Prioritising naturalised plant species for threat assessment: Developing a decision tool for managers

Final Report

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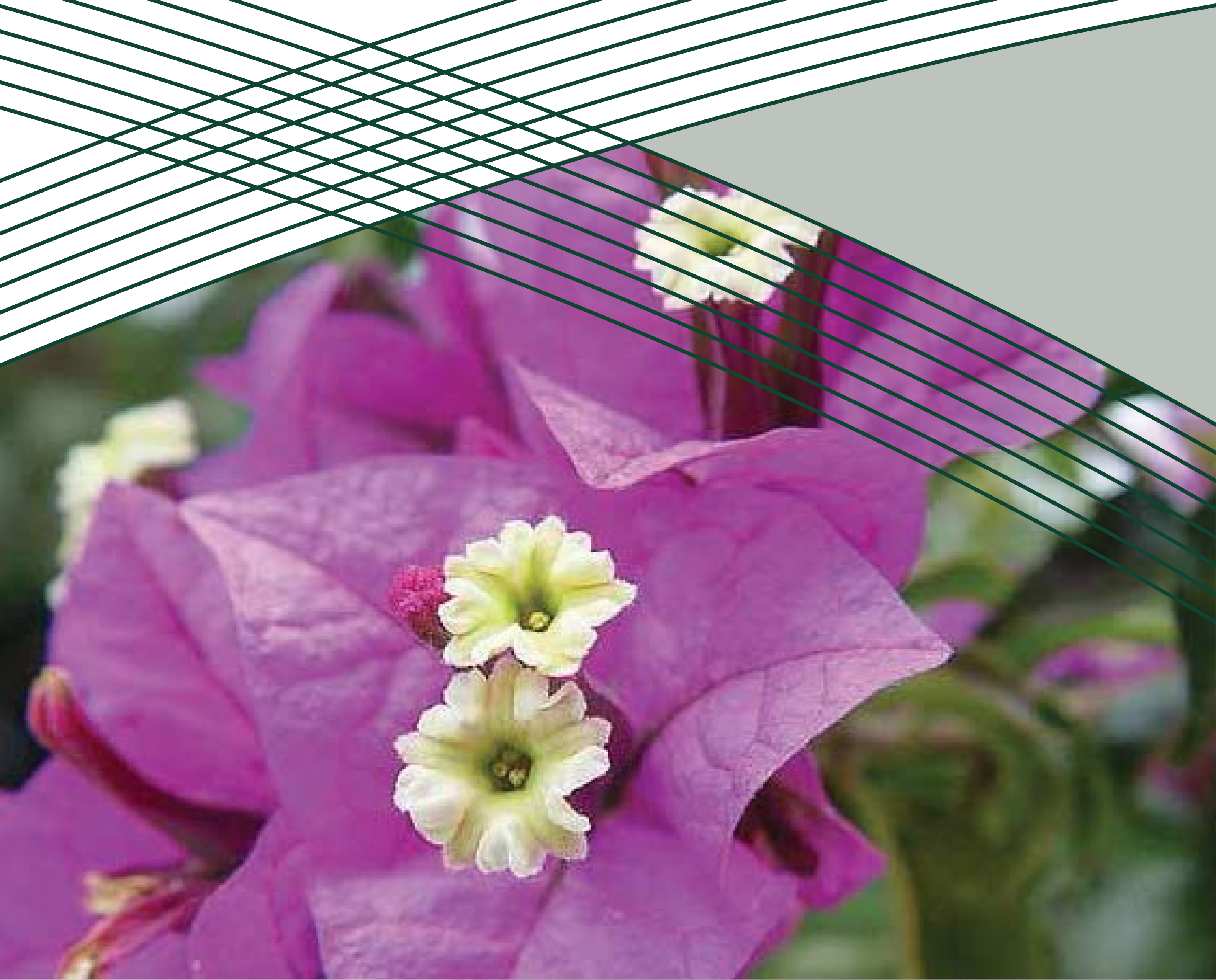

PRIORITISING NATURALISED PLANT SPECIES FOR THREAT ASSESSMENT: DEVELOPING A DECISION TOOL FOR MANAGERS

Macquarie University

Bougainvillea glabra

Solanum lycopersicum

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The role of NCCARF is to lead the research community in a national interdisciplinary effort to generate the information needed by decision makers in government, business and in vulnerable sectors and communities to manage the risk of climate change impacts.

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ABSTRACT

Naturalised, but not yet invasive, plants pose a latent threat to Australia's biodiversity. Approximately 10% of the almost 30,000 non-native plant species introduced to Australia have formed self-sustaining or naturalised populations in the landscape. Whilst some of these naturalised plants have become highly invasive where they pose significant threats to biodiversity, primary production and human health (e.g. the Weeds of National Significance), the majority have yet to become invasive and as such may be described as 'sleeper weeds'. As these species have yet to become invasive, their management is often piecemeal unless they have been assessed as having a high weed risk potential. Given the time and resources required to undertake each weed risk assessment, many of these plants have not been assessed at all.

The potential for changing climate regimes to create more favourable conditions for these plants, and thereby increase their invasive potential, is yet to be assessed. The central aim of this research was to assess the current extent of environmentally suitable habitat for a suite of naturalised, but not yet invasive non-native plants within Australia and to evaluate how projected changes in climate may alter these patterns in the coming decades. We used species distribution modelling – a recognised method for building spatial projections of suitable habitat based on correlations between known occurrences of species and environmental variables – as the basis for assessing the threat posed by 292 naturalised, but not yet invasive plants under current and future climates.

Individual species profiles were created by compiling key trait data, observation records and maps of current habitat suitability and projected change in suitability across Australia. These profiles will serve as the basis to evaluate how the habitat suitability for each species is likely to change in the future under different scenarios. As a second level of assessment, we also constructed vulnerability maps of both current and future time periods by overlaying binary maps for all 292 species. In doing so we identified 'hotspots' of climatically suitable habitat for large numbers of naturalised plants in the Australian landscape, and provided an assessment of the risks posed on a state-wide and national scale. Overall, the southerly coastal areas and Tasmania have the highest risk of invasibility, under both current and modelled future (2035) climates under high (RCP 8.5) emission scenarios based on species numbers.

Finally, we developed a point-based prioritisation scheme, based on: (1) gridded observations per 100,000 km^2 (2) habitat suitability of observations (3) area of habitat suitability (4*)* area of highly suitable habitat and (5) minimum distance between gridded observations and highly suitable habitat. Using this assessment process we classified 4% of Australia-wide species as having a high risk of invasion, 83% as having a medium risk, and 13% as having low risk, under current climate conditions. However, the percentage of high-risk species when assessed at a state and territory scale differed widely between states. Under a future scenario (RCP 8.5 2035) at a national scale we classified 3% of the species as having a high risk of invasibility, 81% as having a medium risk, and 16% as having low risk. It is envisaged that this prioritisation approach for determining weed management priorities for naturalised plants, will be the basis for a tool for allocating economic and human resources for on-the-ground actions now and in the future in light of climate change.

For identified high risk species, long-term management programs and allocation of resources will be required. This information provides vital baseline data for prioritising which naturalised plants to target for weed risk assessments, as well as active management/intervention (e.g. containment and/or eradication) now and in the future.

The outputs generated from this research will be freely available to end-users via a web-based portal. This portal is a decision-support tool that provides end-users with the ability to interrogate individual profiles for 292 species and interactively map emerging weed threats for regions or management units of interest. Additionally, there is species-level habitat suitability information categorised by: the Collaborative Australian Protected Area Database (CAPAD); Local Government Areas (LGA); wetlands of international significance (RAMSAR); Natural Resource Management regions (NRM) and Interim Biogeographic Regionalisation for Australia (IBRA 7) areas.

Our integration of modelling, spatial analysis and species trait information provides a comprehensive assessment of which naturalised plants to target as Australia's climate changes. Such assessments provide significant economic benefits by targeting control to high priority naturalised, but not yet invasive plants before they become significant problem weeds.

EXECUTIVE SUMMARY

Over the last decade, the potential for anthropogenic climate change to affect the distribution, physiology and management of established, invasive species has emerged as a major area for ecological research (Dukes & Mooney, 1999; Hellman et al., 2008). Given the significant economic burden and environmental consequences of invasive species (see Pimentel, 2002) the push to understand how changing climate regimes may alter the dynamics of invasions is unsurprising. However, in the rush to understand how well-established invaders may respond, few studies have focussed on the potential for changing climates to facilitate new invasions, or to enable presently non-invasive naturalised species to become invasive either more rapidly *in situ*, or invade new areas.

Even if protocols such as Australia's Weed Risk Assessment (WRA) system succeed in preventing the entry of new invaders, the next generation of invaders are *already present* as naturalised, but not yet invasive species. Little attention has so far been focused on this large pool of species and our understanding of invasion risk remains incomplete. Understanding how naturalised species may respond to climate change is thus an urgent goal for invasion ecologists and land managers and there is value in developing a prioritisation scheme that assesses current 'sleeper species' in order to gain a better understanding of how weeds will respond to future climatic change.

Naturalised species are non-native organisms that have formed self-sustaining populations that have not yet spread significantly through the landscape from their introduction foci (Richardson et al., 2000). Following their introduction, around 10% of non-native species progress to naturalisation and a similar proportion from this pool go on to become serious invaders (Williamson & Fitter, 1996), although recent data suggests that these percentages may be significantly higher e.g. >20% of naturalised plants in New Zealand are now recognised as major weeds (Williams & Timmins 2002). Progression through these three states (introduced, naturalised, and invasive) is conceptualised as a linear process where species pass through a series of abiotic and biotic barriers (including disturbance regimes), leading to invasion success or failure or in a worst case scenario, driving ecosystem change (Floyd et al., 2006). For example, the transition from introduced to naturalised may involve overcoming barriers to reproduction, (e.g. recruiting local pollinators) (Stokes et al. 2006; Milbau & Stout, 2008), climate (e.g. spreading into areas of suitable climate), and disturbance regimes (e.g. the enhancement or suppression of a previously natural fire regime).

Dubbed the 'invasion-continuum', this model of plant invasions has become a unifying tool for researchers over the last decade. In a recent review, Richardson & Pysek (2012) highlighted the fact that much research has focused on the final transition of the invasion continuum – when species have become widespread and have discernible impacts on native communities. However, as abiotic conditions continue to change under human influences it is increasingly likely that a new suite of plant invaders will emerge and that these species are likely to already reside in the pool of naturalised plants, given the sheer numbers of species involved (e.g. in Australia this pool represents about 3,000 plant species). Therefore, there is a clear need to better understand the potential for naturalised, but not yet invasive species, to emerge as new threats or transformer species.

