SOUTHERN & SOUTH–WESTERN FLATLANDS NRM CLUSTER

CLIMATE CHANGE IN AUSTRALIA

IMPACTS & ADAPTATION INFORMATION FOR AUSTRALIA'S NRM REGIONS

Climate change impacts and adaptation in the Southern & Southwestern Flatlands cluster: review of existing knowledge

June 2013

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Report No. CENRM133

Citation

Ford, B., Cook, B., and Rogers, D. (2013). Climate change impacts and adaptation in the Southern & Southwestern Flatlands cluster: review of existing knowledge. Report No CENRM133, Centre of Excellence in Natural Resource Management, University of Western Australia, Albany.

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Acknowledgements

This Activity received funding from the Department of Environment as part of the Natural Resource Management Climate Change Impacts and Adaptation Research Grants Program, under the Natural Resource Management Planning for Climate Change Fund – A Clean Energy Future Initiative.

Executive Summary

This synthesis report provides a summary of methods utilised and subsequent predictions of the effects of climate change upon biodiversity and agriculture for the Southwestern and Southern Flatlands NRM clusters.

- Climate change predictions for southern Australia include
  - Temperature increases of 0.5°C to 1–1.5°C by 2030 and by 1°C to 4°C by 2070.
  - Rainfall decreases of 5 to 20% by 2030 and by 10 to 40% by 2070.
- Four major threats to biodiversity have been identified
  - addition of new species to a region,
  - altered hydrology patterns,
  - increased fires, and
  - altered land use patterns.
- Concerning agriculture, while unique responses to climate change from different species and ecosystems can be expected.
  - Increased atmospheric CO_2 may result in increased crop productivity through CO_2 fertilisation; however, this is also likely to result in reduced crop protein content.
  - Crop productivity may be reduced indirectly through increased temperatures. An increase in temperature coupled with a decrease in precipitation will result in lower quality crops. Increased temperatures are also likely to provide conditions more amenable to pests.
  - Species distribution modelling (SDM) (aka bioclimatic niche/envelope modelling) has been the most commonly utilised tool for predicting effects of climate change on biodiversity.
- At the time of this report, SW WA taxa modelled included
  - Native trees
  - Freshwater macroinvertebrates
  - Freshwater fishes
  - Amphibians
  - Reptiles
  - Birds
  - Mammals
  - Exotic plants
- The general predicted response of SW WA species to climate change was range contraction and/or distribution shifts, typically to the south and west, with magnitude of impact increasing with scenario severity.
- SA taxa modelled include
  - Native grasses
  - Native trees
  - Amphibians
  - Reptiles
  - Birds
  - Mammals
  - Exotic Plants
- As with SW WA, the typical predicted response of SA species to climate change is range contraction, the magnitude of this response also generally increasing with severity of climate change.
- Concerning agriculture in SW WA, In general, both yield and suitable area for wheat, barley, oats, lupins, and canola are predicted to decrease as a result of climate change.
- In SA, the exposure of wheat crop yields to drying climates was found to vary among soil types and climatic zones, while the impact of future climates on other agricultural industries in SA is less well understood.

1. INTRODUCTION

The Regional Natural Resource Management (NRM) Planning for Climate Change Fund has established eight 'clusters' across Australia to deliver information to NRM organisations. One of these clusters is the 'Southern and Southwestern Flatlands' cluster (hereafter, the 'Flatlands cluster') which incorporates southwestern Australia (an amalgamation of five NRM regions – South Coast, South West, Wheatbelt, Perth, and Northern Agricultural) and the southern part of South Australia (amalgamation of four NRM regions – Eyre Peninsula, Northern and Yorke, Kangaroo Island, and Adelaide and Mount Lofty Ranges).

The Flatlands cluster contains one of five Mediterranean climate regions in the world (others being the Mediterranean Basin, fynbos of South Africa, California and northwest Baja, and central Chile) (Klausmeyer and Shaw, 2009). These ecoregions are characterised by cool winters and hot summers with seasonal rainfall in winter (Di Castri, 1991) and high levels of endemism and diversity (notably vascular plants (Klausmeyer and Shaw, 2009). Like Mediterranean systems elsewhere (e.g. Chrysopolitou et al., 2013), the Mediterranean climate region falling within the Flatlands cluster is projected to be among the most significantly affected by anthropogenic climate change (Underwood et al., 2009; Yates et al., 2010).

Generally as a result of climate change, southern Australia is expected to experience reduced rainfall, elevated temperatures, and increased intensity and frequency of extreme weather events (Easterling et al., 2000; Hughes, 2003), changes which are already happening. Rainfall in regions below 30° S has decreased by approximately 15% over the last 50 years (Nicholls, 2010); and since 1951, temperature has increased 0.1-0.2°C (Hughes, 2003). In southwestern Australia, strong gradients exist for both rainfall and temperature, with annual rainfall decreasing west to east and average temperatures decreasing north to south (Indian Ocean Climate Initiative, 2002). In southern South Australia, annual rainfall decreases from the south to north, while average temperature shows an increase from south to north (Chambers, 2003; Jones et al., 2009). It is predicted that by 2030 average temperature across southern Australia will have increased by 0.5°C to 1–1.5°C based on low or high warming scenarios respectively. These estimates intensify to 1°C to 4°C increase by 2070 based on the respective scenarios (Suppiah et al., 2007). Concerning rainfall, by 2030 decreases of 0-0.5% to 5-10% are predicted under a low warming scenario and decreases of 5-10% is expected with a 10-20% decrease predicted for the south west corner. By 2070 the low and high warming scenarios have relatively converged, and decreases of 10-20% are expected along the south coast and 30-40% in the south west corner (Suppiah et al., 2007).

Of interest are the likely impact of these predicted climatic changes on biodiversity and agriculture. Evidence from the fossil record shows that the ranges of species have expanded and contracted with climate change, and thus it is reasonable to expect that the reduced rainfall and increasing temperatures predicted for the Flatlands cluster will significantly impact on the distribution of species. In a review of the methods available for predicting the consequences of climate change, Sutherland (2006) identified seven main approaches of different methods, these being extrapolation, experiments, phenomenological models, game-theory population models, expert opinion, outcome-driven modelling, and scenarios (Sutherland, 2006). A summary of these approaches is provided in Appendix 1, Table A1.

The purpose of this report is to synthesise the current knowledge and predictions concerning the effects and impacts of climate change of southwestern and southern Australia, particularly the expected impacts upon the biodiversity and agricultural practices in the regions. This information will provide NRM groups in the Flatlands cluster suitable understanding of the approaches utilised and the current state of knowledge regarding predicted outcomes of climate change. This information can then be utilised by the NRM groups to decide upon the required data and suitable methods by which they can prepare for a changing climate, such as determining either locations of potential refugia, suitable agricultural practices/crops, or optimising efficiency of pest control.

2. LIKELY IMPACTS OF CLIMATE CHANGE ON SOUTHERN AUSTRALIAN BIODIVERSITY AND AGRICULTURE

In general, there are four aspects of species biology and ecology which are expected to respond to climate change, these being physiology, distribution, phenology, and adaptation (Hughes, 2000). Firstly, changes in temperature, pressure, and CO_2 concentrations will affect species' physiology, manifesting itself through changes in metabolism, development, and photosynthesis in plants (Walther et al., 2002). Secondly, as climate change results in altered climatic regimes, species will shift their distributions (if able to) to remain in climatically suitable locations. A 3°C increase in temperature will typically correspond to a poleward latitudinal shift of 300-400km or an upward elevational shift of 500m (Hughes, 2000). Thirdly, reoccurring life cycle events controlled or influenced by seasonal or climatic triggers are likely to display temporal shifts under changed climates. A potential outcome of this is asynchrony in important events among interacting species, for example, changes in eucalypt flowering times will result in changes in the availability of nectar (Dunlop and Brown, 2008). Lastly, adaptation to the new climate may be an option for species with short generation times (Hughes, 2000; Steffen et al., 2009). Two recent associated studies by James et al. (2013) and Reside et al. (2013) considered likely areas of future refugia for a number of species at the continental scale based on predicted total change and resulting novelty of future climate. It was suggested by these authors that while precipitation levels and regimes will change, the magnitude of change will typically remain within contemporary variability. The change in temperature however will not, with predictions of mean annual temperature change by 2085 being in the order of five to seven standard deviations from the current temperatures, resulting in almost $1000km^2$ of Australia being consistently predicted across 18 global climate models to have no future temperatures within two standard deviations of current temperatures. This is an important aspect as two standard deviations is essentially the inter annual variability in temperature, thus changes greater than two standard deviations are greater than the variability to which organisms have evolved (James et al., 2013; Reside et al., 2013).

These changes operating at the individual and species levels will then result in changes observed at the assemblage and community levels, such as altered patterns of biodiversity (Hughes, 2000). The general consensus among studies is that the effects of climate change will be individualistic, with unique responses from different species and ecosystems (Dunlop and Brown, 2008). As a result of this process, novel ecosystems, and communities consisting of new combinations of species, will emerge as a result of differing rates of migration by species (Catford et al., 2012). Taken to the extreme, species may be forced to extinction through novel intraspecific interactions or complete loss of suitable habitat within the necessary bioclimatic envelope (Dunlop and Brown, 2008).

