from the last glacial age to 2050, concluding that the plants were moving northward, westward, and in other directions due to heterogeneous topography along altitudinal gradients. These previous studies prove that climate change can influence vegetation distributions in cold environments like Arctic and mountains regions over mid-latitude. However, little research has focused on the distribution change of fire adaptive plants in warm environments at a
global scale or related the distribution shifts to fire risks.

Fires cause threats to the safety of ecosystems and released large amounts of carbon (2.2 Pg C yr\(^{-1}\)) into the atmosphere through biomass burning (van der Werf et al 2017). The frequency and intensity of fires have increased in the past several decades (Abatzoglou and Williams 2016, Cattau et al 2020) due to more droughts and higher temperatures. The carbon emissions of fires are also increasing in response to climate change (Chen et al 2017, Liu and Yang 2020). Fuels, mostly vegetation, are a critical factor in fire development (Bowman et al 2020, Oliveira et al 2021) and carbon emissions as they determine where the fire can happen and how much carbon will be released. The spread and accumulation of plants can lead to more fires under the situation of global warming, especially when the lightning (a major ignition source) risk increases (Chen et al 2021). It is important to accurately estimate the dynamics of vegetation, especially fire adaptive species, for effective fire management and carbon mitigation.

This study focuses on the distribution changes of a fire adaptive species, the Eucalyptus globulus, a fast-growing deciduous tree. The Eucalyptus globulus (also called Tasmanian bluegum) distributes in warm environments over the world (Potts and Gore 1995) and widely grows in America, Europe, Africa, and Australia as an important source of fuelwood (Gomes et al 2021) and pulpwood (Neiva et al 2020). However, several ecological drawbacks make the Eucalyptus globulus a problem. First, it suppresses the survival of other species once it becomes established in a new region, leading to a decrease in species diversity and ecosystem stability (Calviño-Cancela et al 2012). Besides, it is highly flammable while the thick barks protect it from severe fires, and has been adapted to periodic fires (Calviño-Cancela et al 2018), making it a great fuel source for wildfires in the current changing world. The heavy litterfall in the Eucalyptus globulus stands also contributes to fire spreads. It is very difficult to completely remove this species as it spreads through both abundant seeds (Deus et al 2019) and resprouting. These shortcomings of the Eucalyptus globulus arouse many concerns, especially under the situation of increasing fires due to global warming. To facilitate wildfire monitoring and prevention, it is necessary to figure out the distributions and the changes of this fire-prone species under the changing climate for better management and control policies.

Species distribution modeling (SDM) techniques, which relate geolocated occurrence data to environmental variables that support species’ survival and existence, are extensively adopted in species distribution mapping (Messina et al 2019, Gutierrez-Velez and Wiese 2020). The motivation of SDMs is to predict species distributions across geographically broad areas for resource management and species conservation. Methods like generalized additive model (GAM), multivariate adaptive regression splines (MARS), Maxent, boosted regression tree (BRT), and random forest (RF) are often employed to analyze the relationship between occurrence points and environmental variables to characterize species’ ecological niches and distributions. Leathwick et al (2006) estimated the distributions of freshwater fish species with GAM and MARS, finding that there was little difference between the performances of the two models. Fois et al (2015) used Maxent to estimate the distribution of an endangered species, the Gentiana lutea, in Sardinia with high accuracy. Kumar et al (2015) assessed the global establishment of the Cydia pomonella using Maxent and a semi-mechanistic model CLIMEX, where Maxent produced better results. Messina et al (2019) employed BRT to model the current distributions of dengue globally and projected the future distributions in response to climate change, revealing an expansion trend of dengue globally. Lopez-Sanchez et al (2021) estimated the distributions of the eucalypt trees in northern Spain with machine learning models, showing an increase of the eucalypt in Galicia. Crimmins et al (2013) combined regression models and machine learning models to produce ensemble forecasts of the distributions of plants in California. These studies produced high accuracy and robust models in distribution modeling, supporting the use of SDM techniques in mapping the global distributions of the Eucalyptus globulus.

