Climate change, Protected Areas, and Threatened Plants in NSW

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This thesis has been prepared in the style of Global Change Biology. Some sections have been expanded for in-depth discussion of the research. All figures and tables referred to in the text are provided at the end of the thesis.

Abstract

Due to greenhouse gas emissions, the earth's climate is projected to warm substatially over the coming decades. This climatic change could result in widespread changes in species distributions, as the climatic areas within which each species can exist may move in location. If this occurs, existing protected areas may decrease in their effectiveness, as the species that are found within protected areas currently may be unable to live within those areas in the future. To modify conservation strategies for this eventuality, an assessment of how much species distributions may change in relation to protected areas is needed. This study performed such an assessment for the NSW protected area system, by modelling the distributions of 27 threatened plant species in NSW, under the recent climate (for the year 2000) and two future climate change scenarios for 2050, one moderate (atmospheric CO_2 concentration reaching 491 parts per million) and one severe (atmospheric CO_2 concentration reaching 573 parts per million). The bioclimatic modelling programs, BIOCLIM and GARP, were used. To assess how the area of each species suitable habitat within protected areas could change, distributions generated under each scenario were overlayed on a map of protected areas in eastern Australia. Under moderate climate change, threatened plant species projected distributions declined in total size, a trend that became more pronounced under the severe scenario. A number of species projected distributions actually increased within protected areas under a moderate warming scenario, though many others declined, and the vast majority decreased under the severe scenario. If it was assumed that the species could not migrate, the declines under both climate change scenarios became even more pronounced. Whilst there were differences between the projections generated by GARP and BIOCLIM, their projections were consistent for the findings mentioned above. To cope with declines in species distributions, both additions to the protected area system, and off-reserve conservation, are likely

to be needed. Using a landscape-wide conservation strategy is probably the most effective way to cope with the massive ecological changes that climate change will induce.

Introduction

Compelling evidence suggests that the world's climate is warming due to greenhouse gas emissions. Atmospheric CO_2 levels have increased from 280 to ~377 ppm over the past two centuries due to human activities (IPCC 2001; Keeling & Whorf 2005). Atmospheric concentrations of other greenhouse gases (GHGs), including methane, nitrous oxide, and hydrofluorocarbons, have also increased substantially (IPCC 2001). In association with elevated GHGs, global mean surface temperatures rose by 0.6°C from 1900 to the end of the twentieth century (IPCC 2001). Global Circulation Models project increases in Mean Annual Temperature of 1.4-5.8°C by the end of this century (IPCC 2001). Global warming is projected to increase the frequency of extreme climatic events, change rainfall patterns, raise sea levels and alter ocean currents (IPCC 2001). Even if fossil fuel emissions are dramatically reduced in the near future, a certain degree of climate change is inevitable due oceanic thermal inertia (Meehl *et al.* 2005; Wigley 2005).

Species responses to climate change

Climate change will cause pronounced changes in ecosystems, and species responses will include changes in distribution, changes in phenology, *in situ* adaptation, and extinctions. Distributional changes will result because the physiological processes of all species are adapted to particular ranges of temperature and moisture availability (Clark 2003). Thus, the distributions of all species are restricted to regions that are climatically suited to their physiology (Walther 2004; Woodward 1987). In response to climate change, the individuals of many species will migrate or disperse to new, climatically suitable areas (Parmesan & Yohe 2003). Such migrations have already been documented, with hundreds of species having moved an average of 6.1km per decade towards the poles over the past few decades (Parmesan & Yohe 2003). Some species may experience an expansion in the size of their distribution, whilst many others are likely to experience a reduction.

Changes in species phenology will result because the timing of phenological and life cycle events are usually dependent on climatic cues. Already, advances in the timing of flowering, budburst, migrant bird and butterfly arrivals and bird breeding have been observed (Parmesan & Yohe 2003).

Some species will have the capability to undergo microevolutionary changes to adapt to the new climate regimes they encounter. Typically, these may be species with short generation times, high rates of population growth (Hughes 2000), and high levels of genetic diversity (Reusch *et al.* 2005). However, adapatation will be beyond the capability of many species due to the rapidity of climate change (Etterson & Shaw 2001).

Populations and species that are unable to adapt in-situ or to migrate to climatically suitable areas will face extinction if their current range becomes unsuitable. Montane species, for instance, are at a high risk of extinction, as many will completely lose their suitable climatic habitat due to temperature increases on mountain tops (McDonald & Brown 1992). Even under the low levels of climate change that are probably inevitable, 18% of species may be committed to extinction (Thomas *et al.* 2004).

Species are likely to respond individualistically to climate change, with great variation in the magnitude and direction of changes among species from even the same ecological communities (Gryj 1998). Distributional and life cycle changes of species will affect other species with which they interact (Hughes 2000; Klanderud 2005; Menendez & Gutierrez 2004). The individualistic responses of species and the alteration of species-interactions will cause large-scale rearrangements of the community structure of many ecosystems (Graham & Grimm 1990; Gryj 1998).

Effectiveness of protected areas under climate change.

Changes in species distributions in response to climate change may alter the effectiveness of protected areas (Peters & Darling 1985). Most National Parks and nature reserves have been created on an *ad hoc* basis, with little planning for connectivity between reserves, or for representativeness of ecosystem types within the reserve system (Pressey 1994). Whilst protected area systems are often poorly designed, it is a public expectation that reserves will protect the species that are encompassed within them indefinitely (Mansergh & Bennett 1989). Under climate change, this expectation may not be fulfilled, as protected area systems may not have the geographical extent to continue to protect species whose distributions change substantially (Peters & Darling 1985).

If climate change does alter the effectiveness of protected areas, then this change in effectiveness will need to be taken into account in future conservation strategies. Significant additions to most protected area systems may be required to facilitate species range alterations and migrations to new areas under climate change. Such additions may be particularly necessary where sensitive species that rely upon pristine habitat move out of the current reserve system. Off-reserve conservation strategies may increase in their importance, especially if the protected area system proves to be vastly inadequate under climate change.

There is a risk that the NSW protected area system will diminish in effectiveness under climate change. Protected areas cover close to 7% of NSW (Pressey *et al.* 2000). However, many sections of the protected area system have been established with very little planning. Consequently many areas of the state, such as western NSW, are poorly reserved (Pressey & Taffs 2001).

The adequacy of the current NSW protected area system to cope with species range changes under climate change needs to be assessed to enable conservation planning to take place. Models that project the potential distributions of species may assist with such a task (Hannah *et al.* 2005; Papes unpublished; Rutherford *et al.* 1999; Tellez-Valdes & Davila-Aranda 2003). These models project the current and future ranges of a species under particular climatic scenarios. The comparison of these ranges across many species in one region may reveal how well a particular protected areas system may cope with potential shifts in species distributions.

Bioclimatic models

Bioclimatic models use the distribution of localities at which a species has been observed in the wild to project the distribution of habitat that is climatically suitable for the species (the bioclimatic envelope). In using the current known distribution of a species to project its bioclimatic distribution, bioclimatic models make a number of assumptions. The first is that the current known distribution of a species encompasses all of the climates that the species can tolerate (Pearson & Dawson 2003). The second assumption is that the current distribution of the species is at equilibrium with the present-day climate (Malanson *et al.* 1992), in other words, that the distribution of the species is not still adjusting to climatic changes that may have occurred in the past. To project the future climatically suitable distribution of a species, a third assumption is made: that the species will not adapt to climate change (Pearson & Dawson 2003).

A number of bioclimatic modelling software programs exist. Two of the most widely used programs are BIOCLIM (Nix 1986) and GARP (Stockwell & Noble 1992). BIOCLIM identifies the upper and lower limits of a species tolerance for up to 35 climatic parameters based on a species current distribution, and uses these limits to estimate where a species will occur under a given climate (Beaumont *et al.* 2005). GARP generates rules that explain the current distribution of a species, and then uses these rules to project the distribution of the species under a future climate (Stockwell & Peters 1999). The rules are generated by comparing a species current distribution to current climate and topographic variables. The process is one of continual refinement, as an initial set of rules are modified and retested up to 1000 times to produce a final projection of the species distribution (Stockwell & Peters 1999).

It may be important to use two or more modelling approaches in conjunction when projecting the distributions of species (Elith & Burgman 2002). The projections generated by separate modelling programs may differ, due to the unique approaches taken by the separate modelling programs (Loiselle *et al.* 2003; Stockwell & Peterson 2002). BIOCLIM, for example, generates the same projection for a species over multiple runs if identical climatic conditions are used each time. Meanwhile, even where identical climatic conditions are used, the projections generated by GARP over multiple runs for the same species are slightly different (Andersen *et al.* 2003). The use of more than one approach when modelling distributions can provide an indication of the consistency of the projections produced by each.

Modelling of species distributions under a future climate should take the ability of species to migrate into consideration. A species migration ability will determine which areas of its future projected distribution that it can actually reach. Many organisms, such as some plants, have a very low dispersal ability and will not be able to migrate to many or any areas of future habitat. Conversely, many birds and other vertebrates would have the capability to migrate to many or all areas of their future projected distribution. Some species would be able to migrate, but not through geographic areas that are climatically unsuitable for their survival. These species would be unable to reach isolated patches of future climatically suitable habitat that are surrounded by climatically unsuitable habitat (Peterson *et al.* 2002).

Study species

Threatened species are likely to be particularly at risk from climate change, as the ranges of threatened species are often very restricted. The smaller a species range is, the less likely it is that any of its current populations will remain within climatically suitable habitat under climate change (Hughes *et al.* 1996). In addition, threatened species may have a decreased ability to adapt to climate change, as many threatened species have reduced levels of genetic diversity, or lower levels of fecundity (Frankham *et al.* 2003). Because protected areas are partly established to protect threatened species, it is apt to use threatened species as model organisms to assess the impacts of climate change on protected areas.

Threatened plants have been selected as the model species for this study. A significant proportion (5%) of Australian native plant species are threatened, due to habitat clearance, grazing, introduced species, and a range of other threatening factors (Briggs & Leigh 1996).

The use of plant species in this study enabled an exploration of the use of soils as a parameter for modelling distributions. Soil properties are an important influence on the distributions of many plant species (Clark *et al.* 1998). Therefore, it may be important to take soil into consideration when modelling the distributions of some or all plant species. Whilst a few plant modelling studies have included soil (Iverson & Prasad 2002; Zaniewski *et al.* 2002), many other plant modelling studies have ignored it (Pyke *et al.* 2005; Tellez-Valdes & Davila-Aranda 2003; Thuiller *et al.* 2005a; Thuiller *et al.* 2005b). Whether a failure to include soil substantially affects projections of plant species distributions has not been assessed.

The overall aim of this study was to assess the impact of climate change on the effectiveness of the protected areas system in NSW. The bioclimatic models GARP and BIOCLIM were used to model the distributions of threatened plants under the current climate and two climate change scenarios for 2050, moderate and severe, to answer the following questions:

(1) How may the bioclimatic distributions of 27 threatened plant species change in the future?

(2) How may the bioclimatic distributions within protected areas of these species change in the future?

(3) How may the distributions of these species change if they cannot migrate, or can migrate only to areas of their future bioclimatic distributions that are contiguous with their current distributions?

(4) Are the projections generated by two different bioclimatic models, BIOCLIM and GARP, consistent?

(5) Does the inclusion of soil factors in the modelling process substantially affect the projected distributions?

Methods

Approach

This study involved a number of key steps. Firstly, the current and future distributions of the study species were projected using BIOCLIM and GARP, and the size of each projected distribution determined for comparison. Secondly, the projected distributions were overlaid onto a map of protected areas, to quantify the area of each projected distribution that lay within protected areas under each climate scenario. Thirdly, for a subset of species, the total projected distributions, and distributions within protected areas, were overlaid with a soil parent material map to exclude areas of the distributions falling on non-compatible soil parent material types. At each step, the area of the projected distribution for each species was calculated under three migration scenarios: Universal Migration, No Migration, and Contiguous Migration.

Study Area

The study area encompassed south-eastern Australia within the bounds of 24°S-44°S latitude, and 138°E-154°E longitude. Whilst this study is focused primarily on threatened plants of NSW, parts of the distributions of some of these species occur in other states. Therefore, the study area included southern Queensland, eastern South Australia, Victoria, and Tasmania.

Selection of Species.