With the four main threats to Australia's biodiversity associated with climate change being addition of new species to a region (indigenous and exotic), altered hydrology patterns, increased fires, and altered land use patterns (Hennessy, 2010), the south west is likely to be greatly affected. As this region is predicted to experience some of the greatest decreases in precipitation and increases in temperature, increased fires and altered hydrology regimes are highly likely. In addition, the landscape has experienced some of the most intense agriculture related clearing and resultant natural habitat fragmentation across the continent (Yates et al., 2010). The predicted impacts to the biodiversity of southwestern Australia are likely to be exacerbated due to the lack of montane refugia and the southern coastline further restricting species' ability to migrate to suitable climates (Yates et al., 2010), in addition to being one of five global regions consistently predicted by various climate models to experience increased frequency of drought in the future (Prudhomme et al., 2014).

In an agricultural context, a potential positive outcome of increased atmospheric CO_2 is increased crop productivity through CO_2 fertilisation (Amthor, 2001). However, increased production as a result of CO_2 fertilisation is likely to result in reduced protein content (Ludwig and Asseng, 2006), in addition, atmospheric CO_2 concentrations will not change in isolation, plant growth is influenced by the other climatic variables expected to change (such as precipitation and temperature). Increased temperature can increase plant growth and lower the occurrence of frosts (Stokes and Howden, 2010), although, in south west Australia the increase in temperature is coupled with a decrease in precipitation which will result in lower quality crops. Increased temperatures are also likely to provide conditions more amenable to pests, again reducing crop productivity and/or quality (Stokes and Howden, 2010).

3. SPECIES DISTRIBUTION MODELLING

The most commonly used tool for predicting the impacts of climate change on biodiversity has been correlative species distribution, or ‘bioclimatic’ modelling (Pearson and Dawson, 2003; Phillips et al., 2006; Yates et al., 2010). This approach provides reasonably good estimates of potential range shifts with climate change (Elith et al., 2006; Hijmans and Graham, 2006), and is thus thought to be a valuable tool for developing an understanding of the potentially dramatic impacts of climate change on species’ distributions. Briefly, authors model the bioclimatic envelope of selected species under current climatic conditions to identify climatic variables that limit the species current distribution, then based on these results, predict the climatic envelope of the species into the future under various climate change scenarios. When estimating whether species will experience either range contractions or expansions, it is assumed that species can either track shifting climatic envelopes (unlimited dispersal scenario) or will only persist in areas where current and future climate envelopes overlap (no dispersal scenario). Although large distribution data sets are preferable for this modelling, even small numbers of occurrence records have been successfully used to predict species distributions (e.g. Pearson et al., 2007).

Steps in a typical species distribution model (SDM) study based on the use of a statistical model include (i) Collection of geo-referenced occurrence records, usually from museum and herbarium collections for species of interest, (ii) selection of suitable bioclimatic variables, (iii) entering of a subset of the species occurrence records (the ‘training’ data) and environmental variables into a modelling algorithm, (iv) validation of the ability of the model to predict the known species’ distribution using a subset of records (the ‘test’ data), (v) and if the fit to test occurrence records is judged to be acceptable, mapping of the predicted species’ distribution under past , present and future scenarios.

3.1 BIOCLIMATIC VARIABLES

A commonly used set of bioclimatic variables are those available through the WorldClim website (Table 3.1; http://www.worldclim.org/bioclim). These environmental data are formatted to a raster grid, and together with the biological data, are used to build the species’ distribution model. Bioclimatic variables are derived from monthly temperature and rainfall values in order to generate more biologically meaningful variables. These variables represent annual trends (e.g., mean annual temperature, annual precipitation) seasonality (e.g., annual range in temperature and precipitation) and extreme or limiting environmental factors (e.g., temperature of the coldest and warmest month, and precipitation of the wet and dry quarters).

Table 3.1 Bioclimatic variables utilised to define/describe present and future climates.

Code	Bioclimatic Variable
BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (* 100)
BIO4	Temperature Seasonality (standard deviation *100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)

BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

3.2 SPECIES DISTRIBUTION MODELLING ALGORITHMS

Several modelling algorithms are available, including MAXENT (based on maximum entropy), DOMAIN (Gower metric), BIOMAPPER (ecological niche factor analysis), GARP (genetic algorithm) and regression approaches such as generalised linear models (GLM), generalised additive models (GAM), boosted regression trees (BRT) and multivariate adaptive regression splines (MARS). Of these, MAXENT has been shown to perform well when compared to other models (e.g. Elith et al., 2006; Phillips et al., 2006; Pearson et al., 2007), and for southwestern Australian species, has generally been the model of choice. Outputs from these models usually consist of a continuous prediction (e.g. a probability value ranging from 0 to 1), and a threshold value is often set, above which a prediction is classified as the species being ‘present’. There are a variety of methods for setting thresholds of occurrences (Pearson et al., 2007).

In order to test the predictive performance of models, the complete dataset is often partitioned into calibration (the ‘training’) and test (‘evaluation’) datasets, commonly with a spilt of 70% for calibration, and 30% for testing. Alternative approaches have been the use of ‘bootstrapping’, where the dataset is split multiple times, and ‘k-fold partitioning’, where the data are split into k parts of equal size, and each part is used as a test set with the other parts used for model calibration (Pearson et al., 2007).

3.3 GLOBAL CLIMATE MODELS

Environmental data for new climate scenarios is usually generated using global climate models. Based on predicted maximum and minimum temperatures and precipitation, the most relevant future climate scenarios using the RCP3 emission scenarios for Australia have been determined to be CSIRO Mk 3.5, MIROC-M, and ECHO-G (Perkins et al., 2007). Concerning south-western Australia, the CSIRO Mk 3.5 model (Gordon et al., 2010) predicts a decrease in rainfall (magnitude of change increasing in a NW direction) and a small increase in temperature through the south coast (as with rainfall, greater increase in temperature in NW direction). The MIROC-M model (K-1 Model Developers, 2004) predicts a decrease in Western Australian rainfall (magnitude of change decreasing eastwards) and increased temperatures, the change in temperature increasing northwards. The ECHO-G model (Legutke and Voss, 1999) predicts a decrease in rainfall in Western Australia, this decrease greatest at approximately Perth, with magnitude of change decreasing in all directions, and an increase in temperature, this increase being greater further north. As can be seen there is corresponding predictions among the models, essentially decreased rainfall and increased temperature. Further summaries of these models can be found at -

https://wiki.csiro.au/confluence/display/ozclim/Science#Science-CSIRO35

https://wiki.csiro.au/confluence/display/ozclim/Science#Science-MIROC3.2M

https://wiki.csiro.au/confluence/display/ozclim/Science#Science-ECHO

3.4 PREDICTED IMPACTS OF CLIMATE CHANGE ON BIODIVERSITY OF SOUTHWESTERN AUSTRALIA

A total of nine studies have utilised SDM methods to predict range shifts in southwestern Australian species as a result of climate change (Appendix 1, Table A2), either at the scale of Australia or the southwest. Southwestern species/groups for which future geographical ranges have been predicted include Banksias (Fitzpatrick et al., 2008; Yates et al., 2009), the Quokka (Setonix brachyurus) (Gibson et al., 2010), aquatic invertebrates, frogs, fishes, turtles (James et al., 2013; Davies, unpublished), the Western Ringtail Possum (Pseudocheirus occidentalis), Jarrah (Eucalyptus marginata), Marri (Corymbia calophylla), and Peppermint (Agonis flexuosa) Trees (Molloy et al., 2014), the Great Western Woodlands (GWW) (Prober et al., 2012), and mammals, birds, amphibians, and reptiles (Reside et al., 2013) (Figure 3.1). Species counts for each region were not presented by James et al. (2013), and are therefore not incorporated in Figure 3.1.

A summary of inputs is also provided in Appendix 1, Table A2. MAXENT was the software of choice for all of the studies utilising SDMs to predict southwestern Australian species distribution shifts, although Molloy et al. (2014) also utilised DOMAIN in their study of the Western Ringtail Possum to assess the equivalence between methods. The GCMs most suitable for use in southwestern Australia were determined to be MIROC-M, CSIRO Mk 3.2, and ECHO-G by Perkins et al. (2007). While CSIRO Mk 3.2 (or CSIRO models from 2-3.5) and MIROC-M were the two most utilised GCMs, ECHO-G has not been used as much as HADCM3, and MIROC-H (Figure 3.2). Hill et al., (2012), incorporated all 23 GCMs from the IPCC 4th assessment report, both James et al. (2013) and Reside et al. (2013) utilised 18 GCMs, and Prober et al.(2012) based their study on GCM ensemble projections published by CSIRO. Concerning emission scenarios, the most often utilised were (in order of increasing impact) B1, A2b (including A2), A1B, and A1FI, with James et al. (2013) and Reside et al. (2013) basing their analyses on the newer RCP8.5 scenario, which essentially predicts a similar future to that of the A1FI emission scenario (James et al., 2013; Reside et al., 2013) (Figure 3.3).

Timeframes for which future distributions were predicted ranged from 2000 to 2085, with one study being decadal from 2000 – 2080 (Banksias, (Fitzpatrick et al., 2008)), four studies using 2030, 2050, and 2070 (Banksias, (Yates et al., 2009); Quokkas, (Gibson et al., 2010); Mites, (Hill et al., 2012), and the GWW (Prober et al., 2012)), another study created predictions for 2020 and 2050 (WoNS, (O'Donnell et al., 2012)), and Davies (unpub.) analyses were based upon climate predictions for 2020 and 2080. Both James et al. (2013) and Reside et al. (2013) based their future predictions at 2085. The remaining studies solely utilising 2050 (Exotic grasses, (Gallagher et al., 2012); Ringtail Possums, Jarrah, Marri, and Peppermint, (Molloy et al., 2014)) as the future climate reference point (Figure 3.3).

