Modelling Climate Change Impacts on Sleeper and Alert Weeds: FINAL REPORT

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Defeating the Weeds Menace project CEN10, managed through Land & Water Australia

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1. EXECUTIVE SUMMARY

Forty-one alert and sleeper weed species listed nationally were assessed for their change of potential distribution due to climate change. The potential distribution of each species was modelled using CLIMEX, a process model computer program that uses temperature and moisture parameters to develop a growth index, then applies various stress factors to determine an ecoclimatic index, of suitability for survival of the species to determine a predicted distribution in Australia under current climatic conditions.

Information from the literature on the overseas native and introduced distribution, phenology and physiology of each species were used to derive the models. Growth chamber experiments on five species, *Dittrichia viscosa*, *Lachenalia reflexa*, *Pelargonium alchemilloides*, *Retama raetam*, and *Senecio glastifolius*, were used to add information on temperature and phenology to help develop the models. Tests of association were used to confirm the model's prediction of the native distribution. The models were then applied to Australia and the fit to the observed introduced distribution tested using tests of association. The predicted distribution for each species under climate change predictions were made using eight climate change models: Echam 3 in years 2030 and 2070, under high and low emissions, and Hadley 2, in years 2030 and 2070, under high and low emissions. Additional data information and other factors that could be used aside from climate, were identified for each species.

The potential distribution of all sleeper and alert weeds combined was made for the whole of Australia, showing the south east and south west regions to be most at risk from these species collectively. Under climate change there is a general shift southwards for most species, with the shift greatest for wet tropical species (over 1000 km), and much less for south coastal species (because of the lack of landmass). The Natural Resource Management Regions most at threat from alert and sleeper species, under the current climate, and under climate change was shown to be the region of south east Australia, and to a lesser extent, south west Australia.

The weed species predicted to have the highest risk of establishment were *Retama raetam* and *Cuscuta suaveolens*. The species with widest distribution (and highest risk of establishment) under the current climate will decrease in area under climate change (even so, the area of high risk is still large). The most important species with an increased threat under climate change are *Acacia karroo*, *Tipuana tipu* and *Bassia scoparia*.

The most urgent recommendation from this work is that a new set of sleeper weed species needs to be identified for the north of Australia because of the vacuum that will be created by the displacement of species southwards, both native and introduced. Secondly, the predicted displacement of species under climate change enables the identification of management strategies for each species. This could include developing east-west quarantine barriers along potential migration routes. While some of the alert and sleeper species are evidently of low threat, the analysis of potential distribution identifies certain species, such as *Acacia karroo*, *Retama raetam* and *Equisetum arvense*, that could become major problems under any climate scenario and should be managed accordingly.

2. INTRODUCTION

Weeds are among the greatest threats to biodiversity in Australia and a significant cost to agriculture. This cost will increase or decrease as weed species change their distributions in response to future changes in the climate. Thus research on invasive species, such as weeds, has been identified as a national priority (Hilbert et al. 2007). There are few studies specifically demonstrating this change in risk due to weeds both in Australia and overseas.

In Australia, the impact of climate change has been shown to potentially increase the distribution of *Acacia nilotica* due to its ability to invade dryer sites further inland and to spread southwards due to increased temperatures (Kriticos et al. 2003). Experimental assessment of wild oats, *Avena fatua*, showed increased growth with increase of climate change conditions (O'Donnell and Adkins 2001), an observation now made for many plant species. Ziska and Caulfield (2000b) suggested that the continuing increase in atmospheric CO_2, as would be expected under climate change, could directly influence public health by stimulating the growth and pollen production of allergy-inducing weed species such as ragweed, *Ambrosia artemisiifolia*. Ziska and (2000a) also suggest that herbicides will be less effective based on a study of elevated CO2 and quackgrass (*Elytrigia repens*).

The extent of climate change impacts on minimum and maximum temperatures and rainfall are shown in Figures 1, 2 and 3. The extent of changes are those predicted using the Hadley 2 High scenario and the Echam 3 High scenario for 2070. These are two of the eight climate change scenarios used throughout this report for the prediction of future distribution of species. For minimum temperature both models show a warming in January, although it is more, up to 10°C, in northern Australia under Hadley 2. In July both models show that winters will be warmer in the south. For the maximum temperature in summer the Hadley 2 model shows a greater warming than the Echam 3 and in July in the north the increase in temperature is comparatively warmer than the south. The main difference between the Hadley 2 and Echam 3 models are for rainfall in that the Echam 3 predicts wetter summers in the south of Australia. Both models predict dryer winters. Overall the trend is hotter and dryer, except there might be more rain in summer in the south.

Our purpose in this report is to predict the distribution of alert and sleeper weed species in Australia, both under current and climate change conditions. The alert and sleeper weed species have been identified because of their perceived threat to Australian agriculture and environment respectively. Sleeper weeds are defined as “those invasive plants that have naturalised in a region but not yet increased their population size exponentially” (Groves 1999). The weeds that are a threat to agriculture have been called “sleeper” species, while those that are a threat to the natural environment have been called “alert” species. All currently have a very limited distribution, in some cases known from only one site or even considered eradicated. The distribution is shown in Figure 4 and the list with common names in Appendix B, Table 1.

More specifically, in this report we analyse the following:

1. The literature of each of the alert and sleeper species, to obtain information on distribution, temperature and moisture requirements that determine distribution.

2. The temperature required for development of five species, *Dittrichia viscosa*, *Lachenalia reflexa*, *Pelargonium alchemilloides*, *Retama raetam*, and *Senecio glastifolius*, these species were chosen because they are found in Western Australia where the project was based.

3. Develop CLIMEX models for each weed based on the plant's physiology, phenology and distribution in the native habitat.

4. Test and modify the model by comparison with the distribution in parts of the world, not Australia, where the plant is introduced and established.

5. Predict the distribution in Australia using the current climate and to various climate change scenarios.

6. Identify patterns of change in species distributions.

7. Identify the Natural Resource Management regions most affected by alert and sleeper species under climate change conditions.

8. Identify which species represent the greatest threat under current and future climates.

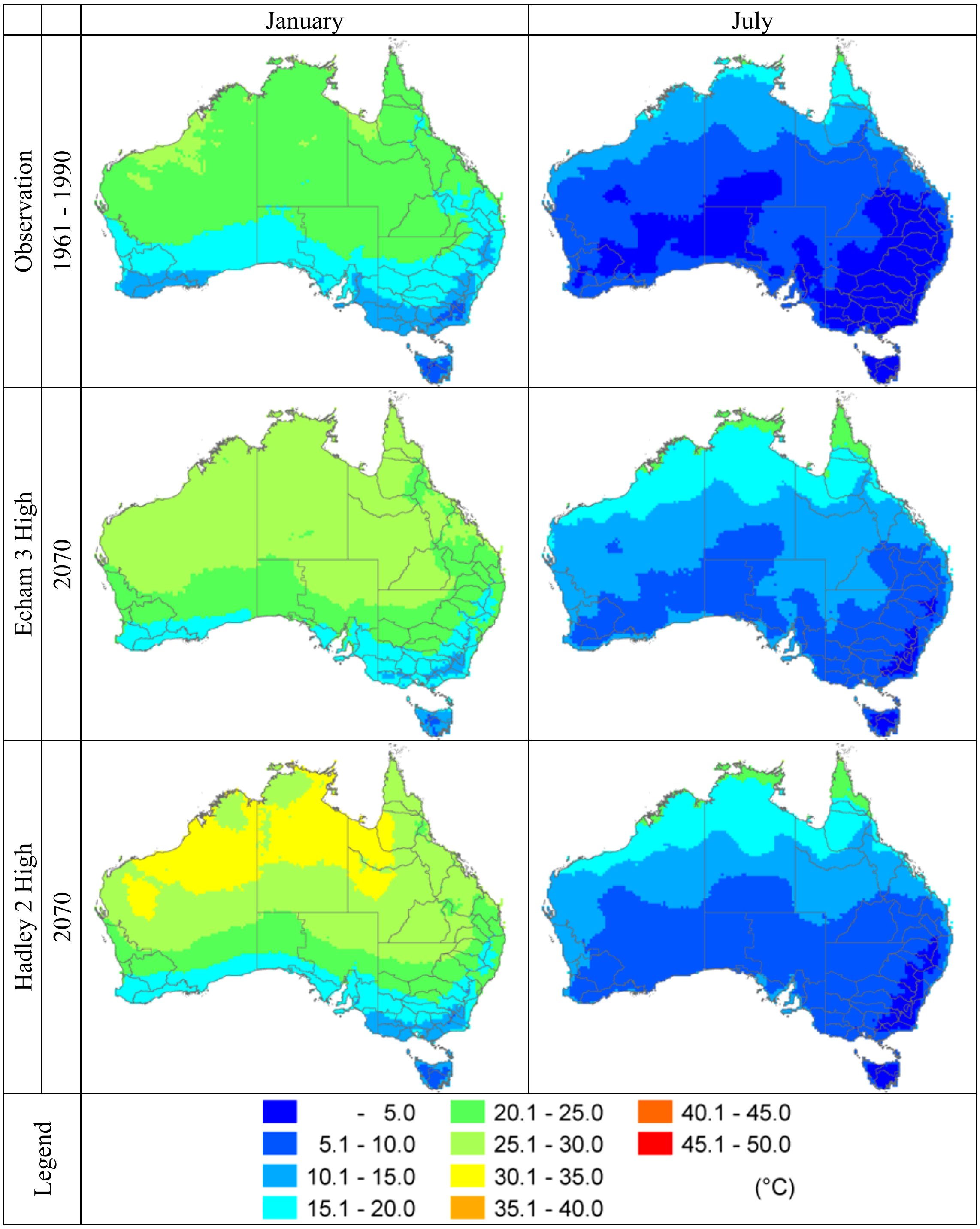


Figure 1. Minimum temperature based on reference period 1961-1990 and predicted for 2070 under the Hadley 2 and Echam 3 models.

