Predicting the potential geographic distribution of weeds in 2080

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Summary Accounting for climate change is an important factor to consider in weed risk assessments and can be useful when planning strategic management approaches and targeting weed education initiatives. Global climate modelling has now reached a sufficient level of maturity that regional climate models can be used with greater confidence to apply future climate scenarios to biophysical models.

Data from four Global Climate Models using four SRES emission scenarios (IPCC 2000) were used to develop a framework for generating climate change surfaces for use in CLIMEX™. The supplied variables were transformed and reformatted and, where necessary, new variables were estimated. Using this framework, future climate surfaces can be generated for any user-defined period up to 2100 and applied to any base climatology by interpolating the change surfaces.

The future climate surfaces have been applied to the climate models of three important weeds in Australia with contrasting climatic requirements (prickly acacia, *Acacia nilotica* (L.) Willd. ex Delile, Siam weed *Chromolaena odorata* (L.) R.M.King & H.Rob., and buddleia, *Buddleja davidii* Franch.) to show a range of possible future distributions for them in Australia.

Keywords Climate change, CLIMEX, *Acacia nilotica*, *Chromolaena odorata*, *Buddleja davidii.*

INTRODUCTION

The potential distribution and relative abundance of invasive species, along with knowledge of their present distribution, provides a synoptic view of the invasion threat. This perspective can be useful for addressing strategic management issues such as resource allocation, prioritising weed problems, evaluating strategic management options, and targeting education and surveillance. CLIMEX models (Sutherst *et al.* 2004) have proven robust, and ideally suited to projecting the potential distribution of invasive species at an early stage of the invasion when the information is of most use to decision-makers.

Climate change poses several challenges for those charged with managing invasive species such as weeds. Changing climate shifts the climatic limits that will eventually constrain the range of an invasive species. In some cases, this will be entirely bad news, where the weed simply increases its range in response to increasing temperatures. If the topography is relatively shallow, then it is possible for even a moderate increase in temperature to have a profound impact on the potential distribution of a species. Increasing temperatures may also allow some sleeper weeds to become invasive. Species with restricted ranges in cool locations such as orange hawkweed, *Heiracium aurantiacum* L. in Australia (Groves *et al.* 2002, Brinkley and Bomford 2002) may be presently constrained by an inadequate annual heat sum for reliable reproduction and are able to persist by reproducing in only the most favourably warm years. Increasing temperatures may allow this weed to rapidly increase seed production, become invasive and expand its range into more favourable habitat. In other cases, a weed problem may diminish in some areas or shift as a result of climatic change.

Given the range of potential responses, it is important for decision-makers and others affected by weeds to have tools with which to assess the likely impacts of climate change on the future potential distribution of weeds.

In order to assess the likely impact of climate change on the potential distribution and relative abundance of weeds (and other pests) it is necessary to employ modelling tools. The modelling tools that are of most value are climate-based models used for weed risk assessment (Kriticos and Randall 2001). The method, in brief, is to build a model of weed distribution using historical distribution and climate data, and then change the climate dataset to a future climate scenario and re-run the model. However, future climate scenarios are novel climates because each of the climatic variables will respond to the aerosol emissions scenarios independently, resulting in complex change surfaces for temperature, vapour pressure and rainfall. For habitat models that are derived inferentially from species distribution data this change in the relationship between variables poses a major challenge. Descriptive models rely upon information about the same system in which they attempt to project the model response variable (viz. species' relative abundance). Such models are generally poorly suited to extrapolation beyond the data space used to develop the model. The inferential models that are best suited to overcoming this challenge are those that employ process-based mechanisms that do not rely implicitly upon the relationships between the meteorological variables remaining constant. Two such models exist, namely, Stash and CLIMEX (Sutherst and Maywald 1985, Sykes *et al.* 1996, Kriticos and Randall 2001, Sutherst *et al.* 2004). Another approach that may be used is to develop a process-based model derived entirely from physiological data (Peter *et al.* 2003), although these models suffer from a different sort of problem. They are built using observations of instantaneous responses to environmental variables, and the responses need to be applied to climate surfaces composed of long-term averages that hide varying degrees of variability in the extremes. For example, a long-term monthly average of daily minimum temperature of 2.5°C equates on average to several frost days per month. For a highly frost-sensitive species, using a critical cold tolerance threshold of 0°C would give misleading results in terms of the potential distribution.