Twenty seven vulnerable and endangered plant species were modeled (Table 1). Species were chosen from the Endangered Plant Species List (Schedule 1) and the Vulnerable Plant Species List (Schedule 2) of the NSW Threatened Species Conservation Act (1995). Under this Act, a species is listed as endangered if its risk of becoming extinct within NSW in the near future is very high. A species is listed as vulnerable if, within the medium term future, its risk of becoming extinct within

NSW is high. Species were selected from these lists based on two criteria: firstly, that the species was represented by at least 20 collection records in Australia's Virtual Herbarium (www.chah.gov.au/avh), an online database containing the collection records of the major State herbaria of Australia. This was necessary to ensure that a sufficient number of records was available for modeling, because projections of species distributions are inaccurate with a low number of species records (Kadmon *et al.* 2003). The second criterion was that published maps or descriptions of the geographical distribution and soil affinities of the species were available.

Species were initially short-listed based on the number of collection records available. Expert advice was sought as to which of these species had sources of other information available (eg. published papers, recovery plans) on their distributions and soil affinities (D. Keith, pers. comm.). Investigation of these sources enabled species that fulfilled both criteria to be identified.

Data collection

(i) Species collection localities

Collection localities (latitude/longitude) for the species were obtained from Australia's Virtual Herbarium, the North Coast Regional Botanic Gardens Herbarium (Coffs Harbour), and Janet Cosh Herbarium at the University of Wollongong.

A common problem with herbarium records is inaccurate locality data, due to mistakes during specimen collection and identification, or data entry. To identify incorrect records, the collection localities for each species were plotted on a map of Australia in ArcMap™ Version 9.1 (ESRI 2005), and compared with published maps or descriptions of the distribution of each species. Points that fell beyond the published range of a species were removed from the dataset. The accuracy of the remaining records may still vary - for instance, most recent herbarium records have been collected with the help of a Global Positioning System, whilst older records were not.

However, any points inaccurate enough to have affected the outcomes of modelling were likely to have been removed during this step.

(ii) Climate datasets.

Climate data for south-eastern Australia was obtained from the OzClim program (Jones *et al.* 2001), which contains current and future climate projections produced by various climate models. The OzClim model has been jointly developed by the International Global Change Institute (IGCI), University of Waikato and CSIRO Atmospheric Research.

The climate parameters used were annual and seasonal values of mean temperature, maximum temperature, minimum temperature and mean precipitation (Table 2), all with grid cells 0.25º in resolution. Data for a model of the year 2000 climate were obtained from OzClim as a current climate baseline with which to make comparisons with future scenarios. This model was generated by the CSIRO Division of Atmospheric Research Limited Area Model (DARLAM), a regional climate model for the Australian region. Global atmospheric CO_2 concentration reached 367 parts per million in the year 2000 (IPCC 2001).

Projections of future climates contain a certain level of uncertainty. This stems from the difficulties involved in modelling the complexities of the atmosphere, and in the atmospheric concentrations of greenhouse gases that are used (a factor dependent on human decisions over the following decades). To address different possible outcomes of climate models that these uncertainties generate, two future climate scenarios for the year 2050, one moderate and one severe, were used.

The future climate scenarios are based on greenhouse gas emission scenarios developed by the Special Report on Emissions Scenarios (SRES) of the Intergovernmetal Panel on Climate Change (IPCC 2000). The "moderate" scenario for 2050 is based on the greenhouse gas emission levels given in the Special Report on Emission Scenarios (SRES) B1 scenario. The SRES B1 scenario assumes a peak in global population in the mid twenty-first century followed by a decline, increased environmental awareness among governments, the public and the media, reductions in use of material resources, and a switch to non-fossil fuels and clean sources of energy (IPCC 2000). Under SRES B1, global anthropogenic CO_2 emission levels increase from 7.3 GtC/yr (gigatonnes carbon per year) in 1990 to 11.3 GtC/yr in 2050, but decline shortly thereafter (IPCC 2000). The global atmospheric concentration reaches 491 parts per million by 2050 under this scenario, and 538 parts per million by 2100 (IPCC 2001).

A scenario for the 2050 Australian climate under the SRES B1 emissions scenario was generated using DARLAM, under the assumption of low climate forcing (a low influence of greenhouse gases on determining global temperature). This combination created a wet, warm climate change scenario (Beaumont *et al.* 2005).

The “severe” scenario for 2050 is based on the greenhouse gas emission levels given in the SRES A1F scenario. The future world described by the SRES A1F scenario consists of rapid economic growth over the twenty-first century, continued use of fossil-fuel intensive energy sources and a similar pattern of population growth as the B1 scenario (IPCC 2000). Under SRES A1F, global anthropogenic CO_2 emission levels reach 23.9 GtC/yr in 2050, increasing to 28.2 GtC/yr by 2100 (IPCC 2000). The global atmospheric CO_2 concentration reaches 573 parts per million by 2050 under this scenario, and 976 parts per million by 2100 (IPCC 2001).

A scenario for the Australia climate under the SRES A1F emissions scenario was generated using the CSIRO Mark 2 Global Coupled Model under the assumption of high climate forcing. This combination created a hot, dry climate change scenario (Beaumont *et al.* 2005).

(iii) Topographic datasets.

Three topographic layers were used: elevation, aspect, and slope, all at a grid cell resolution of 0.025º. These layers were part of the AUS40 Digital Elevation Model developed by the Centre for Resource and Environmental Studies, at the Australian National University (AUS40.DEM 1999). The 0.25º grid cells of the climatic layers were divided into 0.025º cells to match the resolution of the topographic layers.

Modelling Programs.

(i)BIOCLIM.

BIOCLIM projects species distributions by calculating the "climatic envelope" of the species, then identifying geographical areas with climates that fall within the climatic envelope (Nix 1986). For a given number of climatic parameters (eg. mean annual temperature, mean annual rainfall) BIOCLIM identifies the upper bound and lower bound within which the species is found for each parameter. These limits, which constitute the climatic envelope, are then used to define the geographical areas that the species could occur in under a given climate (Nix 1986).

Whilst up to 35 climatic parameters can be used in BIOCLIM, the use of too many climatic parameters will lead to over-fitting of the bioclimatic model (Beaumont *et al.* 2005). The more climatic parameters that are used, the more specific the requirements of the species become, and the smaller the projected range of the species will be. It is therefore necessary to restrict the climatic parameters used in BIOCLIM to those which are likely to be biologically important for the species.

In this modeling project, only the following parameters were used for BIOCLIM: minimum winter temperature, maximum summer temperature, mean annual temperature, mean annual precipitation, mean precipitation of the driest season, slope, elevation and aspect. The reasons for using each of these parameters are as follows:

- *Mean annual temperature*: This parameter is widely used as a projective variable in modeling the distributions of species (eg.Iverson & Prasad 1998; Thuiller *et al.* 2005b; Zaniewski *et al.* 2002), in order to represent the strong influence that temperature has on the distributions of most species.

- *Minimum winter temperature*: Extremes of temperature may influence the distributions of plants (Thuiller *et al.* 2003). Extreme cold temperatures can be lethal to plants, and also affect the rate of development processes, the ability to flower, and other physiological processes (Prentice *et al.* 1992; Woodward 1990). The coldest temperatures experienced by a plant are likely to be minimum winter temperatures.

- *Maximum summer temperature*: High temperatures can affect the survival of plants through damaging biochemical structures involved in photosynthesis (Weis & Berry 1988). High temperatures also can interact with limits in moisture availability to produce water stress. The warmest temperatures experienced by a plant are likely to be maximum summer temperatures.

- *Mean annual precipitation*: The amount of water available to a plant annually is a known determinant of plant distributions (Fensham *et al.* 2005).

- *Mean precipitation of the driest season*: Rainfall within the driest season influences the ability of plants to make it through the dry season. As the driest season varies geographically (Gentilli 1972), the season used for a species depended on where that species was found. The maps of rainfall from OzClim for the current scenario were visually assessed to determine the driest season in each part of NSW. For alpine species and species from western NSW, mean summer precipitation was used. For species on the east coast of NSW, mean winter precipitation was used.

- *Slope, aspect and elevation*: Slope, aspect and elevation are known to be important influences on the distributions of many plant species (Ashton 1976; Duarte *et al.* 2005; Srutek & Dolezal 2003). Slope affects soil drainage, aspect affects the amount of solar radiation received, and elevation has various effects on plants through influencing temperature, exposure to wind, orographic precipitation and cloud cover, and so forth.

Modeling with BIOCLIM can either be performed using the BIOCLIM program, or by following the BIOCLIM procedure in a Geographic Information System (GIS). The latter approach was used in this study. The program DIVA-GIS (Hijmans *et al.* 2005) was used to extract the values of each climatic parameter that each point locality of each species occurred in. The 2.5 and 97.5 percentiles of each parameter were identified for each species using Microsoft Excel. A query was performed in ArcView 3.2a to identify the geographical regions that fell within these percentiles for all parameters. The areas within these percentiles were regarded as being the "core" habitat for the species.

(ii) GARP (Genetic Algorithm for Rule-Set Production)

GARP is a widely used program for projecting the potential distributions of species under particular climate scenarios. GARP utilizes a genetic algorithm, in which the refinement of a model for a species distribution is achieved by continual repeats (iterations) of the model modification process.

GARP creates a model of a species distribution under the current climate using the sighting or collection localities of the species as the input data (Stockwell & Noble 1992). Species localities are randomly divided by GARP into two sets: a training dataset and a validation dataset. The training dataset is used to create the rules of the model for the species distribution. The validation dataset is used to assess the accuracy of the model for projecting the distribution of the species.

At the start of GARP, a set of rules are created that explain aspects of the distribution of points in the training dataset. These rules are of four types: Atomic, Range, Negated Range, and Logistic Regression. An Atomic rule says that a species will occur at a particular value of a parameter, for example, the species will be present where the Annual Mean Temperature is 22°C (Stockwell & Peters 1999). A Range rule says that a species will occur between a particular range of values (Payne & Stockwell 2001), for example, where Minimum Annual Temperature is between 1°C and 4°C, and where Mean Winter Rainfall is between 120 and 400mm. Range rules are similar to BIOCLIM, except that BIOCLIM uses every climatic parameter that is provided as input to the model by the user, whilst a Range rule does not have to include every climatic parameter that is available (Payne & Stockwell 2001).

A Negated Range rule is similar to a Range rule, except that species is present where the values of the parameter do not fall within the values given within the rule (Payne & Stockwell 2001). For instance, a species may be present where Mean Annual Temperature does not fall between 23°C and 25°C. A Logistic Regression rule is a logistic regression equation that explains an aspect of the species distribution (Stockwell & Peters 1999). The final model of the species distribution may consist of many different rules.

Once a random set of rules is created, the utility of each rule in explaining aspects of the distribution of the species is assessed. To do this, data points in the training dataset are sampled and the number of data points that are explained by each rule are assessed (Payne & Stockwell 2001). Those rules that explain a significant number of the data points are retained in an "archive", and those which are not useful are discarded (Payne & Stockwell 2001).

Once a set of useful rules has been created and placed in the "archive", new variations of those rules are created by two genetic processes: recombination and mutation. Recombination allows different components of two rules to be exchanged (Stockwell & Peters 1999). Mutation changes the value of a variable in a pre-existing rule. The utility of the modified rules in explaining aspects of the distribution of the species are tested. If the utility of a modified rule is greater than that of the old rule, the modified rule is kept, and if not, then it is discarded (Payne & Stockwell 2001).

GARP continually alters rules by this process until the rate of change of rules in the “archive” falls below a set level (the Convergence limit), or the iterations of the rule modification process reaches a set number (the Maximum Number of Iterations) (Payne & Stockwell 2001). Once the model creation process has finished, the projective accuracy of the model is tested on the distribution of data points in the validation dataset using a one-tailed χ^2-test (Andersen *et al.* 2003). This tests whether the points in the validation dataset fall within areas of the projected distribution more frequently than is expected by chance (Andersen *et al.* 2003). This test incorporates measures of the two types of errors that can occur: omission errors, locations where the species is projected to be absent but is actually present; and commission errors, where the species is projected to be present but is actually absent (Andersen *et al.* 2003). It is usual practice to run GARP multiple times and combine the models with the greatest projective accuracy produced to create a more robust projection of the species distribution (Andersen *et al.* 2003).

Once GARP has created a model, it can be used to create a projection of the species distribution under a future climate. GARP performs this task by identifying geographical areas under the future climate that fulfill rules of the model.

GARP requires presence/absence information on a species distribution to create a model. When presence-only information is used as an input, such as species collection localities, GARP uses pseudo-absence information in place of known-absence information. To do this, GARP randomly samples “pseudo-absence” points in grid-cells in which no species collection localities fall. However, the sampling of pseudo-absences from climates that are very different from those in which the species is recorded can skew the results of the model. Therefore, it is necessary to restrict the sampling of pseudo-absences to a region of a set distance surrounding the area of the species localities.