In this study, the SDM techniques were adopted to explore the distribution changes of the Eucalyptus globulus in future climate, illustrating the response of the fire adaptive species to climate change. Four typical models: GAM, BRT, Maxent, and RF were employed to estimate the distributions of the Eucalyptus globulus. Occurrence data from the Global Biodiversity Information Facility (GBIF) and climate variables from the WorldClim database were used to train the four models. The outputs of the four models were combined to produce an ensemble prediction. The trained models were used to map the current spatial distributions of the Eucalyptus globulus and predict the future distributions in 2060 under the shared socioeconomic pathway (SSP) 245 and SSP585. The main goal of this study is to estimate the distributions of the Eucalyptus globulus and assess the distribution changes in the future climate. To be specific, there are three objectives: (a) to estimate the ecological niche and the current distribution of the Eucalyptus globulus; (b) to project the future distributions under different carbon emission scenarios; (c) to investigate the distribution changes of the Eucalyptus globulus.
2. Data materials and methods

2.1. Data sources

2.1.1. Occurrence points

In this study, the occurrence points of the *Eucalyptus globulus* were downloaded from the global biodiversity information facility (GBIF) (Gbif.Org 2021), which is a platform for scientists to share biodiversity data worldwide. The data are free and open access, containing observations of plants, animals, fungi, and microbes for ecosystem conservation and sustainable development. The data record includes the name, date, location, and genus of the organism. In addition, some ancillary information such as reference ID, collection organization, and country of the corresponding record may also be archived.

2.1.2. Environmental variables

Environmental variables downloaded from WorldClim (www.worldclim.org) were used to map the spatial distributions of the *Eucalyptus globulus*. The WorldClim provides multi-year accumulations of climatic factors such as global temperature and precipitation. The commonly used bioclimatic variables offered by the WorldClim (Fick and Hijmans 2017) were employed in this study for SDM. The bioclimatic variables were derived from monthly temperature and rainfall data, containing 19 environmental factors (bio1 to bio19, table S1 (available online at stacks.iop.org/ERL/17/024008/mmedia)). The latest version (version 2) of the current bioclimatic variables, derived from the accumulation of years 1970–2000 at a spatial resolution of 5 min, was used to estimate the current distribution of the *Eucalyptus globulus*. Other environmental variables such as potential evapotranspiration (PET) (equation (S1)) and climatic moisture index (CMI) (Eq (S2)) were calculated using the R package ‘envirome’ (Title and Bemmels 2018) based on the 19 bioclimatic variables to show the water availability and also used for the distribution modeling.

For future projection of the distributions, the Coupled Model Intercomparison Project Phase 6 (CMIP6) climate projection data were adopted. The 5 min bioclimatic variables, during years 2041–2060 under scenarios of SSP245 and SSP585 derived from eight global climate models (GCMs): BCC-CSM2-MR (Wu et al 2018), CNRM-CM6-1 (Voldoire 2018), CNRM-ESM2-1 (Seferian 2018), CanESM5 (Swart et al 2019), IPSL-CM6A-LR (Boucher et al 2018), MIROC-ES2L (Tachirii et al 2019), MIROC6 (Shiogama et al 2019), MRI-ESM2-0 (Yukimoto et al 2019), were downloaded separately from the WorldClim (www.worldclim.org/data/cmip6/cmip6_clim5m.html). The PET and the CMI were also derived from the future bioclimatic variables for distribution mapping.

2.2. Methods

As the current environment variables provided by the WorldClim come from 1970 to 2000, only the occurrence points observed during 1970 and 2000 were used for distribution modeling, resulting in 6644 points. The occurrence data were cleaned to remove replications, empty locations (missing latitude/longitude), and records with wrong locations (located in the ocean), producing 4712 points. Besides, the environmental filtering method developed by Varela et al (2014), which provided high accuracy for species distribution mapping, was adopted to filter the occurrence points to remove the redundancy and spatial biases. Finally, there were 998 occurrence points left, mainly located in Australia, Europe, and America, for the *Eucalyptus globulus* mapping (figure S1).