In Australia, almost 30,000 non-native plant species have been introduced since European settlement and approximately 10% of these are recognised as naturalised (Randall, 2007). Whilst some of these naturalised plants pose significant threats to biodiversity, primary production and human health (e.g. the Weeds of National Significance), the majority have yet to become invasive. Some of these 'sleeper weeds', are almost certain to pose a latent threat to native biodiversity (Groves et al., 2005; Groves, 2006). In a global context, Australia has the highest number of naturalised plant species of any biogeographic region (Richardson & Pysek, 2012).

This pool of naturalised plants is taxonomically distinct from the Australian flora (e.g. 26% of naturalised plants come from plant families not native to Australia, based on comparative data from the Australian Plant Census; www.anbg.gov.au/chah/apc/about-APC.html) and their establishment has therefore led to the ongoing homogenisation of Australia's unique flora with other regions of the world. In addition, the number of newly naturalised plant species continues to grow annually. For example, Groves & Hosking (1998) found that over a 25-year period, 295 species, or approximately 12 new plants each year, were recorded as naturalised

We assessed the potential for climate change to affect the distribution of 292 naturalised, but not yet invasive alien plants in Australia. We developed both continent and state/territory-level spatial assessments to identify regions under both current and future climates where the risk of invasion is most concentrated. Overall, we found that the southern coastal regions and Tasmania are at the highest risk, with arid areas at least risk. In addition to the detailed species-based assessment, we also developed a preliminary, point-based prioritisation scheme that ranks species so that detailed weed risk assessments can focus on those species that pose the largest threat now and in the future.

We applied the prioritisation scheme under two levels of spatial assessment and found results differ significantly between states and territories and at a national level. A major output of this project has been the creation of a dedicated website (weedfutures.net) that includes a searchable database for use as a decision tool for land managers so they can more effectively and efficiently prioritise resources to cope with emerging weed threats.

1. OBJECTIVES OF THE RESEARCH

1.1 To determine the potential threat from naturalised but not yet invasive alien plants under climate change

Our objective was to provide a pre-emptive understanding of which naturalised plants may be subject to increasing or decreasing favourable biophysical conditions in Australia as the climate changes. We explored this question using a combination of species distribution modelling (SDM; Thuiller et al., 2005) and spatial analysis, focussing on a representative sample of approximately 10% of Australia's currently known naturalised plants (n = 292 species. For the process used to select these species see section 2.2 below). We assessed the invasion potential on both national and state-wide scales for each of the 292 species by combining species habitat suitability maps of current and future conditions, and calculating the distance between highly suitable habitat and known gridded observations.

We also determined continental and state-wide hotspots that are climatically suitable for a high proportion of naturalised species. Additionally we describe the amount of suitable habitat for each species at smaller scales deemed relevant to management, these include: the Collaborative Australian Protected Area Database (CAPAD); Local Government Areas (LGA); wetlands of international significance (RAMSAR); Natural Resource Management regions (NRM) and Interim Biogeographic Regionalisation for Australia (IBRA 7) areas. The results for these smaller-scale analyses can be found on our website.

1.2 To compile a database of naturalised species and their key traits

The invasion success of many introduced plants may be influenced by key plant traits and how these traits may be influenced by important ecological drivers. It is critical that the interaction between invasive potential (based on habitat suitability) and traits be examined. Compiling this information is often a lengthy process but the information is crucial to weed risk assessment. We constructed a database of naturalised species' attributes including information on lifecycles, seed morphology, dispersal mechanisms, native and exotic ranges, growth forms and where available, environmental tolerances and soil associations. Our database is the most comprehensive national collation for these 292 naturalised plant species (refer to Appendix 3). Based on feedback from weed management experts this information was not included in our prioritisation scheme (detailed in section 1.3) because this information is already included in weed risk management processes. The complete database for all 292 species is available on our website (weedfutures.net) and we anticipate this information will be incorporated into future weed risk assessments.

1.3 To develop a decision tool for managers that prioritises naturalised species that could become invasive under climate change for management programs (e.g. eradication and containment)

Given the number of naturalised plants and the high potential for many more new naturalisations to occur in the future (e.g. as outlined by Groves & Hosking 1998), the Australian Government has established both a Weed Risk Assessment (WRA) system to screen all new plant species imports and a Weed Risk Management (WRM) system to assess the risk of weeds already present in Australia (Downey & Glanznig 2006; Downey et al. 2010a). Both systems rely on a screening protocol to determine the risk relative to the action or management required. Whilst the number of weed risk assessments that have been completed is increasing, this number is still relatively small because considerable resources and time are required for each assessment. In a thorough review of weed risk assessments across the spectrum of weed management, Downey et al. (2010a) highlighted that neither the WRA nor the WRM systems have been developed to address the future weed threat associated with climate change. To address this gap and to assist in prioritising which weeds to assess through a WRA or WRM system, we have developed an approach that ranks species so that WRA and WRM can be carried out on those species that pose the largest threat now and in the future.

The major outcome from this project is an accessible, comprehensive, national overview of potential emerging weed threats in the form of a web-based decision support tool that will be promoted to State and Territory Government departments responsible for managing non-native plants (including managers of protected areas, Natural Resource Management areas and Local Government Areas). The decision support tool enables land managers to make better-informed decisions about the management of naturalised, but not yet invasive plants at a regional level. The website allows access to a comprehensive traits database as well as species-level habitat suitability maps for current and future climate conditions and a spatial vulnerability analysis for a number of jurisdictions.

2. RESEARCH ACTIVITIES AND METHODS

2.1 Study Species

Our study species (n=292) were selected from the approximately 3000 plants documented as naturalised in Australia by Randall (2007) (see Appendix 1 for full list of species). Randall (2007) provides the most comprehensive and authoritative compilation of introduced plant species in Australia, based on published literature to classify species into naturalised and invasive categories. We used four criteria to select a subset of these 3000 species to model. Each selected species must: (1) be primarily terrestrial, and not reliant on the presence of permanent water for growth and reproduction; (2) not be listed as a noxious weed in any State of Australia (www.weeds.org.au/noxious.htm) - such listings assume that the invasive potential of the species has been assessed and that management priorities are thus allocated; (3) not be an Australian native, and; (4) have more than 100 unique geo-referenced records globally available (latitude and longitude co-ordinates – typically derived from herbarium collections) (see 2.3 below) for calibrating species distribution models.

This rule-set yielded a shortlist of ~1300 naturalised plants. This list was further refined, based on the availability of data on traits, resulting in a final list of 292 species. The final species selection encompassed a range of functional plant types (e.g. vines, trees, shrubs, grasses, herbs), and/or species that already had trait data complied, and/or species that pose a threat to human health because they are allergenic or poisonous. We recently become aware that *Cynara cardunculus*, is listed in Noxious in Victoria, however, it is still included in the analyses.

2.2 Species records

Species records were downloaded from Australia's Virtual Herbarium (AVH; http://avh.ala.org.au/search) and the Global Biodiversity Information Facility (GBIF; http://data.gbif.org/occurrences/) in June 2012. A series of data cleaning procedures were then used to refine the ~3.5 million records: (1) records with no associated latitude or longitude coordinates were discarded; (2) amongst the remaining non-Australian records we removed those most likely to have been collected from cultivation by systematically searching the locality description for the words 'garden', 'nursery', 'greenhouse', 'ornamental', 'experimental' and 'cultivated' in English, French, Dutch, Spanish, Portuguese, and Italian; (3) for Australian records with no associated latitude and longitude coordinates but having a locality description, we used the Geoscience Australia Gazetteer of Australian Place Names Search (www.ga.gov.au/place-names/) and Google Earth (www.google.com/earth/index.html) to assign approximate coordinates.

In addition (for Australian observations), we manually processed the records containing the words 'garden', 'nursery', 'greenhouse', 'ornamental', 'experimental' and 'cultivated' to limit false removals (e.g. a weed growing next to garden, versus purposely planted as an ornamental in a private garden). This step increased the number of Australian records; (4) the final dataset was then mapped using Rx64 2.15.2 (R Core Team, 2012) and the package Raster 2.0-21 (Hijmans & Van Etten, 2012) and clipped to a mask of global land surface boundaries (land mask created from gridded climate and soil layers used in modelling); (5) we removed duplicate records so there was only one record for each species per 8 km x 8 km equal area grid cell across Australia, thereby defining a record as presence within a specific grid cell and hereafter referred to as gridded observations, and; (6) for 139 species that had more than 200 records, we further reduced the number of records in densely sampled regions of Europe and the USA so that one record for each species was permitted to occur in each 24 km x 24 km equal area grid cell. This step reduced sampling bias in the areas where species have been extensively and systematically collected and recorded in GBIF. By applying this procedure, we removed approximately 75% of the records from the densely sampled regions, resulting in an effective 'up-weighting' of records from outside these locations. After implementing this suite of data cleaning procedures, the total number of records across the 292 species examined was 353,698 and ranged between 36 records for *Hemizonia pungens*, and 8065 records for *Poa pratensis* (average of 1211 records per species).

2.3 Climate and soil data

A combination of five bioclimatic variables and one soil characteristic was used to build models of suitable abiotic habitat for each naturalised plant under baseline climate conditions: mean annual temperature (MAT; °C), maximum temperature in the warmest month (MTWM; °C), minimum temperature in the coldest month (MTCM; °C), annual precipitation (AP; mm), precipitation seasonality (co-efficient of variation of AP) and topsoil clay fraction (TCF; % weight). We used Aikaike's Information Criterion (AIC), Bayesian Information Criterion (BIC), and expert opinion to choose the most parsimonious set of environmental variables from the broader set of bioclimatic variables and soil characteristics for model calibration (Burnham & Anderson, 2002). The climate variables chosen encompass both mean and extreme temperature and precipitation conditions across species ranges and were derived from raw data (maximum temperature, minimum temperature, precipitation) provided on the Worldclim website (www.worldclim.org) for the period 1950-2000, at a 5 arc minute resolution. We refer to the baseline climate as current conditions.