In this project, Desktop GARP Version 1.1.3 was used. All twenty climatic parameters and three topographic parameters (Table 2) were input into GARP for use in modeling. Unlike BIOCLIM, GARP only uses those parameters that appear to have a true correlation with the species distribution; therefore, over-fitting of the model is not an issue. The convergence limit was set to 0.01 (that is, GARP will end if the number of rules changed in the archive per iteration falls below 1 in 100) and the Maximum number of iterations was set to 1000 (L. Beaumont, pers. comm.). A buffer of 300km was established around species point localities for the sampling of pseudo-absences. GARP was run 100 times per species, and the ten best models generated for each species were combined to create a final projection. Projected presence grid cells that occurred in five or more of the ten best models were included in the final model. Projected presence grid cells occurring in less than five models were excluded from the final projection.

Terminology used to discuss modeled distributions

This modelling procedure has taken into account climatic parameters and topographic parameters, but not biotic factors that may influence distributions. Therefore, the projections produced by this project are projections of species bioclimatic envelopes (the distribution of climatically suitable habitat for a species). For the sake of being succinct, the term "projected distribution" will be used to refer to a species projected bioclimatic envelope from this point.

National Parks and Nature Reserves

A digital map of all National Parks and protected areas within South Eastern Australia was used to quantify the area of species projected distributions under protection. This map included all National Parks, Nature Reserves, State Recreation Areas, and other conservation areas in NSW, the ACT, Queensland, Victoria, and South Australia. State Forests, Timber Reserves, and

Resource Reserves also featured in the original version of this map, but were deleted for the purpose of this study as the primary purpose of these areas is not the conservation of species. The map consisted of data from the NSW National Parks and Wildlife Service, Environment ACT, the Queensland Environmental Protection Agency, the Victorian Department of Sustainability and Environment, and the South Australian Department for Environment and Heritage.

The protected areas in this map were intersected with the projected distributions of each species in ArcView 3.2a (ESRI 2000), which identified only the areas of the projected distributions that were contained within national parks.

Changes in species distributions.

For each species, the areas of current and future projected distributions were calculated for (i) the total projected distribution and (ii) projected distribution within protected areas. In addition, the areas of the projected distributions were calculated under three migration scenarios:

- (a) Universal Migration: Where the species has the ability to migrate from its current distribution to all areas of its future projected distribution (Figure 1a).
- (b) No migration: Where the species cannot migrate. Its future distribution will be the areas of its current projected distribution that co-incide with its future projected distribution (Figure 1b).
- (c) Contiguous migration: Where the species can migrate, but cannot disperse across areas of projected unsuitable habitat. Therefore, its future distribution will be the areas of its future projected distribution that connect with the areas of its current projected distribution (Figure 1c).

Incorporation of soil into models

While climate ultimately determines species distributions on a broad scale, soil properties such as texture, pH, and nutrient content, are also important, especially at a more local scale. The impact of taking soil factors into account in projecting the distributions of five species was assessed in this project. Ideally, a modeling project should incorporate several different properties of soil into models for projecting the distributions of plant species (Iverson & Prasad 2002). However, such an undertaking was beyond the scope of this study. Instead, only soil parent material was taken into account. Soil parent material has been correlated with the distribution of plant species and vegetation types in various studies (Clark *et al.* 1998; Enright 1978; Hutchinson *et al.* 1999; Murashkina *et al.* 2005; Vankat *et al.* 1977). Soil parent material should act as a good surrogate for the soil properties that influence plant distributions, as the properties of soil are strongly influenced by the material or bedrock from which it formed (Mckenzie *et al.* 2004).

A digital map of soil parent material, the Australian Soil Resources Information System Lithology map, was obtained from the Australian Natural Resources Data Library (http://data.brs.gov.au/asdd/php/basic_search.php). This map displays soil parent material across agricultural regions of Australia as a grid of cells 0.0025° in resolution (Johnston *et al.* 2003). The classes of soil parent material displayed in this map are listed in Appendix 1. The map was converted from a grid to a vector layer (consisting of polygons rather than a grid of cells) for the purposes of this study.

Soil parent material was taken into consideration in the projection of the distributions of *Diploglottis campbellii*, *Grevillea beadleana*, *Zieria granulata*, *Austrostipa wakoolica*, and *Uromyrtus australis*. These species were chosen as their distributions are likely to be limited in a large part by soil, as indicated by information in recovery plans and published literature. The collection locality points of each species were overlain on the soil parent material map in ArcView 3.2a, and a query was performed to identify the soil parent material classes on which the points occurred. The current and future distributions of each species, as projected using GARP and BIOCLIM, were overlaid in ArcView 3.2a with the classes of soil parent material identified in the previous step. Only those areas of the projected distribution that coincided with the selected soil parent material classes were included in the final projected distribution.

The area of the projected distributions of these species produced using soil in the models were compared to distributions produced without taking soil into consideration.

Results

(i) *Modelled distributions under current climate*

The distributions projected by GARP for five of the 27 species (*Swainsona recta, Senecio garlandii, Acacia bynoeana, Cynanchum elegans, Acacia ruppii*) appeared to be far larger than their actual distributions. When visually compared with the distribution of collection localities for each species, the projected distributions of these species extended in several directions for up to several hundred kilometres beyond where they were known to occur. There are two methods to deal with over-estimation in this program: firstly, the climatic parameters used can be changed, or secondly, the duration of the model-refinement process can be lengthened, by increasing the maximum number of iterations and decreasing the convergence limit (A.T. Petersen, pers. comm.). I used the second option to refine the models of these five species. They were remodelled with the maximum number of iterations increased to 10 000, and the convergence limit reduced to 0.001. The remodelled distribution of one species, *A. bynoeana*, was larger than the original distribution, so the original was used.

GARP created a very poor model for the species *Tetratheca juncea*, as the current projected distribution barely coincided with the distribution of collection localities used as input. This may have been because the climatic parameters that are the primary influence on the distribution of *T. juncea* in the wild were not included in the set of climatic parameters used (Table 2). *T. juncea* was therefore excluded from all further analysis.

The total sizes of the projected distributions produced by BIOCLIM and GARP for each species under each climate scenario are shown in Appendix 2. These distributions were created under the assumption of universal migration, where the species can migrate to all areas of its future projected distribution. The following two sections deal with the sizes of species distributions under the universal migration scenario.

(ii) Changes in species distributions under climate change

The size of the projected bioclimatic distributions of most species decreased under the moderate climate change scenario, and decreased further under the severe scenario (Figure 2a, 2b). BIOCLIM projected an average decrease of 21% under the moderate scenario, and 62% under the severe scenario. The respective declines projected by GARP were 5% and 42%. Under the severe scenario, GARP projected the extinction of one species (*Pultenaea parviflora*) whilst BIOCLIM projected the extinction of two (*Brachyscome papillosa* and *Zieria granulata*).

Under the moderate scenario, the majority of species were projected by GARP to decrease by less than 20% in the size of their distribution, whilst under the severe scenario most were projected by GARP to decrease by more than 20% (Figure 3a, 3b). Under the moderate climate scenario, BIOCLIM projected the majority of species to decrease by less than 40%, whilst under the severe scenario most were projected by BIOCLIM to decrease by more than 40% (Figure 3a, 3b).

(iii) Changes in species distributions within protected areas under climate change

Under the moderate scenario, the projected distributions of many species within protected areas decreased. However, the projected distributions of some species (9 in BIOCLIM, 13 in GARP) increased within protected areas (Figure 4a, 4b). The average changes in sizes of species distributions within protected areas were a decrease of 3% (BIOCLIM) and an increase of 6% (GARP). Of those that decreased, the majority (9 in BIOCLIM, 10 in GARP) experienced a decline of less than 20% in area (Figure 6a).

Of the 13 species GARP projected to increase within protected areas under the moderate scenario, six increased in the overall size of their distribution. The other seven decreased in their total size, so their increases within protected areas were solely attributable to shifts in their range. In other words, under moderate climate change, the distributions of these species moved into contact with a greater area of protected land than their current distributions were in contact with. Of the 9 species that BIOCLIM projected to increase within protected areas, five did so solely because of shifts in their range, as their total sizes decreased.

Two species, *Austrostipa wakoolica* and *B. papillosa*, substantially increased within protected areas, a projection that was consistent across both bioclimatic models (Figure 4a, 4b). These large increases occurred because the distributions of these species are projected to shift into the path of a number of large National Parks under the moderate climate change scenario. *A. wakoolica* and *B. papillosa* are currently found in south-western NSW and northern Victoria, where there is a relatively sparse distribution of protected areas. Under moderate climate change, their distributions are projected to move into the section of north-west Victoria where three large National Parks, Wyperfield NP, Murray-Sunset NP, and Big Desert NP, are located (Figure 5a, 5b).

Under the severe climate change scenario, the distributions of most species were projected to decrease. This projection is consistent across both models for 22 species (Table 5). The average decline in species distributions within protected areas projected by BIOCLIM is 51%, and by GARP is 29%.

Proportions of species total distributions contained within protected areas.

For most species, the proportion of their total projected distribution that is contained within protected areas remains relatively consistent under the current and the two future scenarios (Figure 7a, 7b). Two notable exceptions are the alpine species *Discaria nitida* and *Ranunculus anemoneus*. Both BIOCLIM and GARP project substantial increases in the proportions of these species distributions found within protected areas under the severe scenario. Under the current climate scenario, both species have substantial proportions of their distributions encapsulated in protected areas, particularly Kosciuszko National Park. Under the severe scenario, the projected distributions of these species retreat into this and other alpine national parks. This increases the proportion of their total distribution that is within protected areas, even though the size of their distribution decreases overall.

(iv) Effects of migration assumption

The no migration scenario

When species distributions were modelled under the assumption they were unable to migrate, the decrease in the size of projected distributions under climate change was more pronounced. For instance, under moderate climate change, BIOCLIM projected an average decrease of 36% under the no migration scenario, compared to 21% under the universal migration scenario. Within protected areas under moderate climate change, BIOCLIM projected an average decrease of 31% under the no migration scenario, compared to 3% under the universal migration scenario. The finding of a more pronounced decline in projected distributions under the no migration scenario was consistent across both climate change scenarios and both bioclimatic models.

The contiguous migration scenario

When species distributions were modelled under the assumption that they can migrate to areas of their future projected distribution that are contiguous with their current distribution, the decrease in the size of projected distributions under climate change was also more pronounced. For instance, under moderate climate change, GARP projected an average decrease of 12% under the contiguous migration scenario, compared to 5% under the universal migration scenario. Within protected areas under moderate climate change, GARP projected an average decrease of 8% in size of distributions, compared to an increase of 6% under universal migration (Table 3). Notably, across both climate change scenarios and both bioclimatic models, the declines under the contiguous migration scenario were not as severe as those projected under the no migration scenario.

The inability to migrate, or to migrate to only contiguous areas, substantially increased the number of extinctions projected by BIOCLIM to occur under the severe climate change scenario. BIOCLIM projected the extinction of five species under the no migration and contiguous migration scenarios, compared to only two species under the universal migration scenario (Table 3). Six species were projected to become lost from protected areas under the no migration and contiguous migration scenarios, compared to only two under universal migration. GARP projected the loss of four species from protected areas under the no migration and contiguous migration scenarios, compared to only one under universal migration.

(v) Comparison of BIOCLIM and GARP

The projections generated by BIOCLIM and GARP were not always consistent. This is demonstrated by an examination of the direction of change in the size of species projected distributions under the climate change scenarios (i.e. whether a species increases or decreases the size of its distribution). Under the moderate scenario, BIOCLIM and GARP gave consistent projections as to the direction of change in the sizes of species distributions for 20 species, and were inconsistent on the other six (Table 4). Under the severe scenario, they agree on 22 species. For distributions within protected areas, BIOCLIM and GARP gave consistent projections on the direction of change for 17 species under the moderate scenario and 23 species under the severe scenario (Table 5).

These figures indicate a trend towards greater consistency between the models under the more severe climate change scenario. This is because more species are projected to decline under the severe scenario by both BIOCLIM and GARP, so the direction of change for a species is more likely to be consistent across both models (Table 4, 5).

The projections generated by BIOCLIM tended to be more pessimistic than those generated by GARP. The average decline in species distributions projected by BIOCLIM was always substantially greater than that projected by GARP (See sections (ii) and (iii) above). In addition, wherever BIOCLIM and GARP disagree on the direction of change of a species distribution, the majority of these instances involve GARP projecting an increase and BIOCLIM projecting a decrease (Table 4, 5).