Previous attempts to use data from global circulation models were undermined by immaturity in the state of climate modelling science (Kriticos 1996) where subsequent sets of predictions contrasted strongly (Climate Impact Group 1992, Climate Impact Group 1996). This led to the need to use sensitivity analyses, or ‘synthetic’ scenarios to assess the likely impacts (IPCC-TGCIA 1999, Kriticos *et al.* 2003a, Kriticos *et al.* 2003b). There are now many institutions worldwide that have developed global circulation models and it appears that the science of projecting future climates has matured to the point where it is suitable for regional biophysical assessments.

However, the future pattern of greenhouse gas aerosol emissions is extremely uncertain. In order to provide some degree of comparability between impact assessments of climate change, the Intergovernmental Panel on Climate Change (IPCC) has developed a set of standard emissions scenarios and a set of guidelines for impact assessments so that the results are as directly comparable as possible. The standard emission scenarios have been dubbed SRES (Special Report on Emissions Scenarios). The Climate Research Unit (CRU) at the University of East Anglia distributes a dataset of 20 future climate scenarios (five models by four emissions scenarios). These scenarios are consistent with assumptions about future emissions of greenhouse gases and other pollutants and their effect on global climate. However, they are not predictions of future states.

MATERIALS AND METHODS

Assessment of the likely impact of climate change on the distribution of a species involves three major steps: 1) modelling the effect of climate on the distribution of the species under current climatic conditions; 2) generating future climate scenarios; and 3) using the future climate scenarios in the distribution model.

CLIMEX models for three species were used to explore the effects of climate change on three weed species in Australia: *Acacia nilotica* (L.) Willd. ex Delile, a dry tropical species, *Chromolaena odorata* (L.) R.M.King & H.Rob., a wet tropical species and *Buddleja davidii* Franch., a temperate species. These species were selected to provide a degree of contrast in climatic preferences. The models for *A. nilotica* and *C. odorata* have been published previously (Kriticos *et al.* 2003b, Kriticos *et al.* 2005). The derivation of the *B. davidii* model is described elsewhere (Kriticos and Potter 2006).

The TYN SC 2.0 dataset of climate change scenarios was downloaded from the CRU website. This dataset consists of 0.5 × 0.5 degree regular grids of precipitation, mean temperature, diurnal temperature range, vapour pressure and cloudiness for significant land areas. The dataset includes output from five Global Climate Models (GCMs):

- CGCM2 – Canadian Centre for Climate Modelling and Analysis GCM #2 (Kim *et al.* 2002).
- CSIRO-Mk2b – Australian Commonwealth Scientific and Industrial Research Organisation, Model #2b (Hirst *et al.* 2000).
- ECHAM4 – German Climate Research Centre, European Centre/Hamburg Model #4 (Zhang *et al.* 1998).
- HadCM3 – UK Hadley Centre for Climate Prediction and Research Coupled Model #3 (Gordon *et al.* 2000).
- PCM – US National Centre for Atmospheric Research Parallel Climate Model (Dai *et al.* 2001).

The data are taken from model runs with the following four SRES scenarios: A1, A2, B1 and B2 (Table 1). The vapour pressure data for the CGCM2 model as supplied by the Climate Research Unit as part of the TYN SC 2.0 dataset were corrupted, and so the CGCM2 data was abandoned for this exercise.

Prior to being used for a modelling project, the climate scenario datasets had to be extracted and manipulated to generate a set of surfaces of monthly averages for daily minimum temperature, maximum temperature, and total rainfall and to estimate relative humidity at 0900 and 1500 hours based on vapour pressure. The Python programming language and ArcGIS version 9.0 were used to transform the data and estimate the missing variables.

Table 1. Special Report on Emission Scenarios scenario markers and calculated variables. Scenarios are ordered based on their potential for impact. Source IPCC-TGCIA (1999).