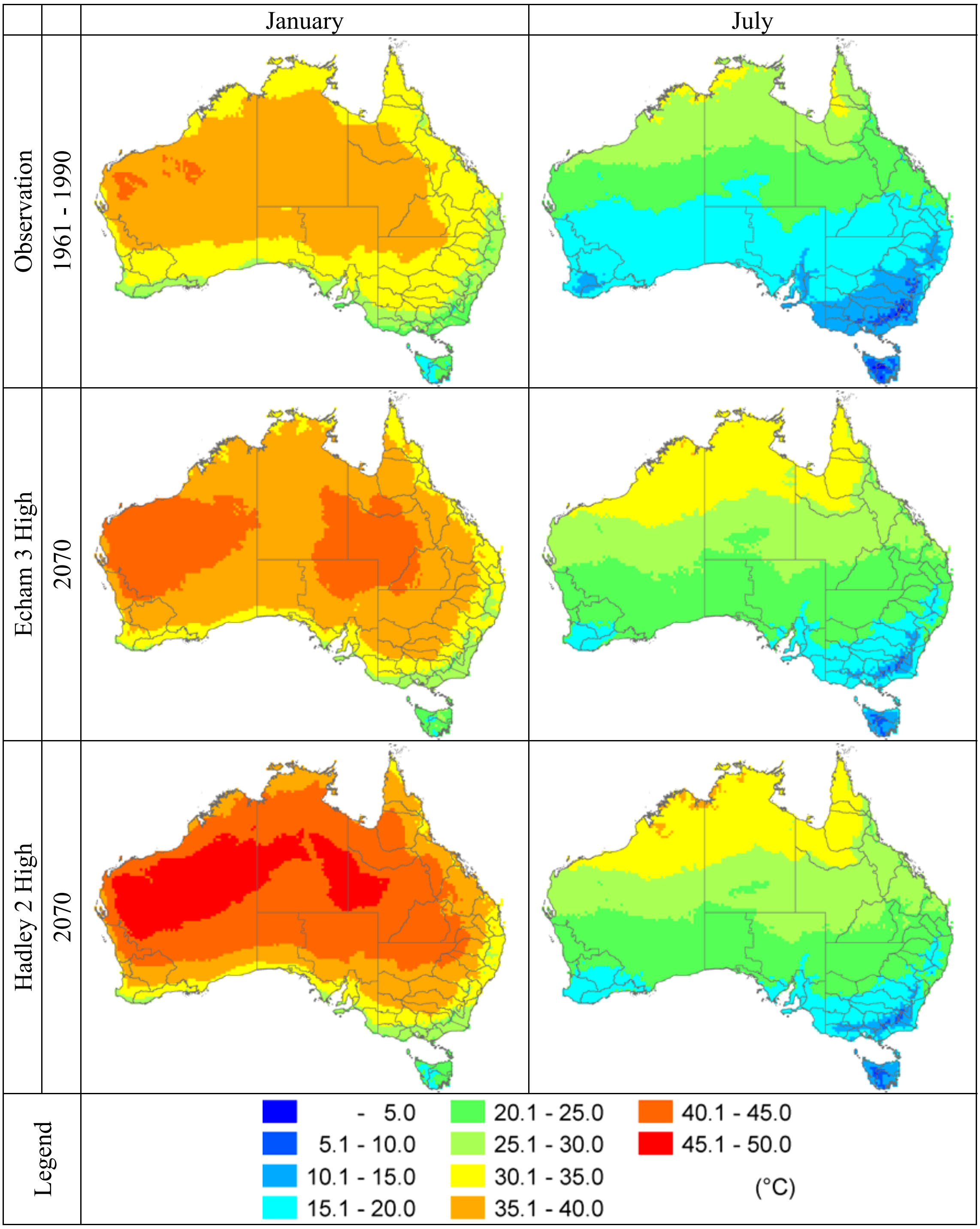


Figure 2. Maximum temperature based on reference period 1961-1990 and predicted for 2070 under the Hadley 2 and Echam 3 models.

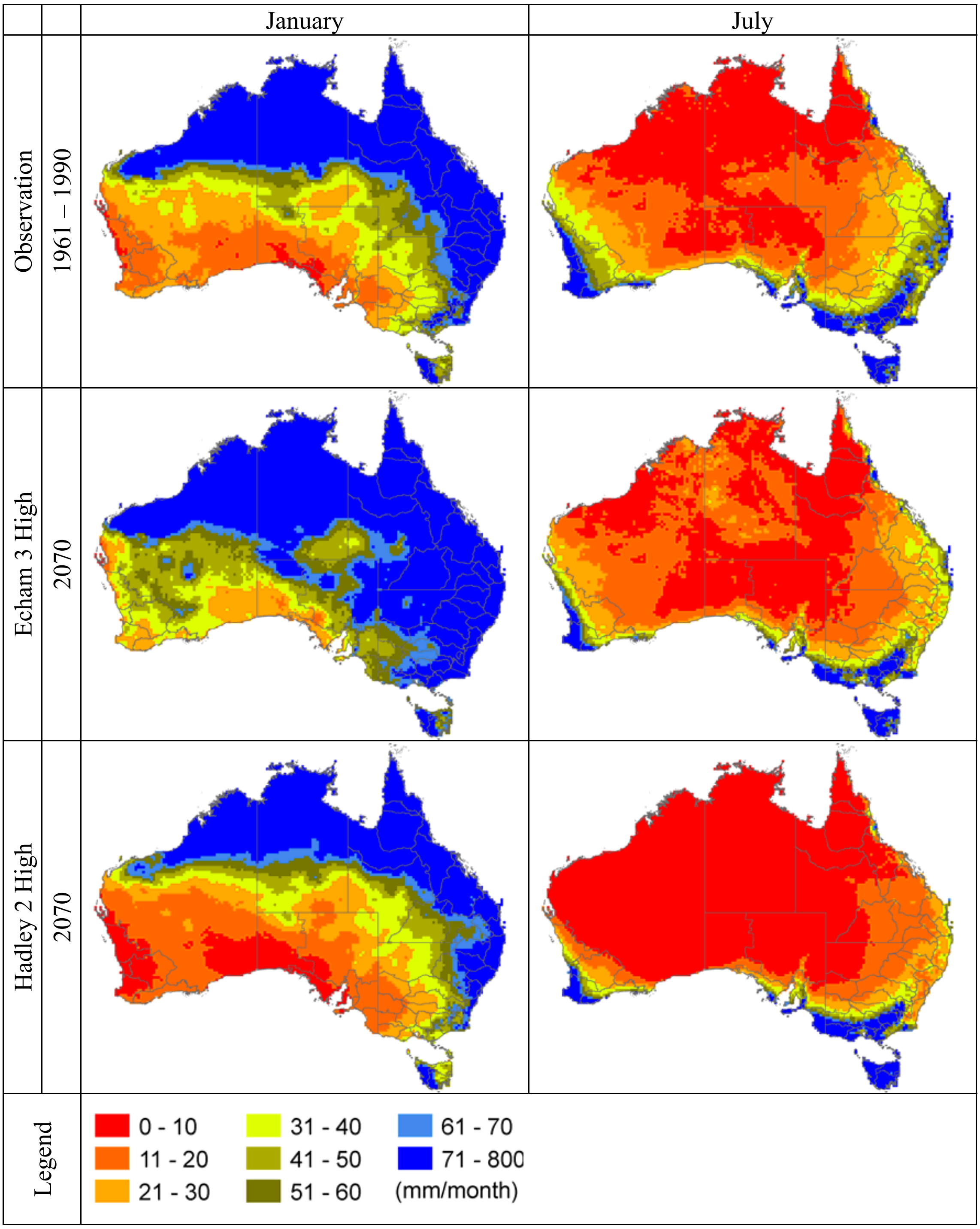


Figure 3. Rainfall based on the reference period 1961-1990 and predicted for 2070 under the Hadley 2 and Echam 3 models.

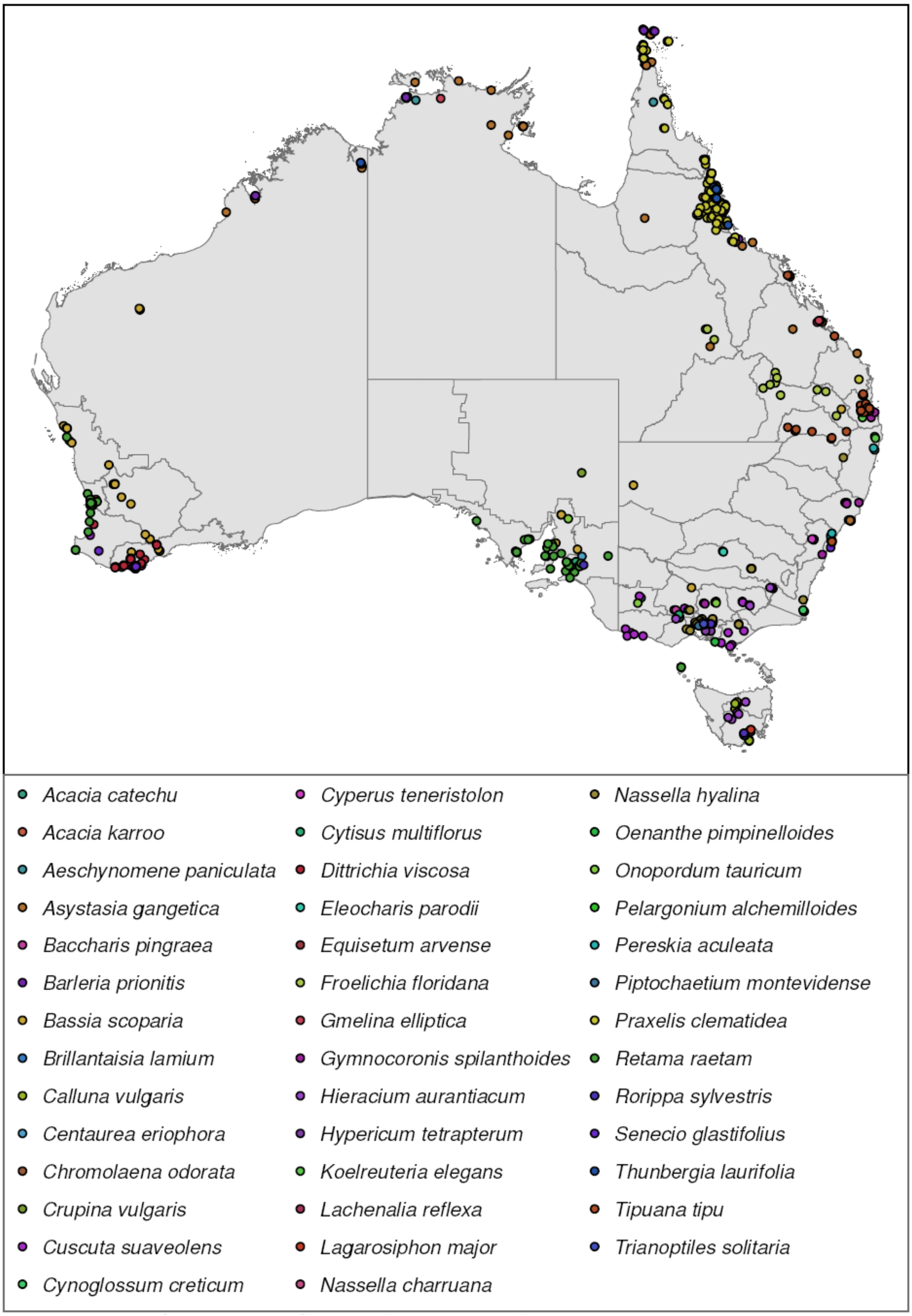


Figure 4. Distribution of 41 alert and sleeper species in Australia studied for climate change impacts.