Concerning the bioclimatic predictor variables, annual mean temperature (BIO1), mean temperature of warmest quarter (BIO10), and annual precipitation (BIO12) were the most utilised overall. Isothermality (BIO3), minimum temperature of the coldest month (BIO6), precipitation seasonality (BIO15), and precipitation of driest quarter (BIO17) were also often utilised. Three studies utilised all 19 bioclimatic variables and although important variables differed with species, variables associated with average and seasonal rainfall dominated in importance. In addition, three studies (Fitzpatrick et al., 2008; Gibson et al., 2010; Prober et al., 2012), incorporated evapotranspiration attributes, Fitzpatrick et al. (2008) included length of growing season, and soil characteristics were incorporated by Fitzpatrick et al. (2008) and Yates et al. (2009) (Figure 3.4).

Overall, the general predicted response of species to climate change was range contraction and/or distribution shifts, typically to the south and west, with magnitude of impact increasing with scenario severity

(Appendix 1, Table A3). The bioclimatic variables which appear to be the most influential in southwestern Australian species distributions may differ according to the invasiveness of the species. For the Banksias, Mites, Quokka, and GWW the most important bioclimatic variable was precipitation or its derivatives (Fitzpatrick et al., 2008; Gibson et al., 2010; Hill et al., 2012; Prober et al., 2012), whereas temperature was the driving variable for the exotic grasses and weeds of national significance (WoNS) (Gallagher et al., 2012; O'Donnell et al., 2012). Both James et al. (2013) and Reside et al. (2013) determined that temperature was more important than precipitation with respect to locations of future refugia in freshwater and terrestrial realms.

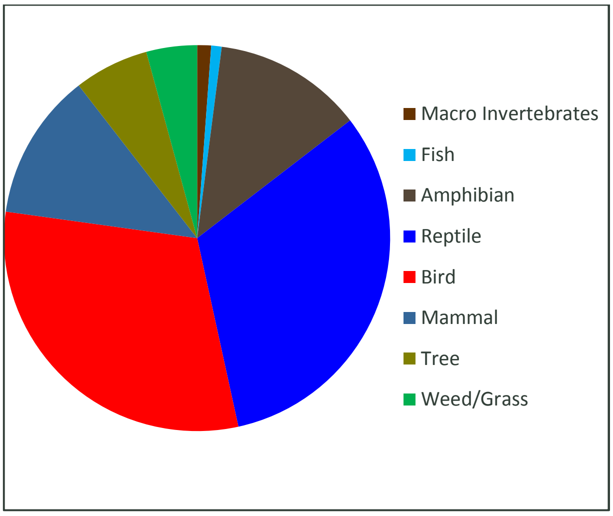

Figure 3.1 Summary of species utilised in SDM analyses incorporating southwestern Australia. Notes: 10 macro invertebrates utilised were considered at the family level, Tree includes two studies of 18 and 100 Banksia species, and the GWW; Weed/Grass includes studies of 72 weed and 11 grass species, both Macro Invert and fish include two invasive species each.

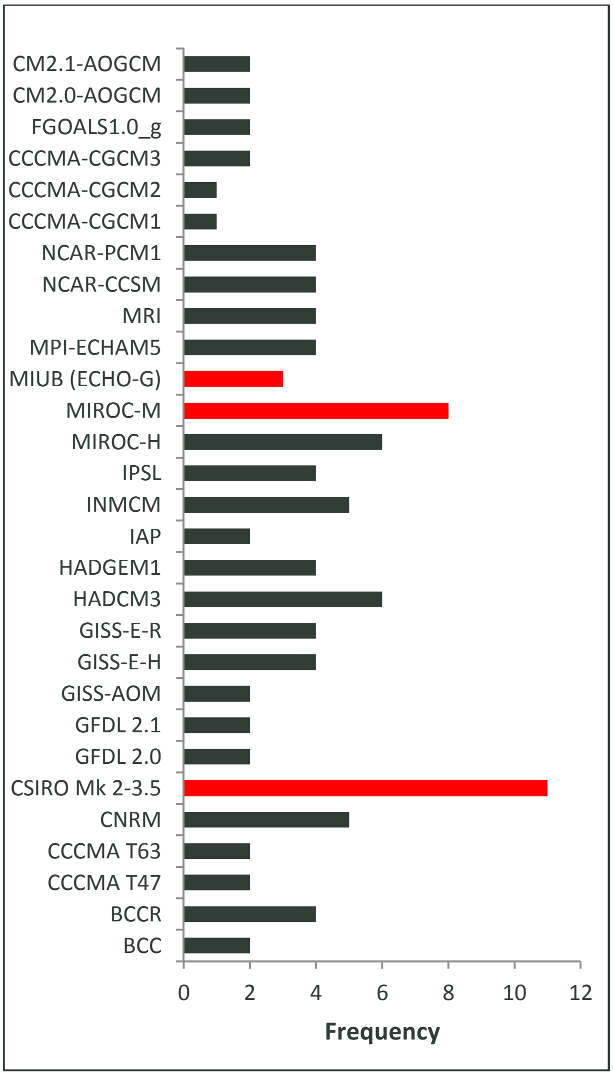

Figure 3.2 Frequency of GCM use in studies incorporating southwestern Australia, with GCMs recommended for southwestern Australia in red.

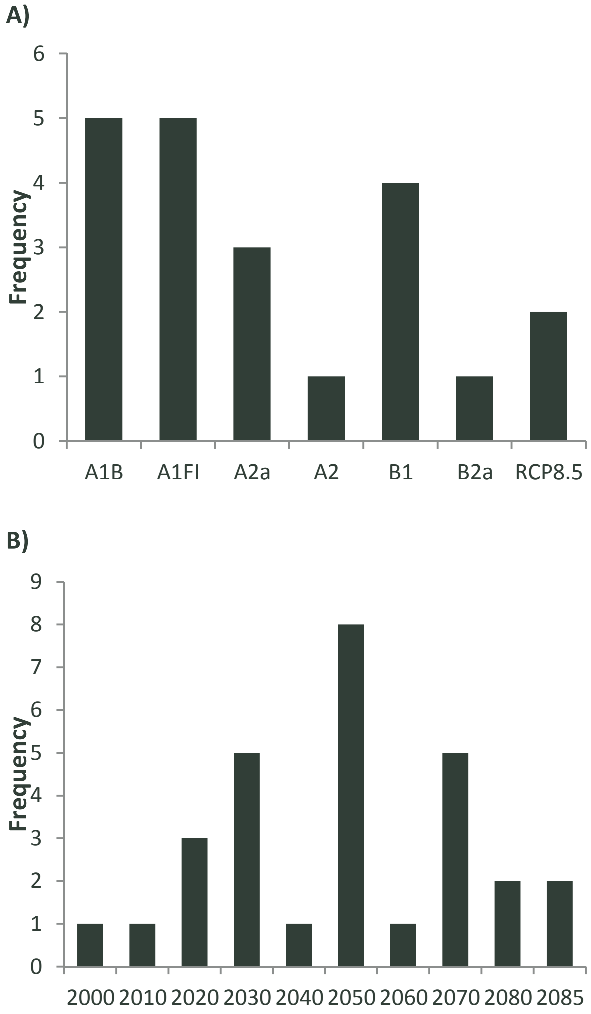

Figure 3.3 Frequency of A) emission scenarios and B) timeframes used in SDM studies incorporating south west Australia

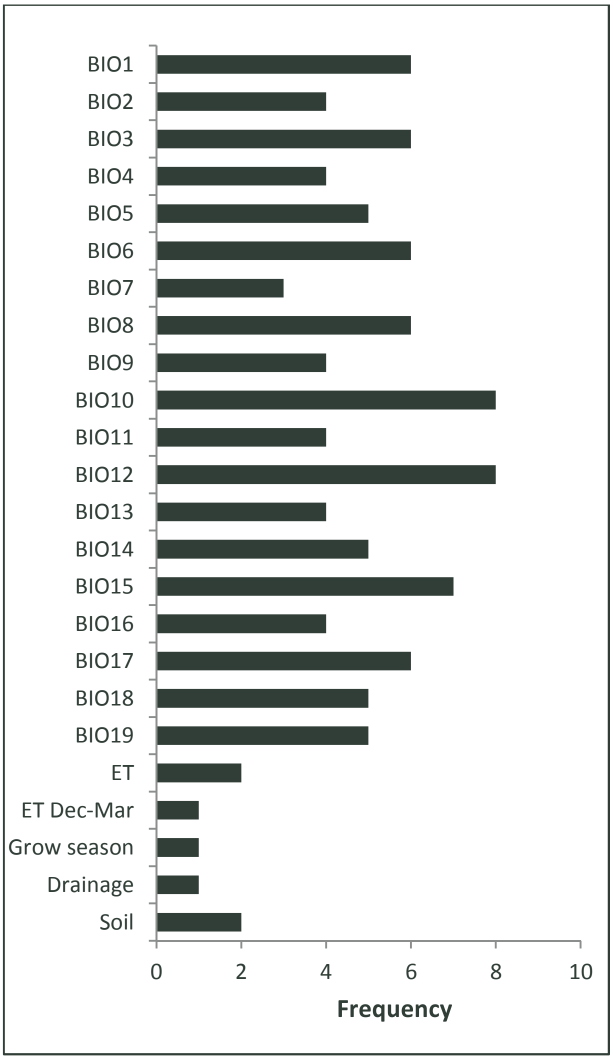

Figure 3.4 Frequency of predictor variable use in SDM studies incorporating southwestern Australia. (ET = evapotranspiration, Grow season = growing season length incorporating precipitation and evaporation, Drainage = measure of riparian habitat, Soil = various measures of soil characteristics).