	SRES marker scenarios for 2100			
Scenario	B1	B2	A1	A2
Population (billion)	7.2	10.4	7.1	15.1
CO_2 concentration (ppm)	547	601	680	834
Global annual-mean temp. change (°C)	2.04	2.16	2.52	3.09

The climate change scenarios were constructed for each variable (v), global climate model (g) and SRES scenario (s) as follows. The value (x) at a particular grid-box (i) in a particular year (y) and month (m) is:

$$x_{vgsiym} = c_{vim} + r_{viym} + (p_{vgsim} * t_{gsy})$$

where (c) is the observed climatological mean from 1961–90, (r) is the residual from the observations after anomalising relative to 1961–90 and detrending against global temperature, (p) is the pattern of response to radiative forcing (expressed as anomalies relative to 1961–90, per degree of global temperature change) and (t) is the global temperature change (relative to 1961–90).

For CLIMEX analyses where biological models have been fitted to the standard 1961–1990 climatological means, models should ideally be fitted to the climatological mean c_{vim} and then projected using a scenario that ignores the residual term for interannual variability:

$$x_{vgsiym} = c_{vim} + (p_{vgsim} * t_{gsy})$$

The residual term should be of use to generate a time series for comparing the variability in habitat suitability through time. In this project, the chosen future scenarios were taken from the 30 year period around 2085, dubbed the 2080s. GCMs frequently produce strong inter-decadal variability, and the IPCC-TCGIA (1999) recommend using 30 year means in order to reliably detect the climate signal against the background noise.

Extracting the climatological means and generating CLIMEX variables CLIMEX uses five climate variables: monthly averages of total daily precipitation, daily maximum temperature, daily minimum temperature, relative humidity at 0900 hours and relative humidity at 1500 hours. The change scenarios provide four relevant variables: monthly averages of total daily precipitation; average daily temperature; diurnal temperature range; and average daily vapour pressure. Daily minimum and maximum temperatures were calculated from the average temperature and diurnal temperature range values. Relative humidity values for 0900 and 1500 hours were estimated based on vapour pressure values and estimates of saturation vapour pressure.

RESULTS

The modelled climate suitability of each of the case study weed species under the reference climate (1961–1990) is presented in Figure 1. These potential distribution maps represent the reference distributions against which future climate scenarios may be compared. These potential ranges indicate the characteristic climatic preferences of each of the species. *C. odorata* is largely confined to the coastal (moist) tropics, *A. nilotica*'s range extends into the arid interior and sub-tropics, whilst *B. davidii* is restricted to the southern regions with temperate and Mediterranean climates.

The range of projected potential distributions for *C. odorata* in the 2080s (Figure 2) is relatively minor. All 2080s scenarios indicate that the potential range of *C. odorata* will extend further southward (poleward) in a narrow coastal band into northern New South Wales. Some scenarios indicate that its range could extend further inland from mid- to southern Queensland. This is most evident in the Echam4 model, which is a relatively wet model.

The 2080s projections for *A. nilotica* (Figure 3) generally indicate a southern trend that is most pronounced in New South Wales. This is due to the degree day sum increasing. Several of the model results include patches of unsuitable habitat within the large marginally suitable habitat in central and south-western Australia. This limitation is due to periodic dry stress, which is most apparent in the relatively dry Hadley3 model.

The model results for *B. davidii* (Figure 4) generally indicate that the area of suitable habitat in Australia will contract southwards as temperatures increase.

DISCUSSION

The projected future climate suitability of the case study weeds (Figures 2–4) illustrate two major sources of uncertainty: a) that due to the state of climate modelling, and; b) that due to uncertainty in global greenhouse emission patterns. Whilst it would be possible to combine the results of this modelling to provide an 'average' result, this would implicitly assume that each of the emissions scenarios and model results are equally valid. There is no evidence that this is the case and it may be preferable to be mindful of the range of