3. METHODS

3.1 Literature searches

Literature searches and Database searches were based upon the current recognised scientific name of the weed together with any other synonyms/ Latin names for that plant as listed in Randall (2002) The Global Compendium of Weeds (see http://www.hear.org/gcw/html/index.html). If fewer than 50 references (total) were returned for a particular species then the search was expanded to include the whole of the genus. To further refine the search and therefore maximise obtaining all relevant information (especially in Scopus), the following keywords were also stipulated to be needed in addition to the plant species name:

Contains "temperature OR loca* OR clim* OR growth OR conditions OR distrib* OR model OR (degree* AND day*) OR moisture OR threshold OR taxon*" (where *=any character/s)

Only the 1000 most relevant matches were exported/saved from Scopus. Many of these sources (eg GRIN, PIER, Manfelds World database, and Randall, 2002) also cite key papers and these were also sourced if relevant as many preceded the years covered by some of the online database searches.

Standard databases (CABI, ISI Web of Science etc) were searched using the species name and synonyms. Later during the project JSTOR became available for online searches. Each species name and major synonyms were searched in JSTOR to detect publications mentioning the species. A similar search was done of the on-line journal resources of the CSIRO library.

3.2 Distribution mapping

In this report we differentiated between the database records where we knew the exact collection locality (a dot), where we knew the location to the accuracy of Brummitt (2001) level 4 base unit (= localised region) and where we only knew the location to a more generalized region (i.e. an area consisting of several of Brummitt (2001) base units). Botanical database records historically related principally to internationally defined political countries. However these countries can vary several million fold in size and often may consist of several physically separated areas as they incorporate islands. Botanists realised they needed to assign records to more biologically based units and so an International Working Group on Taxonomic databases (TDWG) was formed to produce Plant Taxonomic Database Standards (Brummitt, 2001). Under this system, the base unit (which Brummitt, 2001 refers to as level 4) can be either a country of an average size and with a discrete boundary or an individual state within a much large country. Existing botanical records may however refer to a political country (e.g. India) or a general region within a political country (e.g. Southeast Brazil). These areas may consist of several of Brummitt (2001) base units. The data for the world distribution per country or region was obtained from the literature or web-based sources.

We also noted if the plant was considered to be native or exotic at each location. If there was any doubt in the plant's origin then it was marked as being exotic because the CLIMEX models are initially fitted to the known distribution of the plants within their native distribution.

Data on point locations of the species presence was obtained from online databases, from herbarium records (Australia and South Africa), and from maps of point information published in taxonomic treatments of the species. Electronic data were imported directly into ESRI ArcMap. However, the coordinates in some data were inappropriate or vague. For example, it was unclear whether some points were in the Southern or Northern Hemisphere. There were some points whose longitudes and latitudes seemed to have been entered confusedly. We amended them where possible, based on other information attached to the data such as country name. Published distribution maps were scanned, geo-referenced and digitised so they could be added to the database, ensuring that they were not duplicates of online sources. In some cases the published collection record was provided with a place name indicating a precise locality enabling the point to be plotted after determining the longitude and the latitude.

Herbarium records were not included if the information in the database indicated that the plant was only growing under cultivation or within botanic gardens.

3.3 CLIMEX models

The CLIMEX program (Sutherst and Maywald 1985, Sutherst et al. 2004) was used to develop a model for the distribution of each alert and sleeper species, which was then used to predict the potential distribution in Australia. CLIMEX uses climate averages from meteorological stations around the world and calculates a "population growth index" GI, based on temperature, moisture required for the species being modelled. Various stress indices, such as cold or hot temperature stress, wet or dry moisture stress are added to the model if appropriate based on the literature or phenology or observed distribution. The stress factors reduce the GI values to produce an annual overall measure, the "Ecoclimatic Index" (EI), of the favourableness of the location for the species. Examples of the method are given in Scott and Yeoh (1999) and Scott and Batchelor (2006). See Sutherst and Maywald (1985) and Sutherst et al. 2004 for the definition of parameters used in CLIMEX. The flow chart of the CLIMEX method is shown in Figure 5.

3.3.1 Growth chamber experiments

The details of the methods of the measurement of growth of *Dittrichia viscosa*, *Lachenalia reflexa*, *Pelargonium alchemilloides*, *Retama raetam*, and *Senecio glastifolius* under constant temperatures are given in Appendix A.

3.3.2 Chromosome counts

The chromosomes were counted in one species, where it was important to decide on which distribution to use from the region of origin. Details of the methods for chromosome counts are given in the species account for *Pelargonium alchemilloides* in Appendix B.

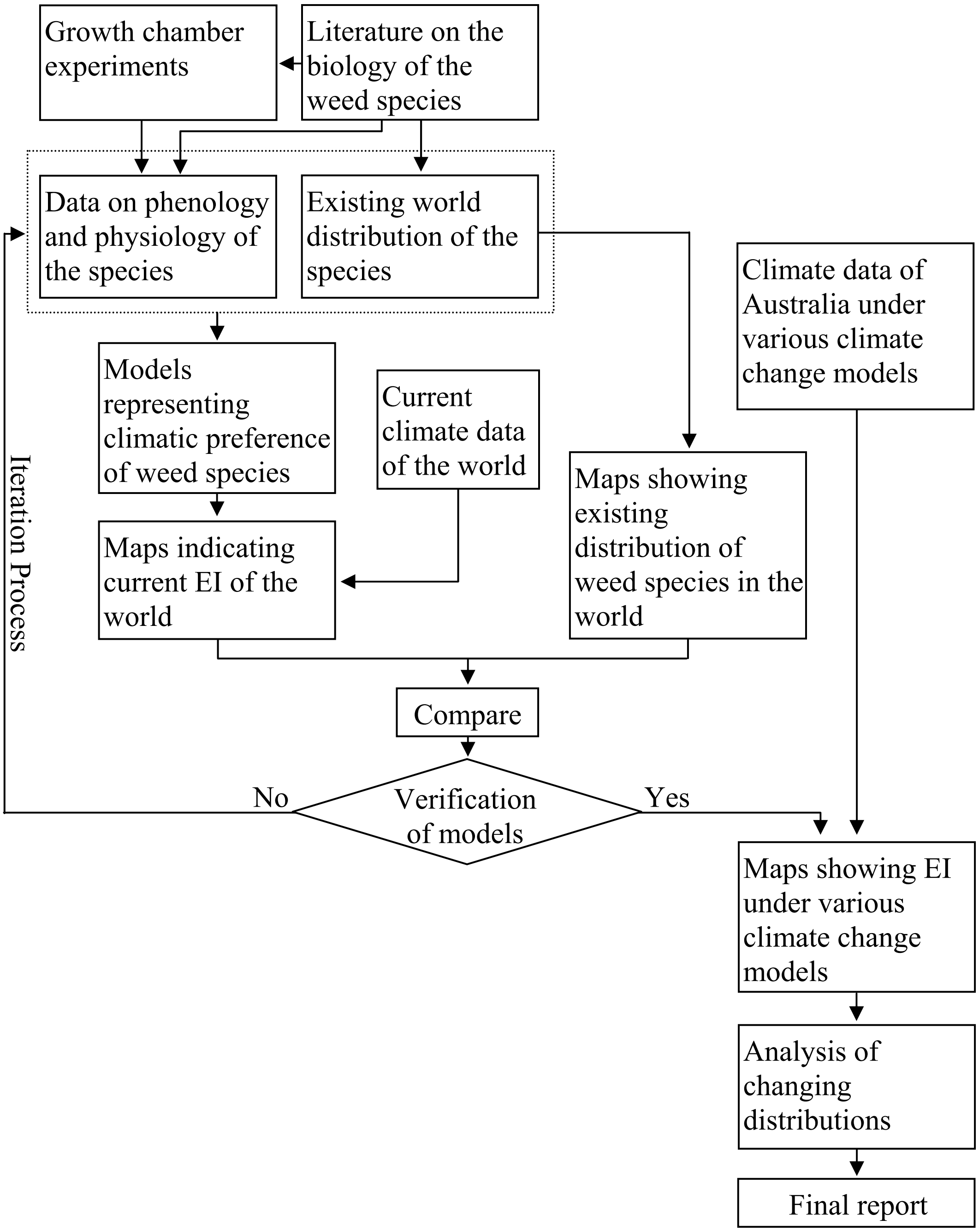


Figure 5. Flow chart of how the CLIMEX models were developed.

3.4 Climate change scenarios

The CLIMEX program has a simple facility to change globally the temperature or rainfall. This was not used because it fails to capture the regional differences expected under climate change. Instead, we used the climate change addition to CLIMEX provided by Kriticos (2006), and described as follows:

“Eight future scenario datasets are provided, covering two time periods, two GCMs [global climate models] and two emissions scenarios taken from the third assessment report of the Intergovernmental Panel on Climate Change (IPCC 2000). The Hadley centre mark 2 (HadCM2) and Echam mark 3 (ECHAM3) GCMs were selected because they represent the range of projected results in terms of temperature and rainfall across the Australian region. The HadCM2 model projects relatively large decreases in rainfall model, whereas the Echam model projects relatively large increases in rainfall (Ruosteenoja et al. 2003)” (Kriticos 2006).