(vi) Species distributions modelled with consideration of soil parent material

The inclusion of soil parent material in the projection of species distributions resulted in smaller projected distributions. These distributions were on average 69% of the size of distributions projected without taking soil into account. Distributions within protected areas, when projected with soil parent material, were on average 59% of the size of distributions within protected areas projected without soil parent material.

By excluding species distributions from areas with a large coverage of conservation reserves, the inclusion of soil parent material may affect the estimates of the size of distributions falling within protected areas. An example of this is *Austrostipa wakoolica* under the moderate climate change scenario. When projected with soil parent material, the resulting distribution is 74% of the size of the distribution projected without soil parent material (averaged across GARP and BIOCLIM) (Figure 8a). However, its distribution within protected areas was 8.5% of the size of the same distribution projected without soil parent material (Figure 8b). The inclusion of soil parent material excludes *A. wakoolica's* distribution from occurring within the area of the three large National Parks in north-west Victoria.

Discussion

This study has indicated that, under climate change, threatened plant species projected distributions decline in total size, and in size within protected areas. Whilst a number of species projected distributions actually increase within protected areas under a moderate warming scenario, the vast majority decrease under the severe scenario.

Many other bioclimatic modelling studies examining the impacts of climate change on plant species have projected substantial declines in species total distributions (Huntley *et al.* 1995; Miles *et al.* 2004; Thuiller *et al.* 2005b). For instance, projection of the distributions of over 1000 European plant species suggests that, by 2080, more than half could decline sufficiently to be classed as vulnerable or endangered by the IUCN (Thuiller *et al.* 2005b). Several studies project that the ranges of some plant species will expand even though the ranges of many others decline (Iverson & Prasad 1998; Midgley *et al.* 2003). In this study, the projected distributions of a small number of species (3 in BIOCLIM, 7 in GARP) increased under moderate climate change. Overall, however, the notion that the distributions of most species will decline under climate change is supported across many studies.

Other modelling studies that have projected responses of species within protected areas to climate change have produced mixed results, but overall indicate a decline of many species within reserves (Table 6). Eight National Parks in the US are projected to lose up to 20% of mammal species currently protected within them (Burns *et al.* 2003). A number of cactus species are projected to disappear from the Tehuacan-Cuicatlan Biosphere Reserve in Mexico (Tellez-Valdes & Davila-Aranda 2003). Up to one third of plant species are projected to disappear from the Melkbosrand/Augrabie Falls National Park in South Africa (Rutherford *et al.* 1999). Plant species have an increased probability of declining in nature reserves in the south of Britain under climate change, though northern British Nature reserves will increase in their suitability for many plant species (Dockerty & Lovett 2003; Dockerty *et al.* 2003). Whilst these studies are limited in their taxonomic and geographic coverage, they broadly agree with this study that species will decline within protected areas under climate change.

The distributions of some species in this study were projected to increase within protected areas under moderate climate change. Many of these species did so solely because of movements of their distribution, rather than increases in the size of their distribution. This indicates that the position of a protected area is an important contributor to its effectiveness under climate change. A protected area that is located in the path of a migrating species will be more effective at protecting that species than one that is not.

Migration scenarios.

Under a no migration scenario, many species suffered greater declines in the size of their distribution than under universal migration, and the number of extinctions under the severe scenario increased. For many of the plant species modelled, the no-migration scenario could be closer to the truth than the universal migration scenario. A number of the species are ant dispersed, such as *Acacia pubescens, Zieria granulata*, and *Pultenaea parviflora* (Table 1) and seeds dispersed by ants are typically carried only a few metres from the parent plant (Hughes *et al.* 1994). Observational evidence provided in recovery plans suggests that other species, such as *Endiandra floydii* and *Pimelea spicata*, experience very poor levels of dispersal (Table 1). The ability of the above species to disperse to new areas of suitable habitat created by climate change is likely to be low.

Other species may have the capability to disperse far greater distances. *Cynanchum elegans* is wind dispersed, whilst *Diploglottis campbellii, Tasmannia purpurascens* and *Davidsonia johnsonii* are likely to be bird dispersed due to their fleshy fruits (Table 1). Some wind and bird dispersed seeds are capable of rare long distance dispersal events, from hundreds of metres to kilometres of distance from the parent plant (Higgins & Richardson 1999). However, little is known about the frequency of long distance dispersal events (Higgins & Richardson 1999), nor whether long distance dispersal events will allow plants to keep up with climate change (Pearson & Dawson 2005). Migration rates of plants from the palaeoclimatic record are around ten times lower than the rate needed to keep pace with the projected rate of climate change (Leishman *et al.* 1992). Even the species that are capable of long distance dispersal may be unable to reach all areas of their projected future distributions.

A further obstacle to migration of many of the modelled species is the low levels of fecundity reported for a great number of species. Recovery plans for *Cynanchum elegans*, *Davidsonia johnsonii, Acacia bynoeana, Acacia pubescens,* and *Uromyrtus australis* report that all have low levels of seed production. Low levels of seed production may decrease the chance of successful dispersal due to the decreased number of dispersal events a plant is capable of (Clark & Ji 1995).

Under the contiguous migration scenario, the projected distributions of species were smaller than under universal migration, but larger than under no migration. The contiguous migration scenario accounts for the possibility that many plants will be unable to disperse across large areas of climatically unsuitable habitat, because of their limited dispersal distance (Peterson *et al.* 2002). To migrate a long distance, new individuals will have to grow and produce more seeds at points along the way to facilitate further migration. In climatically unsuitable habitat, this would not be possible, hindering migration across these areas to isolated patches of climatically suitable habitat. For species in this study that are able to disperse shorter distances, the contiguous migration scenario scenario may provide the best projection of their future distributions.

Comparison of BIOCLIM and GARP

The projections of BIOCLIM were consistently more pessimistic than those made by GARP. One possible explanation for this may be the approach taken by each program. BIOCLIM uses only one rule type, in which the values of climatic parameters within which the species exists are identified to form the climatic envelope (Nix 1986). GARP, meanwhile, is capable of using four rule types – atomic rules, range rules, negated range rules, and logistic regression rules (See Methods) (Stockwell & Peters 1999). The ability of GARP to continually modify and test rules explaining aspects of a species distribution enables it to explore more climatic and topographic niche space within which the species could exist (Stockwell & Peterson 2002). It may be because GARP explores many more possible rules for the species occurance, and is not limited to one rule type, that it has generated species distributions that are not as restricted as those produced by BIOCLIM.

BIOCLIM's projections may also have been more pessimistic because only the "core" areas of a species potential distribution were projected. It is common practice in studies using BIOCLIM to exclude the most extreme values from the range of values that the species can occur within for each climatic parameter (Beaumont *et al.* 2005). This is done to exclude climatic areas in which sink populations may exist. The resulting projected distribution represents the "core" distribution of the species, where it is hypothesised that all populations are able to reproduce. Potentially, if the full range of values for each climatic parameter had been modelled in BIOCLIM, the resulting distributions would have been closer to the size of the distributions projected by GARP.

Comparisons of the accuracy of projected distributions produced by BIOCLIM and GARP have been made by two studies. Elith and Burgman (2002) used a measure of accuracy of projected distributions, Receiver Operating Characteristic (ROC) curves, to evalute BIOCLIM and GARP. When distributions of rare plants in Victoria were projected, there was little difference in the accuracy of the two models. Loiselle *et al.* (2003) evaluated GARP and BIOCLIM using the Kappa statistic, a measure of performance incorporating the number of false postive (commission) and false negative (omission) errors that occur in the projections created by a model. When distributions of Brazilian bird species were projected, GARP was found to have made fewer errors than BIOCLIM overall (Loiselle *et al.* 2003). Interestingly, the areas of species distributions projected by BIOCLIM were larger on average than those projected by GARP (Loiselle *et al.* 2003).

Despite their differences, BIOCLIM and GARP gave consistent projections for the key findings of this study. Both consistently projected that most species will decline in area under both the moderate and severe climate scenarios, and that most will also decline in area within protected areas under the severe scenario (Table 4, 5). The use of more than one modelling approach in further studies is advisable, to gain an appreciation of how reliable the findings of each individual modelling approach may be.

Inclusion of soil in the projections.

The inclusion of soil parent material in the models refined the projections of species distributions, resulting in smaller areas. As demonstrated by *A. wakoolica*, the inclusion of soil parent material can substantially reduce the area of a species projected distribution within protected areas. For future studies, the inclusion of soil factors in the projection of species distributions will be important for species for which soil is known or likely to be a limiting factor.

However, it is important that the soil factor that has the main influence on a species distribution is used in modelling. For instance, *Uromyrtus australis* is known to occur only on soils that are derived from Nimbin Rhyolite, a volcanic soil parent material in north-east NSW (NPWS 2003b; Smith & Houston 1995). The map of soil parent material used did not explicitly map Nimbin Rhyolite, and it was included in the broader class of basalts and gabbros (Johnston *et al.* 2003) Thus, it was not possible to restrict the projected distribution of *U. australis* to Nimbin Rhyolite. A map based on a finer-scale classification of soil parent material that displays Nimbin Rhyolite is needed. In a large modelling project, it may be necessary to assemble a collection of different soil datasets displaying different soil classifications, and customise the modelling of each species to include only the soil dataset that is relevant to that species.

Caveats

Bioclimatic models provide the only means of projecting future distributions of species, knowledge that is important for conservation planning. There are sources of uncertainty involved in bioclimatic models. However, so long as these sources of uncertainty are acknowledged, and the results of bioclimatic models interpreted accordingly, such models can inform conservation decisions in a meaningful way (Pearson & Dawson 2003).

The assumptions of bioclimatic models may not always hold. These assumptions, as stated previously, are (1) that a species distribution encompasses all climatic areas that it can inhabit, (2) that a species distribution is at equilibrium with the current climate, and (3) that a species will not adapt to climate change.The first assumption will be untrue where a species distribution is limited not just by climate but by inter-specific interactions, such as competition, predation, and parasitism (Davis *et al.* 1998a). These factors have been demonstrated to affect the distributions of fruit flies in laboratory experiments (Davis *et al.* 1998b), though for many species these factors are likely to have only local-scale impacts on distribution, or none at all (Hodkinson 1999; Pearson & Dawson 2003). Barriers to dispersal, such as mountain ranges, can also prohibit species from inhabiting regions of climatically suitable habitat (Lawton 1998).

Incomplete sampling of a species distribution due to habitat loss may give the impression that a species has a smaller climatic range than it actually is capable of inhabiting. Habitat loss may wipe out a population of a species before a collector has sampled that population. No record would be made that the species could exist within the climate that population was found in. The impact of this factor, and other violations of the first assumption, will make the projection of a species bioclimatic distribution smaller than it actually is.

Violations of the second assumption will occur where a species distribution is still responding to past climatic changes. For example, long lived individuals of the plant *Tilia cordata* persist in areas of Britain climatically unsuitable for recruitment, as they became established in these areas under a previous, more suitable climate (Woodward 1990).

The final assumption, that a species will not adapt to climate change (Pearson & Dawson 2003), is likely to remain true for the species in this study. Many of the threatened plants in this study reportedly have low fecundity (Table 1), so their ability to adapt rapidly to climate change is likely to be low.

An additional source of uncertainty is whether all the climatic parameters that have an influence on the distribution of a species are included in the bioclimatic model. Climatic variability may have an important influence on the distributions of numerous plant species. For instance, a high variability in rainfall between years affects species living in arid and semi-arid areas (Hobbs & Mooney 1995). To inhabit these regions, plants need to capability to survive long periods of drought, and to respond rapidly to rainfall when it occurs (Fox 1995). Extreme but very infrequent events, such as heat waves, can induce significant mortality in some species and thereby influence distributions (Parmesan *et al.* 2000). For these reasons, it may be important to include indices of extreme events and climatic variability in bioclimatic models.

The lack of such indices in OzClim, the source of climatic information used in this study, prevented the consideration of climatic variability in projecting the distributions of threatened plant species. However, it has recently been found that some indices of climatic variability, such as the seasonality of precipitation, can be created in the program DIVA-GIS using monthly climate data obtained from OzClim.