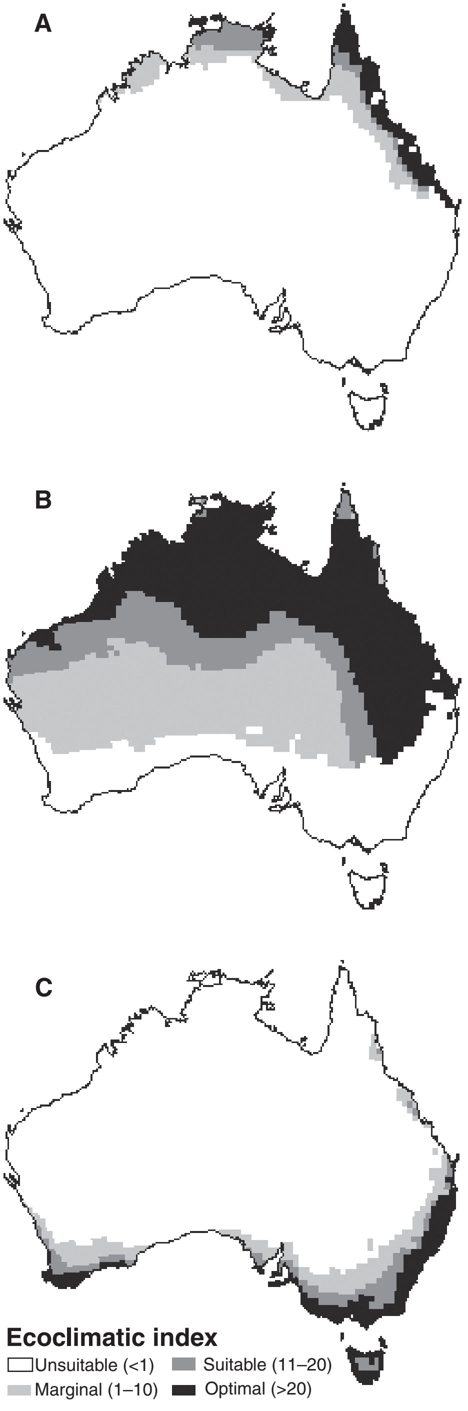

Figure 1. Climate suitability for A) *Chromolaena odorata*, B) *Acacia nilotica* and C) *Buddleja davidii* using CLIMEX with the reference climate average dataset for 1961–1990.

possible future outcomes. It seems clear that the variation in projected future climate suitability due to the specific global climate model formulation is at least as large as that due to uncertainty in patterns of global development and atmospheric pollution. Nonetheless, there seems to be sufficient agreement amongst the simulation results on broad patterns of change.

When interpreting the future climate suitability projections, it is important to bear in mind that these are not predicted future distributions. They are potential distributions, and the actual ranges of the weeds will probably lag behind the potential, depending upon factors such as the dispersal potential of the species, and any management efforts to slow their spread.

Whilst *C. odorata* is presently extremely limited in extent in Australia, climate change will only exacerbate the invasion threat (Figure 2). Any extra range expansion will further hinder affected communities and producers in their future efforts to adapt to the challenges of climate change.

Figure 3 indicates that efforts to educate pastoral producers and others to the future threat posed by *A. nilotica* in New South Wales, the Northern Territory and Western Australia could be worthwhile. Similarly, strategic eradication of outlying populations in New South Wales and the Northern Territory could also be rewarding.

The impact of climate change on the potential distribution of *B. davidii* will generally be to reduce the overall potential impact as its potential range contracts southward (Figure 4). However this may be of little comfort, as its potential range coincides with some of Australia's currently most productive agricultural land, which may also contract in extent.

Emerging challenges As global climates experience rapid changes and species' ranges respond, we will face a set of emerging challenges in projecting further future potential distributions. The methodology employed here implicitly assumes that the species' distributions reflect the reference 1961–1990 climate. However, there is already evidence that species ranges have changed in response to climate changes since 1990 (Parmesan *et al.* 1999). If the distribution data used to build the reference current climate distribution include records from locations that have only recently been invaded, then the utility of the modelling approach will be undermined. In this case the potential distribution could be overestimated. Another confounding problem will be the fact that species ranges are likely to expand and contract at different rates (Franco and Silvertown 1996). As climate changes allow a species' range to shift, it is possible that the range could expand rapidly. Conversely, there may be considerable lag in seeing any concomitant range contraction due to the species persisting for some time in more favourable micro-habitats or as perennial vegetation without reproducing.