The data used is described by Kriticos (2006) as follows:

“This dataset consists of a series of nine Access database files in CLIMEX^{TM} Metmanager format (Sutherst et al. 2004). The database files contain estimates for reference climate data (1961-1990) and projections of future climates for 2030 and 2070, based on two global climate models (GCMs). The dataset includes five variables (monthly means of daily maximum temperature, daily minimum temperature, daily precipitation total, relative humidity at 09:00 hours and relative humidity at 15:00 hours). These data are directly comparable to the corresponding datasets in OzCLIM. A set of polygon shapefiles have been supplied to support mapping of the output from CLIMEX.”

3.5 GIS methods

CLIMEX outputs the predictions as CSV files thus allowing importation into ARCVIEW. For the world a shapefile was established as a fishnet (a grid polygon shapefile) of 61,076 pixels at intervals of 0.5 degrees. For Australia, a shapefile was established as a fishnet of 11,333 pixels at intervals of 0.25 degrees.

3.6 Statistical tests of CLIMEX models

There are no published methods for testing how well the CLIMEX models predict to the distribution of the species being modelled. We developed two approaches to objectively assess the models.

3.6.1 Tests of association between weed presence and Ecoclimatic Index

Frequency distribution tables were created of the EI values of all the pixels in the native distribution and the pixels within which there were collection records. If the two distributions are the same (χ^2 non significant) then it can be concluded that the model and the observed distribution in Australia are not different and that we have no reason to believe the model is inappropriate. If the two distributions are different (χ^2 significant), with collection records pixels more right-skewed than that of the EI value pixels, it can be concluded that model fits but the plants were found preferentially only in the most favourable of the predicted sites rather than spread evenly over all the sites that could potentially be suitable. This is most likely a reflection of the plants not yet having spread to their full potential range within Australian. However, if the two distributions are different (χ^2 significant) and the pixels with collection records were skewed to the left or low EI end of the range of EI values, then the model is a significantly poor fit and should be rejected.

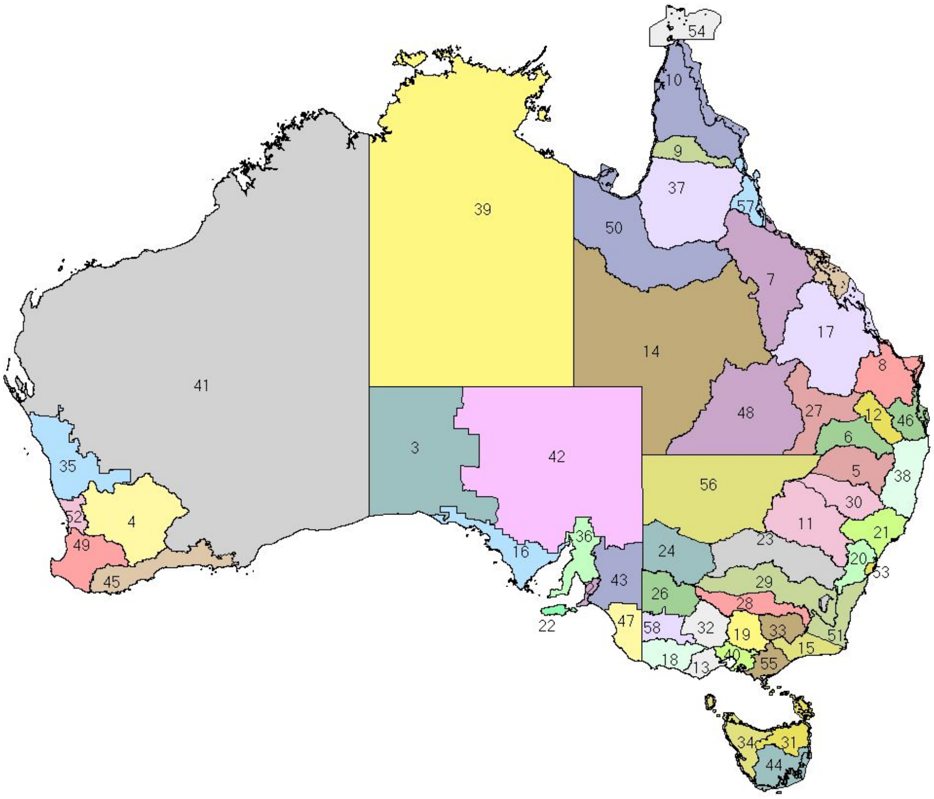
We used a randomisation test of goodness-of-fit, which calculates a χ^2 statistic to test the probability that the two distributions are the same. The probability was calculated by a Monte Carlo method. The choice of a randomisation test of goodness-of-fit was chosen because the number of pixels with collection records was too small for many species to do a standard χ^2 test of association (McDonald 2008). The same method was used to test the prediction of the observed distribution in Australia.

3.6.2 Correlation between collection density and Ecoclimatic Index

For one species, *Equisetum arvense*, there were large numbers of herbarium records or point source data in the online databases. This enabled a testing of the correlation between density of collecting and the Ecoclimatic Index. Details are provided in the species account for *Equisetum arvense* in Appendix B.

3.7 Natural Resource Management regions

NRM regions of Australia are shown in Figure 6. The regions appear as outlines in subsequent maps giving the results for predicted distributions.



Ref	Region_Name	State	Ref	Region_Name	State
1	ACT	ACT	29	Murrumbidgee	NSW
2	Adelaide and Mount Lofty Ranges	SA	30	Namoi	NSW
3	Alinytjara Wilurara	SA	31	North (TAS)	TAS
4	Avon	WA	32	North Central	VIC
5	Border Rivers/Gwydir	NSW	33	North East (VIC)	VIC
6	Border Rivers	QLD	34	North West (TAS)	TAS
7	Burdekin	QLD	35	Northern Agricultural Region	WA
8	Burnett Mary	QLD	36	Northern and Yorke	SA
9	Cape York Northern Gulf	QLD	37	Northern Gulf	QLD
10	Cape York	QLD	38	Northern Rivers	NSW
11	Central West	NSW	39	Northern Territory	NT
12	Condamine	QLD	40	Port Phillip and Westernport	VIC
13	Corangamite	VIC	41	Rangelands (WA)	WA
14	Desert Channels	QLD	42	SA Arid Lands	SA
15	East Gippsland	VIC	43	SA Murray Darling Basin	SA
16	Eyre Peninsula	SA	44	South (TAS)	TAS
17	Fitzroy	QLD	45	South Coast Region	WA
18	Glenelg Hopkins	VIC	46	South East (QLD)	QLD
19	Goulburn Broken	VIC	47	South East (SA)	SA
20	Hawkesbury/Nepean	NSW	48	South West (QLD)	QLD
21	Hunter/Central Rivers	NSW	49	South West Region	WA
22	Kangaroo Island	SA	50	Southern Gulf	QLD
23	Lachlan	NSW	51	Southern Rivers	NSW
24	Lower Murray/Darling	NSW	52	Swan	WA
25	Mackay Whitsunday	QLD	53	Sydney Metro	NSW
26	Mallee	VIC	54	Torres Strait	QLD
27	Maranoa Balonne	QLD	55	West Gippsland	VIC
28	Murray	NSW	56	Western	NSW
29	Murrumbidgee	NSW	57	Wet Tropics	QLD
30	Namoi	NSW	58	Wimmera	VIC

Figure 6. Natural Resource Management regions of Australia.

4. RESULTS

4.1 Growth chamber experiments

The details of the results of the measurement of growth under constant temperatures are given in Appendix A. *Dittrichia viscosa*, *Lachenalia reflexa*, *Pelargonium alchemilloides*, *Retama raetam*, and *Senecio glastifolius* were used to add information on temperature and phenology to help develop the models. Comprehensive information was obtained for *Lachenalia reflexa* for seeds and corms and *Retama raetam* based on seedling growth. *Dittrichia viscosa* and *Senecio glastifolius* were grown from transplanted seedlings because seeds were not available at the start of the project consequently the growth information was limited to part of the development cycle. Even so, the information helps the development of the models.

4.2 Chromosome counts

The chromosomes were counted in one species where it was critical to the development of the CLIMEX model. There are different distributions of *Pelargonium alchemilloides* in southern Africa for each of the four chromosome numbers found in this species. Given that this plant has a very restricted distribution in Australia, near Hamlin Bay in south west Australia, the modelling of potential distribution requires that the chromosome number be known for plants in Australia. Details of the methods and results are given in the species account for *Pelargonium alchemilloides* in Appendix B. The chromosomes are very small and very difficult to count accurately, but corresponded to $2n = 16$, which is the chromosome number of plants from the southern part of South Africa. This includes the area of similar climate to where the plant is introduced in Australia. There is a possibility that $2n = 18$ and this could be determined with an improvement of technique, but the Hamlin Bay plants are definitely not polyploid.

4.3 Predictions of distribution for each species

The development of and results for the CLIMEX models for each of the 41 species are shown in Appendix B. The results show the native distribution, both as on-line records of point locations, and the regions or countries where the plant is found. The maps also show the introduced world distribution with point sources based on herbarium records in Australia. The results then give the CLIMEX model for the world and the predictions to Australia under current climate, and climate change scenarios. The level of change between predictions for today’s and future climates are shown.

One example of a predicted distribution is shown here (Figure 7). The parameter sets for the CLIMEX models for all species are shown Appendix B, Table 3.