Gridded data on TCF were derived from the Harmonized World Soil Database (HWSD; version 1.2; available at http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/). We assumed that this soil factor will remain largely unchanged under future climate scenarios. Particle size determines soil texture and character. Soils with a high proportion of clay particles can hold a large volume of water and retain water and minerals strongly. The cations adsorbed on clay particles are partially available for plant uptake (Gurevitch et al. 2006). Thus TCF provides a reasonable approximation of soil and nutrient availability to plants, particularly within the Australian context of highly-leached nutrient poor soils. Topsoil clay fraction offers a reasonable approximation of soil fertility/nutrient availability and water holding capacity – two factors which are critical for plant growth.

We sourced coarse resolution (0.5 x 0.5 degree or ~50 km x 50 km) climate projections from http://climascope.wwfus.org. Here, we specifically accessed 7 global climate models (GCMs), MRI-CGCM232A, UKMO-HADGEM1, MPI-ECHAM5, GFDL-CM20, UKMO-HADCM3, CSIRO-MK30, CCSR-MIROC32MED, for decades centred on 2035 and 2065 and two Representative Concentration Pathways (RCPs) 4.5 and 8.5, which are low and high emission scenarios, respectively. Fordham (2011) showed the 7 GCMs used are more effective, when used in combination, to simulate seasonal precipitation in Australia than the remaining 11 GCMs used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007). Using scenarios from multiple GCMs helps to represent the uncertainties inherent in predicting future climate scenarios (Beaumont et al., 2008).

RCPs are a relatively new, standardised method for capturing potential warming trajectories which are based on amounts of atmospheric radiative forcing expected by the year 2100, measured in W/m^2 (Moss et al., 2010; Van Vuren et al. 2011). RCP8.5 represents a rising radiative forcing trajectory (i.e. greenhouse gas emissions rising to an equivalent of ~1370 ppm CO_2 equivalent by 2100), whilst RCP4.5 is a more conservative pathway, estimating a stabilisation of radiative forcing by 2100 (~650 ppm CO_2 equivalent after stabilisation at 2100). RCPs have been adopted by the IPCC to replace the Special Report on Emissions Scenarios (SRES) used in the AR4 report (Solomon et al. 2007); RCPs are to be used in the AR5 IPCC report due to be published in 2013. Although new GCM runs for RCPs have not been fully completed, several research groups have implemented methods to utilise knowledge gained from SRES predictions to recreate predictions for the new RCPs using AR4 GCMs (e.g., Meinshausen et al. 2011a, Meinshausen et al. 2011b, Rogelj et al. 2012). The methods used to generate the GCM predictions for the RCP emission scenarios are defined at http://climascope.wwfus.org and in associated publications (e.g., Mitchell and Jones 2005, Warren et al. 2008, Meinshausen et al. 2011a).

Although analyses were conducted on both future time periods (2035 and 2065) for both RCP emissions scenarios (4.5 and 8.5), for the purposes of this report we refer to the future climate as that modelled for 2035 under the climate scenario generated by RCP8.5 (high emissions pathway). We provide all results for each time period x RCP combination on our website.

The monthly RCP data were downscaled to 5 arc minutes using a cubic spline of the anomalies (deviance from modelled current and modelled future); these anomalies were applied to a current climate baseline of 1950 to 2000. The current 5 arc minutes climate used was from Worldclim (www.worldclim.org) and the data were created as defined in Hijmans et al. (2005). The downscaled values were used to create the five bioclimatic variables used for modelling. All downscaling and bioclimatic variable generation was performed using the climate package (VanDerWal et al. 2011) in R.

2.4 Model calibration

The algorithm MaxEnt (version 3.3.3k; Phillips & Dudik, 2008) driven by the dismo 0.7-23 package in R x64 v. 2.15.2 was used to build models of habitat suitability for the 292 naturalised plants in this study. MaxEnt has been used extensively to model species ranges using presence-only data and has consistently emerged as a well-performing approach for this task in comparative studies employing a range of different modelling algorithms (Elith et al., 2006; Graham & Hijmans, 2006).

The calibration of models for naturalised species poses a distinct set of challenges (see Elith et al., 2010 for a thorough exploration of this topic). However, by deliberately and carefully controlling how MaxEnt models are fit under situations where species may not be at equilibrium with climate (e.g. naturalised species which are yet to spread to all suitable regions within a novel range), the reliability of range predictions can be substantially increased (Elith et al., 2010). We have addressed the issue of non-equilibrium when modelling the naturalised plants in this study in three ways. Firstly, models were calibrated using data from both the native range (where species are likely to be at equilibrium with environmental conditions) and from the entire naturalised range, both in Australia and other regions of the world. This step has been shown to improve accurate capture of the fundamental niche of species (Beaumont et al., 2009).

Secondly, we confirmed that the current Australian climate conditions under which each species occurs fell within the two-dimensional climate niche space defined by Annual Mean Temperature (AMT) and Annual Precipitation (AP) from all records outside Australia. That is, we assessed whether the global niche of the species would adequately capture the conditions under which Australian populations occur prior to modelling and found no evidence of climate niche shifts, where species could be shown to be occupying novel environments within Australia (Gallagher et al., 2010). Finally, we reduced the complexity of model fitting procedures in MaxEnt (i.e. only linear, quadratic and product features were calculated) leading to smoother response curves where outlying records had less influence on the modelled distribution. Note that we also tested increasing the beta-multiplier from 1 to 2.5 (*sensu* Elith et al., 2010), but found this step had no significant effect on model predictions across all species. We tested model performance under all combinations of calibration using AIC, BIC (see above) and expert opinion.

Background points used to calibrate models were restricted to areas within the same Köppen-Geiger climate classification, as known occurrences for each species (Webber et al., 2011; Gallagher et al., 2012). Multiple techniques for limiting background point selection have recently been assessed (VanDerWal et al., 2009; Elith et al., 2010) and our method was chosen for its robust performance across all species in a preliminary comparative exercise in which four alternative methods were tested (i.e. random across the globe, random across Köppen-Geiger (preferred method), 800 km distance buffers, known species records from GBIF and AVH within Köppen-Geiger zones).

A gridded Köppen-Geiger climate classification was downloaded from www.koeppen-geiger.vu-wien.ac.at for the period 1951-2000 at a resolution of 0.5°. We re-sampled the resolution to 5 arc minutes so the cell size matched that of our environmental variables; irrespective the accuracy of the data remained at 0.5°. Background points were extracted using the function random Points in R package dismo (Hijmans et al., 2013). For each species, any grid cell could have only one background point, and background points could not occur in the same cells as presence points. We tested a variety of different numbers of background points including 10000, 40000, and maintaining an equal density of points based on the area of Köppen-Geiger zones i.e.

# of points = (area of Köppen-Geiger zones/(average area for all species/2))*10000

The majority of the species performed best using 10000 background points, although for some species the number of background points did not have a substantial impact on the model. When fitting models we used 10-cross validated partitions of the available data to limit spatial bias in the data used to train and test the model and assigned a random seed for each model run. All other MaxEnt settings were set to the default options identified by Phillips et al., (2006).

2.5 Assessing model accuracy and thresholding predictions

We used two statistics to assess model accuracy: (1) the area under the receiver operating curve (or area under the curve (AUC); Fielding & Bell, 2002), and; (2) the binomial test of omission. The AUC is a threshold-independent measure that assesses the rate of correct classification of presence points by the modelled function (Phillips et al., 2006). In circumstances where background points or pseudo-absences are used to replace known absences for a species the AUC can approach, but not reach a value of 1. An AUC greater than 0.75 is considered to provide a useful level of discrimination (Elith et al., 2006). AUC scores have a number of known limitations for assessing model accuracy, such as equally weighting rates of false-presence and false-absences classification and being sensitive to the spatial extent of background data selected (Lobo et al., 2007; VanDerWal et al., 2009). Therefore, we employed a second statistic (the binomial test of omission) to validate model accuracy. This test is based on thresholded model output and calculates the fraction of known presences that were predicted absent and assesses whether the omission rate is lower than that of a random prediction. We omitted 10% of species training records while minimizing the thresholded area of logistic output for each species. Gridded maps of the 7 GCM projections were averaged to produce an average consensus forecast of suitable habitat for each time-step (2035 and 2065) and two thresholds were applied (10%

omission rate and the 0.5 logistic threshold) to depict areas of suitable habitat and highly suitable habitat. Building consensus across multiple GCMs in this way integrates the idiosyncrasies inherent to the different methods for producing future climate projections.

2.6 Species threat assessment

In order to derive species threat assessments we consulted with weed management experts to develop five attributes with which to assess threat level on both national and state-wide scales. They are: (1) gridded observations per 100,000km^2 or the number of 8 km x 8km grid cells with recorded species presence standardised to observations per unit area; (2) habitat suitability of observations or the average logistic model output where the known gridded observations occur under the current and future scenario(s); (3) area of habitat suitability, the region where logistic model output is above or equal to the threshold for a 10% omission rate under the current and future scenario(s); (4) area of highly suitable habitat, the region where logistic model output is greater than 0.5 under the current and future scenario(s); and (5) minimum distance, the smallest distance between the area of highly suitable habitat and the gridded observations under the current and future scenario(s). All above calculations where preformed using R statistical software x64 2.15.3 and the packages raster 2.0-41 and sp 1.0-5 (Hijmans & Van Etten 2012; Pebesma & Bivand 2005).

These five attributes were used in the prioritisation scheme to rank invasion risk of species (see section 2.8).To derive a state level summary of species level assessment, we disaggregated the Maxent models using the state boundaries as defined in the Natural Resource Management (NRM) Regions 2010 (www.environment.gov.au (accessed 1/10/2012)). These boundaries are comparable to the Australian Standard Geographical Classification (ASGC) Digital Boundaries 2011 (www.abs.gov.au/geography). However, the NRM state boundaries do not include internal water bodies, and the coastal edges of Australia are buffered. Due to differences in accuracy of species records, state boundaries and the scale of climate, the lower level of detail in the NRM defined state boundaries was more comparable to our data. For the purpose of this preliminary threat assessment we compared the extent of currently suitable habitat to that modelled for 2035 under the climate scenario generated by RCP8.5 (high emissions pathway). We also provide results for RCP4.5 in 2035, RCP4.5 in 2065, and RCP8.5 in 2065 on the website but elected to use the 2035 high emissions scenario in this assessment because it is likely to be the most relevant for management decisions in the next two decades.