To assist with overcoming the climate range correspondence problem, databases of species distributions such as the Global Biodiversity Information Facility should include the observation or collection date, and where this is absent, the date of acquisition of the digital record. Whilst this measure will be necessary, it may not always be sufficient. When analysing species distribution records, it would be a simple matter to assume that post-1990 distribution records that in-filled a species range were not due to post-1990 climate changes. However, it may be that the in-filling records are for habitats that would have been climatically unsuitable under the reference climate e.g., a high elevation area that was too cold or wet during the reference period.

Another option to address the requirement to match species' distributions to the appropriate climate is to periodically update the reference climate. However, the challenge will remain to correctly assign historical distribution records to the appropriate climate, as species may not expand their range at the same rate as climatic limits are relaxed due to climate change.

At present, the problem of matching distribution records to appropriate climates is likely to be a relatively minor source of error for range projections.

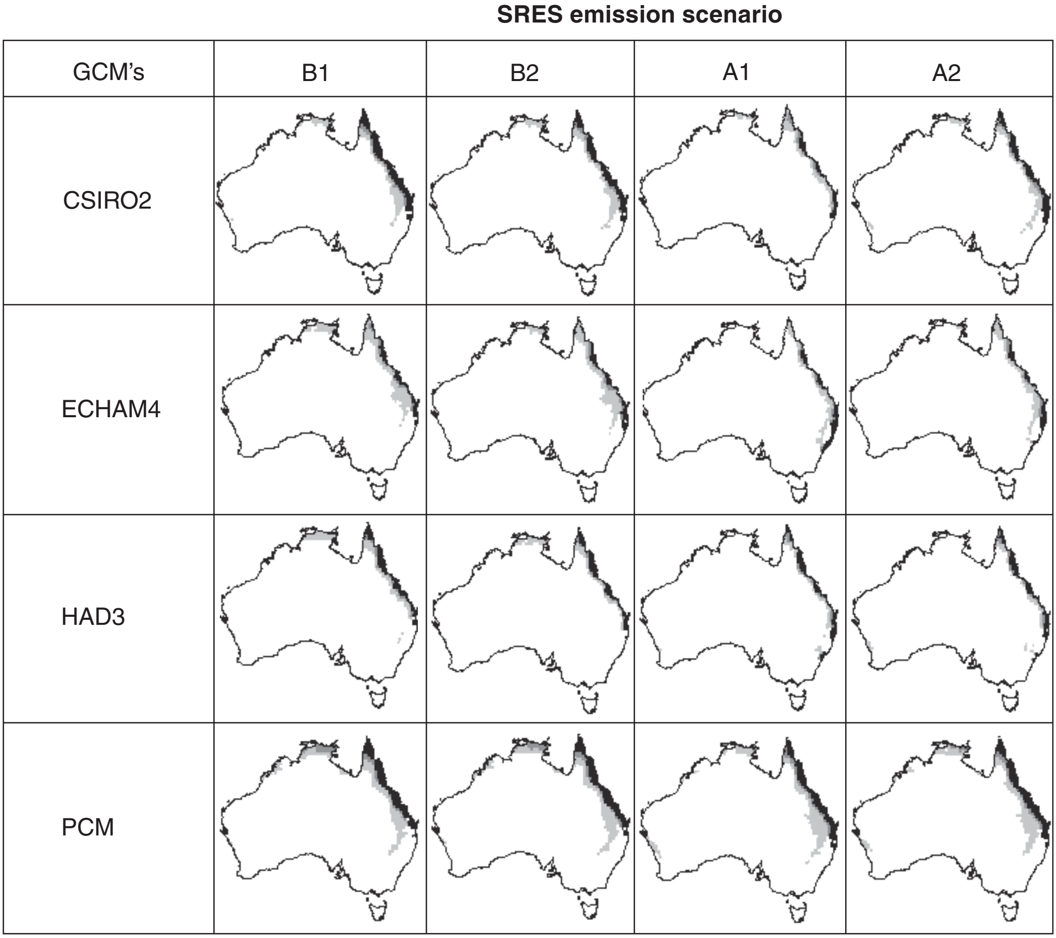

Figure 2. Climate suitability for *Chromolaena odorata* in the 2080s projected using CLIMEX. Each column includes results for a different SRES emission scenario, and each row represents the results for a different GCM. The map legend is the same as for Figure 1.