To evaluate the correlations among the variables, the Pearson correlation coefficients \( r \) among the 19 bioclimatic variables, PET, and CMI were calculated. Some variables were highly correlated (figure S2), e.g. min temperature of the coldest month and mean temperature of the coldest quarter \( r = 0.91 \). To avoid multicollinearity and reduce redundancy, a quick selection procedure was developed here to select the subset with low correlations among the variables. First, the variables were regarded as highly correlated when \( |r| > 0.7 \), a threshold commonly used in species modeling (Leathwick et al 2006). Two metrics were used to help remove the highly correlated variables: (a) the number of variables correlated with the focal variable, \( N \); and (b) the average absolute correlations (average \( |r| \) of the focal variable with the rest variables, \( R \). The variable with the largest \( N \) and the highest \( R \) was removed and the correlation matrix was updated with the rest of the variables. This process was iterated many times until the absolute correlations among the remaining variables were lower than 0.7. Finally, 12 variables remained for the *Eucalyptus globulus* distribution modeling, including Isothermality (the ratio of temperature diurnal range and annual range), min temperature of the coldest month, temperature annual range, mean temperature of the wettest quarter, mean temperature of the driest quarter, mean temperature of the warmest quarter, precipitation of the driest month, precipitation of the wettest quarter, precipitation of the warmest quarter, precipitation of the coldest quarter, PET, and CMI.

As only occurrence points of the *Eucalyptus globulus* were obtained from the GBIF, 1000 absence points (the so-called pseudo absence data) were produced here randomly based on the 5 min pixels. The 1000 absence points were located in different pixels, avoiding all the occurrence points and the corresponding pixels. The 1000 absence points and the 998 occurrence points were combined for distribution modeling. For each point, the corresponding values of the 12 environmental variables were used as predictors \( X \) and the presence (\( Y = 1 \))/absence (\( Y = 0 \))
was employed as the response. The dataset was split into training data (70%) and testing data (30%) randomly. Four commonly used models, i.e. GAM, BRT, Maxent, and RF, were adopted to estimate the distributions of the *Eucalyptus globulus*, overcoming potential biases from a single model. The training data were used to train the four models and the testing data were used to check the accuracy. Four metrics: area under the receiver operating characteristic curve (AUC), kappa, sensitivity, and specificity were employed for accuracy assessment. The R package ‘pROC’ (Robin et al 2011) was employed to train the models and map the distributions.

After the training procedures, the environmental variables were input into the four models to produce the distribution maps of the *Eucalyptus globulus*. The four distribution maps were combined by the median value to produce the ensemble prediction as shown in Eq (1), where $p_i$ is the ensemble prediction of the $i$th pixel, $p_i^\text{GAM}$, $p_i^\text{BRT}$, $p_i^\text{Maxent}$, and $p_i^\text{RF}$ are the probabilities of the $i$th pixel derived from the four models, respectively. With the ensemble map, a distribution map (presence vs absence map) was further derived based on the threshold (0.551) calculated from the receiver operating characteristic (ROC) curve using the package `pROC’ (Robin et al 2011). The threshold was also used in deriving future distribution maps. Future projections of environmental variables under SSP245 and SSP585 during 2041–2060 derived from the eight GCMs were input into the trained models to produce future distributions separately. For each scenario, one ensemble prediction from the four models (GAM, BRT, Maxent, and RF) was produced with environmental variables derived from a GCM. Predictions of the eight GCMs were combined by the median value to produce the ensemble prediction under each scenario. The current distribution map and the future prediction maps were compared to investigate the distribution changes.

$$p_i = \text{median}(p_i^\text{GAM}, p_i^\text{BRT}, p_i^\text{Maxent}, p_i^\text{RF}).$$

(1)