2.7 Assessing vulnerability at national, state-level and regional scales under both current and future climates

To assess the vulnerability at a national scale, state level and at finer scales relevant to management (LGAs, IBRA 7 regions NRM areas, the reserve system (CAPAD) and wetlands of national importance (RAMSAR)), regional shapefiles were downloaded in October 2012 from www.abs.gov.au/AUSSTATS (LGA), www.environment.gov.au (IBRA 7, RAMSAR, CAPAD and NRM regions). The Raster package's extract function was used to extract the percentage of suitable habitat and the number of gridded observations for each species for current and future scenarios. Based on feedback from end-users and their needs, the results from the small scale regional vulnerability analysis (LGAs, IBRA 7 regions, NRM areas, CAPAD reserves and RAMSAR wetlands) is not included in this report but it is available from our website.

To further assess vulnerability at a national and state-wide scale we looked at potential hotspots of future weed invasions. We utilised the binary maps depicting areas of suitable and unsuitable habitat (10% omission) for all species (section 2.5) under both current and future conditions (RCP 8.5 2035). For each state and territory, and for Australia as a whole, we overlaid species that had suitable habitat within the specified region. Potential hotspots of invasion were then mapped based on the premise that areas that are suitable for many species are invasion hotspots.

2.8 Developing a prioritisation scheme

Given the complexity of the current assessment systems (WRA and WRM) and the time needed to gather and collate information across a wide range of criteria to carry out these assessments, we developed a simplified prioritisation scheme that ranks species so that WRA and WRM can be conducted on those species that pose the greatest threat now and in the future. We applied this prioritisation scheme to the 292 species to assess the *likelihood* that the species may have an increase in invasion risk in the future (i.e. with climate change). This prioritisation scheme can be used to assist in prioritising which weeds to assess through a WRA or WRM approach, at any specified level (e.g. national, state, NRM).

We applied a points-based scoring system using the five critical attributes (described above in section 2.6) to assign each species to one of five categories of increased invasion risk.

Attribute	**Description**
1.	Gridded observations per 100,000km^2
2.	Habitat suitability of observations
3.	Area of suitable habitat
4.	Area of highly suitable habitat
5.	Minimum distance between known occurrence and area of suitable habitat

Points-based scoring system

Each attribute had an equal weighting of 10 points, while each species was assigned a score of 2, 4, 6, 8 or 10 points for each of the five attributes using set criteria for each point value relative to each attribute (see below). All species were assigned scores based on the spread of the data (histograms) at both state and national scales (refer to Appendix 4 for histograms on which we based our point scoring system). The points were then summed for each species to give a total score out of 50. Species were placed into risk categories of low, medium and high based on the following scale:

Likelihood scale (points)	**Risk description**
≤24 points	Low risk of invasion
25-39 points	Medium risk of invasion
≥ 40points	High risk of invasion

While designation of any point score is arbitrary in absolute terms, it is the relative score that is of importance. Further, by designating a set of clear, transparent rules to assign points, such an assessment can be updated rapidly, given new information, or alternative expert opinion. As such, this preliminary assessment provides a framework for improved ongoing evaluation as more information becomes available (see Gaps & Future Research Directions section below).

1. Gridded observations per 100,000 km^2 (log_{10})

A spatial assessment of the threat across the species distribution is essential for quantifying impacts. This attribute standardises the number of 8 km x 8 km grid cells with recorded species presence per area. This is a static variable and is used in the prioritisation scheme for future scenarios although we do not expect observations of species to remain in stasis in the future.

Points	Criteria	Risk
2	< -1	low
4	-1 ≤ x < -0.5	low to medium
6	≤ -0.5 ≤ x < 0.75	medium
8	0.75 ≤ x < 1.8	medium to high
10	≥ 1.8	high

2. Habitat suitability of observations for each time period

This attribute was based on the average logistic model output where the known gridded observations occur.

Points	Criteria	Risk
2	no observation	low
4	0 < x < 0.2	low to medium
6	0.2 ≤ x < 0.62	medium
8	0.62 ≤ x < 0.72	medium to high
10	0.72 ≤ x < 1	high

3. Area of suitable habitat for each time period

This attribute provides a measure of the potential spread of naturalised species and is calculated as the *percentage of a region that is determined to be suitable using the 10% omission rate (log_{10})*.

Points	Criteria	Risk
2	<0.8	low
4	0.8 ≤ x < 1.4	low to medium
6	1.4 ≤ x < 1.7	medium
8	1.7 ≤ x < 1.9	medium to high
10	≥ 1.9	high

4. Area of highly suitable habitat for each time period

The greater the suitability the more likely a naturalised weed species would disperse into a given area under the right conditions. This is calculated as the percentage of a region that is determined to be highly suitable using the 0.5 logistic threshold (log_{10}).

Points	Criteria	Risk
2	< -0.4	low
4	-0.4 ≤ x < 0.7	low to medium
6	0.7 ≤ x < 1.4	medium
8	1.4 ≤ x < 1.8	medium to high
10	≥ 1.8	high

5. Minimum distance

This attribute provides information as to the likelihood that a species could disperse across the landscape if suitable conditions existed. It is the minimum distance between the area of highly suitable habitat and closest observations ($\log_{10}$)

Points	Criteria	Risk
10	< 1	high
8	1 ≤ x < 1.7	high to medium
6	1.7 ≤ x < 2.5	medium
4	2.5 ≤ x <3.4	medium to low
2	≥ 3.4	low

The score for each species, for all states and territories and nationally, for both current and future conditions (RCP8.5 2035) is shown in Appendix 5a and 5b.

2.9 Trait data

Twenty five plant databases (Table 1) were searched to collate information on plant traits (Table 2). To ensure accuracy, family, genus and species names were checked with the Australian Plant Census (APC) website. There were 32 species for which the taxon in APC had not yet been treated or for which there were no matching taxon names. For these species, the genus and species names used have been accepted by either the Plant List website or the USDA Germplasm Resources Information Network (GRIN). Family names were sourced from the Angiosperm Phylogeny Website (APGIII). The above procedures resulted in numerous family and species name changes from the original Randall (2007) list.

Table 1: The twenty-five plant databases and e floras searched to collect information on plant

Database	URL
Australian Plant Census (APC)	http://www.anbg.gov.au/chah/apc/
Angiosperm Phylogeny Website (APGIII) Version 12	http://www.mobot.org/mobot/research/apweb/
The Plant List	www.theplantlist.org/
KEW: Seed Information Database	http://data.kew.org/sid/sidsearch.html
Plant Threats to Pacific Ecosystems	http://www.hear.org/pier/scientificnames/byfamily.htm
FLORABASE	http://florabase.dec.wa.gov.au/browse/profile/179
Germplasm Resources Information Network	www.ars-grin.gov/cgi-bin/npgs/html/tax_search.pl?Agrostis%20gigantea
THE WEEDS NETWORK	http://invasivespecies.org.au/traction?type=single&proj=wra&rec=718&brief=n&rsin=/link%20wra718%20%27Weed%20Risk%20Assessments%20
Hawaiian ecosystems at risk	http://www.hear.org/
Ecocrop	http://ecocrop.fao.org/ecocrop/srv/en/cropView?id=3046
Global Invasive Species Database	www.issg.org/database/species/ecology.asp?si=1365&fr=1&sts=&lang=EN
Grasslands index	www.fao.org/WAICENT/FAOINFO/AGRICULT/AGP/AGPC/doc/GBASE/latinsearch.htm
Protabase	http://database.prota.org/
Frlht Environmental Information System	http://envis.frlht.org/
eFloras	http://www.efloras.org
Flora Europaea	http://rbg-web2.rbge.org.uk/FE/fe.html
Royal Botanic Garden Edinburgh	http://rbg-web2.rbge.org.uk/FE/fe.html
Plants Database: United States Department of Agriculture Natural Resources Conservation Service	http://plants.usda.gov/java/
Brisbane Rainforest Action & Information Network	www.brisrain.webcentral.com.au/01_cms/details.asp?ID=308
Flora of Malesiana	http://floramalesiana.org/html/fmonline.html
Flora of Mozambique	www.mozambiqueflora.com/
Flora of NSW	http://plantnet.rbgsyd.nsw.gov.au/search/simple.htm
Flora of the Nilgiris	http://opendata.keystone-foundation.org
Flora Zambesiaca	http://apps.kew.org/efloras/fz/intro.html
Australian National Herbarium Specimen Information Register	www.anbg.gov.au/cpbr/program/hc/hc-ANHSIR.html

Table 2: Summary of the trait database showing all categories of collated information and the number of species with corresponding information for each trait out of a possible total of 292

Trait	**Number of species for which data were available**
Species	292
Synonyms	265
Family	292
Accepted name in *the Plant List*	287
Common names	286
Longevity	292
Growth form	292
Dispersal mode	166
Dispersal morphology	110
Leaf longevity	49
Maximum height (m)	238
Fruit type	200
Reproductive age	31
Capable of vegetative reproduction	52
Reproduction comments	102
Flowering time	213
Native range	266
Native range details	245
Exotic range	292
Exotic range details	292
Habitat type invasive	211
Soil types invasive	140
Seed weight (g)	226
Temperature optimum for growth	24
Temperature minimum for growth	8
Number of known infestations in Australia	292
Cultivated	279
Time since first herbarium record	279

3. RESULTS AND OUTPUTS

3.1 Species Profiles

Each species profile contains key trait data (section 2.9), a map showing species records (section 2.2), maps of current habitat suitability (section 2.5), and projected change in suitability (difference between current conditions and future conditions) in Australia for current and future conditions (2035 & 2065, RCP 4.5 and RCP 8.5) (see Appendix 2 for full set of species profiles). These maps do not show species occurrence or likelihood of occurrence, but rather habitat suitability based on the average climate and soil conditions across 5 arc minute grid cells.

For the current distribution maps, the grey and yellow areas are locations with no or low suitability. Suitability increases as the intensity of colour changes from yellow to red and then black. The maps of future change in suitability show areas with decreasing suitability in yellow and increasing in red. The areas in grey are areas where suitability does not change.

3.2 Regional level species threat assessment

Of the 292 species *Bromus rubens* had the largest number of gridded observations within Australia (2019) and was present in all states and territories with the exception of Tasmania (TAS), Queensland (QLD), and the Northern Territory (NT). *Solanum americanum* and *Briza minor* were the next most detected species, with 1907 and 1233 gridded observations, and were present in all states and territories. At the state and territory scale, the species with the most gridded observations were: Australian Capital Territory (ACT), *Holcus lanatus*; New South Wales (NSW),*Solanum americanum*; NT, *Solanum orbiculatum*; QLD, *Chloris virgate*; South Australia (SA), *Bromus rubens*; TAS, *Isolepis marginate*; Victoria (VIC), *Bromus rubens*; Western Australia (WA), *Isolepis marginate*.