However, as global warming proceeds, it is likely to become a more serious issue.

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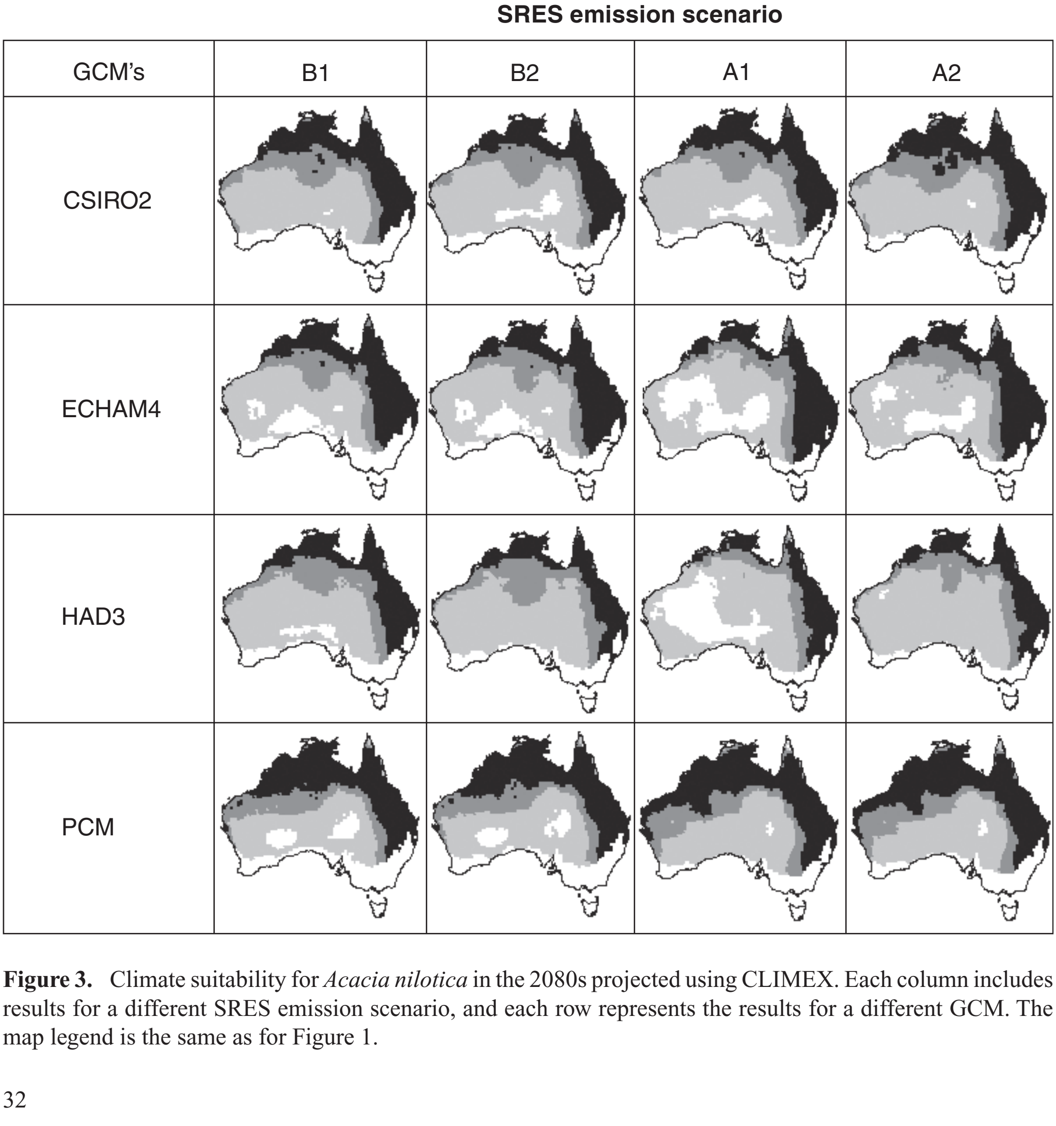

Figure 3. Climate suitability for *Acacia nilotica* in the 2080s projected using CLIMEX. Each column includes results for a different SRES emission scenario, and each row represents the results for a different GCM. The map legend is the same as for Figure 1.