3.4.1 NATIVE BIOTA: BANKSIA SPECIES

The ranges of southwestern Australian Banksias were found to differ according to scenario and current distribution of each species (Appendix 1, Table A3). Fitzpatrick et al. (2008) utilised 100 species in their analyses and predicted that 66% of these species will experience range contractions by 2080 regardless of GCM and emission scenario used, and 85% of species were predicted to experience contractions under seven of nine GCM – scenario combinations. Stable or expanding ranges were forecast for 6% of species. Five species were predicted to become extinct across all scenarios and 24 species were predicted to become extinct in at least one scenario. In general, range contraction was predicted as opposed to range shift and though migration ability was included in the analyses, it was found that migration rate did not significantly alter predicted outcomes, however migratory ability became more important as the scenario impact increased (Fitzpatrick et al., 2008).

In their analysis of the effect of climate change on the geographical distribution of 18 species of Banksia, Yates et al. (2009) also incorporated land use/transformation and performed analyses based on both unlimited and zero dispersal abilities of the species. It was found that changes in climate change scenario, land use, dispersal ability, and current geographical distribution (northern, southern, or widespread) of each species influenced the future range predictions. The northern species were predicted to increase their ranges under unlimited dispersal, but under zero dispersal ranges were found to contract. Ranges of the southern species were found to contract regardless of dispersal ability; however extent of contraction increased with increasing severity of climate change. All widespread species were predicted to contract under zero dispersal assumptions, while unlimited dispersal resulted in increased range size for three species and range contractions for two species. The inclusion of land transformation by this study resulted in increased magnitude of contractions and reduced extent of range expansions of Banksias, regardless of dispersal or current geographical range. Concerning direction of predicted range shifts, northern species presented the greatest mean distances and tended to move more eastwards than the others, while the southern species presented the smallest distribution shifts and in a more westerly direction (Yates et al., 2009).

3.4.2 NATIVE BIOTA: QUOKKA

In their study of the effects of climate change upon Quokkas, Gibson et al. (2010) predicted the Quokka to experience range contractions and a southward migration of their current geographical distribution. This study also incorporated dispersal ability and land use/transformation as predictive variables. While full dispersal ability under the lowest impact scenario was found to result in an initial increase in Quokka geographical range, by 2070 the range returned to its original size. Under the medium severity scenario, the Quokka is predicted to lose over half its range by 2070, while near extinction is predicted under the high impact scenario and the same timeframe, regardless of dispersal assumption incorporated. As the Quokka is currently found mostly within DEC managed land and state forest, and predicted ranges typically also occur within these areas, changes in land use does not greatly affect the predicted range of this species.

3.4.3 NATIVE BIOTA: AQUATIC FAUNA

The geographical ranges of fish, frog and aquatic macroinvertebrate species are predicted to contract under climate change scenarios in south-western Australia, with potential distributions becoming confined to the south-west corner and coastal regions (Davies, unpublished). A general trend in climate change scenarios indicated that declines in species' distributions will be most severe under the A1B scenario, followed by the A2a and B2A scenarios.

Modelling also predicted that aquatic species will be more heavily impacted by expected declines in and changes to the precipitation regime rather than increases in atmospheric temperatures. Some invertebrate species adapted to arid and saline conditions showed overall range expansions, however this was not universal and indicated that responses to climate change will be species specific. Overall species' sensitivity to climate change was expected to be influenced by a combination of species biology, current distribution, rarity, and habitat preferences (Davies, unpublished).

Climate change associated impacts upon aquatic fauna at the national level was investigated by James et al. (2013), focussing on potential refugia for freshwater fish, crayfish, turtles, and stream frogs. Stream frogs are not found in southwestern Australia and are therefore not discussed in this section. When making predictions of the future impacts as a result of climate change, this study based results upon both relative change in climate and novelty of the future climate, novel climate being measured by the number of standard deviations the predicted climate was from the current climate (James et al., 2013). The suitability of future climates was assessed by comparing predicted richness (through SDM) as a proportion of current richness for each group. Concerning predictions for south western fauna, freshwater fish are expected to lose suitable inland environments, while the south west coast presented one of the greatest areas of variability in predicted richness. This loss of fish richness in southwestern Australia is attributed to decreased annual accumulated runoff, predicted temperature change (potentially greater than 10 standard deviations of current temperature), vegetation clearance, and salinisation (James et al., 2013). Freshwater crayfish suitable environment and richness in southwestern Australia are predicted to remain stable, however this study did not include the crayfishes of the Engaewa genus, which display high endemism and thus the inclusion of which would be likely to change predicted outcomes. While a general prediction of reduction of suitable environment for turtles at the continent scale was predicted by 2085, southwestern Australia was predicted to remain stable with respect to this habitat, thus being identified as a potential region of refugia for turtles (James et al., 2013). The findings of this study were then incorporated into the determination of the suitability of freshwater RAMSAR wetlands to future conditions under climate change scenarios, this aspect of their study is discussed in the relevant later section of this report (Native habitat: RAMSAR wetlands).

3.4.4 NATIVE BIOTA: WESTERN RINGTAIL POSSUM AND ASSOCIATED ARBOREAL HABITAT

The ngwayir (western ringtail possum Pseudocheirus occidentalis) is an arboreal species endemic to south-western Australia. The range and population of this species have been significantly reduced through multiple anthropogenic impacts. Classified as Vulnerable, the ngwayir is highly susceptible to extremes of temperature and reduced water intake. Ngwayir distribution was determined by Molloy et al. (2014) using three different species distribution models and ngwayir presence records related to a set of 19 bioclimatic variables derived from historical climate data, overlaid with 2050 climate change scenarios. MAXENT was used to identify core habitat and demonstrate how this habitat may be impacted. A supplementary modelling exercise was also conducted to ascertain potential impacts on tree species that are core habitat for ngwayir. All models predicted a contraction of up to 60% in the range of the ngwayir and its habitat, as a result of global warming, towards the south-west of the project area with a mean potential distribution of 10.3% of the total modelled area of 561,059 km^2. All three tree species modelled (Jarrah, Marri and Peppermint) are predicted to experience similar contractions in range. Populations of ngwayir persisting outside core habitat present major conservation opportunities.

3.4.5 NATIVE BIOTA: GREAT WESTERN WOODLANDS

The study by Prober et al. (2012) was focussed more on describing a climate change adaptation framework than on reporting the predicted impacts of climate change on the GWW, however the predicted shifts in suitable climate for the GWW were documented. The GWW was modelled by using the Coolgardie bioregion. Range contraction was the general prediction, with contraction extent increasing with severity of emission scenario. Some southerly direction shift of suitable climate was also predicted, however by 2070 under the high (A1FI) emission scenario no suitable climate remained.

3.4.6 NATIVE BIOTA: MITES

At the continental scale, indigenous species range shifts have been predicted for mites (Hill et al., 2012), and two studies have considered species distribution shifts of exotic plants (grasses – Gallagher et al. 2012, WoNS – O'Donnell et al. 2012) (Table 2). Hill et al. (2012) predicted the future distributions of three Blue Oat Mite species, Penthaleus major, P. falcatus, and P. tectus across southern Australia. The future distributions of all species were predicted to contract and become fragmented. Considering only southwestern Australian occurrences, predictions were for the ranges of P. major to contract further to the south west, the range of P. falcatus to contract further to the south coast, and for the range of P. tectus to contract but remain in the same location (Hill et al., 2012).

3.4.7 NATIVE BIOTA: TERRESTRIAL FAUNA REFUGIA

Future terrestrial refugia at the continental scale were predicted through a number of methods by Reside et al. (2013). Based upon records of 239 mammal, 599 bird, 218 amphibian, and 625 reptile species, areas of potential refugia were first predicted by locating regions of least climate shift (where species will be able to shift distributions to remain within climatic envelope), in addition to utilising SDMs to determine species richness, change in species richness, and species turnover (based upon number of immigrants and emigrants) for each grid cell. Based on distance required to move to remain within one or two standard deviations of current precipitation and temperature respectively, the majority of species will not have to move more than 50km to remain within their precipitation envelope. However, temperature changes are predicted to be much more extreme, and as a result moving greater distances is required to remain within temperature envelopes, with much of Australia requiring species to shift more than 500km by 2085. This analysis identified as potential refugia, the west coast between Cape Naturaliste to Perth and isolated spots along the south coast in the south west and the Flinders Ranges in South Australia (Reside et al., 2013). Based upon the median of 18 GCMs and RCP8.5, the distributions of nearly 1700 species were modelled across Australia for 2085 and species richness was calculated as the sum of presences in each grid cell. Of the groups considered, total species richness is predicted to remain relatively stable along the lower west coast and south west corner, with decreases in the rest of the south west, with similar patterns observed for analyses performed upon each taxonomic group in isolation. This pattern strongly matching that of the temperature change predictions mentioned above, and was again repeated when species movements were predicted, with areas of species immigration matching those of predicted richness increase or stability and relative stability of temperatures (Reside et al., 2013). Most of southwestern Australia was also deemed as suitable future refugia to some extent, based on both climatic and species richness and movement stability.