At the state and territory scale, NSW had the most species with gridded observations (205), with 71% of these within highly suitable habitat under current conditions (Table 3) and 64% under future climate (Table 4). An additional 12% of those observations occurred within 25 km of highly suitable habitat under current conditions and 14% predicted under future climate. NT had the least species with gridded observations (83) (across all states and territories) and only 40% of these species had gridded occurrences within highly suitable areas under both current and future climates.

Prunus domestica

Family: Rosaceae

Growth form: Tree

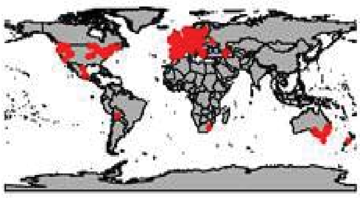
Native range: Europe, Mediterranean

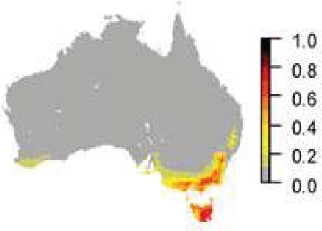
Exotic range within Australia: NSW, SA, TAS, VIC

Dispersal mode: Abiotic - garden waste, refuse

Gridded observations in Australia (excluding cultivated): 66

Observations | **Current habitat suitability**





Future change in suitability

yellow is decreasing, grey is stable, and red is increasing

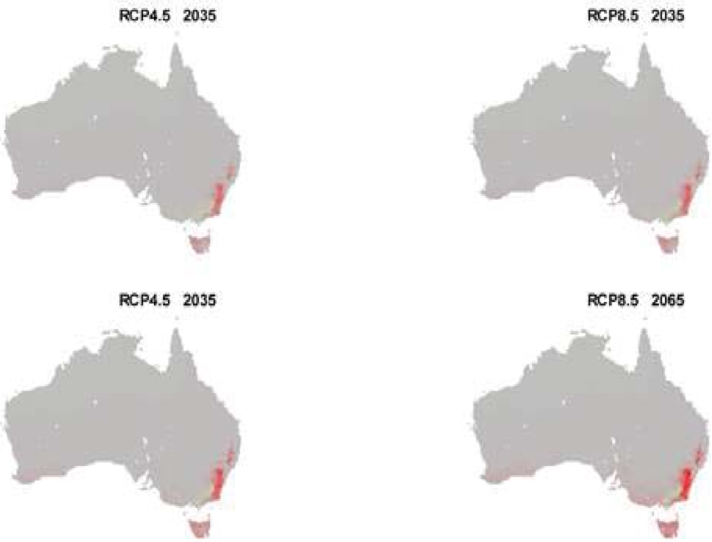


Figure 1: An example of the layout of each species profile is shown above. Refer Appendix 2 for a complete set of profiles

Table 3: Species occurrences and highly suitable habitat under current conditions

	ACT	NSW	NT	QLD	SA	TAS	VIC	WA
Species with gridded observations	99	205	83	152	151	143	184	158
Average habitat suitability of observations	0.55	0.52	0.52	0.51	0.62	0.69	0.63	0.53
Species within highly suitable areas	48	145	34	93	90	119	136	79
Species within 25 km of highly suitable areas	74	169	36	102	92	127	161	92
Species within 100 km of highly suitable areas	91	197	39	112	105	133	183	99

Table 4: Species occurrences and highly suitable habitat under future climate (RCP8.5 2035)

	ACT	NSW	NT	QLD	SA	TAS	VIC	WA
Species with gridded observations	99	205	83	152	151	143	184	158
Average habitat suitability of observations	0.5	0.48	0.52	0.49	0.62	0.67	0.63	0.52
Species within highly suitable areas	39	134	34	91	89	119	134	77
Species within 25km of highly suitable areas	70	162	36	98	92	126	159	90
Species within 100 km of highly suitable areas	88	190	39	109	104	132	181	96

3.3 Assessment of vulnerability at national, state-level and regional scales under both current and future climates

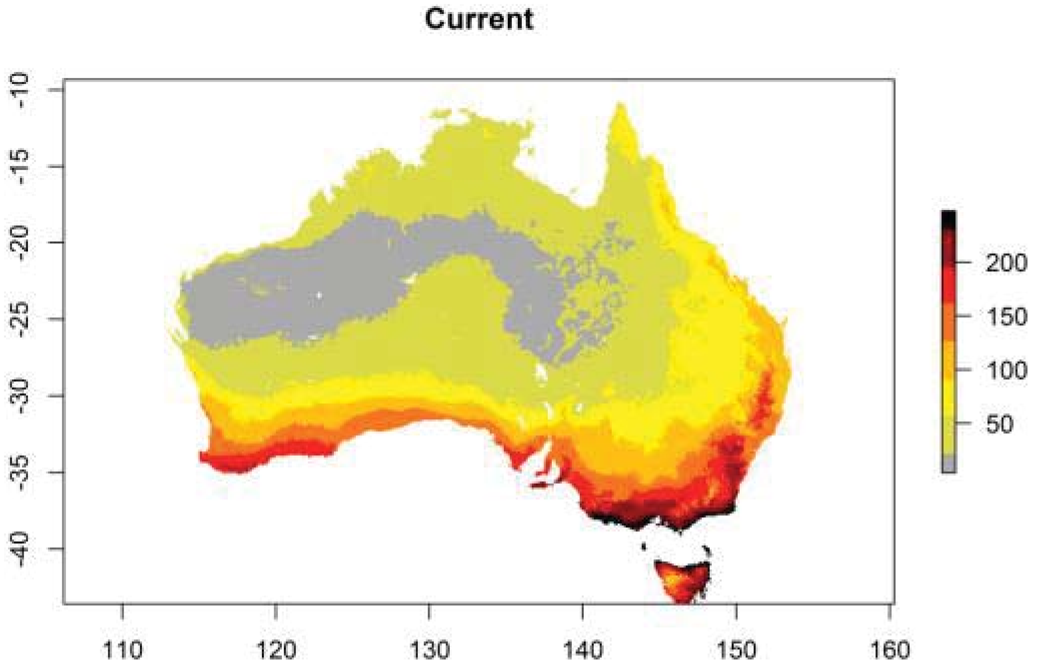
We constructed vulnerability maps of both current and future time periods by overlaying binary maps (10% omission threshold) for all 292 species. Under the current climate and RCP 8.5, 2035 at a national scale, the areas of Australia that are the most suitable for multiple species are coastal VIC, the eastern part of SA, and TAS (Figure 2). The southern coastal region of NSW as well as the Great Eastern Ranges and the southern tip of Australia are also vulnerable hotspots for invasion (Figure 2). Under current conditions there was a maximum of 248 species with suitable habitat in a single grid cell (out of a possible maximum of 292). The continent-wide mean was 61.7 species with suitable habitat per grid cell. The southeast of the country displayed the highest overall vulnerability. However, under future conditions the vulnerability is set to decrease overall. The maximum number of species with suitable habitat under future conditions stayed the same but the mean decreased to 58.9.

Under current conditions, the state level analysis focused on only those species that had suitable habitat within each state or territory. The maximum number of species with suitable habitat in a single grid cell varied from 60 in the NT to 248 in TAS (VIC: 247, NSW: 237, SA: 225, WA: 200, ACT: 194, QLD:126). For most states and territories, under RCP 8.5 2035 the maximum number of species with suitable habitat remains the same or decreases (by one or two) with the exception of the ACT where it decreases from 194 to 185. NT had the lowest mean suitability for current (28) and future conditions (29) and TAS had the highest (198 and 196, respectively).

For the ACT (Figure 3) under the current climate, the level of vulnerability is highest in the north eastern section of the territory. Vulnerability is set to decrease under RCP 8.5 2035, however, the area of most concern remains the north east. Under the current climate, NSW shows the same patterns of vulnerability as those displayed at the continental scale (Figure 4). Under the future climate, vulnerability is also set to decrease, with the areas of most concern centred on the Great Eastern Ranges. NT shows the largest variation from the pattern of vulnerability seen in the continental analysis (Figure 5). The coastal region of the state displays the highest level of vulnerability and the south-easterly sections are the areas with moderate vulnerability. Under RCP 8.5 2035, the southern areas of the territory are the most vulnerable.

At the continental level, QLD had low levels of vulnerability (Figure 6) but the state level analysis shows that the areas within the state with high vulnerability are along the eastern coast and the south west of the state. Under the future climate the area of vulnerability moves westward. Under the current climate, SA, TAS, and WA exhibit the same pattern as those seen in the continental scale analysis (Figures 7, 8, 9). Although the northern regions of TAS are clearly shown in the vulnerability maps, with a minimum of 67 species having suitable habitat in this region, there are slight shifts in vulnerable areas under future climate conditions and the minimum number of species decreased to 63 under RCP 8.5 2035. The southern extent of the state of VIC is vulnerable under current climate conditions; this pattern is somewhat dispersed under future climate conditions.

Refer to www.weedfutures.net for information on suitable habitat and number of gridded observations for each species within LGA, NRM, IBRA 7, CAPAD and RAMSAR regions. Due to the small size and linear shapes of many RAMSAR wetlands and some CAPAD areas we were not able to provide this information for all sites.