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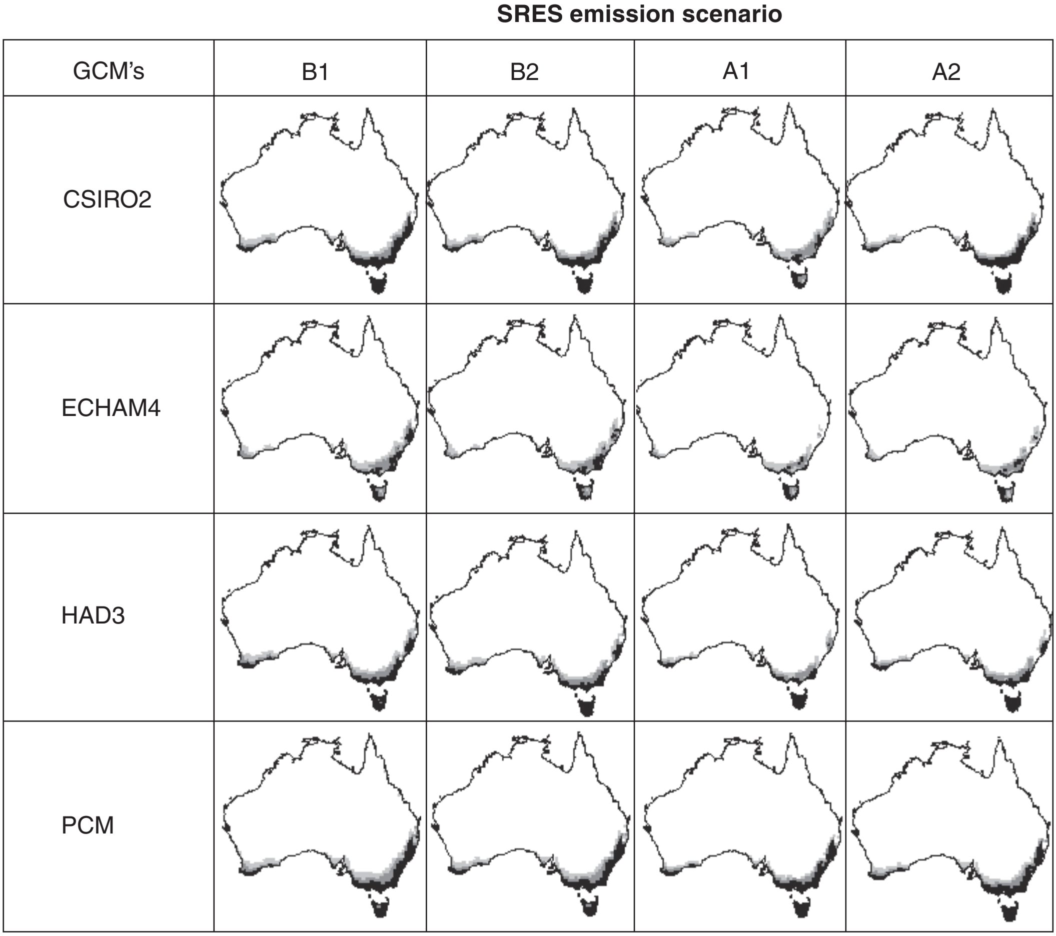

Figure 4. Climate suitability for *Buddleja davidii* in the 2080s projected using CLIMEX. Each column includes results for a different SRES emission scenario, and each row represents the results for a different GCM. The map legend is the same as for Figure 1.

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