The final source of uncertainty is the capability of the modelled species to survive in off-reserve areas where they are projected to occur. The capability of a threatened plant species to exist in an off-reserve area will depend on the amount of native vegetation left in that area, and the disturbance regime of that vegetation. Areas of the matrix that are devoid of native vegetation would be unsuitable for most or all of the species modelled. Areas retaining vegetation but that are highly or moderately disturbed by grazing are likely to be unsuitable for many species (Auld & Denham 2001). Fire regimes may be inappropriate for the survival of many species in off-reserve areas (Gill 2001). Vegetation that is significantly fragmented may have an altered suitability for many species (Saunders *et al.* 1991). Vegetation fragments often have a different microclimate to continuous vegetation, for instance, increased amounts of solar radiation at the edges of fragments increase the air temperature for some distance into the fragment (Saunders *et al.* 1991). If disturbance regimes are inappropriate or native vegetation has been cleared or highly fragmented, then a species may not be able to survive in many off-reserve areas that fall within its projected habitat.

The incorporation of these factors into projections of species distributions under future climates is unfeasible, as it would be near impossible to project fire and disturbance regimes at a far off date with any accuracy.

Conservation implications

The finding of declines of many species distributions within protected areas under climate change, particularly the severe scenario, has repercussions for conservation strategies under climate change. Declines in species distributions due to climate change are likely to result in extinctions (Thomas *et al.* 2004), as the area of many species distributions will become too small to support viable populations. Thus, many species may become lost from protected areas when their populations within reserves decline in size substantially. In addition, as the projected distributions are models of species climatically suitable habitat, their actual distributions may be smaller, and so would decline to a smaller size than this study has projected.

If a policy of long term protection of species within protected areas is to be pursued, substantial expansion of the protected area network may be required to curb species declines. There is an existing need to expand protected areas in many regions of NSW to enhance the representativeness of the NSW protected area system (Pressey *et al.* 2000; Pressey & Taffs 2001; Pressey *et al.* 2002). Such expansions may serve the dual purpose of both increasing the representativeness of the reserve system, and increasing its ability to cope with climate change. Reserve additions should take into account the likely directions of migration of species under climate change, so that new reserves are well placed to protect migrating species.

However, the expansion of protected areas alone is unlikely to be sufficient to conserve species under climate change. There are limits to the expansion of the protected area system. A large proportion of un-reserved native vegetation occurs on private land, especially in the east of NSW (Pressey *et al.* 2000). As private land cannot be incorporated into the protected area system unless it is purchased, which is frequently unfeasible, large areas of native vegetation in NSW cannot be acquired for reservation.

A whole-landscape approach to conservation is likely to be more effective than the protected area system alone as a conservation-strategy under climate change. A whole-landscape approach recognises the roles that protected areas have to play in conservation, but also emphasises the importance of conservation in off-reserve regions (Soule *et al.* 2004). Because species distributions are projected to dramatically decline under climate change, it will become increasingly important to preserve them whereever they occur, whether on or off reserves. Emphasis upon whole-landscape conservation will provide a better outcome for species that are likely to move out of protected areas due to shifts in their distribution under climate change.

It has already been recognised that whole-landscape conservation is important (Figgis 2004), for reasons that extend beyond climate change. Long-distance species movements are likely to occur even in the absence of climate change. Large areas of habitat and landscape connectivity are important for evolutionary processes and speciation (Soule *et al.* 2004). Management for large-scale disturbances, such as fire, and hydrological processes, cannot be confined to within reserves, but has to consider surrounding landscape (Soule *et al.* 2004).

Landscape-wide conservation strategies are now required for NSW. An example of a landscape-wide conservation initiative already planned is the WildCountry project, spear-headed by the Wilderness Society. The concept behind this project is to create massive landscape linkages across a number of high-conservation priority areas of Australia. Within NSW, the WildCountry project, as currently planned, encompasses the south-west corner of the state (Wilderness Society 2005). Some programs also exist to facilitate off-reserve conservation, including voluntary schemes where landowners enter into a contract with the government that requires them to preserve native vegetation on their land (Figgis 2004). The co-operation of land-owners is obviously vital to off-reserve conservation. It will be important to generate recognition among land owners and the wider public that protected areas, whilst important, do not provide a sufficient conservation strategy by themselves.

In addition to landscape wide-conservation, translocation is likely to become an important conservation tool. As demonstrated by the no-migration scenario, the inability to migrate increases the risk of extinction under climate change. For many plants with low dispersal abilities, translocation to climatically suitable areas may be their only chance of continued persistence (Kutner & Morse 1996).

Future directions

This study has demonstrated the utility of bioclimatic models for exploring the possible consequences of climate change for species conservation. Further studies could use bioclimatic models to identify high priority areas for conservation under climate change. The modelling of large numbers of species from many taxa can identify areas that are likely to harbour high species diversity under climate change. National Parks or off-reserve conservation strategies can then be planned for these areas.

Bioclimatic models also have an application in identifying species that are likely to require translocation under climate change. For species that have little ability to migrate, projection of their future climatically suitable habitat will identify if any areas of their current distribution are likely to remain inhabitable in the future. Species with no overlap between their current distribution and future climatically suitable habitat can then be identified as high priorities for translocation. The projection of their future climatically suitable habitats will also identify locations that are likely to be good candidates to translocate such species to.

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Table 1: the threatened plant species used in this study

Family	*Species*	*Habitat*	*Growth form*	*Level of risk*	*Dispersal and/or fecundity levels*	*Driest season within species range, as used in BIOCLIM (see methods)*	*Reference*
Asclepiadaceae	Cynanchum elegans	Dry rainforest, and sclerophyll forest, in eastern NSW	Twiner	Endangered	Seed has tuft for wind dispersal, low levels of seed production occur	Winter	(NPWS 2002a)
Asteraceae	Brachyscome papillosa	Salt bush plains, grassland and woodland, in south west NSW	Perennial herb to 40cm	Vulnerable		Summer	(DEC 2005)
Asteraceae	Senecio garlandii	Woodland in south west slopes	Perennial sub-shrub	Vulnerable		Summer	(DEC 2005)
Brassicaceae	Lepidium monoplocoides	Semi-arid regions, western NSW	Annual herb or perennial forb	Endangered		Summer	(DEC 2005)
Casuarinaceae	Allocasuarina defungens	Coastal heath, central to north coast	Shrub	Endangered		Winter	(DEC 2005)
Cunoniaceae	Davidsonia johnsonii	Subtropical rainforest, North East NSW	Medium sized rainforest tree	Endangered	Very low level s of seed production, probably vertebrate dispersed as have fleshy fruits	Winter	(NPWS 2004a)
Fabaceae	Acacia bynoeana	Sclerophyll forest, central eastern NSW	Shrub to 1m high	Endangered	Low levels of seed production, minimal dispersal of seeds locally	Winter	(NPWS 1999)

Fabaceae	Acacia pubescens	Open woodland and forest, central eastern NSW	Shrub to 1.5m	Vulnerable	Seed dispersal is probably by ants, seeds travel only a few metres. Low level of seed production, high levels of seed predation	Winter	(NPWS 2003a)
Fabaceae	Acacia pubifolia	Dry shrubby woodland, north east NSW	Tree 3-8m tall	Endangered		Winter	(DEC 2005)
Fabaceae	Acacia ruppii	Shrubland and dry open forest, North east NSW	Shrub 1-2m tall	Endangered		Winter	(DEC 2005)
Family	*Species*	*Habitat*	*Growth form*	*Level of risk*	*Dispersal and/or fecundity levels*	*Driest season within species range, as used in BIOCLIM (see methods)*	*Reference*
Fabaceae	Pultenaea parviflora	Cumberland plain, Sydney	Shrub to 1.8m	Endangered	Localised dispersal of seeds, by ants only	Winter	(NPWS 2002b)
Fabaceae	Swainsona recta	South west slopes, also in ACT.	perennial herb to 35cm	Endangered		Summer	(DEC 2005)
Lauraceae	Endiandra floydii	Subtropical rainforest, north east NSW	to medium sized tree to 15m	Endangered	Large seeds with no obvious dispersal mechanism, probably are poorly dispersed	Winter	(NPWS 2004c)
Myrtaceae	Angophora inopina	Central coast	Small tree	Vulnerable		Winter	(DEC 2005)
Myrtaceae	Eucalyptus benthamii	South west sydney, in riparian habitats	40m tree	Vulnerable		Winter	(DEC 2005)

Myrtaceae	Uromyrtus australis	Subtropical rainforest, north east NSW	12m tree	Endangered	Low numbers of flowers and fruit reported	Winter	(NPWS 2003c)
Poaceae	Austrostipa wakoolica	Floodplains in central and south west NSW	Grass	Endangered			(DEC 2005)
Proteaceae	Grevillea beadleana	Eucalypt forest, north east NSW	Shrub to 2.5 m	Endangered		Winter	(DEC 2005)
Ranunculaceae	Ranunculus anemoneus	Alpine areas, vincinity of Mt. Kosciuszko	Rhizomic perennial herb	Vulnerable		Summer	(DEC 2005)
Rhamnaceae	Discaria nitida	High altitude areas, mostly within Kosciusko NP	shrub, to 2.6 m	Vulnerable		Summer	(DEC 2005)
Rutaceae	Zieria granulata	coastal lowlands, Illawarra region	Shrub to 6m	Endangered	Seeds are forcibly ejected from the mature fruit, and are ant dispersed	Winter	(NPWS 2005)
Sapindaceae	Diploglottis campbellii	Subtropical rainforest, north east NSW	Medium sized rainforest tree	Endangered	Possibly bird dispersed, as fruits are fleshy	Winter	(NPWS 2004b)
Solanaceae	Solanum karsense	Floodplains in south west NSW	Forb to around 30cm	Vulnerable		Summer	(DEC 2005)
Thymelaeaceae	Pimelea spicata	Cumberland plain and Illawarra region	Shrub to 50cm	Endangered	Dispersal is probably very low, most seedlings are within 30cm of an adult plant	Winter	(NPWS 2004d)
Tiliaceae	Corchorus cunninghamii	Subtropical rainforest, north east NSW	Shrub to 1.5 m high	Endangered		Winter	(DEC 2005)

Tremandraceae	Tetratheca juncea	Forest and woodland on central coast	Shrub to 60 cm	Vulnerable	Low levels of fecundity	Winter	(GROSS *et al.* 2003)
Winteraceae	Tasmannia purpurascens	Rainforest, alpine woodland in Barrington Tops	Tall shrub	Vulnerable	Probably bird dispersal, as fruits are fleshy	Winter	(Peacock 1995)

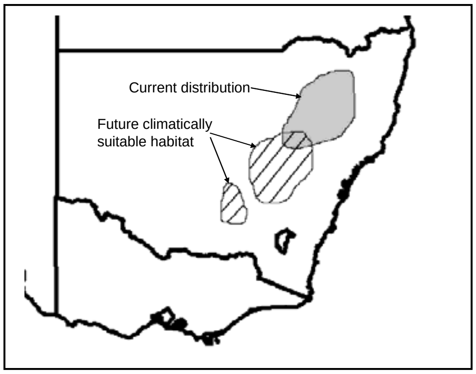
Climatic Parameters		BIOCLIM	GARP
Precipitation	Annual		
	Summer		

	Autumn		
	Winter		
	Spring		
Maximum temperature	Annual		
	Summer		
	Autumn		
	Winter		
	Spring		
Minimum temperature	Annual		
	Summer		
	Autumn		
	Winter		
	Spring		
Mean temperature	Annual		
	Summer		
	Autumn		
	Winter		
	Spring		
Topographic Parameters			
	Slope		
	Aspect		
	Elevation		

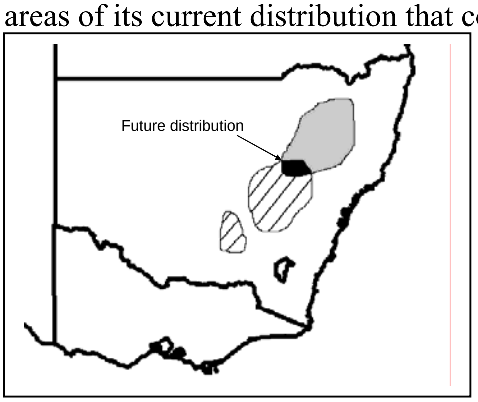
Table 2: Parameters used in BIOCLIM and GARP. The grey squares indicate that a parameter was included as input into the model.

Figure 1.

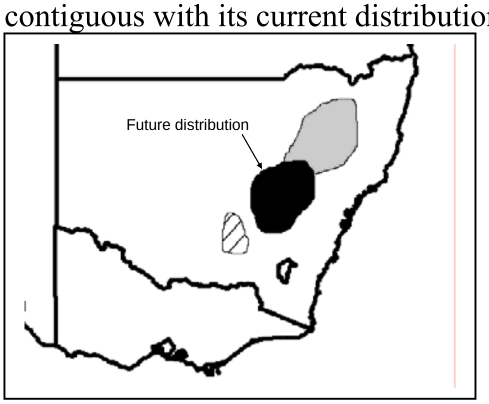
a. Universal migration: This image depicts the current distribution of a plant species, (shaded gray), and the future areas climatically suitable habitat, consisting of two disjunct patches (shaded with diagonal lines), one overlapping with the current distribution (Patches B and C). Under a scenario of Universal migration, the species is able to migrate to and occupy both patches of its future climatically suitable habitat.