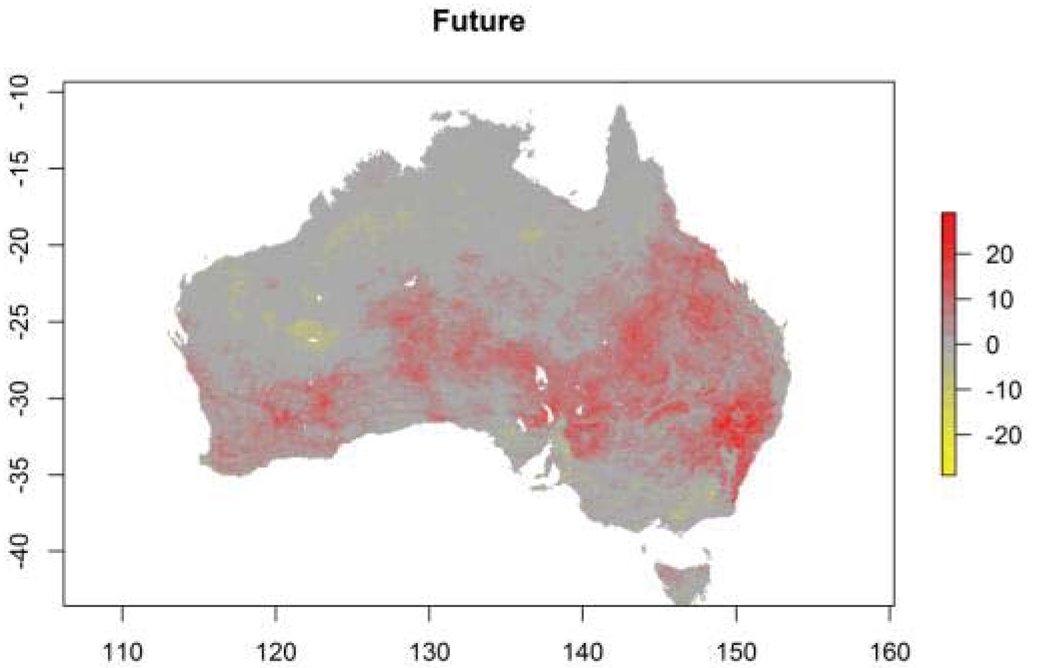


Figure 2: Current vulnerability at a national level, calculated by overlaying binary maps (19% omission threshold) for all 292 species and the future change in the number of species with suitable habitat at the national level from current conditions to RCP 8.5 2035

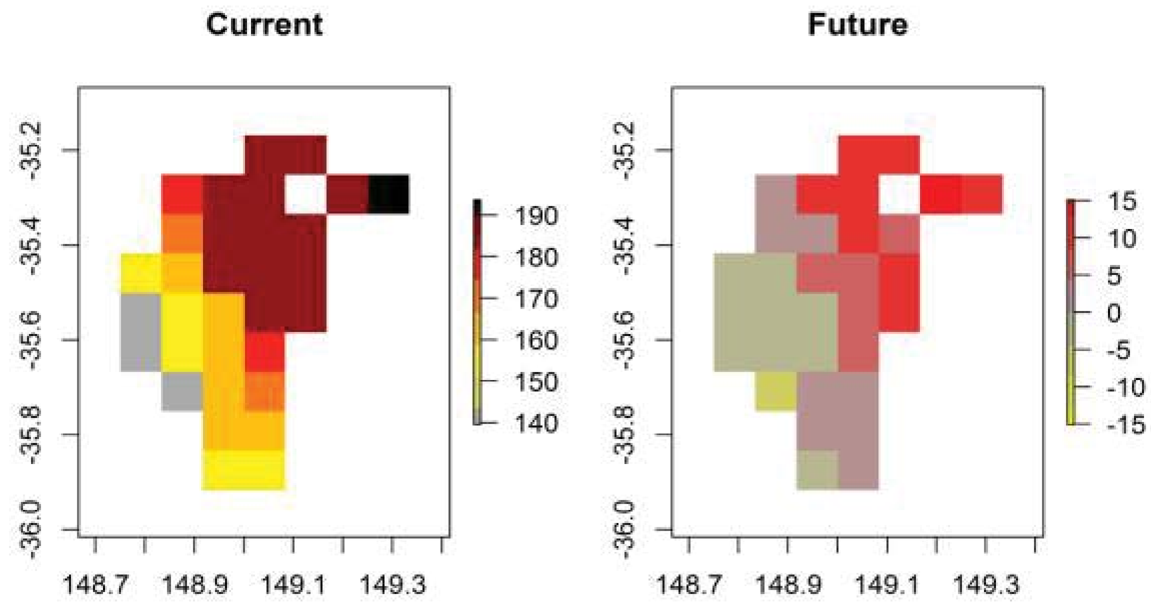


Figure 3: Current map indicates the number of species with suitable habitat and the future map (RCP 8.5 2035) shows the change in number of species, where red represents an increase in species numbers with suitabel habitat and yellow a decrease of the ACT

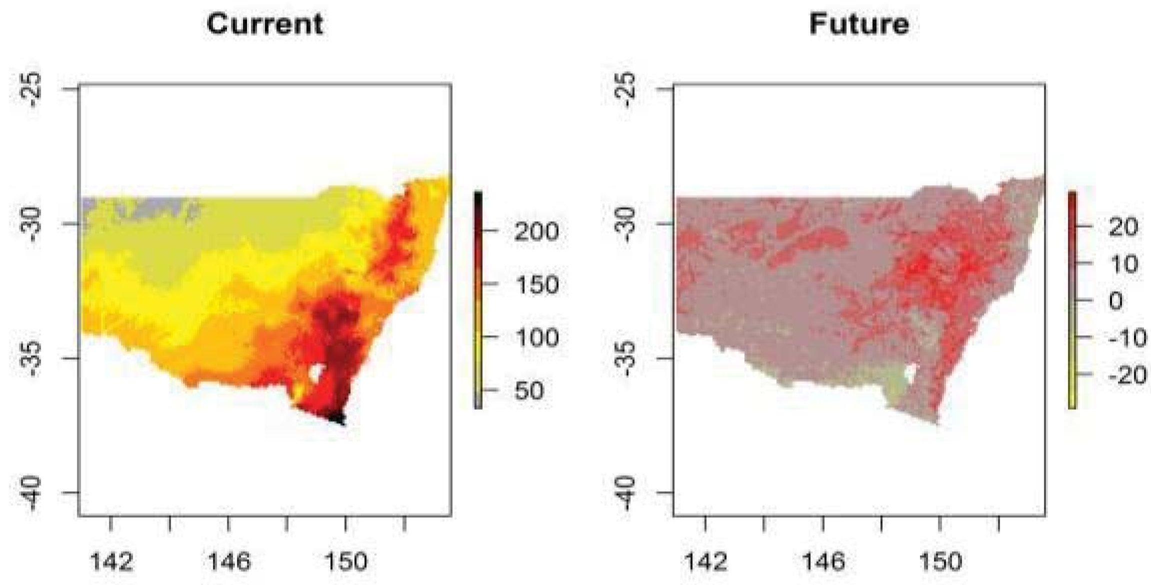


Figure 4: Current map indicates number of species with suitable habitat and future map (RCP 8.5 2035) indicates change in number of species where red represents an increase in number of species with suitable habitat and yellow a decrease for NSW

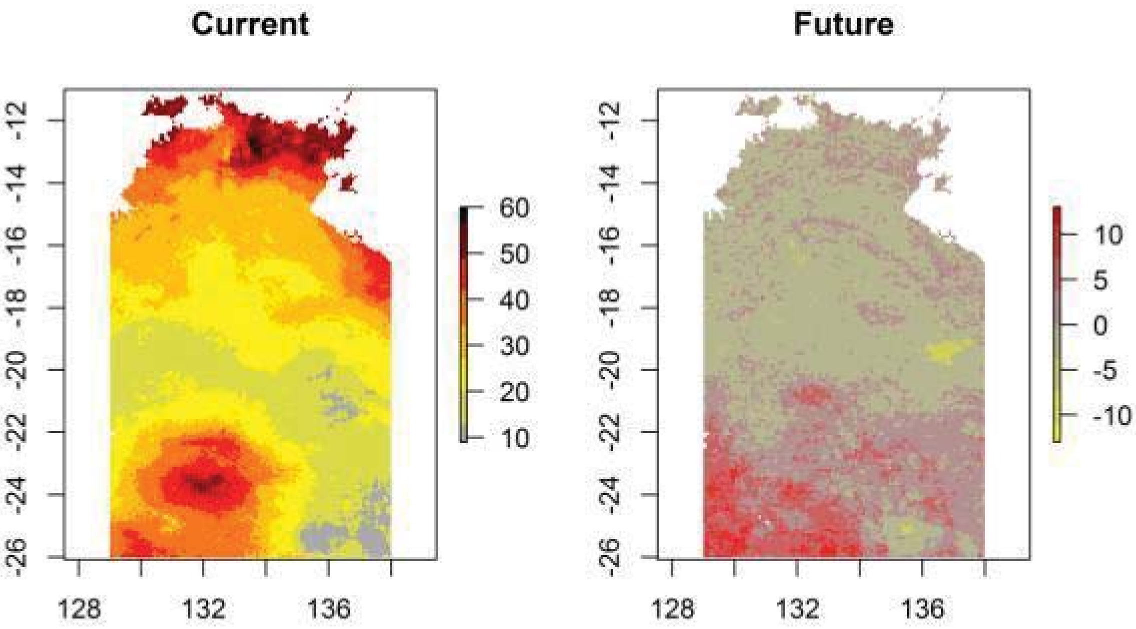


Figure 5: Current map shows number of species with suitable habitat and the future map (RCP 8.5 2035) shows change in the number of species where red represents an increase in number of species with suitable habitat and yellow a decrease for NT

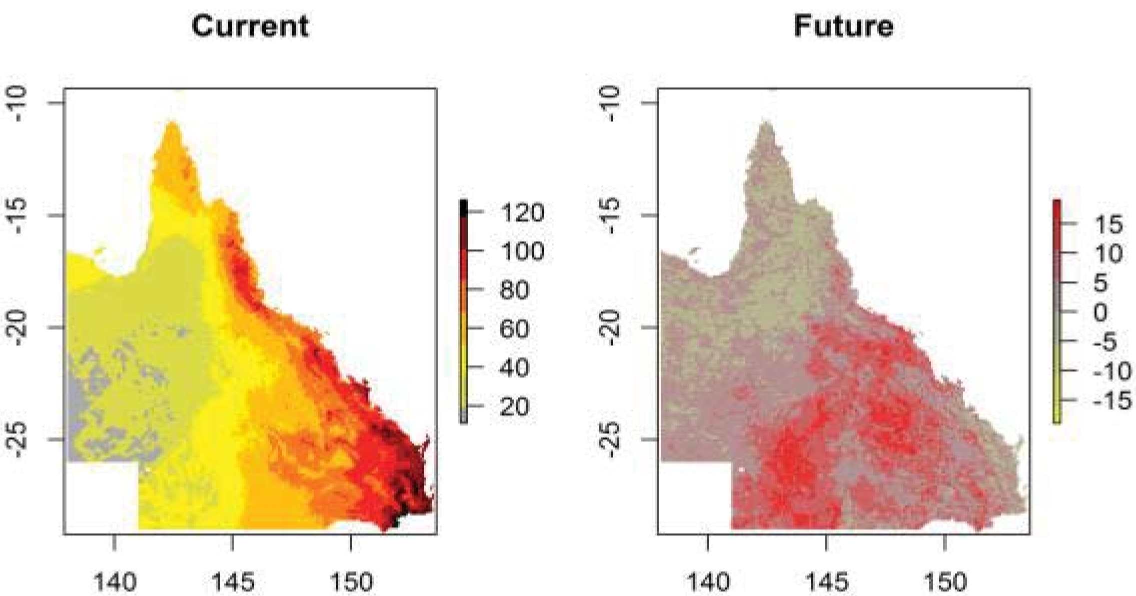


Figure 6: Current map shows the number of species with suitable habitat and the future map (RCP 8.5 2035) shows change in the number of species where red represents an increase in the number of species with suitable habitat and yellow a decrease for