3. Results

3.1. Distribution maps in 2000

The estimation of the four models got high accuracy in mapping the distributions of the *Eucalyptus globulus*. The AUC and kappa of the four models are above 0.95 and 0.87 (table 1), respectively, revealing the high accuracy of the four models. The sensitivity and the specificity are all greater than 0.93, which means both the omission errors ($=1 - $ sensitivity) and the commission errors ($=1 - $ specificity) are very small. The high accuracy is consistent in both the training data and the testing data, indicating the stability of the models. Figures 1(a)–(d) shows the probabilities of the distributions produced with the four models, where the distributions of the *Eucalyptus globulus* are comparable. The patterns of the probability maps are similar though BRT overestimates the background probability of the absence regions. For instance, the probability in Greenland is close to zero in the other three models, but BRT gives approximately 0.19. The ensemble map (figure 1(e)) produced with the four probability maps is close to the probability maps from GAM, Maxent, and RF. The overestimation of the background is avoided in the ensemble map. With all the samples, the AUC, kappa, sensitivity, and specificity of the ensemble map are 0.991, 0.932, 0.976, and 0.964, respectively, indicating the high accuracy of the estimation. The *Eucalyptus globulus* is mainly located in southern Australia, Europe, and coastal regions of South America and North America as shown in figure 1(f). There are few *Eucalyptus globulus* trees in the high latitudes as the *Eucalyptus globulus* grows in warm environments.

When comparing the relative importance of the variables in distribution modeling (figure 2(a)), min temperature of the coldest month and PET are the two most important variables, whose relative importance is approximately 65% in sum. The rest of the variables such as isothermality and precipitation of the coldest quarter, also contribute to the distribution modeling, but the relative importance is lower. The ecological niche of the *Eucalyptus globulus* is illustrated with the two most important variables here. As shown in figures 2(b) and (c), the presence (occurrence) points are aggregated in the scatterplot while the absence points give no signs of aggregation. The aggregation of the presence points reveals the effectiveness of the variables in capturing the niche of the *Eucalyptus globulus*. Based on the presence points, the *Eucalyptus globulus* prefers the average of the min temperature of the coldest month to be 3.04 °C (sd = 2.77) and the average PET of 1052 mm yr⁻¹ (sd = 182.74). The response curves (figure S3) reveal that the *Eucalyptus globulus* is sensitive to the min temperature of the coldest month as only a narrow window (approximately 0 °C to 7 °C) is suitable for its existence. The *Eucalyptus globulus* can stand the variation of PET from low to moderate but high PET can threaten its survival. As for precipitation of the coldest quarter and isothermality, high values are favorable for the *Eucalyptus globulus*.

3.2. Projections in 2060

The future distributions of the *Eucalyptus globulus* were produced under scenarios of SSP245 and SSP585 with climatic data from 2041 to 2060. The ensemble predictions of the eight GCMs for the two scenarios are presented in figures 3(a) and (b), respectively. The probability maps of the SSP245 and the SSP585 are comparable with very high probabilities in southern Australia, Europe, and coastal regions of South America and North America. Besides, the difference of probabilities between the two scenarios (figure S4) shows that the probability in the Northern
Table 1. Accuracy of the four models: the GAM, BRT, Maxent, and RF in mapping the distributions of the *Eucalyptus globulus*.

| Models  | Training data |   |   | Testing data |   |   |
|---------|---------------|---|---|--------------|---|---|
|         | AUC           | Kappa | Sensitivity | Specificity | AUC | Kappa | Sensitivity | Specificity |
| GAM     | 0.993         | 0.934 | 0.973 | 0.961        | 0.982 | 0.918 | 0.948 | 0.970 |
| BRT     | 0.987         | 0.906 | 0.960 | 0.946        | 0.979 | 0.877 | 0.930 | 0.947 |
| Maxent  | 0.986         | 0.919 | 0.964 | 0.954        | 0.985 | 0.915 | 0.958 | 0.957 |
| RF      | 0.998         | 0.987 | 0.997 | 0.996        | 0.987 | 0.925 | 0.962 | 0.963 |

Figure 1. The distributions of the *Eucalyptus globulus* in 2000, which were derived from different models: (a) GAM, (b) BRT, (c) Maxent, (d) RF, (e) the ensemble of the four model outputs, and (f) the distribution of the *Eucalyptus globulus* in 2000.