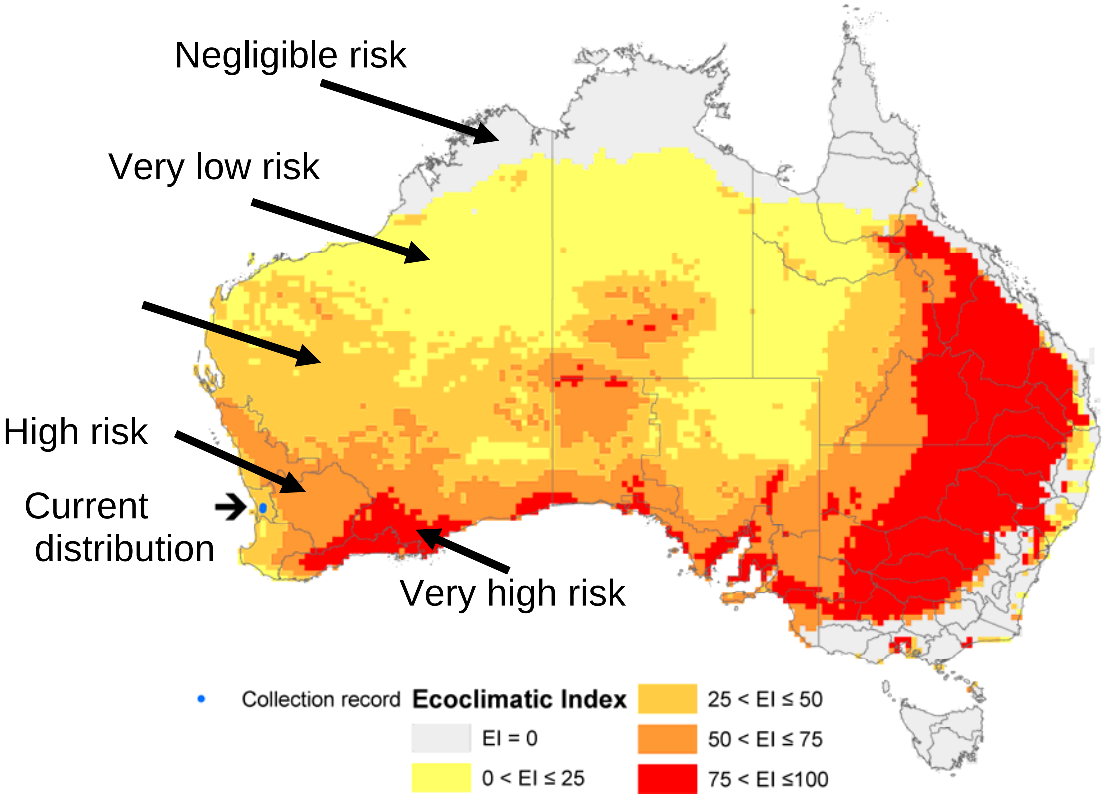


Figure 7. Example of a CLIMEX prediction to Australia under the current climate showing the Ecoclimatic Index (EI). The weed being modelled is *Acacia karroo* and the interpretation is shown of the risk of establishment associated with EI.

4.4 Statistical tests of predicted distributions

Equisetum arvense was the species with a large number of distribution records. This enabled the collection intensity to be tested against the EI value showing a highly significant relationship (see Appendix B species account for *Equisetum arvense*).

4.4.1 Test of prediction to region of origin

Most species had relatively few collection records in the area of origin. A test of association between the collection records and EI values showed that most of the models matched the observed overseas distributions (Appendix B, Table 4). This would be expected because the overseas distribution was used to guide the development of the model. However, the model is based on plant physiological parameters which are independent of the distribution points hence it is useful to verify statistically that the models do predict the overseas distributions.

The results in Appendix B, Table 4 can be interpreted as follows. Twenty six of the 41 models had more distribution points located in pixels with high (> 50) EI values than would be expected if the distribution was random. That is, the collection dots trended to be located in the orange or red parts of the maps and there were proportionally fewer collection points in areas of no prediction of yellow. Three species, *Aeschynomene paniculata*, *Chromolaena odorata*, and

Cytisus multiflorus had predictions in the same proportion of the frequency of EI values, but with most collection points at the high EI end. It is not possible to conclude that the model is a superior predictor of collection points in these cases, only that the model matches the distribution of collection points. Further development of the model is recommended. In two cases, *Baccharis pingraea*, and *Hypericum tetrapterum* there were more collection points at the low end of the EI scale. These models will need to be examined and revised. For ten species the numbers of collection points we were able to obtain from the overseas databases were too few to be able to make meaningful predictions.

4.4.2 Test of prediction to Australia

Table 5 provides the statistical test of the CLIMEX model prediction to Australia. A model that has high EI values for the collection points in Australia is predicting more of the distribution than at random. Thirty of the models had significant, and most were highly significant, association with the existing distribution. Eight models were equivocal, but at least the collection points occurred in the region where EI had a value. Three models appeared not to match the observed distribution. For two of these, *Acacia karroo* and *Barleria pionotis*, it is likely to be because some of the collection records are plants from botanical gardens, not freely naturalised. The third species, *Baccharis pingraea* already had a poor match overseas, but it is possible that this species is miss-identified, or the overseas distribution includes a complex of species, which would explain the poor-matching results (see species account in Appendix B).

4.5 Combined CLIMEX predictions

Each of the alert and sleeper species has a prediction model in the species accounts in Appendix B. These were combined to produce a national map of the threat from alert and sleeper species. The average of the EI values per pixel is shown in Figure 8 with the location of collection records for all species. Because the species are spread around Australia the average values show that there are no regions where EI averaged above 75 and relatively few quarter degree squares averaged above 50. The locations of these values shows regions of particular concern for the 41 alert and sleeper species, chiefly in the eastern mountain ranges and southern coasts (Figure 8).

In Figure 9 the range of EI values has been grouped above EI = 45 so that the regions at most risk are highlighted. This clearly shows that the eastern slopes of the Great Dividing Range, and southern regions near the south cost, including coastal Tasmania, are at most risk. In contrast most of the north and centre of the country have a low overall risk.

The summarised change in predicted distribution under climate change is shown in Figure 9 and the change in EI is shown in Figure 11. In the predictions to 2030 there is a reduction of risk over northern and central Australia. Risk is increased in south east Australia in the Hadley 2 models, whereas for the Echam 3 models risk increases in the southern half of WA and southern South Australia. This is due to the increased rainfall predicted in Echam 3. In the predictions to 2070 the trends observed in 2030 continue. The Hadley 2 model shows a substantial reduction in risk across most of Australia and an increased risk in south east and Tasmania. This reduction in risk is due to the increase in temperature making the environment unsuitable for the 41 species. The Echam 3 model also shows a decrease in risk in north east Australia and across northern and central Australia.

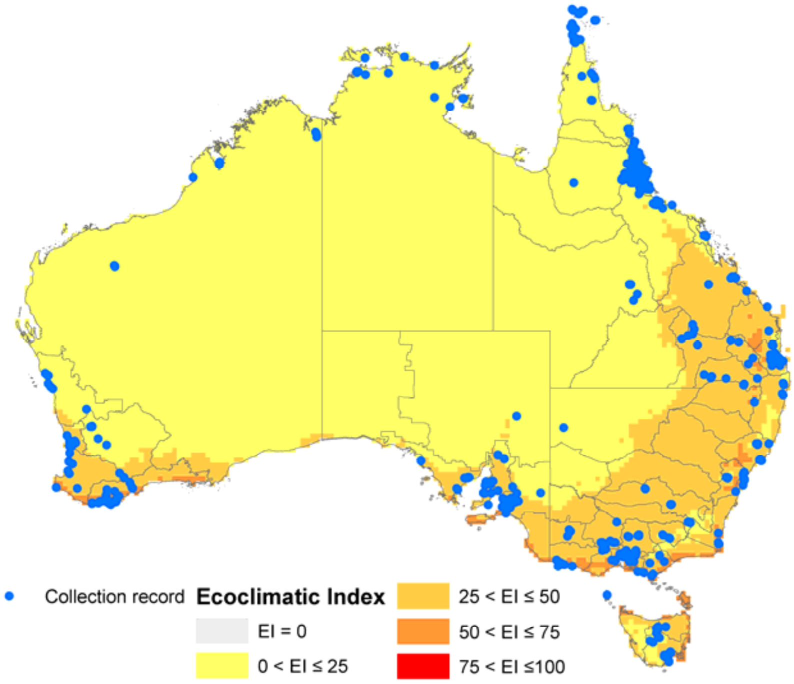


Figure 8. Average Ecoclimatic Index (EI) across 41 species for the period 1961 – 1990 grouped in intervals of 25 and showing the collection records for all species.

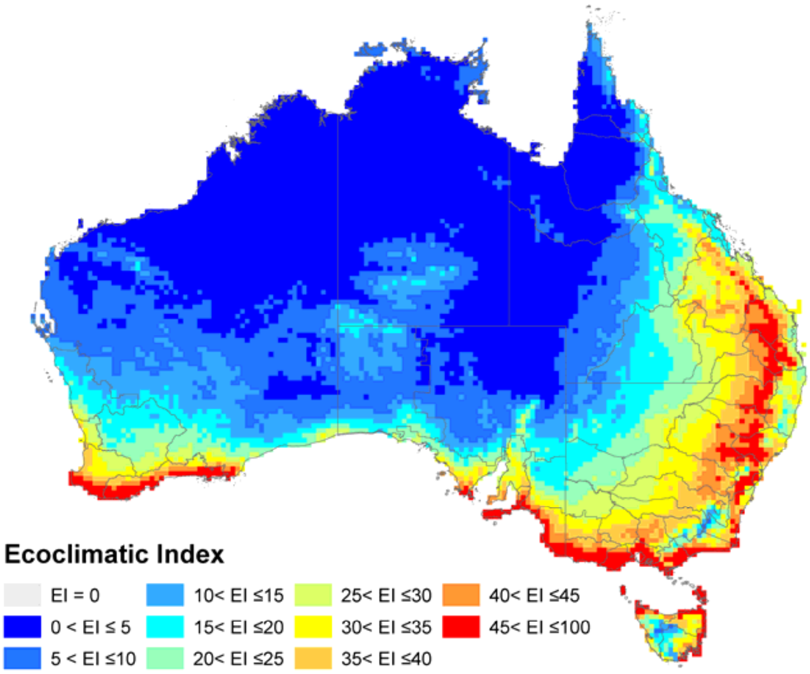


Figure 9. Distribution of Ecoclimatic Index (EI) values across 41 species for the period 1961 – 1990, grouped in intervals of 5 with values over 45 to 100 grouped to show the highest EI average scores.