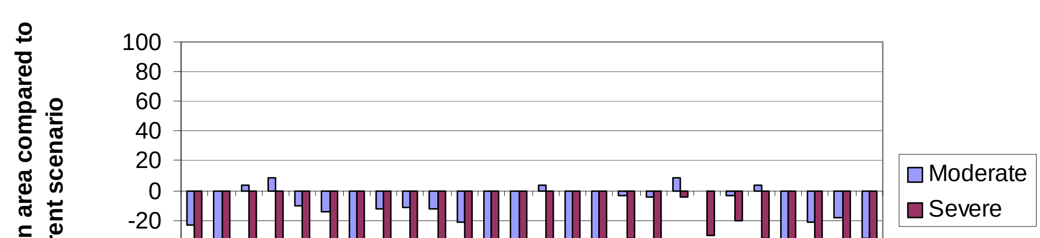


b. No migration: If the species is unable to migrate, its future distribution will consist only of those areas of its current distribution that co-incide with areas of future climatically suitable habitat.



c. Contiguous migration: If the species is able to migrate, but cannot cross climatically unsuitable areas, its future distribution will be those areas of future climatically suitable habitat that are contiguous with its current distribution.





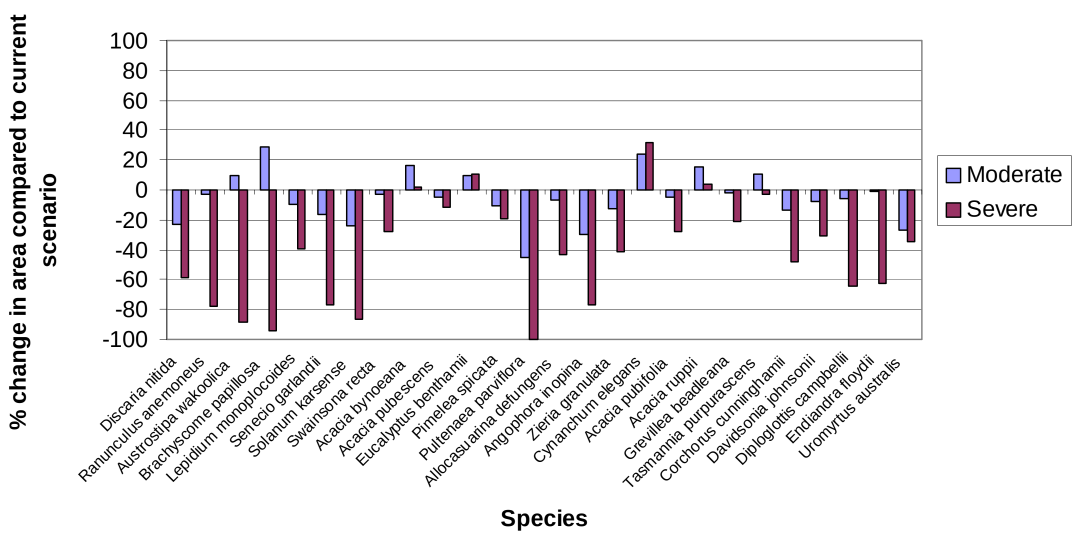
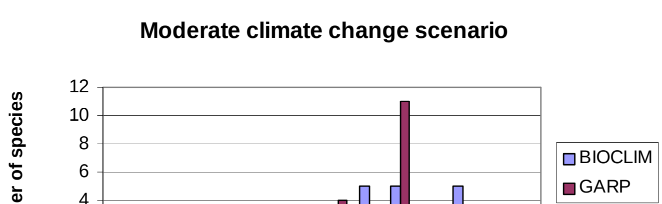


Figure 2b. Percent change in area of future projected distributions compared to the current projected distribution for 27 threatened plant species, as modelled in GARP.



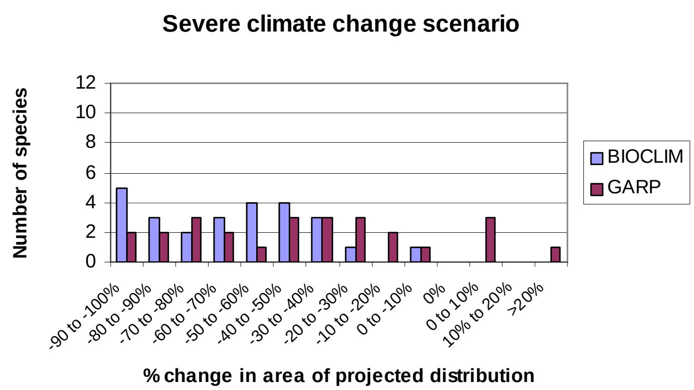
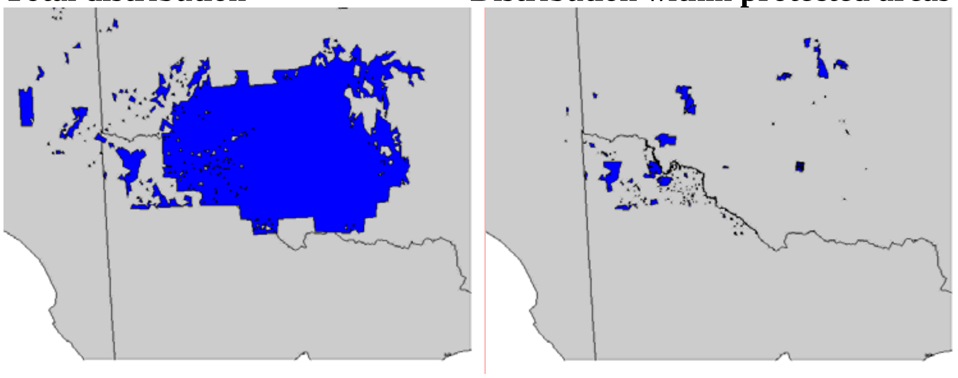


Figure3b. Frequency distribution of changes in projected distributions of 27 threatened plant species, under the severe climate change scenario.

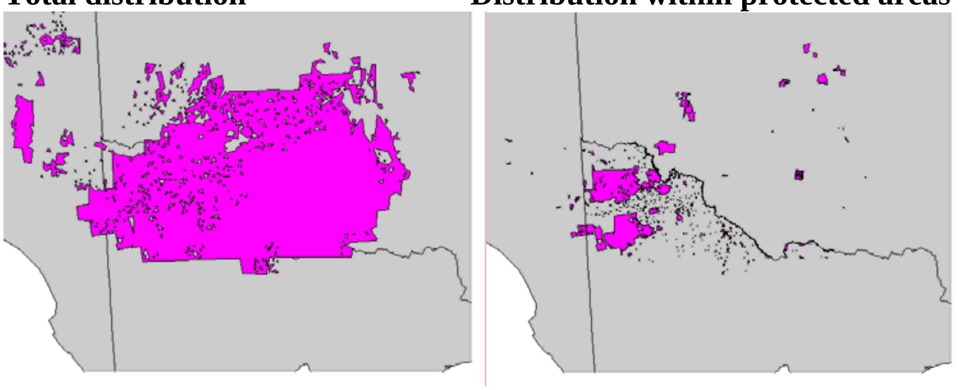
Current Scenario

Total distribution **Distribution within protected areas**



Moderate Scenario

Total distribution **Distribution within protected areas**



Severe scenario

Total distribution **Distribution within protected areas**

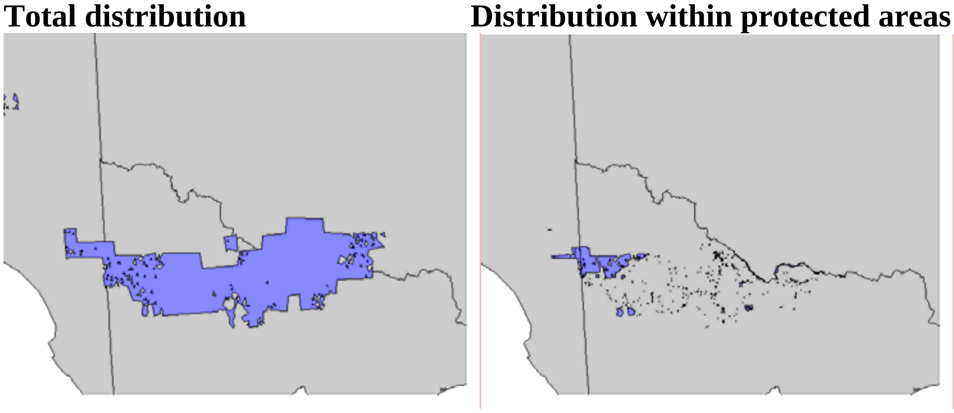
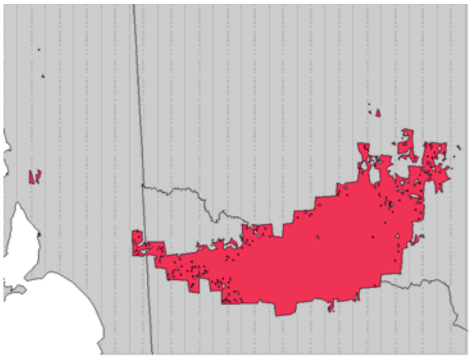
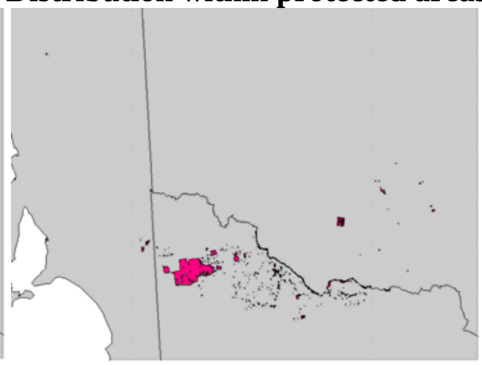


Figure 5a: Positions of the projected distribution of *B. papillosa* under current and future climate scenarios, as modelled by GARP.

Current Scenario

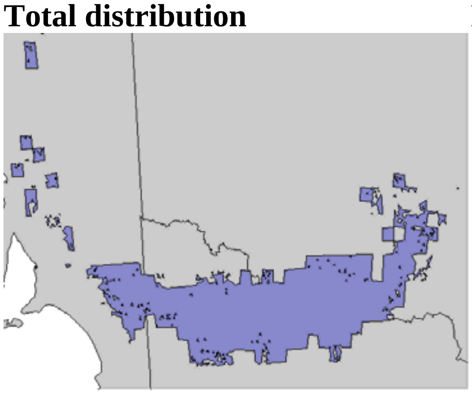
Total distribution **Distribution within protected areas**

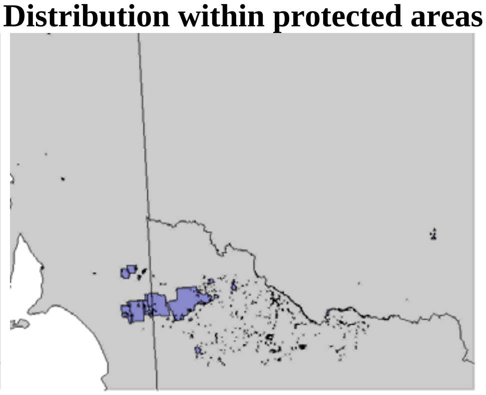




Moderate Scenario

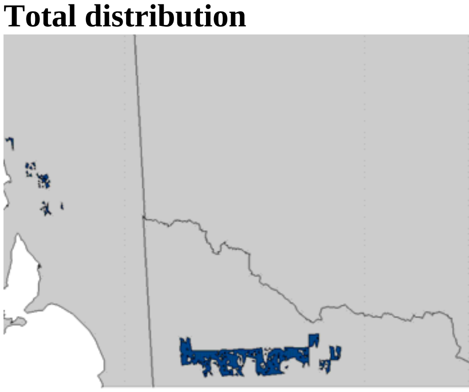
Total distribution **Distribution within protected areas**





Severe Scenario

Total distribution **Distribution within protected areas**



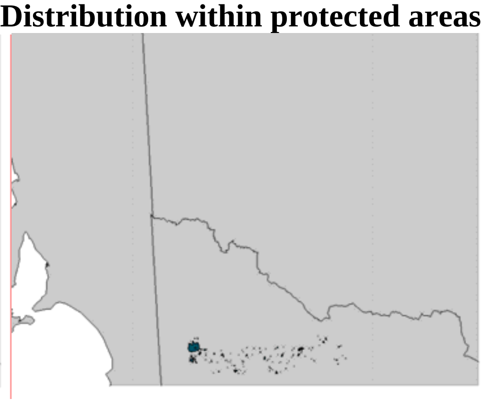


Figure 5b: Positions of the projected distribution of *A. wakoolica* under current and future climate scenarios, as modelled in GARP.