Hemisphere is higher under SSP585, especially in Europe. This phenomenon reveals that Europe is more favorable for the establishment and spread of the *Eucalyptus globulus* under high emission scenarios.

The distribution of the *Eucalyptus globulus* in 2000 is significantly different from the distributions under SSP245 \((p < 0.001)\) and SSP585 \((p < 0.001)\) in 2060 using the Mann–Whitney test. The differed maps (figures 3(c) and (d)) between the future projections and the probability map in 2000 reveal that the probabilities in the Northern Hemisphere increase significantly \((p < 0.001)\) under both scenarios. However, in the Southern Hemisphere, the probabilities decrease significantly \((p < 0.001)\), especially in southern Africa and eastern South America, though the probabilities in northern Australia and southernmost of South America increase slightly. These results confirm that the survival chance of the *Eucalyptus globulus* in the Northern Hemisphere will increase in response to future climate change, especially in North America and Europe.

The global distribution of the *Eucalyptus globulus* decreases 7.92% and 10.16% under SSP245 and SSP585, respectively, while large expansion exists in the mid-latitude of the Northern Hemisphere (figures 3(e) and (f)), especially in Europe and the western US. As shown in figure 4, most of the expansions occur between 40°N and 60°N in both SSP245 and SSP585. There are also a few expansions in the southernmost of South America (between 40°S and 5°S).
The loss of the *Eucalyptus globulus* is dominant in the Southern Hemisphere and the low-latitude of the Northern Hemisphere, corresponding to the regions from 20°S to 40°S and from 20°N to 40°N in figure 4. The expansion and loss of the *Eucalyptus globulus* are comparable under SSP245 and SSP585. Due to future climate change, the mid-latitude of the Northern Hemisphere will be more suitable for the survival and spread of the *Eucalyptus globulus*.

4. Discussion

The distribution of the *Eucalyptus globulus* in 2000 was produced with four commonly used methods: GAM, BRT, Maxent, and RF, which got high accuracy in estimating the distributions. The ensemble result (figure 1(e)) derived from the four models’ outputs shows that southern Australia, Europe, and coastal regions of South America and North America have high probabilities for the *Eucalyptus globulus*. Eastern North America, southern Africa, and eastern Asia have medium probabilities while high latitudes such as Greenland and Alaska have low probabilities. Typical regions of the existence of the *Eucalyptus globulus* include New South Wales in Australia, New Zealand, Spain, Chile, and California (figure 1(f)). These results are consistent with the ecological niche (figure 2) and the response curves (figure S3) illustrated by variables such as the min temperature of the coldest month and PET. The *Eucalyptus globulus* is sensitive to temperatures and prefers environments with warm climates. Low temperatures, e.g., −5°C, can cause more than 50% of tissue mortality for the *Eucalyptus globulus* (Almeida et al 1994). Low to moderate PET values are superior for the *Eucalyptus globulus* and high PET often leads to great water losses, which harms the tree. High isothermality, which means the summer-to-winter temperature oscillation is close to the day-to-night temperature oscillation, provides favorable temperature seasonality for the *Eucalyptus globulus*. Isothermality is also confirmed to be useful in Lopez-Sanchez et al (2021). High precipitation in the coldest quarter, which means high winter precipitation, helps to save water for the next
Figure 3. Projections of the distribution of the *Eucalyptus globulus* in 2060: (a) ensemble prediction under SSP245 and (b) SSP585; the difference between the probability in 2060 and the probability in 2000 under (c) SSP245 and (d) SSP585; the distribution difference between 2060 and 2000 under (e) SSP245 and (f) SSP585.