This report also considered other methods (as opposed to SDM) to investigate potential refugia, these are discussed in the relevant section below (Predictions for southwestern Australian biota).

3.4.8 NATIVE HABITAT: RAMSAR WETLANDS

Of the 12 RAMSAR wetlands in Western Australia, eight are located in the south west. James et al. (2013) incorporated the SDM models reported above for aquatic fauna with climate change prediction for surfaces and spatial extent and location of RAMSAR sites to determine their effectiveness in species conservation under future climate regimes. The southwestern Australian RAMSAR sites were found to be the least useful in terms of future suitability and thus refugia, as the species richness for all the taxa considered (fish, crayfish, and turtles) was predicted to decline. This predicted outcome was hypothesised to be due to decreases in precipitation and both local and accumulated run off (James et al., 2013).

3.4.9 EXOTIC BIOTA: GRASSES

Gallagher et al. (2012) considered the climatically suitable future ranges of 11 species of exotic grasses across Australia. Currently three of these are found in the south west, Cortaderia selloana, Eragrostis curvula, and Sporobolus africanus, however the south west region was deemed climatically suitable by 2050 for a further three species, being Nassella hyalina, Pennisetum polystachion, and Piptochaetium montevidense. The result of the MAXENT modelling for this study was range contraction for all species considered. Concerning the climatically suitable geographical area for the species currently found in southwestern Australia, Cortaderia selloana is predicted to contract further south west, while the ranges of Eragrostis curvula and Sporobolus africanus contract to the south coast (Gallagher et al., 2012).

3.4.10 EXOTIC BIOTA: WEEDS OF NATIONAL SIGNIFICANCE

The 72 WoNS species considered by O’Donnell et al. (2012) were utilised to determine potential invasion hotspots across Australia for 2020 and 2050, by summing the predicted climatic suitability across all species. Two hotspots were detected, one in south east Australia, the other in southwestern Australia. The southwestern hotspot extended approximately from the Capes (Naturaliste & Leeuwin) to Albany and 100km inland, covering 29,000km^2. Under climate change, the south west hotspot is predicted to contract further south, reducing in size to approximately 18,000km^2 by 2020 and 5,000km^2 by 2050. The number of species found in the southwest hotspot, according to Australia’s virtual herbarium, is 39; the current climate was found to be suitable for 53 species, this number decreased to 48 species by 2020, and 47 species by 2050.

3.5 PREDICTED IMPACTS OF CLIMATE CHANGE ON BIODIVERSITY OF SOUTHERN AUSTRALIA

The predicted impact of climate change on South Australian biota in the Flatlands cluster has been investigated using a range of approaches, which have attempted to tackle impacts at a number of levels. The primary focus of investigations in South Australia has been predictive distribution modelling of native and exotic plant species under alternative climate regimes, with a particular geographic focus on the Adelaide Geosyncline (which incorporates parts of the Adelaide & Mt Lofty Ranges, and Northern and Yorke NRM regions) (Appendix 1, Table A2). The technical approaches taken to understand these include a range of statistical modelling approaches (e.g. Maximum Entropy, Generalised Additive Models, Logistic Regression) using known distribution data, much of which forms part of systematic biological surveys of flora and fauna undertaken over a number of years in SA, or records for species collated as part of past NRM programs. However, a number of species-specific studies have also attempted to incorporate population genetics (McCallum et al., 2013), meta-population models (Fordham et al., 2012) and demographic models (Harris et al., 2012) (Appendix 1, Table A2).

Due to the large number of species utilised by Reside et al. (2013), reptiles and birds make up nearly 80% of SDM based studies of South Australian flora and fauna (Figure 3.5). As the data utilised by continental scale studies has been described in a previous section, it will not be repeated here. For studies considering South Australia, NCAR-CCSM was the most utilised GCM, followed by GFDL (2.0 &2.1), then BCCR and CSIRO-CC60. Five of the seven SA based studies(Crossman et al., 2008; Crossman et al., 2011; Guerin et al., 2013; Guerin and Lowe, 2013; McCallum et al., 2013) utilised BCCR, CSIRO-CC60, GFDL, and NCAR-CCSM GCMs, while Harris et al.(2012) incorporated GFDL, HADCM3, MIROC-H, MIROC-M, MIUB, MPI-ECHAM5, MRI-CGCM, and NCAR-CCSM GCMs, and CSIRO-Mk3.0, GFDL, HADCM3, HADGEM1, MIROC-M, MPI-ECHAM5, MRI-CGCM were utilised by Fordham et al.(2012) (Figure 3.6). The SRES emission scenarios (SRES, 2000) was the scenario utilised the most in SA studies (Figure 3.7). Under this scenario, warming is predicted to be in the order of 0.2-1.6°C in coastal areas to 0.6-1.8°C inland by 2030, and 0.6-1.8°C in coastal areas to 1.2-5.5°C inland by 2070.The next most utilised scenario is a future of CO_2 concentrations stabilising at 450ppm by 2100 with temperatures reduced from the SRES predictions by25% in 2030 and 48% in 2070 (Suppiah et al., 2006). Concerning timeframes, climate at 2030 and 2050 were the futures most often predicted, followed by 2070 (Figure 3.7). In addition, two studies incorporated annual time graduations, Fordham et al.(2012) from 2015 to 2080, and Harris et al.(2012) to 2100. The bioclimatic variables most often utilised by the SA studies were (in decreasing order of use) minimum temperature of the coldest month (BIO6), annual precipitation (BIO12), maximum temperature of the warmest month (BIO5), annual mean temperature (BIO1), and mean diurnal range (BIO2) (Figure 3.8). As with southwestern Australia, the typical predicted response by species to climate change is range contraction, the magnitude of this response also generally increasing with severity of climate change. The incorporation of demographic and management variables into several of the studies provided greater resolution predictions into likely outcomes of climate change.

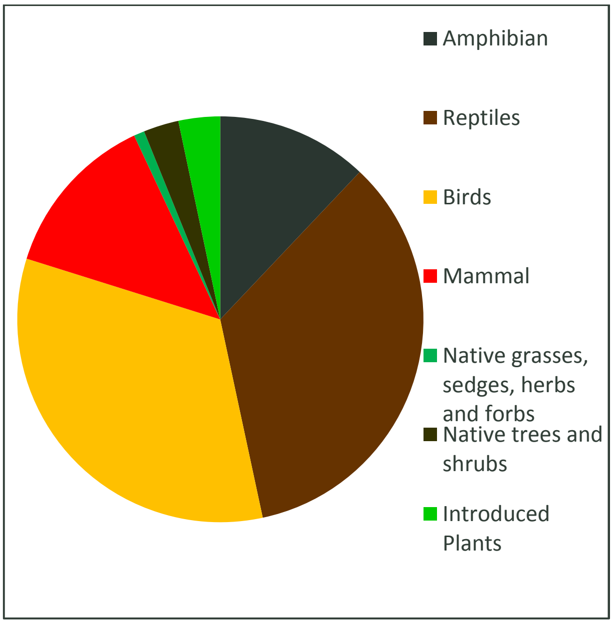

Figure 3.5 Summary of species utilised in SDM analyses incorporating South Australia.

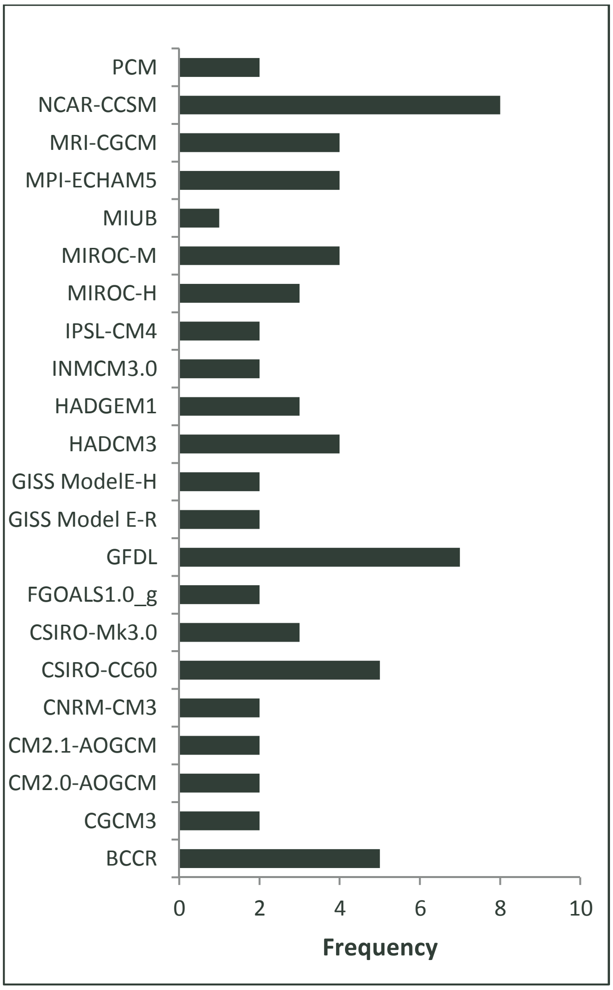

Figure 3.6 Frequency of GCM use in studies incorporating South Australia.