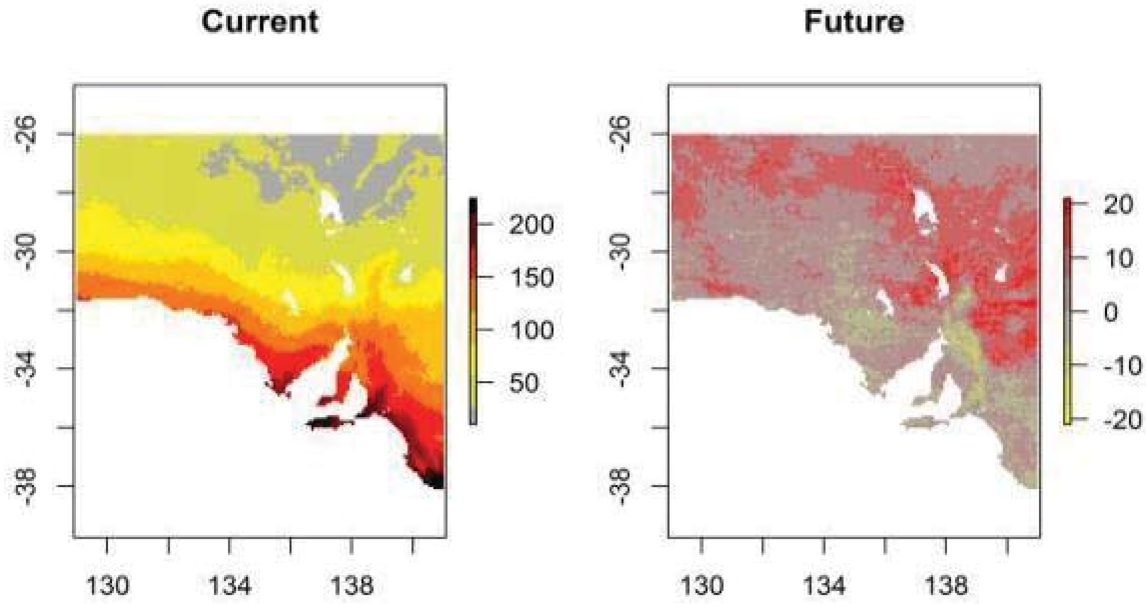


Figure 7: Current map shows the number of species with suitable habitat and the future map (RCP 8.5 2035) shows change in the number of species where red represents an increase in the number of species with suitable habitat and yellow a decrease for SA

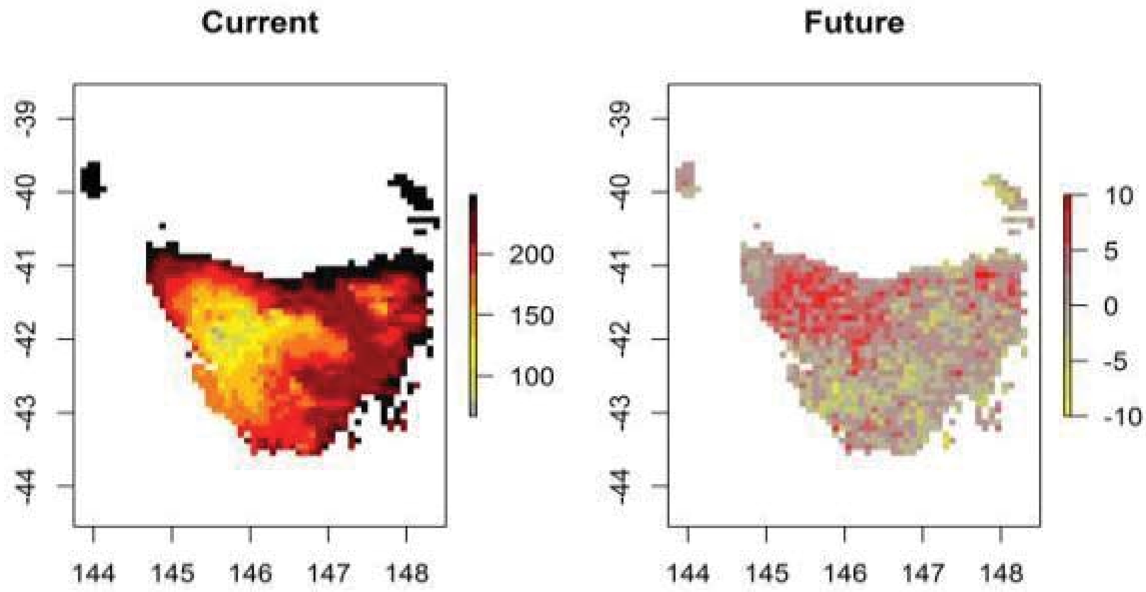


Figure 8: Current map shows the number of species with suitable habitat and the future map (RCP 8.5 2035) shows change in the number of species where red represents an increase in number of species with suitable habitat and yellow a decrease for TAS

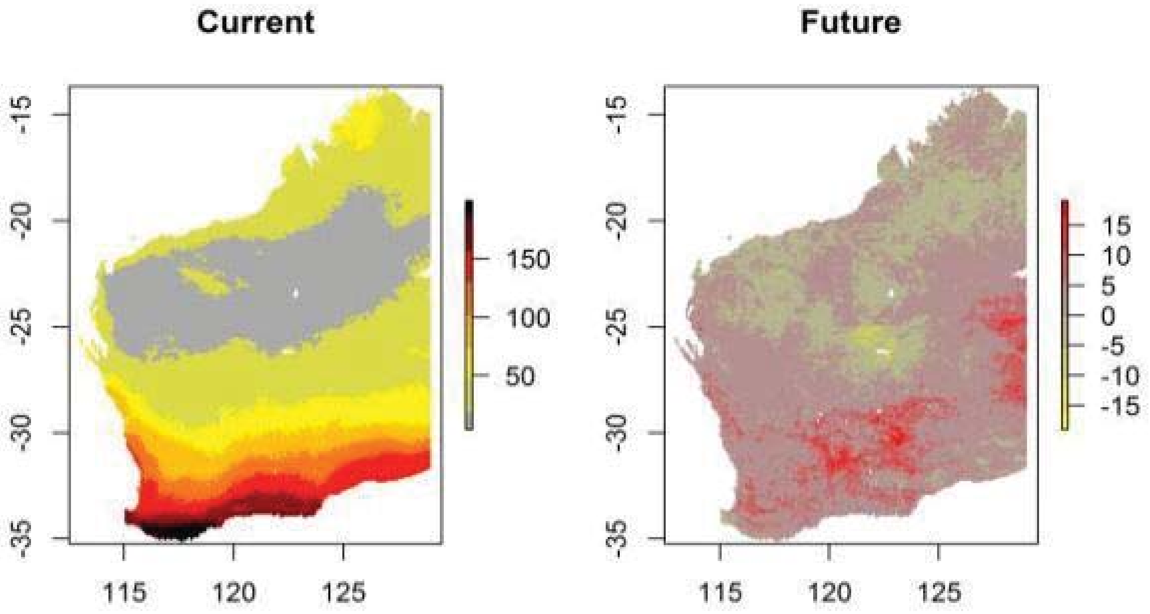


Figure 9: Current map shows the number of species with suitable habitat and the future map (RCP 8.5 2035) shows change in the number of species where red represents an increase in the number of species with suitable habitat and yellow a decrease for WA

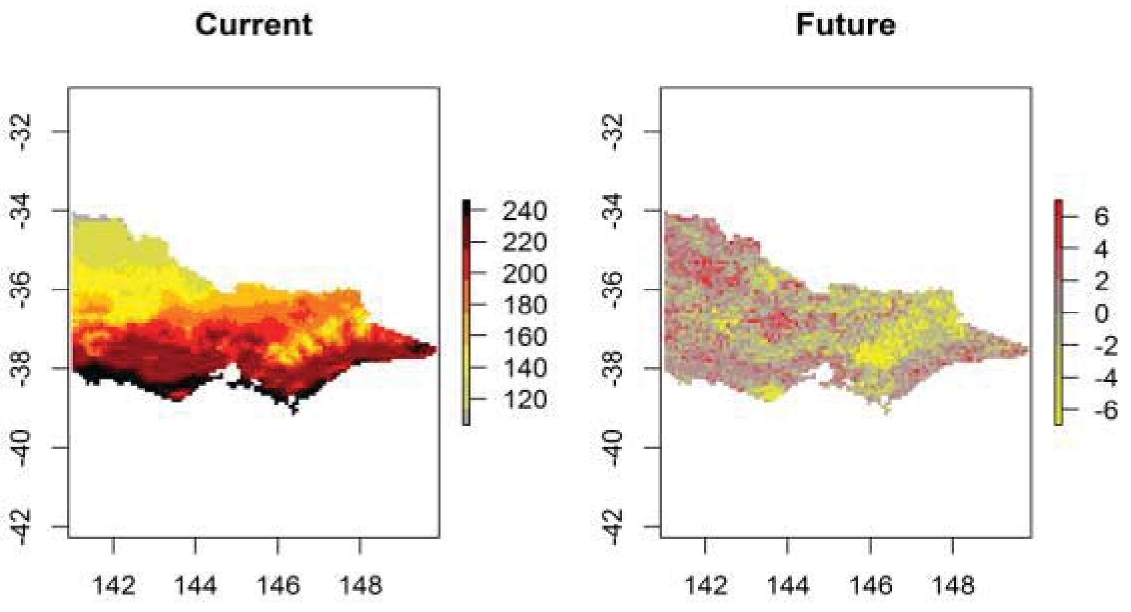


Figure 10: Current map shows the number of species with suitable habitat and future map (RCP 8.5 2035) shows change in number of species where red represents an increase in number of species with suitable habitat and yellow a decrease for VIC

3.4 Species-based prioritisation scheme

Using the points-based system described above, species scored between 12 and 44 points under the current climate at a national scale. The majority of species were ranked as having a medium risk of invasion (25-39 points) under the current time period (Table 5). There was large variation across states and territories in terms of invasion risk, with TAS and VIC having the greatest number of high risk species and WA having the least (Table 5).