Spring and contributes to the growth of the *Eucalyptus globulus* trees. Other types of factors such as terrain (elevation, slope, aspect) and soil (nutrients, carbon content) are also important but not included in this study since we used a very coarse spatial resolution, 5 min (~10 km), for the whole Earth. The effects of terrain and soil on distribution modeling are significant at spatial resolutions of 100–250 m (Austin and van Niel 2011, Lopez-Sanchez *et al.* 2021). However, coarse spatial resolutions tend to override small-scale interactions of ecosystems. The effects of terrain decrease as coarse pixels reduce terrain variations. The properties of soil are also influenced by climate at large scales. Climatic variables are important for large-scale studies since the climate is directly related to global energy and water distributions. The high accuracy of the four models confirms that climatic variables are good enough for producing global distributions of the *Eucalyptus globulus*.

For future projections, the distributions of the *Eucalyptus globulus* in 2060 under scenarios of SSP245 and SSP585 were mapped with projected climatic data during 2041–2060. Europe, coastal regions of South America and North America, and southern Australia have very high probabilities (figures 3(a) and (b)) of the existence of the *Eucalyptus globulus* under both SSP245 and SSP585. Comparing the future projections in 2060 and the probability in 2000 (figures 3(c) and (d)), it is significant that the probability of the *Eucalyptus globulus* increases in the Northern Hemisphere, especially in North America and Europe. The distribution of the *Eucalyptus globulus* in the mid-latitude of the Northern Hemisphere expands while the rest of the world shows great losses (figure 4). These results reveal that the survival chance of the *Eucalyptus globulus* increases in the Northern Hemisphere, especially in the mid-latitudes, in future climate scenarios, confirming the northward expansion of vegetation in response to climate change. Previous studies focus on species such as tundra, shrub, and spruce in cold environments (Mekonnen *et al.* 2021) while this study demonstrates that the fire-adaptive species in warm environments also shows the tendency of northward shift due to climate change. The decrease of the *Eucalyptus globulus* in the rest of the world, especially in the Southern Hemisphere and low latitudes of the Northern Hemisphere, is related to rising temperatures and increasing PET, which further lead to more droughts and heatwaves. For example, the Amazon forest has suffered from record-breaking droughts.
Figure 4. The percentage of distribution changes of the *Eucalyptus globulus* along the latitude under future scenarios of (a) SSP245 and (b) SSP585 compared with the total distribution in 2000, where positive values mean expansions and negative values show losses. The red lines show 0%.

Figure 5. Annual fire occurrence probability based on 10 year average over the *Eucalyptus globulus* distributed regions in 2000.

(Jiménez-Muñoz et al 2016) and has shown signs of degradation (Yang et al 2018, Qin et al 2021) in the past decades due to global warming. Under the scenario of SSP245, the mean global temperature is predicted to increase by 1.5 °C. In this way, low latitude regions will face extremely high temperatures and water loss, increasing the challenges of survival and growth for plants.
Fire probabilities over the presence regions of the *Eucalyptus globulus* are high when analyzing fire occurrences over the distribution map in 2000. The global fire emissions database (GFED) (van der Werf *et al* 2017), which provides monthly global burned area from 1997 to 2016, was resampled to 5 min and adapted to show the fire occurrence. When the burned area of a pixel is greater than zero, we assume fire happens in the pixel. The 10 year average annual fire probability from 1997 to 2006 was calculated over the *Eucalyptus globulus* distribution regions in 2000. As shown in figure 5, southern Australia, coastal regions of South America and North America, and western Europe have very high probabilities of fire occurrence, which means fires can happen almost every year over these regions. Other regions like New Zealand have lower probabilities of fire. The average fire probability over the presence regions of the *Eucalyptus globulus* is 60.48%. Using the MCD12C1 yearly land cover map (Friedl and Sulla-Menashe 2015) in 2001, we calculated the average fire probability over the global forest (evergreen, deciduous, and mixed forest), 53.65%, which is significantly lower ($p < 0.0001$ by Mann–Whitney test) than that of the *Eucalyptus globulus* presence regions. When considering only deciduous forest and mixed forest as the *Eucalyptus globulus* is a deciduous tree, the average fire probability is 48.79%, which is also significantly lower ($p < 0.0001$). In this way, the new regions encroached by the *Eucalyptus globulus* could reach a fire probability of approximately 60% without considering other factors like fire management and human activities. Besides, due to global warming, the fire frequency could increase (Balch *et al* 2017, Cattau *et al* 2020), leading to even higher fire risks. This result demonstrates why the shifts of fire adaptive species are important to fire risk management and global fire dynamics. As is known, the movement of vegetation directly relates to future fire distributions since the distribution of plants determines where the fire can happen (Miller and Urban 2000, Sah *et al* 2006, Pausas and Paula 2012). Combined with the increase in temperatures and human ignitions (Syphard *et al* 2007, Balch *et al* 2017), ecosystems in the Northern Hemisphere will face the challenge of more fires in the future. It is necessary to pay more attention to the dynamics of fires and vegetation development for better fire management and carbon mitigation.