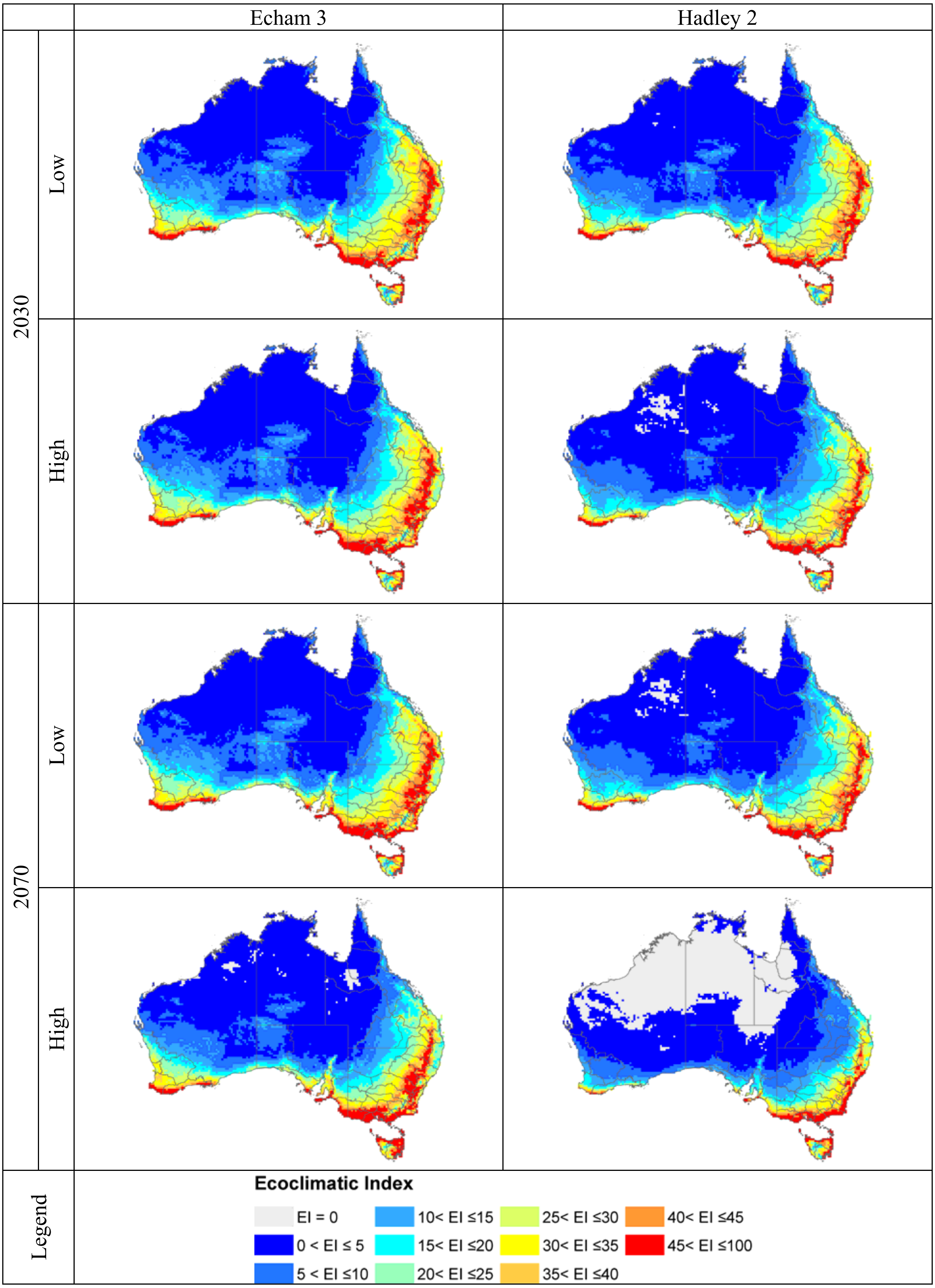


Figure 10. Average Ecoclimatic Index for 41 alert and sleeper species in intervals of 5 with values over 45 grouped for Echam 3 and Hadley 2 climate change models for low and high emissions in 2030 and 2070.

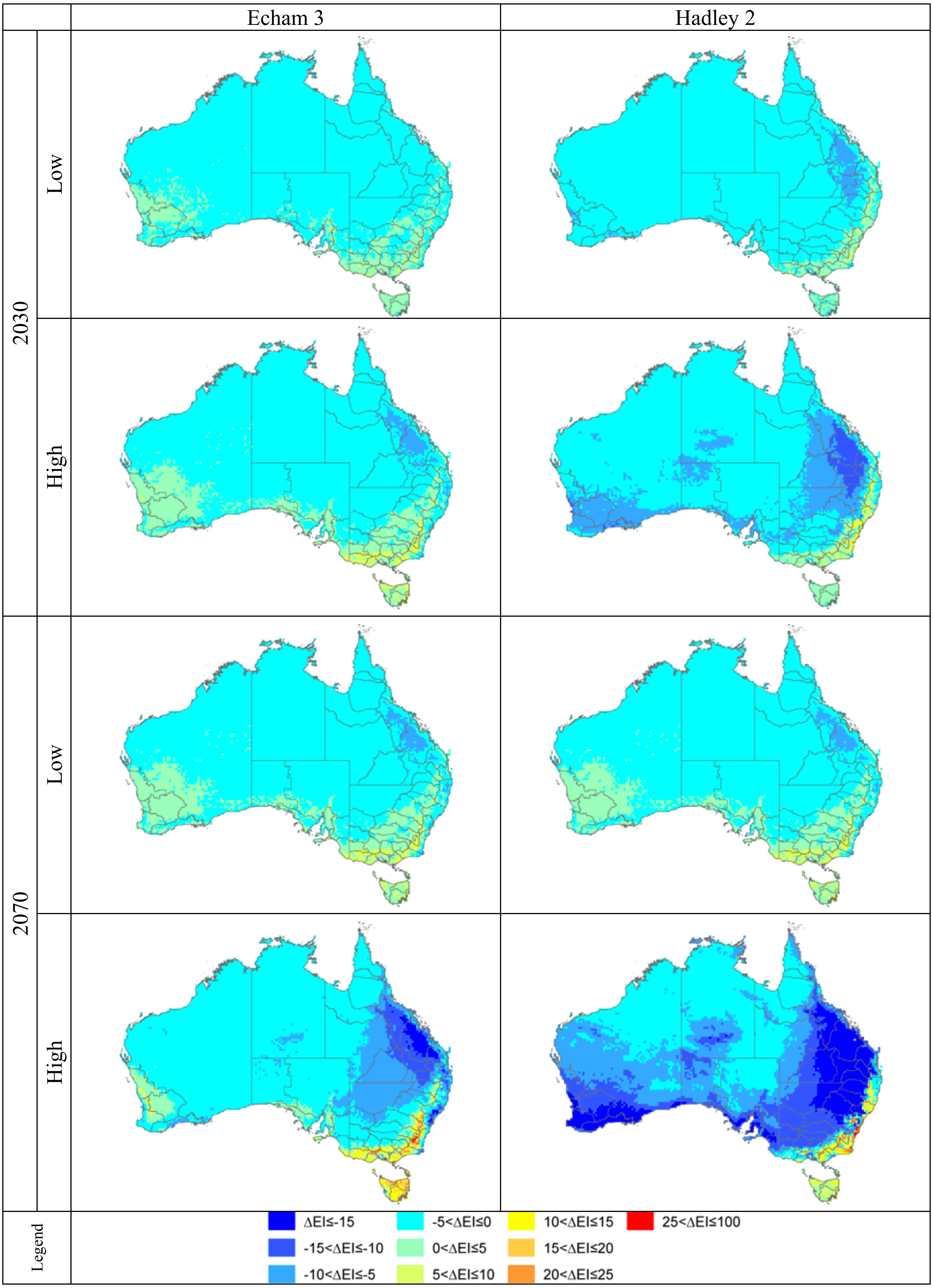


Figure 11. Difference in the average Ecoclimatic Index for 41 alert and sleeper species between today's and Echam 3 and Hadley 2 climate change models for low and high emissions in 2030 and 2070.

4.6 Natural Resource Management regions

4.6.1 Species per region

The regions most at risk from alert and sleeper species among the 56 Natural Resource Management regions of Australia are identified in Figure 12 for today's climate and the projected climate of 2070. Under the current climate the NRM regions most threatened by alert and sleeper species are on the eastern and south eastern coast of Australia. Under climate change the area of greatest threat contracts to the south east. The number of species with a high likelihood of establishment increases from about 19 or 20 to up to 29 in the south east and Tasmania. This is about a 20% increase in the number of species.

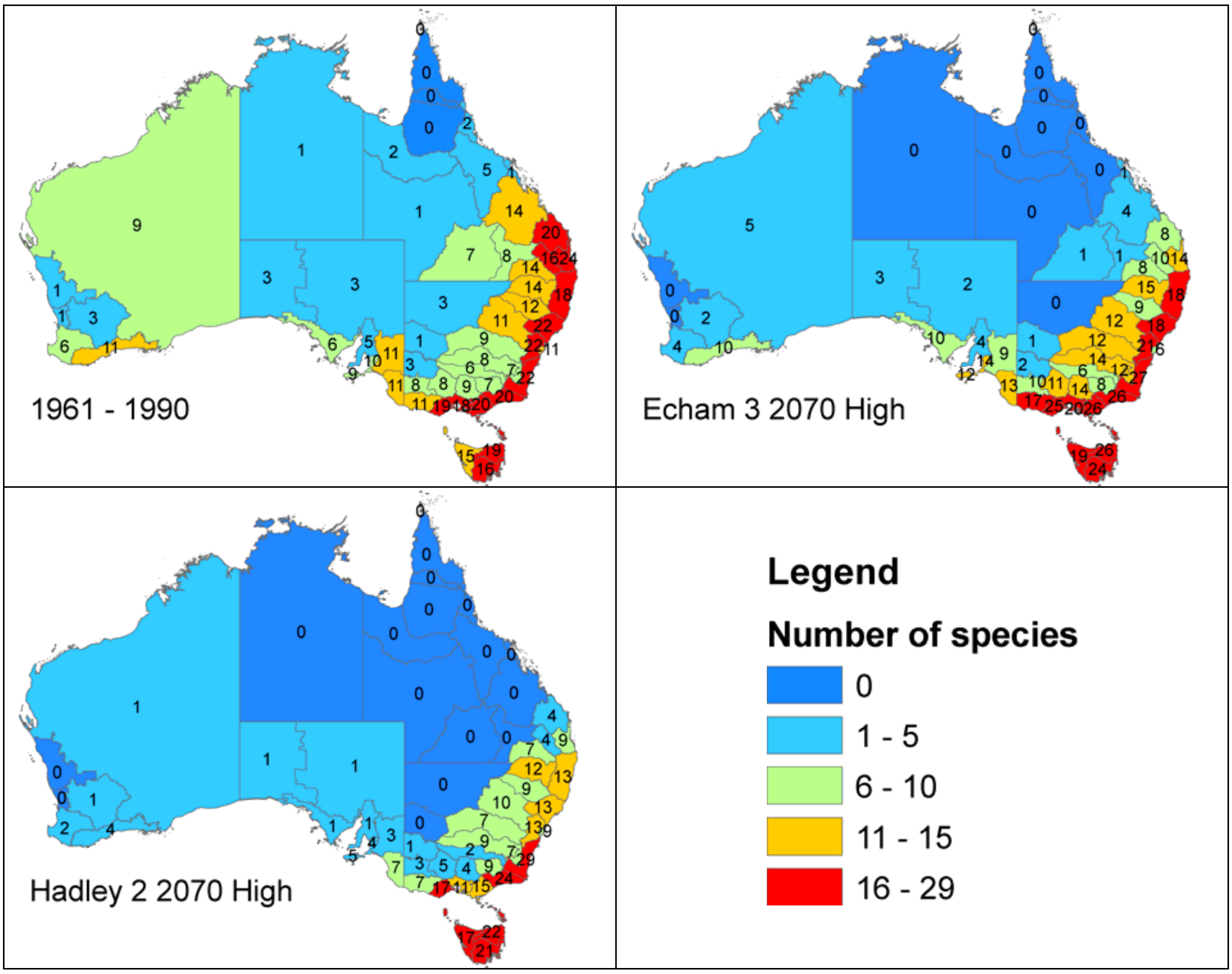


Figure 12. Number of species with maximum EI over 90 in NRM regions.