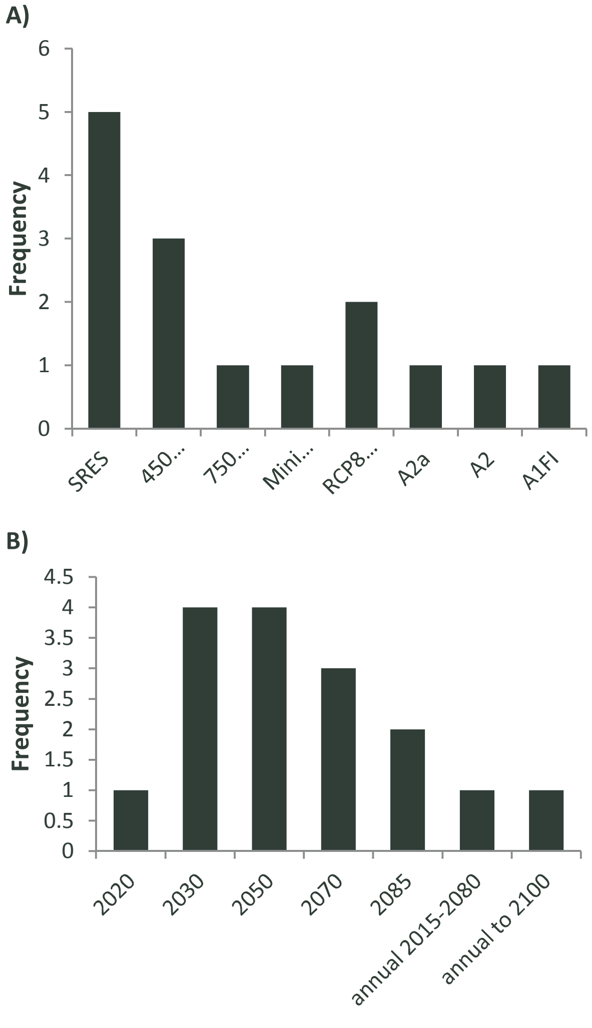

Figure 3.7 Frequency of A) emission scenarios and B) timeframes used in SDM studies incorporating South Australia.

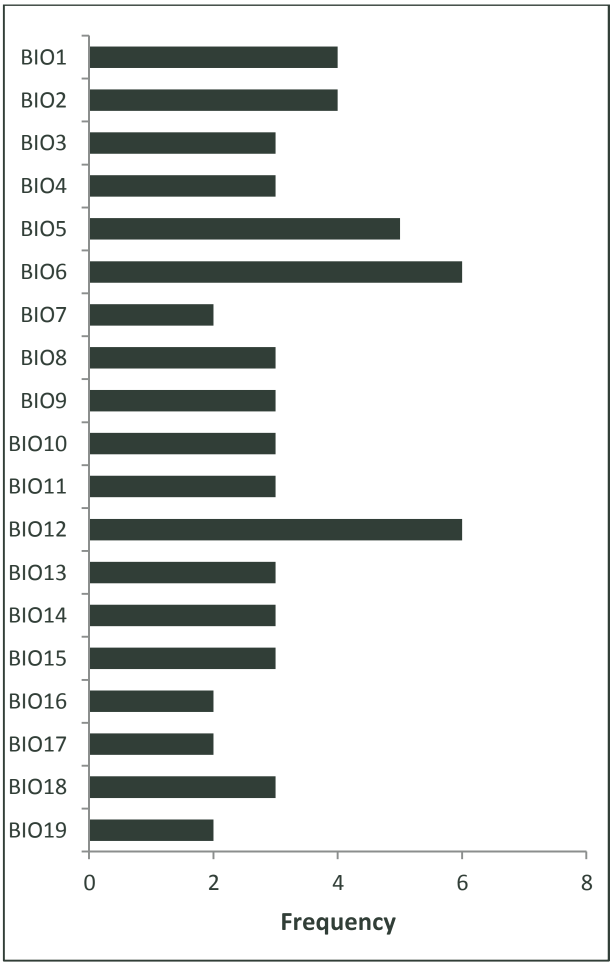

Figure 3.8 Frequency of predictor variable use in SDM studies incorporating South Australia.

3.5.1 NATIVE BIOTA: FLORA

Within the Adelaide Geosyncline, climate response predictions using SDMs have almost exclusively focused on native and exotic plant species. Within this limitation, however, the list of species for which predictive distribution models have been developed is significant. Guerin and Lowe(2013) modelled the predicted distribution of 20 vascular plant species under two alternative future climates, and found that the southern Mt Lofty Ranges and northern Flinders Ranges were likely to be relatively stable for these species with regard to climatic envelopes for these species, while the northern Mt Lofty Ranges and southern Flinders appeared to be most sensitive. Suitable climate tended to contract in range as opposed to southerly distribution shifts. Northern species and populations tended to be more affected by climate change, with predictions of widespread species contracting southwards, and northern species utilising altitudinal refugia (Guerin and Lowe, 2013). This study highlights the spatial heterogeneity of climate responses, and the need to articulate this spatial variation for the purposes of planning.

Crossman et al.(2008) also developed models of predicted distribution for a large number (889 species) of native flora species with more than 10 (for threatened species) or 20 (for non-threatened species) records. Range contraction was the general predicted response of these species' habitat to climate change, with range contraction increasing with severity of climate change scenario. They identified a list of native species (Acacia triquetra, Allocasuarina robusta, Prostanthera eurybioides, Pultenaea kraehenbuehlii, and Stackhousia aspericocca) likely to be sensitive to future climates in the southern Mt Lofty Ranges, including species that have formal conservation ratings. This study also performed similar analyses on exotic species in the Adelaide Mt Lofty Ranges NRM, the results of this are discussed in the relevant section below (Exotic biota: Flora)

3.5.2 NATIVE BIOTA: GLOSSY BLACK COCKATOO HABITAT

Beyond the Adelaide Geosyncline, there have been limited attempts to predict responses of biota to future climates using SDMs in SA. There have been little, if any impact studies that specifically address the terrestrial biota of the Eyre Peninsula, while the impact of future climates on the terrestrial biota of Kangaroo Island is restricted to the threatened Glossy Black

Cockatoo (Harris et al., 2012). This study modelled the predicted changes in the range of Drooping Sheoak (Allocasuarina verticillata), the seeds of which account for 98% of the Glossy Black Cockatoo diet (Harris et al., 2012).Under the lower impact future climate scenario, the geographical range of A. verticillata was predicted to remain much the same, yet significant range contractions to the higher altitude western region of the island were predicted under the high impact future climate scenario. The predicted response of the cockatoo incorporated aspects of the species' demography and is discussed in the relevant section below.

3.5.3 NATIVE BIOTA: AQUATIC FAUNA

The freshwater refugia study by James et al. (2013) considered the potential refugia of freshwater fishes, turtles, crayfish, and stream frogs. As with the south west, stream frogs were not included in the analyses for the South Australian Gulf, in addition, crayfish were not included for this region. Future richness of freshwater fishes in the South Australian Gulf region was predicted to remain stable, although this prediction was also associated with large variability across the GCMs utilised. It should be noted however, that the region South Western Plateau region was deemed to be the area likely to experience the greatest loss of freshwater fish richness. Very little change is predicted in the richness of freshwater turtles in this region.

3.5.4 NATIVE BIOTA: TERRESTRIAL FAUNA REFUGIA

In the report concerning future terrestrial refugia based on SDM analyses, Reside et al. (2013) predicted the Flinders Ranges to be a large region of refugia from increased temperatures. This study also found that refugia measures based on species richness and movement were concordant with the results of refugia based on temperature analyses. In South Australia, Gawler and the Flinders Lofty Block are predicted to increase in species richness, while most of coastal South Australia (with the exception of the Eyre Peninsula) and the Flinders Ranges were found to display as much, if not more, suitability as potential refugia than the south west (Reside et al., 2013).

3.5.5 NATIVE BIOTA: MITES

At the continental scale, Hill et al.(2012) predicted fragmentation of mite populations as a result of climate change. The predicted effects of climate change on these mites in South Australia were comparable to those of the south west, with range contraction into the Flinders Ranges being predicted for Penthaleus major and P. falcatus, with magnitude of contraction increasing with severity of climate change scenario. P. tectus also demonstrated range contraction but to a lesser extent, with the population also being located more northerly in the ranges, with an additional remnant population also located on the Eyre Peninsula.

3.5.6 EXOTIC BIOTA: GRASSES

Of the 11 exotic grass species modelled by Gallagher et al.(2013), four are currently found in South Australia (Cortaderia selloana, Eragrostis curvula, Nasella neesiana, and Sporobolus africanus), with future conditions being predicted to be potentially suitable for an additional three species (Nasella hyalina, Nasella trichotoma, and Piptochaetium montevidense). Concerning the predicted future distributions of the four species currently found in South Australia relative to the modelled current suitable climate, southward contractions to the coast are predicted for all.

3.5.7 EXOTIC BIOTA: WEEDS OF NATIONAL SIGNIFICANCE

The south east weed invasion hotspot identified by O'Donnell et al.(2012) included the lower Eyre Peninsula, the Yorke Peninsula, the Fleurieu Peninsula, and Kangaroo Island. As with the predictions concerning the south west hotspot, the geographic range of the south east hotspot is predicted to contract, the magnitude of this contraction increasing with time.