Table 5: Risk of invasion at both the state, territory and national scales under the current climate. The total number of species that fall within each risk category is displayed

Invasion risk	NSW	ACT	NT	QLD	SA	TAS	VIC	WA	AUS
Low	108	153	253	185	184	112	88	197	38
Medium	143	65	29	94	93	67	69	89	244
High	41	74	10	13	15	113	135	6	10

Under the future climate at a national scale species scored between 12 and 42 points. The majority of species ranked as having medium invasibility under the future time period. Once again there was large variation across states and territories in terms of invasion risk (Table 6).

Table 6: Risk of invasions at both the state, territory and national scales under the future climate. The total number of species that fall within each risk category is displayed

Invasion risk	NSW	ACT	NT	QLD	SA	TAS	VIC	WA	AUS
Low	120	159	253	190	192	115	87	202	49
Medium	136	63	29	92	86	66	72	86	238
High	36	70	10	10	14	111	133	4	5

Refer to Appendix 5a and 5b for the total risk of invasion score of each species at both state/territory and national scales under both current and future time periods.

3.5 Website

The major outcome from this project is a website (www.weedfutures.net) that is the front end to the species profiles and maps. The website is the portal to an accessible, comprehensive, searchable database of potential emerging weed threats and can be used to inform adaptive management strategies at a national to regional level.

The website contains a full set of trait data which is more detailed than that shown on the species profiles and includes: dispersal mode, growth form, soil associations, tolerance or sensitivity to other key stressors, native range, and exotic range. The website also has the maps of the global gridded observations, current and future habitat suitability maps for the years 2035, 2065 and the RCPs 4.5 and 8.5, and detailed information as to which species are present at a number of spatial scales and for a number of different jurisdictions including LGA, NRM, IBRA 7, CAPAD and RAMSAR regions. Additionally the databases for the state level and national-scale threat assessments are available.

3.6 Manuscripts

We are currently preparing a manuscript titled, "*Next-generation invaders? Naturalised plants in Australia under future climates".* This manuscript examines the introduction history of the 292 naturalised plant species and assesses which regions of Australia may be most vulnerable to plant invasions. This manuscript can be used to devise pro-active management strategies and locate target regions for monitoring and eradication. The manuscript will be completed in the first half of 2013. We envisage that two additional papers will be prepared, one investigating how naturalised plants may affect Australia's protected area network under future climates and one examining prioritisation strategies for naturalised plants in Australia under climate change, and the incorporation of this information into formal weed risk assessment protocols.

3.7 Weed management workshop

A project follow-up workshop will serve to apply some of our report's findings into practice in the form of a risk assessment that will address future climate change. The workshop will bring together members from the Weed Risk Management Forum (WRMF) which is a national level forum that aims to streamline weed risk management across states and territories. We anticipate discussion generated at this workshop will aid in the development of a process to design and roll out focused monitoring programs to address weed risk under climate change. Additionally, the draft manuscript examining prioritisation strategies for naturalised plants in Australia will be written in collaboration with the workshop attendees.

4. DISCUSSION

Richardson and Pysek (2012) highlighted that to date, much research has focused on the final transition of the invasion continuum-i.e. on species that have become widespread and have discernible impacts on native communities. However, as abiotic conditions continue to change under human influences it is increasingly likely that a new suite of plant invaders will emerge and these species are likely to already reside in the pool of naturalised plants. Being able to predict which species are likely to become invaders will allow weed managers to more effectively target weed control resources while these 'sleeper species' are still in the early stages of invasion. The central aim of this research was to determine the potential threat from naturalised but not yet invasive non-native plants under climate change.

To do this, we assessed the current extent of environmentally suitable habitat for a suite of naturalised plants within Australia and evaluated how projected changes in climate may alter these patterns in the coming decades. Our research has provided a searchable tool for managers to pro-actively prioritise management and eradication actions for the weeds of the future. By providing maps of current and potential future distributions, and by identifying what is known about each species, the gaps in our knowledge become clearer, on a species-by–species, or region-by-region, basis. This information can then be used in weed risk assessments to prioritise control and eradication efforts.

Our 292 individual species profiles revealed huge differences amongst species both in terms of spatial variability and likely future invasion risk. Interestingly, *Cotoneaster divaricates* was found to not have any suitable habitat and all recorded Australian observations were restricted to garden locations. Other species such as *Citrullus lanatus* are widespread throughout all states and territories and is projected to have an increase in habitat suitability under climate change. This species is also a high risk species in all states and territories and for Australia.

The species threat assessments were important for detailing state/territory and national level risk. By comparing species at both national and state-level scales we were better able to identify those species which should be a priority for future weed assessment processes at a scale relevant to decision-makers. The species with the most gridded observations differed widely between states and territories. Interestingly, *Bromus rubens* had the largest number of gridded observations at a national level and was also found to be most widely observed in both VIC and SA.

The threat assessments for TAS and ACT were confounded by their climatic differences from the other states and territories. All states and territories, except for these two, contain vast areas of arid regions that are not suitable for many of the 292 study species. TAS had 64 species where 100% of the state was modelled under the current climate as suitable habitat and ACT had 119 species. The small size of these states also confounded the number of gridded observations per 100,000 km^2. This value is calculated based on the number of observations within a state and the area of a state. In the ACT, if a species has 1 observation this translates to 44.6 gridded observations per 100,000 km^2 but if a species has 1 observation in WA this results in a value of 0.04. In future assessments the number of gridded observations per 100,000 km^2, the area of suitable habitat, and the area of highly suitable habitat may need to be weighed differently to account for the size of the different states. It may also be worth exploring the differences in the number of observations based on the distance from populated areas.

By combining the habitat suitability maps for all species modelled in this study we can assess potential invasibility of different regions at both national and state-level scales. Our spatial assessment of invasion risk of naturalised species revealed that the southerly coastal regions and TAS are at highest risk of future weed problems, with arid regions the least affected. Overall, tropical and semi-tropical regions were found to be less at risk than the more temperate areas. The results from this project are consistent with our previous work on the potential changes in invasion “hotspots” based on the 72 Weeds of National Significance (WoNS), which also showed that the south east of Australia will be at greatest risk of future weed problems as the climate changes (O’Donnell et al 2012).

Our approach was based on assessing how suitable the habitat is likely to be under climate change and it should be highlighted that this may or may not facilitate naturalised weed dispersal. Overall, we found that the invasion potential for naturalised plant species will decrease at both national and state-level scales. However, this is species dependent with many species such as *Citrullus lanatus* predicted to increase under climate change. To date, most research has focused on how climate change will increase the number and severity of invasions, but our research shows that there may be circumstances in which invasion potential of some species will be reduced. Research has documented this for aquatic plant species, where warmer temperatures are thought to expand the pool of invasive species but also reduce the success of coldwater invasive species (Rahel & Olden 2008).

The preliminary assessment performed in this project now provides a list of species for both current and future time periods at both national and state and territory scales that should be prioritised for a full weed risk assessment prior to the design of an active management program. These species could also be the subject of an awareness raising program directed at the nursery industry, home gardeners, and bush regenerators, amongst others, regarding their potential to become serious weeds. The species ranked as having medium invasion risk should be given a full weed risk assessment within the next two to three years.

5. GAPS AND FUTURE RESEARCH DIRECTIONS

Our study is an initial first step in assessing future invasion risk. Given that we only examined 292 species, it is critical that future examination of the remaining 3000+ naturalised, but not yet invasive plant species occur to determine the future weed threats.

Using our point-based species prioritisation scheme we identified species at both the state and territory scale and national scale as having a high invasion risk. Focusing research, survey, and ultimately eradication efforts on these species is thus likely to be the most cost-effective use of resources to prevent future weed problems. Having identified these species as posing threats under current and future conditions, more detailed assessment as to their likely impacts on biodiversity and ecosystem function is justified. Once such an assessment of likely impacts has been made, further refinement of our threat assessment will be possible. Specifically, a modified version of Downey et al.'s (2010b) triage matrix in which species are assessed based on *invasive potential*, but also *invasive consequences*, as shown in table below:

Table 7: Modified version of Downey et al's (2010b) triage matrix - species assessed based on invasive potential and invasive consequences

Risk	Consequence (invasive potential)			
		High	Medium	Low
Likelihood (changed distribution relative to climate change)	High	1	2	6
	Medium	3	4	8
	Low	5	7	9

Our trait database is the most comprehensive national collation for the 292 naturalised plant species modelled for this report. Currently the database contains attributes including information on lifecycles, seed morphology, dispersal mechanisms, native and exotic ranges, growth forms and where available, environmental tolerances and soil associations. Additional traits that could confer a high risk of invasion consequences would be the ability to fix nitrogen (and therefore transform soil nutrients and facilitate invasion of additional species), to provide habitat for feral animals, to outcompete co-occurring native species by having high relative growth rates, ability to modify fire regimes and recruit or re-sprout after fire, and/or shade tolerance.

Our intention is that this database will be updated continuously as new information becomes available and our prioritisation scheme provides a basis for such additional ecological information to be sought systematically and added to the existing trait database. Provided the website can be maintained long-term it will also provide a location for the success or failure of management actions for individual species and regions to be recorded, as part of an adaptive management knowledge cycle.

One of the primary aims of this report was to ensure the prioritisation scheme developed provides a basis for incorporation into state-based risk assessment processes. However, our scheme should be one of the many tools used to assess and prioritise species. In order to improve our understanding of introduced plant species, we advocate for a holistic approach where a range of different types of information about introduced species and the different communities they invade are incorporated into the risk assessment process. Both functional characteristics (e.g. van, Kleunen et al. 2010) and genetics (Prentis et al. 2008 are thought to play important roles in determining invasiveness. A broad assessment of the future ecological impact of invasive (Downey 2010b) based on an assessment of existing alien natives may be a way forward to further our understanding of these complex processes. Refinement of this approach to employ ecological impacts linked to species functional and phylogenetic characteristics would provide a solid basis for assessing the 'sleeper' species from an observational background of proven invasive potential and ecological impact. Looking at both traits and ecological impact could benefit weed risk assessment processes under both current and future climate conditions.

An additional avenue of research would be to look at the relationship between human population density and introduced plants. Very few studies have looked at this relationship; however, it has been suggested as an explanation for the high level of idiosyncrasy observed in studies of invasions (Moles et al. 2012).

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