Forest Ecology and Management 430 (2018) 196–203

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Species distribution modelling tools and databases to assist managing forests under climate change

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ARTICLE INFO

Keywords:
Bioclimatic analysis
Climate change
Extinction
Database
Forest management

ABSTRACT

This paper examines progress made with species distribution modelling (SDM) for trees under climate change. Following brief background information, the main focus is on developments in the last five years. Correlative SDMs have become the most commonly used approach for analysing potential climate change impacts on areas suitable for particular species. The use of SDMs has been criticized, but responses to these criticisms are provided and limitations may not be as great as has been suggested. For many species SDMs are the only potential source of data for learning about likely climate change impacts, and suitable occurrence data for SDM analyses exist for about 50 000 tree species. SDM papers have already been published presenting analyses for more than 1000 tree species under projected climate change. Most SDM climate change analyses adopt an 'equilibrium assumption' that tree species natural distributions provide a reliable estimate of their climatic requirements. However, in addition to natural distribution data, data from trials outside their natural distributions are desirable to determine their intrinsic climatic adaptability. Progress is described in relation to climatic data, soil data, species distribution data, species and provenance trial data, descriptions of species climatic requirements, mapping of suitable areas and integration of species and environmental data. Desirable future objectives are identified for each of these topics.

1. Introduction

Managing trees under climate change is a great challenge for forestry in the present century (Millar et al., 2007). It will involve adjustments in ecological, social and economic systems (Spittlehouse and Stewart, 2003). These changes will need to be evidence-based and underpinned by appropriate models and data. Immense progress has been made in developing tools and databases to support forestry decision-making under climate change, but major challenges remain.

The aim of this review is to provide an overview of some of the key recent advances relevant to determining where particular tree species may be able to grow in either natural forests or plantations under current and future climatic conditions. The focus is mainly, but by no means entirely, on species of the genus *Eucalyptus* as they have advantages for climate change studies. For example, eucalypts have very poor dispersal capabilities (Booth, 2017a), so the survival of existing stands is the key issue for the present century. The great complications of assessing possible dispersal to and establishment at other sites are avoided. Eucalypt species and provenances have also been extensively tested outside their natural distributions, so knowledge of their climatic adaptability beyond their natural distributions is good at least for the commercially important species (Jacobs, 1981, Booth et al., 2015).

There has been a great increase in species distribution modelling (SDM) since the first package called BIOCLIM became available in 1984 (Nix, 1986; Booth et al., 2014). For example, Dyderski et al. (2018) identified 124 papers from the Web of Science published between 1996 and early 2017 that analysed more than 500 tree species distributions and produced projections based on at least one climate change scenario. Most of these papers focussed on threatened, invasive or plantation species. The contents of these papers, including abstracts and ten important features, were summarised in an Excel spreadsheet available as an appendix to the Dyderski et al. (2018) paper. For example, the geographic spread of the studies was as follows: Global (2), Africa (8), Asia (36), Australia (4), Europe (32), North America (38) and South America (4). Though widely used the SDM approach is not without some limitations for examining how tree species will respond to climate change (Keenan, 2015). However, these limitations may be less for eucalypt species than many other tree species (see Table 1).

If they are available the use of more detailed process-based models may be desirable for studying climate change impacts. But presently their applications are confined to a very small number of relatively well-known species of commercial importance (see, for example, the climate change analyses of *E. globulus* and *E. nitens* plantations by Battaglia et al., 2009; Battaglia and Bruce, 2017). In contrast, three

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https://doi.org/10.1016/j.foreco.2018.08.019
Received 7 June 2018; Received in revised form 7 August 2018; Accepted 10 August 2018

Table 1
Limitations of species distribution models (SDMs) for predicting the impacts of climate change on forests identified by Keenan (2015) and responses particularly relevant to eucalypts.

Challenge	Response
• Predicting capacity of species to move	• Eucalypts have very poor dispersal capabilities, therefore the key issue is whether they will survive where they are currently located (see Booth, 2017a)
• Local adaptation (refugia)	• Trials can indicate climatic adaptability of provenances (Eldridge et al., 1993), but there is a need for higher resolution data to detect refugia (Austin and Van Niel, 2011)
• Uncertainty in predicting future climate	• A challenge for all models. Some uncertainty is inevitable until specific global mitigation actions are agreed and enforced
• Predicting and incorporating effects of extreme events on tree populations	• See, for example, Yan Hong (2001) 'Frost prediction for Australian tree species in China'. Absolute (i.e. record) minimum temperature is an appropriate estimate for use in SDMs
• Lag effects and gene flow within species -species still responding to past changes	• Eucalypt species and provenance trials can provide insights (Booth et al., 1988, Booth, 2017b). Genomic studies are providing useful information (Supple et al., 2018)
• Epigenetic effects i.e. growing conditions influencing ability of progeny to cope with drier or warmer conditions	• More research is needed, but progeny trials outside natural distributions (Eldridge et al., 1993) could provide some insights
• Biotic effects (diseases and insect pests)	• Can be modelled using SDM or more complex models (see, for example, Berthon et al., 2018 rust paper using Maxent SDM)
• Phenology and life history traits	• Overseas trials provide insights e.g. poor flowering of *E. nitens* in South Africa (Germishuizen and Gardner, 2015)
• Mutual benefits with other plants or animals that may respond differently to climate	• Unlikely to be critically important if trees are already well established at particular sites
• Competition effects	• Not very important when considering vulnerability of established stands. Competition is mainly during establishment