3.5.8 EXOTIC BIOTA: FLORA

Crossman et al.(2008; 2011) also investigated the predicted response of introduced plant species (126 species) to future climate scenarios in the southern Mt Lofty Ranges. Of the 126 species incorporated in the study, the majority of species distributions were predicted to contract; however, the ranges of nine were predicted to expand. Of these, Oncosiphon suffruticosum, Ulex europaeus and Vicia sativa presented the greatest potential range expansion and thus threat (Crossman et al., 2008; 2011). In addition, Crossman et al.(2011) attempted to incorporate seed dispersal models into climate response predictions for exotic plant species, as a way of understanding not only where the suitable climatic envelope for each species was likely to occur, but what was the probability of the species being able to disperse in order to remain within climatically suitable areas. This study was then used to determine which species were likely to be potential weed risks under future climates.

3.6 STUDIES INCORPORATING DEMOGRAPY INTO SDM METHODS

At a species level of organisation, a number of investigations relevant to southern South Australia have attempted to incorporate genetic, life history and demographic parameters into climate response models. The most comprehensive of these have focused on nationally threatened fauna – Kangaroo Island Glossy Black Cockatoo Calyptorhynchus lathami halmaturinus (Harris et al., 2012) and Pygmy Blue Tongue Lizard Tiliqua adelaidensis (Fordham et al., 2012). A third study predicted the effects of climate change upon Abalone (both Blacklip (Haliotis rubra) and Greenlip (H. laevigata)) (Fordham et al., 2013).

3.6.1 NATIVE BIOTA: GLOSSY BLACK COCKATOO

Although the habitat of the Glossy Black Cockatoo (A. verticillata) is predicted to decrease under high impact scenarios, incorporation of the cockatoo's life history characteristics (survival, fecundity, and age of first breeding) suggest that the factor likely to have a more profound impact upon the survival of this species is successful management of the Brush-Tail Possum (Trichosurus vulpecula), on Kangaroo Island (Harris et al., 2012).

3.6.2 NATIVE BIOTA: PYGMY BLUE TONGUE LIZARD

Fordham et al.'s(2012) study predicting the future impacts upon the Pygmy Blue Tongue Lizard considered the effects of climate change directly and indirectly upon the species, in addition to incorporating life history characteristics. The indirect effects of climate change were modelled through predictions of habitat change, in this case habitat being measured by modelling two indicator species of grassland habitat (Aristida behriana and Cryptandra campanulata), while demographic features considered were adult survival, fecundity, intrinsic population growth, and carrying capacity. Across all combinations of variables, climate change is expected to negatively impact abundances of the lizard, with the biggest differences in predictions being attributed to the utilisation of indirect/direct impacts as opposed to climate change scenario. Managed relocation of the lizards was deemed the better management response, resulting in greater predicted abundances than increasing habitat carrying capacity through artificial burrows (Fordham et al., 2012).

3.6.3 NATIVE BIOTA: ABALONE

In their study predicting the response of two species of abalone to climate change, Fordham et al. (2013) compared the results of different predictive methods. In addition to SDMs (referred to as ecological niche models (ENM) in the text), the authors utilised a coupled niche-population model and a biophysical ecological niche model. The coupled niche-population model incorporated life history and biophysical characteristics, of the specie and fishery related impacts, while the biophysical ecological niche models were based on ENMs but also incorporated thermal tolerances and the temperature associated mortality of recruits. While ENMs predicted slight changes in range sizes of both species as a result of climate change, the coupled-niche and biophysical ENM models both predicted range contractions for both species of abalone, with the niche models predicting lesser magnitude contractions than the biophysical models under the greater impact climate change scenario. Furthermore, it was predicted through the latter two modelling methods that both the range size and abundance of H. rubra will decrease in the future, however while the range size of H. laevigata is also predicted to contract, the population size of this species is not (Fordham et al., 2013). These attempts to incorporate features of species' ecology into climate response models provide examples of how such models can be improved, an approach advocated by other investigators (Keith et al., 2008).

4. OTHER APPROACHES FOR PREDICTING IMPACTS

Literature searches found four studies considering the effects of climate change in southwestern Australia using methods other than SDMs to predict future scenarios. Two of these studies were conducted at the ecosystem level, while species considered were Eucalypts (Hughes et al., 1996), and birds (Chambers et al., 2005) (Appendix 1, Table A4).

In a similar manner to SDMs, Klausmeyer and Shaw(2009) and Turner et al.(2011) utilised climatic data, GCMs, and emission scenarios to predict distribution shifts, however these studies analysed the geographical shift of climatic regions as opposed to species. Also considering processes at the ecosystem level, Catford et al.(2012) provide four recommendations to predict future impacts upon and changes to riparian ecosystems. Hughes et al.(1996) compared the current climatic variability experienced by Eucalypt species to expected future temperature and precipitation regimes to investigate the potential climatic shift presented to the Eucalypts. Chambers et al.(2005) provides a literature review of expected impacts to Australian birds, while Ludwig and Asseng (2006) utilised a full factorial design to test the impacts of predicted altered temperature, rainfall, and CO_2 concentrations on wheat production and quality.

4.1 PREDICTIONS FOR SOUTHWESTERN AUSTRALIAN BIOTA

In general, the alternative approaches utilised to investigate climate change impacts in southwestern Australia arrived at similar conclusions to that of the SDM methodology. Some of the predicted scenarios include - fragmented landscapes, reduced and degraded habitat, contraction of ecosystem range, loss of suitable habitat and/or bioclimate, and altered agricultural productivity.

The future Mediterranean climate extent was predicted by Klausmeyer and Shaw (2009). It was found that overall, on a global scale, the geographical area which complied with Aschmann's definition (Aschmann, 1973) of a Mediterranean climate increased by 106 to 111% of its current extent from low to high impact scenarios. However, this result was not consistent among the separate Mediterranean climate regions. The Mediterranean climate in southern Western Australia and southern South Australia was predicted to decrease in geographical area from 77 to 49% of its current extent from low to high impact scenarios respectively. This was the greatest decrease in area found among the Mediterranean climate regions and was due to warming winter temperatures not conforming to the definition of a Mediterranean climate (Klausmeyer and Shaw, 2009).

Novel riparian ecosystems in Australia arising due to climate change were forecast by Catford et al. (2012). Concerning the south west, they predicted an increase in exotic flora and extent of landscape fragmentation, decreased riparian zone area, homogenisation of associated biota, and decreased canopy cover potentially resulting in algal blooms and anoxic conditions. It is also projected that the south west riparian ecosystems present greater vulnerability to climate change than other Australian riparian systems as a result of their geographical isolation and high levels of endemism (Catford et al., 2012).

Based on 819 species of Eucalypts, Hughes et al. (1996) used the frequency distribution of species across binned temperature and rainfall ranges to compare the current climatic variability in which these species are found to the predicted future climates and the magnitude of climatic change expected. Approximating with a continent wide increase in temperature of 3°C, Hughes et al. (1996) determined that more than 50% of Eucalypt species distributions currently experienced less than 3°C annual temperature variability, resulting in complete climatic envelope displacement for these species. Considering an increase in temperature of 5°C, the number of species completely shifted out of their climatic envelope increases to 73%. Twenty three percent of Eucalypt species were found to possess geographic distributions experiencing ranges of 1.2 fold or less in average annual precipitation. The predicted change in rainfall of 20% across southern Australia exceeds this, resulting in another predicted climatic change which exceeds the current climatic variability experienced by a significant number of species. This study also mapped the distribution midpoints of species with distributions across low climatic variability. Although these species were found to exist Australia-wide, notable concentrations were detected along Western Australia’s mid-west coast (≈500km centred at 30°S), and south coast (≈Albany to Esperance) (Hughes et al., 1996).

Chambers et al. (2005) provided a literature review of expected climate change impacts to Australian birds. Potential impacts for southwestern Australian birds include – south-westward distribution shifts, habitat loss for wetland and tree associated species, migratory pattern alterations, and loss of narrow climatic range species.

Potential refugia locations across the continent were also investigated by Reside et al. (2013) based on species turnover (beta diversity) analysed through generalised dissimilarity modelling (GDM). In essence, this method is a regression of species turnover against that of environmental variables (Ferrier et al., 2007). In addition, topography was also integrated into the study to account for its effects upon the climatic variables and soil moisture. The effect of dispersal potential was also considered, yet very little difference was found between dispersal potentials of 1, 10, or 50km for species of Proteales, thus following analyses were based on an estimated dispersal capacity of 10km. Incorporating vascular plants, invertebrates and vertebrates in the analyses (mammals, birds, reptiles, amphibians, wasps &bees, beetles, spiders, lilies &onions, daisies, peas, fruitless seed plants, Myrtales, grasses &sedges, Proteales, and fungi), and utilising the GFDL and MIROC GDMs with the 6.0 and 8.5 RCPs, this study determined locations of potential refugia based on predicted turnover of species, with lower changes in species composition reflecting greater refugia potential. In explaining the turnover patterns observed for each group analysed, with the exception of amphibians, the environmental predictors explained more variability than geographic features, with the climate variables being the most important. Regolith was also found to be important for plants, particularly the Fabales and the W.A. endemic Tingle trees (Reside et al., 2013). Further to this, potential refugia location analyses were based upon Proteales (banksias, grevilleas etc.), Fabales (peas including acacias), reptiles, and amphibians. Potential future refugium for these four groups in southwestern Australia is concentrated along the coastline. This study then utilised the same methods to investigate at high resolution (30m) the potential refugia for the Tingle mosaic in southwestern Australia, the results of which are depicted in Figure 4.1.