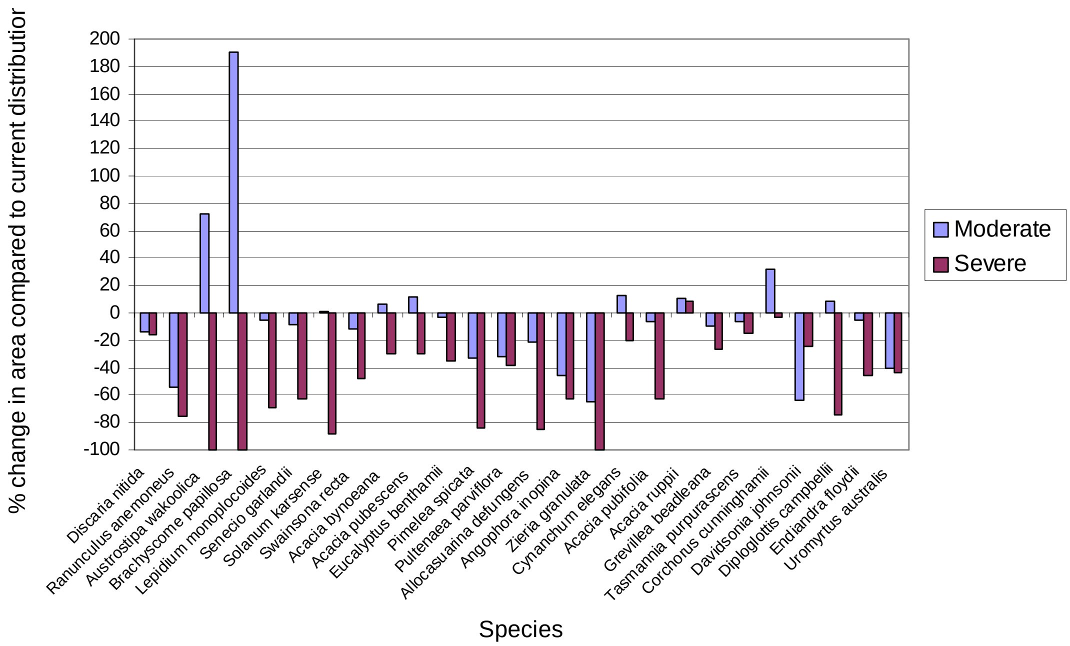


Figure 4a: Percent change in area of future projected distributions within protected areas compared to current projected distributions within protected areas, as modelled in BIOCLIM, for 27 threatened plant species.

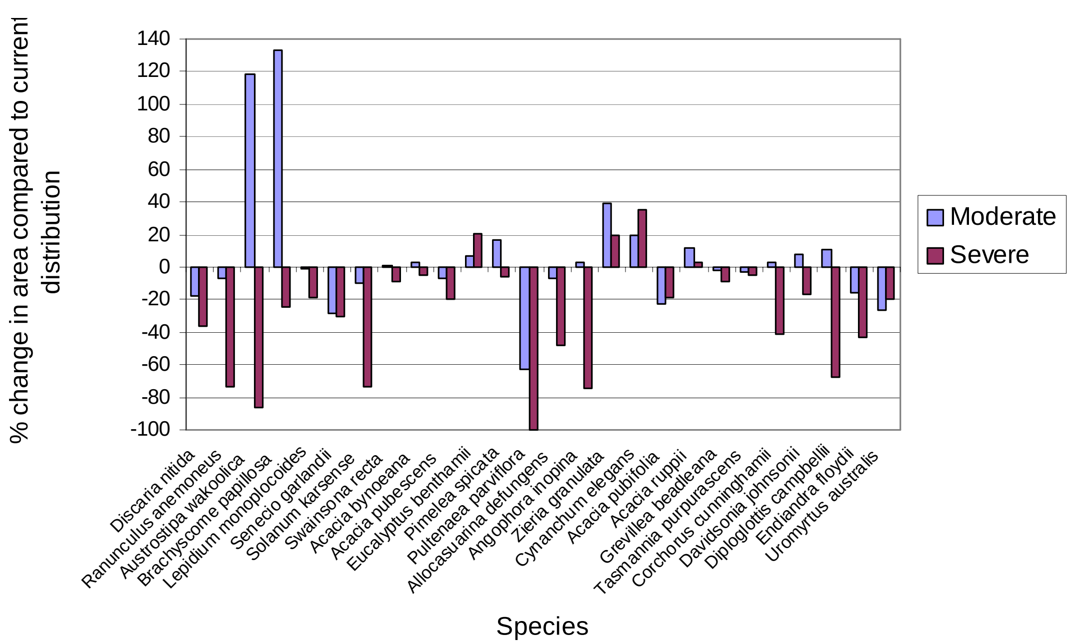


Figure 4b: Percent change in area of future projected distributions within protected areas compared to current projected distributions within protected areas, as modelled in GARP, for 27 threatened plant species.

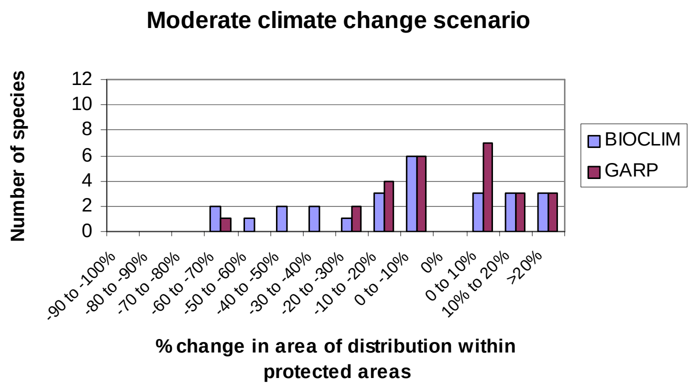


Figure 6a. Frequency distribution of changes in projected distributions within protected areas of 27 threatened plant species, under the moderate climate change scenario.

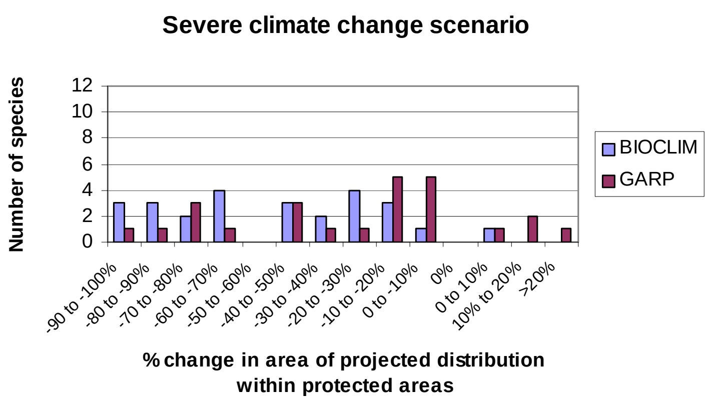


Figure 6b. Frequency distribution of changes in projected distributions within protected areas of 27 threatened plant species, under the severe climate change scenario.

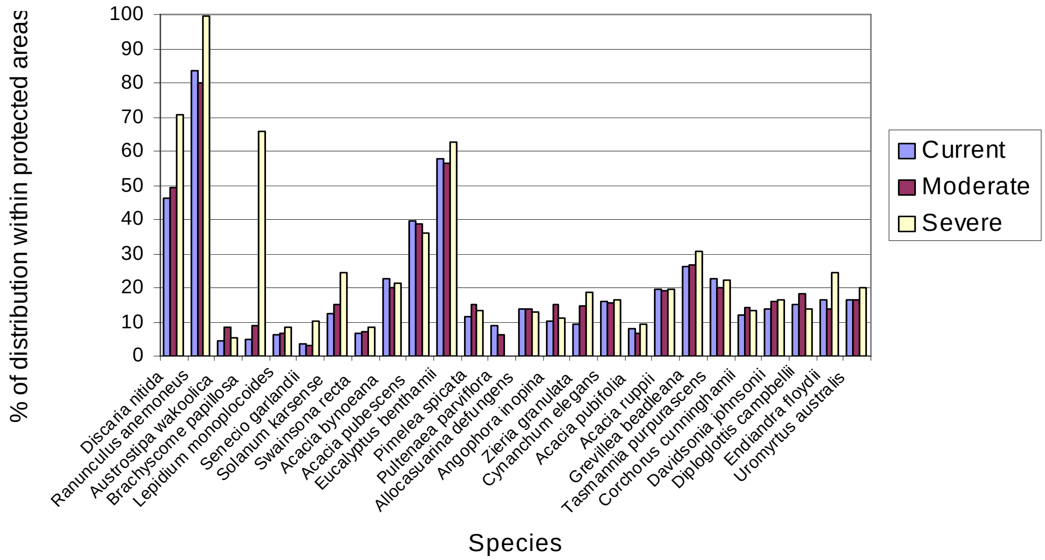


Figure 7a. Proportion of projected distributions of 27 threatened plant species that are contained within protected areas under current and future climate scenarios, as modelled in BIOCLIM.

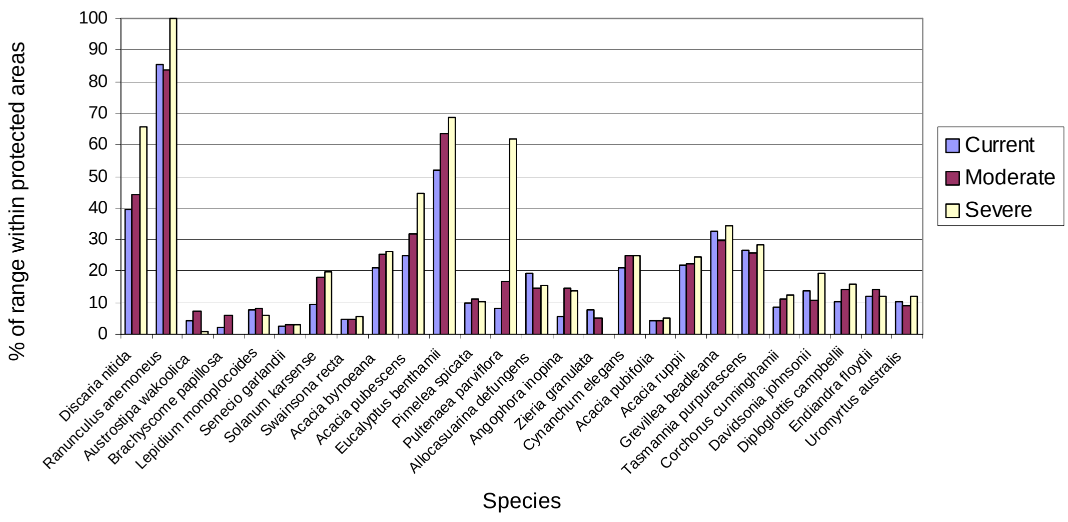


Figure 7b. Proportions of projected distributions of 27 threatened plant species that are contained within protected areas under current and future climate scenarios, as modeled in GARP.

			Average % change in area			Number of extinctions		
			Universal Migration	No Migration	Contiguous Migration	Universal Migration	No Migration	Contiguous Migration
Total distribution	Moderate	BIOCLIM	-21	-36	-26	0	0	0
		GARP	-5	-33	-12	0	1	1
	Severe	BIOCLIM	-62	-74	-68	2	5	5
		GARP	-42	-65	-50	1	1	1
Distribution within protected areas	Moderate	BIOCLIM	-3	-31	-22	0	0	0
		GARP	6	-31	-8	0	1	1
	Severe	BIOCLIM	-51	-68	-64	2	6	6
		GARP	-29	-62	-52	1	4	4

Table 3. Average percent changes in sizes of distributions compared to the current scenario, and number of extinctions, under three migration scenarios. Refer to text for an explanation of each migration scenario.