When comparing the distributions of the *Eucalyptus globulus* under SSP245 and SSP585 in 2060 (figure S4), the Northern Hemisphere has higher probabilities under SSP585, especially in Europe. However, the probabilities in the Southern Hemisphere are lower under SSP585. These results indicate that high carbon emissions can lead to greater chances of distribution shift for the *Eucalyptus globulus*. Notably, Europe is more sensitive to high carbon emission scenarios. If the Earth went to higher carbon emission pathways, the *Eucalyptus globulus* would get larger probabilities of establishment and spread in Europe, leading to higher fire risks.

Apart from climate change, human activities such as deforestation, agriculture expansion, urbanization, and afforestation will also affect the spread of the *Eucalyptus globulus*. As we know, disturbed regions provided by deforestation are great space for the establishment of new plants since there are enough illuminations, no strong competitors, and mixed soil layers (tillage), all of which are favorable for plant growth. Agriculture expansion, urbanization, and afforestation will occupy some potential lands suitable for the spread of the *Eucalyptus globulus*, causing ecological obstacles for its establishment. However, the abandoned farmlands will again offer opportunities for the growth of the *Eucalyptus globulus*. Human activities like deforestation and urbanization can also impact fire occurrences. Deforestation and agriculture expansion often go with fire usages to clear land. Urbanization increases the interface between human habitats and wildland, also called wildland urban interface (Radeloff *et al* 2018), raising the risk of human-caused wildfires. However, other activities like fire management and suppression (Bowman *et al* 2011, Roos *et al* 2020) are reducing fire risks. For example, prescribed fire usage like forest thinning and fuel reduction (Stephens *et al* 2009) can help to reduce large fires and protect habitats. In projects of afforestation/reforestation, the selection of fire-tolerant and less flammable species can also decrease fire threats. These effects confirm the importance and complexity of human effects on plant dynamics and fire risks analysis.

5. Conclusions

Fires have become more frequent and intense due to high temperatures and more droughts induced by global warming. The distributions of fuels are also changing in response to climate change. This study illustrated the distribution changes of the typical fuel-wood, the *Eucalyptus globulus*, in future climates. The global distributions of the *Eucalyptus globulus* decrease under future climatic scenarios. However, the probability of the existence of the *Eucalyptus globulus* in the Northern Hemisphere increases significantly, especially in the mid-latitude of the Northern Hemisphere, where the distributions expand in North America and Europe. Besides, high carbon emission scenarios lead to a greater probability of distribution shift. Our findings reveal that the fire adaptive species shows the trend of northward shifts in response to climate change. It is necessary to pay more attention to the high carbon emissions and increasing fire risks in the Northern Hemisphere. This study serves as a complement to fire dynamics monitoring by evaluating the distribution changes of fuels in the changing climate, unraveling the challenge of northward expansion of fires in the future.
Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.15468/dl.8a9bty.

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