4.6.2 Regions per species

The white weeping broom, *Retama raetam*, is by far the species that threatens the most regions both today's and under future climates. Four other species are considerable threats (Table 1). These species are predicted to be widespread under the current climate so it is not surprising that they decline in the future. Nine of the species, *Crupina vulgaris* and below in Table 1, have an increase in the number of regions with a high probability of establishment under climate change. The greatest increase is for *Bassia scoparia*, a species likely to respond well to summer rainfall as indicated under the Echam 3 model.

Table 1. Number of NRM regions with weed species with EI greater than 90. The remaining species, not shown do not have EI values as great as 90.

Weed species	1961-1990	Climate change model	
		Echam3 2070 High	Hadley 2 2070 High
Retama raetam	32	21	22
Cuscuta suaveolens	21	16	12
Cynoglossum creticum	17	11	12
Froelichia floridana	12	10	1
Cytisus multiflorus	11	7	9
Equisetum arvense	9	1	1
Dittrichia viscosa	8	3	4
Hieracium aurantiacum	8	3	2
Centaurea eriophora	6	4	3
Rorippa sylvestris	6	6	2
Crupina vulgaris	5	7	5
Onopordum tauricum	5	3	2
Acacia karroo	4	6	4
Tipuana tipu	3	6	0
Bassia scoparia	2	8	4
Baccharis pingraea	1	2	3
Calluna vulgaris	1	1	1
Gymnocoronis spilanthoides	1	1	0
Lagarosiphon major	1	0	0
Piptochaetium montevidense	1	0	0
Cyperus teneristolon	0	3	0
Hypericum tetrapterum	0	1	0
Nassella hyalina	0	1	0
Oenanthe pimpinelloides	0	1	0
Number of species	20	22	16

4.7 Direction of species displacement

Figure 13 shows the direction and distance species are predicted to be displaced under climate change (Echam 3 model). Some displacements are up to 1000 km in the north. Species in the south have less potential distance available for displacement.

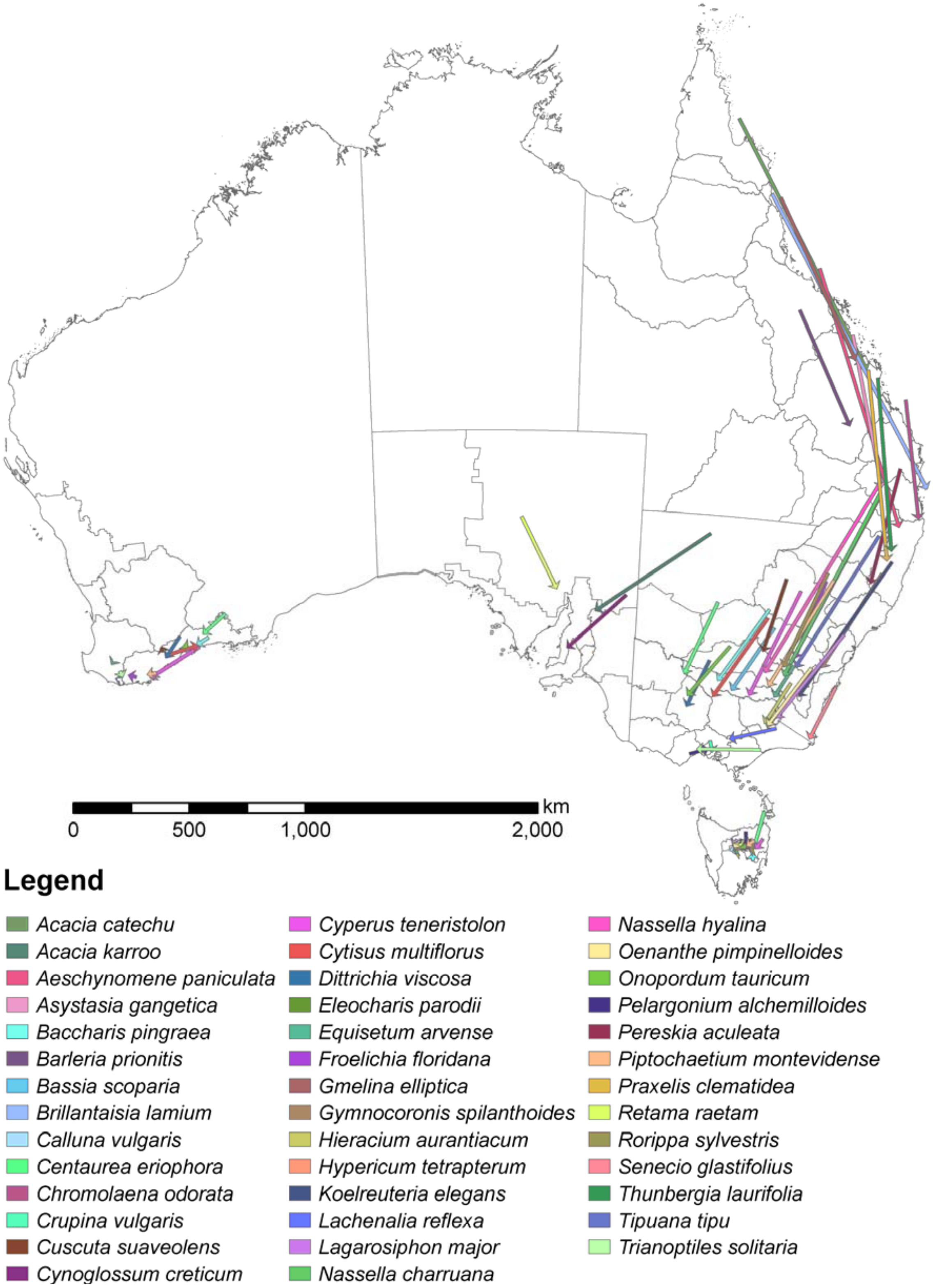


Figure 13 Direction of predicted movement of species under the climate change scenario of Echam 3 from the prediction distribution of today to the future distribution in 2070.

5. KNOWLEDGE AND ADOPTION PLAN

5.1 Target audience

Our primary target audience, in a very general sense, are policy makers and land managers across Australia. More specifically, the aim of this project is to predict which weeds will be favoured and therefore be of a higher threat status under various climatic-change scenarios. An important audience is the scientific community involved in climate change research, especially those working on adaptation to climate change risk and policy related to this area. Finally, Land & Water Australia and the Defeating the Weed Menace R&D program and CSIRO are stakeholders in this project and thus are a target audience.

5.2 Communication outputs

This report delivers information to identify the relative risks of alert and sleeper weed ingress within Australia due to climate change. This addresses, in part, output 1 of the DTWM R&D program managed by Land & Water Australia. It also addresses objective 1.4.1 of the Australian Weed Strategy (Assess the risk of new weed problems arising from climate change and promote awareness of potential impacts).

In the K & A plan we anticipated that we would produce 2 types of publications. The first would just be a 1 or 2 page flyer that is specifically designed to be cheap to produce and light and easy to read. It is essentially an executive summary which informs the general public that the subject has been considered, the research done and the predictions made. The second type of publication is the detailed website with all the species information. Both activities can be completed once the final report is accepted.

5.2.1 Website

The scientific community and the policy makers/land managers that are likely to make direct use of the information will however want to scrutinise the data in more detail. The full results, including bibliographies, experimental data, model parameters and current/predicted distribution maps will therefore need to also be produced, but these will be quite substantial and so their dissemination will be directed only to those that need or specifically want to know. Reference to the full report will be made in the widely distributed 1 or 2 page fliers. To ensure the results are adopted by the most relevant NRM regions, direct contact with the appropriate state agriculture department and NRM coordinators will be made and copies of the final report actively given to them.

5.2.2 On the ground impact

Our attempts to obtain the alert and sleeper species has helped draw attention to these species and this project in the regions where they are established. For example, as part of obtaining information on *R. raetam* and *L. reflexa*, we have had several meetings and have attended several workshops run by the Swan Catchment Council, NRM region. We also assisted this NRM region by reviewing/commenting upon their draft strategic plan for the eradication of *R. raetam*. Whilst obtaining *P. alchemilloides* we explained the aims of this project to DEC Nature conservation officers who are involved with the control of this weed in the South West Catchment Council NRM region. As well as this, staff from the Department of Agriculture and Food and the South Coast Regional Initiative Planning Team (SCRIPT) NRM region are now aware of this project and has been involved with helping us obtain *D. viscosa*, *S. glastifolius* and *P. alchemilloides* plants. The models we developed on the potential distribution of these weeds will help these regions with developing future eradication plans, for example to determine the delimitation survey areas, and determining the economic return from potential eradication efforts.

5.2.3 Presentations

The following presentations were made during the term of the project:

- Canberra at the Knowledge and Adoption workshop in 6-8 February 2008.
- An oral paper at the 16th Australian Weeds Conference, 18-22 May 2008, Cairns, Queensland.
- Cape to Coast Weed workshop in Margaret River, WA.