SDM studies have examined the likely impacts of climate change on many *Eucalyptus* and closely related *Corymbia* species (which were previously classified as eucalypt species). These studies considered the likely impacts on 819 species (Hughes et al., 1996), 108 species (Butt et al., 2013) and 657 species (González-Orozco et al., 2016). The Hughes et al. (1996) paper did not project future distributions using a climate change scenario, so it was not listed by Dyderski et al. (2018), though the Butt et al. (2013) paper was listed. The González-Orozco et al. (2016) analysis projected future distributions and fell within their assessment period, but was missed by Dyderski et al. (2018). Including this analysis would have increased the number of tree species distributions assessed under climate change to over 1000. There are no other broad-scale analyses of the likely impacts of climate change on most eucalypt species using alternative approaches. Accordingly, as SDMs are the only source of climate change impact information for many eucalypt and other tree species it is worthwhile to recognize their limitations, but also to consider how they may provide useful information.

In the latest SDM study of eucalypt distributions González-Orozco et al. (2016) made it clear that they were aware of concerns about the 'equilibrium assumption'. This implies that analysis of just the current natural distribution provides a reliable indication of a species climatic requirements under climate change. Various authors have pointed out the need to analyse not only the natural distribution, but also occurrences outside the natural distribution (see Booth, 2017b for a review of the 'equilibrium assumption'). González-Orozco et al. (2016) attempted to address the issue by using models which avoid 'over-fitting' (see Booth, 2017c for a discussion of some of the limitations of the González-Orozco et al., 2016 analysis and how they might be overcome). Despite some limitations the paper provides much useful information, including maps of projected responses for the 657 species as part of the supplementary information. An advantage of the approach is that it can be applied to large numbers of species. A disadvantage, in comparison to use of data from both the natural distribution (i.e. realized niche *sensu* Hutchinson, 1957) and trials outside the natural distributions (c.f. fundamental niche *sensu* Hutchinson, 1957), is that it assumes all variables have climatic adaptability beyond the realized niche. The analyses in Booth et al. (1988) suggest that this is not the case, but more work is needed examining species climatic responses in locations outside their natural distributions.

The requirements for using SDM techniques to deliver "a global climatological audit to assist conservation and sustainable development" in forests under climate change were outlined by Booth (1991). The paper identified five key objectives related to climatic data, species distribution data, species and provenance trial data, descriptions of species climatic requirements and mapping of climatically suitable areas. These topics are used here as section headings. Within each section, progress is described and then desirable future objectives are outlined. An extra section has been added after climatic data to consider soil data. The biodiversity database known as the Atlas of Living Australia (ALA) has integrated elements of the five key objectives into one unified system freely available on the internet (spatial.ala.org.au) and this is described in a separate section.

2. Topic areas

2.1. Climatic data

The outstanding achievement in relation to global climatic data has been the development of the WorldClim database (Hijmans et al., 2005). This has recently been updated with WorldClim 2 (Fick and Hijmans, 2017) providing improved climatic databases for land areas of the world. These were developed by applying thin plate spline methods (Hutchinson, 1991, 2013), which were originally used to prepare Australian interpolation surfaces for the BIOCLIM package. The WorldClim 2 website (worldclim.org/version2) provides access to average monthly data for minimum, mean and maximum temperatures as well as precipitation. The 19 bioclimatic variables originally created for BIOCLIM are also available. Climate change scenario data for four representative concentration pathways (RCPs) used in the Fifth Assessment of the Intergovernmental Panel on Climate Change (IPCC, 2014) are available at the original WorldClim site (worldclim.org). Both the WorldClim and WorldClim 2 data are available at resolutions down to 30 s (i.e. 0.5 min or about 1 km^2). The fact that the Hijmans et al. (2005) paper has been cited more than 13 000 times in the Google Scholar reflects its general dominance in this area. However, other climatic databases including CliMond (Kriticos et al., 2012), CHELSA (Karger et al., 2017), MERRAClim (Vega et al., 2017) and ENVIREM (Title and Bemmels, 2018) have been developed for specialised needs.

2.2. Climatic data – Desirable future developments

The BIOCLIM package as launched in 1984 (Nix, 1986, Booth et al., 2014) included interpolation relationships and estimated climatic