Climate Change Scenario	Projection	Number of species
Moderate	BIOCLIM and GARP project increase	3
	BIOCLIM and GARP project decrease	17
	Total: models are consistent	20
	BIOCLIM projects increase, GARP projects decrease	2
	GARP projects increase, BIOCLIM projects decrease	4
	Total: models are inconsistent	6
Severe	BIOCLIM and GARP project increase	0
	BIOCLIM and GARP project decrease	22
	Total: models are consistent	22
	BIOCLIM projects increase, GARP projects decrease	0
	GARP projects increase, BIOCLIM projects decrease	4
	Total: models are inconsistent	4

Table 4: Summary of the projected directions of changes in 27 threatened plant species distributions made by BIOCLIM and GARP

Climate Change Scenario	Projection	Number of Species
Moderate	BIOCLIM and GARP project increase	7
	BIOCLIM and GARP project decrease	11
	Total: models are consistent	18
	BIOCLIM projects increase, GARP projects decrease	2
	GARP projects increase, BIOCLIM projects decrease	6
	Total: models are inconsistent	8
Severe	BIOCLIM and GARP project increase	1
	BIOCLIM and GARP project decrease	22
	Total: models are consistent	23
	BIOCLIM projects increase, GARP projects decrease	0
	GARP projects increase, BIOCLIM projects decrease	3
	Total: models are inconsistent	3

Table 5. Summary of the projected directions of changes in 27 threatened plant species distributions within protected areas made by BIOCLIM and GARP

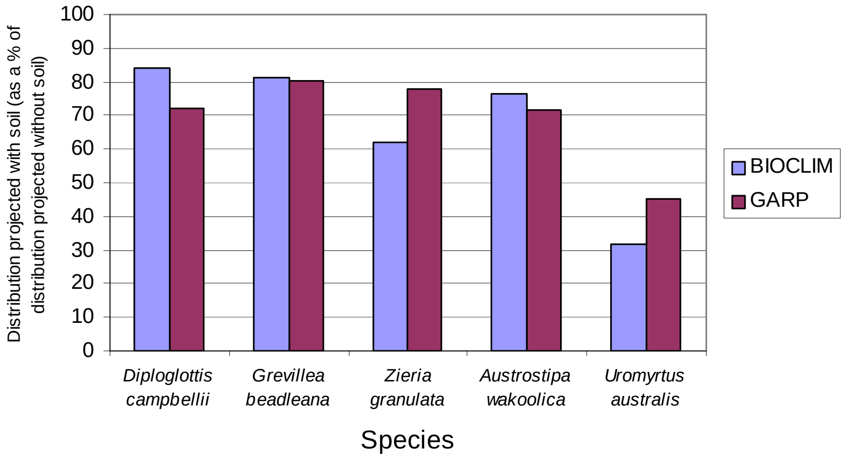


Figure 8a. The impact of including soil parent material in modelling on the projections of species distributions under moderate climate change. Each bar represents a species distribution projected with soil expressed as a percentage of its distribution projected without soil. The 100% line indicates that distributions projected with and without soils were equal in area. Any value below 100% indicates that the inclusion of soil in modelling has reduced the size of the species projected distribution.

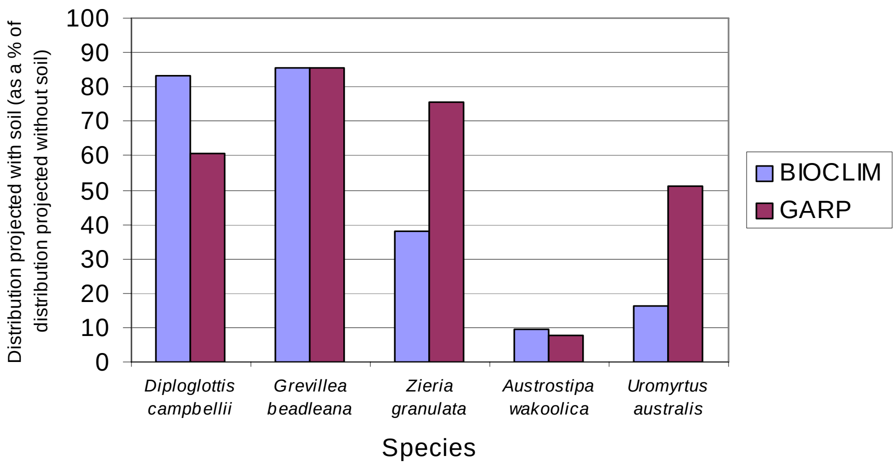


Figure 8b. The impact of including soil parent material in modelling on the projections of species distributions within protected areas, under moderate climate change. Each bar represents a species distribution projected with soil expressed as a percentage of its distribution projected without soil.

Appendix 1

The classes of soil parent material displayed in the ASRIS soil parent material dataset, as listed in (Johnston *et al.* 2003):

Granites (adamellite)
Granidorites (tonalities)
Acid Pyroclasitics and Lavas
Andesites, diorites, and associated pyroclastics
Basalts, Gabbros
Serpentites, ultrmafic intrusives and extrusives
Highly siliceous sediments
Fine grained sediments
Coarse sediments – quartz rich
Coarse sediments – lithic/feldspathic
Coarse sediments – undifferentiated
Calcareous sediments
Banded iron formations
Highly metmorphosed sequences
Lacustrine
Sands (beach, aeolian)
Estuarine/lagoonal
Residual and colluvial surfaces
Duricrusts
Alluvium/colluvium – Fine grained unconsolidated material
Alluvium/colluvium – Coarse grained unconsolidated material
Alluvium/colluvium – Mixed unconsolidated material

Johnston RM, Barry SJ, Bleys E*, et al.* (2003) ASRIS: the database. *Australian Journal of Soil Research*, **41**, 1021-1036.

Appendix 2

	Current	Moderate	Severe
Discaria nitida	22511	17301	11431
Ranunculus anemoneus	1419	657	300
Austrostipa wakoolica	93131	96025	936
Brachyscome papillosa	68133	73881	0
Lepidium monoplocoides	267046	239535	109227
Senecio garlandii	26959	23143	9360
Solanum karsense	58673	30812	3261
Swainsona recta	102907	90004	45526
Acacia bynoeana	23353	20605	13182
Acacia pubescens	6665	5809	2612
Eucalyptus benthamii	5169	4084	2520
Pimelea spicata	3821	2311	599
Pultenaea parviflora	729	245	60
Allocasuarina defungens	4097	4233	790
Angophora inopina	1762	378	269
Zieria granulata	653	353	0
Cynanchum elegans	50768	48925	34269
Acacia pubifolia	18111	17308	5779
Acacia ruppii	48481	52750	46481
Grevillea beadleana	36615	36255	25467
Tasmannia	23317	22489	18579

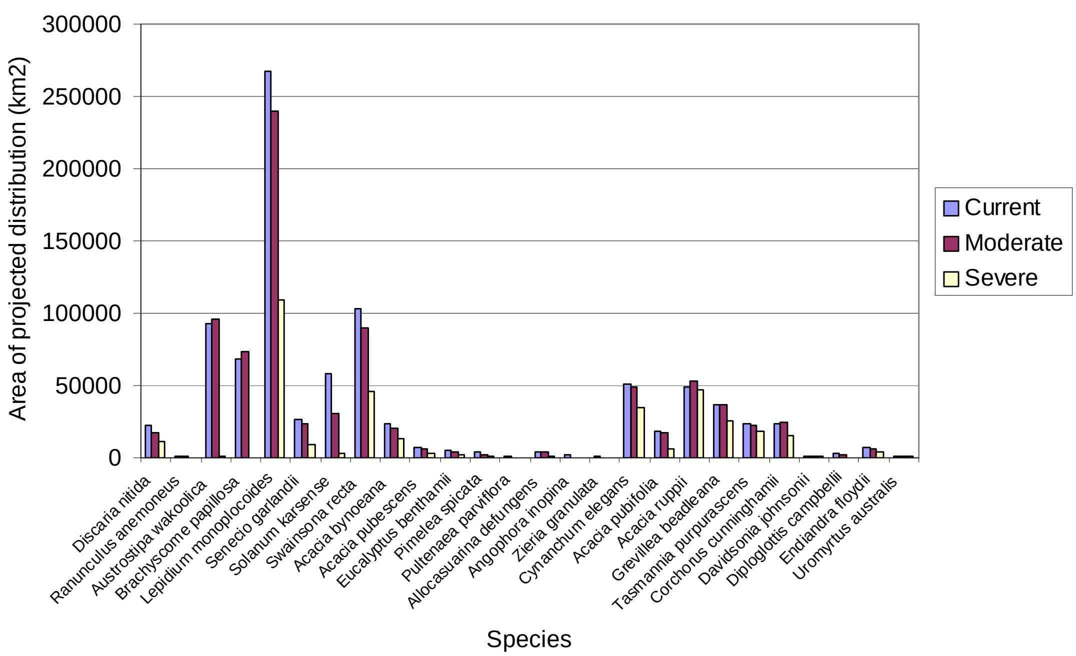


Figure A1. Total size of species projected distributions under each scenario, as modelled in BIOCLIM.

	Current	Moderate	Severe
Discaria nitida	29045	22328	12144
Ranunculus anemoneus	2540	2460	568
Austrostipa wakoolica	97220	106228	10773
Brachyscome papillosa	115027	148030	6612
Lepidium monoplocoides	379170	342984	228888
Senecio garlandii	54205	45416	12723
Solanum karsense	73203	55256	10021
Swainsona recta	203505	197610	145839
Acacia bynoeana	65422	76202	66964
Acacia pubescens	13551	12898	11963
Eucalyptus benthamii	4273	4671	4716
Pimelea spicata	16206	14517	13072
Pultenaea parviflora	327	178	0
Allocasuarina defungens	19832	18461	11212
Angophora inopina	3193	2243	748
Zieria granulata	7403	6455	4329
Cynanchum elegans	154702	192367	204064
Acacia pubifolia	40375	38305	29026
Acacia ruppii	40309	46428	41763
Grevillea beadleana	40938	39958	32240
Tasmannia purpurascens	18471	20398	18002
Corchorus cunninghamii	28520	24766	14905

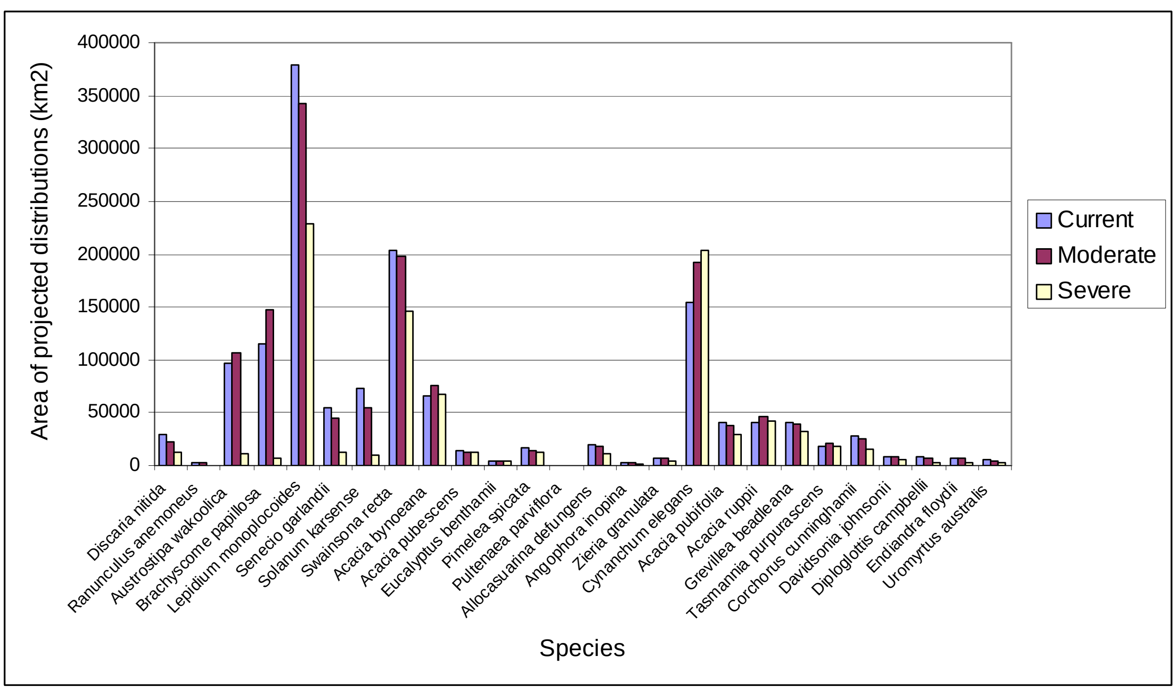


Figure A2. Total size of species projected distributions under each scenario, as modelled in GARP.