In the K&A plan we mentioned that we would attempt to organise a presentation or seminar within the most critical NRM region so that the results can be explained in more detail. The completed analysis identifies the south east regions, but at this stage it is impractical to make a presentation in person.

5.2.4 Publications

Scott, J.K., Batchelor, K.L. and Yeoh, P.B. (2008). Modelling climatic change impacts on sleeper and alert weeds. Proceedings of the 16th Australian Weeds Conference. (eds R.D. van Klinken, V.A. Osten, F.D. Panetta and J.C. Scanlan) pp. 143-145. 18-22 May 2008, Cairns, Queensland. Queensland Weed Society, Brisbane.

5.3 Future communication activities

The time taken to review and submit scientific papers means that any papers submitted will be after the completion of the project. Potential scientific publications which could be extracted from the report include:

- A review paper on the impact of climate change on alert and sleeper weed species.
- Plant physiology and predicted distribution of two *Lachenalia* species, potential weeds in Australia.
- *Retama raetam*, a major threat to Australia.
- Predicting the distribution of *Dittrichia viscosa* and *Senecio glastifolius*.
- *Pelargonium alchemilloides*, chromosome number and predicted distribution in Australia
- A review and predicted distribution of *Equisetum arvense*, a major threat to Australia

A presentation on alert and sleeper weed species and climate change will be given at the South Australian Weeds meeting in Adelaide 2-3 October 2008 and at the VegFutures conference in Toowoomba 20-23 October 2008.

A press release can not be considered once the full report is available on the web and the two page flyers completed.

6. DISCUSSION

The 41 species assessed in this study were selected species, not randomly chosen, covering most regions of Australia (except north west Australia – see below) (Figure 4). There is a wide spread of plant families, functional types and life-forms. Thus, they are representative of invasive plant species and not selected as examples that might be relevant to climate change. This makes the group of 41 species good candidates for making generalisations on the likely consequences for climate change for invasive plants, and indeed for all plant species in Australia.

The main pattern is for a predicted displacement southwards. It is not an extension of the current distribution southwards because the original region of climatic suitability changes to be unsuitable. Species in the north of Australia will have the potential to have the greatest displacement, over 1000 km. While this is possible for weeds, which mostly have excellent dispersal capability, this indicates that native plants will have difficulty to make the same scale of displacement.

The threatened area decreases for species that have the widest distribution under current climate. However it increases for many species that currently have a restricted potential distribution. Overall the threatened area decreases only because weeds in the south of Australia become compressed against the southern coast.

The weed threat in southern Australia, especially in the lower south west and south east will increase because not only will current threats remain, but there will be additional threats from the north. Based on the high EI values there will be approximately a 20% increase in weed species threat.

Despite the reduction of rainfall under some climate change models, there is not a predicted increased threat of most of the species to the interior of the continent. The increased rainfall in the north west of Australia as predicted by the Echam 3 models (Figure 3) has not influenced the predicted distributions for the 41 weed species. However, no sleeper or alert species specifically from the Pilbara or Kimberly regions of Western Australia were included in the list of 41 species. This region has many pristine habitats and identification of sleeper weed species would have greater benefit for the conservation of ecosystems than, for example, in highly developed and disturbed regions of southern Australia.

Finally, the trend for displacement southwards shows that there will be a considerably reduced threat in the north of Australia, from the current set of alert and sleeper species. This implies that there will be a vacuum for a new set of invaders.

6.1 Modelling issues

The CLIMEX climate change models for both Hadley 2 and Echam3 2030 high and 2070 low give very similar results for Australia. It was checked to confirm that they were derived separately (D. Kriticos pers. com 2007). However, the work of Rahmstorf et al. (2007) shows that the low and mid scenarios are unlikely because the climate change factors are tracking at the high side of the range. This implies that the Echam 3 2070 high and the Hadley 2 2070 high are the projections that should be considered.

The original distribution was used to help guide the interactive process to develop the CLIMEX models. However, significant errors can occur with distribution records, even if based on data from herbaria (c.f. Miller et al. 2007). We found obvious errors in the overseas databases (e.g. records locating collections in the ocean), but it was impossible to check all records. Even so, the CLIMEX modelling process avoids using climate station data (which would happen if relying on the recorded distribution) so it will be more robust than climate matching approaches. Other caveats to the modelling approach are as follows.

6.1.1 Abiotic versus biotic factors

The CLIMEX models assume that distribution is determined by climate. Clearly this is not always the case as some species have distributions that are, in part determined by edaphic factors such as soil structure or pH, or by predators or diseases which exclude them from certain areas. Also physical barriers (mountains, oceans) can play a role in determining distribution. However, physical factors such as temperature and moisture must provide the broad envelope of the potential (or fundamental) distribution. The other factors, such as soil pH, further define the distribution from within the climatic envelop.

6.1.2 Microhabitats

The second assumption is that climatic data from weather stations are representative of the climate that impinges on growth of the plant. The most obvious example where this is not the case is for aquatic species. Other species might inhabit a microhabitat, for example river banks, which also would not be described by broad climatic requirements.

6.1.3 Extreme events

The CLIMEX modelling is based on climate averages. It is well recognised that extreme events, e.g. days of extreme temperature, or frost, could determine the limits to a species distribution. Climate change may lead to more extreme climatic events and a different modelling approach would be needed to capture this possibility.

6.2 Level of weed threat

The review of the literature made it evident that there is almost no evidence that some of the species would become weeds. For some species, e.g. *Acacia karroo* and *Equisetum arvense* there is considerable information overseas that leads to the conclusion that the species is a significant threat. For some species there is no evidence they represent a threat e.g. *Pelargonium alchemilloides*.

6.3 Management recommendations

The predicted distributions point to likely patterns of spread which could be prevented by adopting management options.

Some of the alert and sleeper weeds have considerable evidence for their threat as weeds that they should be the subject of urgent review with a perspective of eradication. These species include *Acacia karroo*, *Equisetum arvense* and *Retama raetam*.

Spread of individual species could be prevented by establishing containment lines. High priority containment lines should be those that prevent spread in the direction of displacement due to climate change. In most cases this would be on the southern side of the current distribution. For example, *Lachenalia reflexa* is largely restricted to the Perth metropolitan area. Containment and control activities should focus on the southern side of the distribution.

If we take the set of 41 species as representative of what will happen to plant species under climate change in Australia then the overall trends in displacement point to the usefulness of establishing east-west quarantine barriers that can filter out the exotic species, while allowing native species to migrate southwards. Existing political boundaries, such as the Queensland – New Wales border, the New South Wales – Victoria border and the Bass strait should be investigated as barriers to climate change driven migration of exotic species.

6.4 Future research

The prediction models can be improved as additional information is obtained. The example of *Chromolaena odorata*, where successive CLIMEX models were developed leading to the currently accepted model (Kriticos et al. 2005 and references within) shows how the models can be improved. Many of the alert and sleeper species have very little information about their climatic requirements. Studies on the physiology of these plants would quickly add information that could be used in the CLIMEX models. Most of the species require further study and the issues are listed at the end of each species account in Appendix B.

The CLIMEX models are only addressing climatic conditions. Obviously, the models could be enhanced by adding layers of soil type etc. The climate change models should also be upgraded to correspond with those of the 4th ICCC report.

6.4.1 Testing of predicted distributions

When a widespread species has its distribution predicted it is usual that most of the highly favourable climatic region is already occupied by the weed, especially if the weed has been present for a long time in Australia. There are opportunities from the study of alert and sleeper species to test the concept of predicting species distributions because the area of high potential establishment are not yet occupied. The following examples could be used to test the models.

1. The Bolivian rosewood or tipu, *Tipuana tipu* is a tree that has established in Queensland. Its predicted distribution includes the area of establishment, but also includes south west

Australia. In the south west it is extensively planted as a street tree and we have observed that it produces abundant seed. This means that its potential for establishment can be tested without changing the risk from this species.

2. A second weed that could be tested is white weeping broom, *Retama raetam*, because it has large seeds that can be readily stimulated to germinate by cutting the seed coat. The large size makes the seed easy to recover or to contain in a mesh cage. This plant is predicted to be a major threat to inland Australia and quantifying further this risk by experimental plantings would be potentially very beneficial.

6.4.2 New weed invasion of the north of Australia

The general trend is for a displacement south for the regions most suitable for weed establishment of the current set of sleeper and alert species. The weed species from the far north of Australia are expected to have the greatest (over 1000 km) displacement southwards. It can be expected that native species will have the same southerly displacement. This implies that that there will be a considerably reduced threat from the current set of alert and sleeper species and the opening of an opportunity for new invasion. A new set of sleeper species needs to be identified for the north of Australia. The following steps needs to be addressed:

1. Which weed species are a changed threat from the countries to the immediate north of Australia following climate change.

2. What is the future climate of the north of Australia and how does that match to existing climatic regions of the work and which weeds are significant problems in those areas.

3. Given the changed climate, what are the new threats from exotic introduced species already present, for example as garden plants or in agriculture.

4. What are the current sleeper species from the Kimberly and Pilbara and what is there response to climate change.

6.4.3 New quarantine barriers to protect the south

The southerly migration predicted for most species implies that quarantine barriers, of an east-west direction, would reduce the threat to southern Australia. Research is needed to determine to most strategic place for these barriers, the width of the containment or “cordon sanitaire” area in relation to dispersal pathways and dispersal distance. New approaches are needed to address the issue of allowing the spread southwards of native species, while preventing invasion by exotics.

7. ACKNOWLEGEMENTS

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The OzClim model has been jointly developed by International Global Change Institute (IGCI), University of Waikato and CSIRO Atmospheric Research. (see http://www.dar.csiro.au/impacts/ozclimacknowledg.html).

We also thank the WA Department of Environment and Conservation for help with distributions of species in Australia. The South African National Biodiversity Institute is thanked for the use of data from the National Herbarium, Pretoria (PRE) Computerised Information System (PRECIS). Most of the weeds with a distribution in southern Africa were mapped using the data from PRECIS.

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APPENDIX A: GROWTH RATES OF SELECTED PLANT SPECIES AT DIFFERENT AMBIENT TEMPERATURES

Please contact authors for this information.

APPENDIX B: RESULTS OF CLIMEX MODELS

Please contact authors for this information or see appendix B on this website.

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