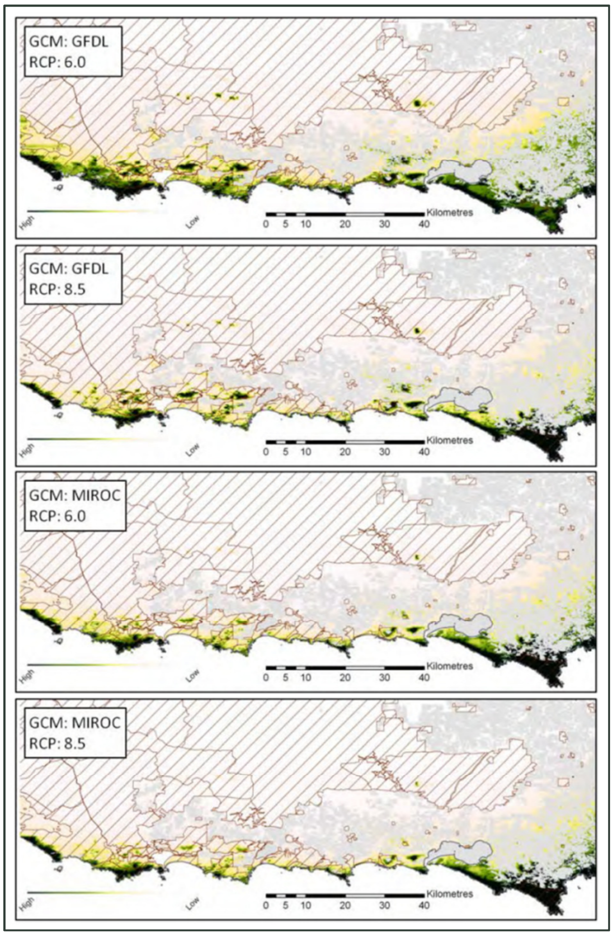

Figure 4.1 Potential future refugia for the Tingle mosaic. Hatched areas = protected land, Grey = cleared land. Figure from Reside et al. (2013)

Climate change is also expected to impact the marine environment. Potential impacts in the southern Australian marine realm include increased temperatures, ocean acidification, alteration to storm (disturbance) regimes, and disease outbreaks (Wernberg et al., 2011a). The ocean off southwestern Australia has increased in temperature by 0.013°C / year since 1951, while the ocean off the south coast of Australia has increased by 0.011°C / year since 1950, with future increases in the order of 1-3 over the next 100 years (Wernberg et al., 2011a). Similar to terrestrial ecosystems, increased ocean temperatures are likely to result in species poleward distribution shifts (Poloczanska et al., 2007). Ocean acidification due to increased atmospheric CO_2 concentrations decreases the calcification ability of organisms (i.e. shells of molluscs). An example of the impact of ocean acidification in southern Australia is upon calcified coralline algae. These species are an integral aspect of temperate Australian rocky substrate ecosystems, utilising up to 80% of substrate in suitable habitats. Ocean acidification is likely to impact the growth and recruitment of these species with associated ecological flow-on effects (Poloczanska et al., 2007; Wernberg et al., 2011a). Increased intensity and occurrence of storms will alter the disturbance regime to which the flora and fauna have adapted to and result in changes in structure in the communities through features such as removal of large patches of macroalgae, major habitat providing species in southern Australia (Poloczanska et al., 2007; Wernberg et al., 2011b). As with the terrestrial realm, southern Australian marine life is rich in endemics and thus extinction risk as a result of climate change is high (Poloczanska et al., 2007).

4.2 PREDICTIONS FOR SOUTH AUSTRALIAN BIOTA

To date, predicting biotic responses to future climates has largely been limited to the species level of biological organisation. In order to gain a more comprehensive understanding of the impact of climate change on biodiversity in southern Australia, we need to increase our understanding of the potential impacts of climate change on ecosystems. While the biotic components of ecosystems are, by definition, comprised of individual species, these species can often occur across different ecosystems, and are thus exposed to different biotic interactions and play different functional roles in these different ecological communities. One exception to this is the work undertaken by Guerin et al. (2013), who modelled the turnover of 1389 species of indigenous vascular plants using Generalised Dissimilarity Models (GDMs) as a function of geographic and climatic distance, to predict areas of low and high turnover under two alternative future climate scenarios and two time points (2030 and 2070). These investigations identified areas where rapid species turnover is likely to occur under future climates, potentially leading to rapidly changing ecosystem structure, function and composition in these areas. It was predicted by Guerin et al.(2013) that by 2030 under the low impact scenario the assemblages would display a difference of 0.25 (a value of 1 representing no species in common), and by 2070 under the most extreme scenario utilised, the assemblages would be 0.95 different from current assemblages. Regions in the study area which displayed rapid species turnover and are thus more likely to be subjected to species compositional changes as a result of climate change were where current average temperatures ranged from 15-17°C and average rainfall from 400-600mm. This corresponded with the lower slopes of the Mount Lofty Ranges and the higher altitude regions of the Flinders Ranges (Guerin et al., 2013). This work could also potentially act as a model for identifying biophysical settings that are likely to be relatively sensitive to future climates, in other landscapes of southern and southwestern Australia (Anderson and Ferree, 2010; Groves et al., 2012).

Kritikos et al. (2010)predicted future effects of climate change on weeds in South Australia, considering impacts upon both natural and agricultural biota. This study determined that, as with native flora, increased temperatures are likely to allow weed species to migrate further south and to higher latitudes. In an agricultural light, a possible threat is the greater genetic diversity found in weeds among a crop, potentially providing an adaptive and competitive advantage to the weeds in a changing climate. Furthermore, the tolerance of weeds to herbicides is testament to their resilience, a feature indicating that they are likely to cope with the altered climates as well, if not better, than their associated crops. In natural systems, predictions concerning weeds in South Australia include the likelihood that weed species likely to disperse great distances and effectively re-establish in new regions are those dispersed by animals moving through native vegetation corridors (Kriticos et al., 2010). On a regional level, the southern parts of the state are expected to experience greater weed threat under a dryer, warmer future. Through the Eyre Peninsula, Northern and Yorke, Adelaide and Mount Lofty Ranges and parts of the SA Murray Darling Basin regions, the climate suitability is expected to decrease for weeds; however, this will also be the case for native vegetation and crops in the region. The Kangaroo Island, South East and parts of Adelaide and Mount Lofty Ranges and parts of the SA Murray Darling Basin regions are expected to be more susceptible to weed invasions due to warmer temperatures. Recommended actions include determination of potential range shifts of weed species and implement control/eradication measures prior to movement of these species to inhibit them from entering regions of future climate suitability (Kriticos et al., 2010).

Investigations in South Australia to date have largely focussed on the relationship between standard bioclimatic variables (as listed above) and known species distributions. Temperature and rainfall, however, are not the only physical variables that are likely to change under a future climate. For example, Harris et al. (2012) highlighted the importance of a change in fire regime under future climates in predicting the persistence of the threatened Glossy Black Cockatoo on Kangaroo Island. Fire plays an important role in many temperate Australian ecosystems, and the relationship between climate, fire regime and biodiversity thus needs to be better understood (e.g. Yates et al., 2010). Investigations have also largely focussed on terrestrial biodiversity, while aquatic and marine biodiversity will respond to climatically driven features beyond temperature and rainfall. For freshwater aquatic ecosystems, surface-water and ground-water hydrology are key drivers of persistence, and so understanding the relationship between future climates and hydrology will also be critical. In South Australia, a preliminary climate change risk assessment has been undertaken for broadly defined water-dependent ecosystems (Harding, 2012). This initial assessment identified catchments in the southern agricultural, coastal, and Flinders Ranges areas as high priorities for further risk assessment. For near coastal terrestrial ecosystems, changes in sea level under future climates will have obvious implications. In South Australia, sea level rise risk assessments have been undertaken for the State’s coastline, with implications for assessing the risk to near-coastal terrestrial ecosystems (e.g. Caton et al., 2011). For marine ecosystems, water temperature and acidity have been highlighted as key drivers. Wernberg et al. (2011a) highlighted that marine species at the northern edge of their distribution (e.g. giant kelp) were likely to be at risk from climate change, while other species (e.g. sea urchin) were likely to benefit with regard to their distribution. Importantly, Wernberg et al. (2011a) also emphasised the central importance of synergistic interactions between climate change and other drivers, such as overharvesting and habitat destruction, in determining the viability of temperate marine species.

In their nation-wide analyses considering climate responses of Australian bird species (Garnett et al., 2013) discuss general trends concerning the impacts of climate change upon Australian birds. While detailed regional predictions were not made, it was discussed that 39 (23%) of the 167 Australian terrestrial and wetland bird species most at risk from climate change were found in southwestern Victoria and southern South Australia, similarly, 17 (10%) of these species inhabit Kangaroo Island. General comments made regarding Australian birds and climate change included – threats to birds are likely to intensify, not change, coastal species are the most at threat due to sea-level rise, and that habitat fragmentation is not a major issue concerning the future of birds. Forecasts predict that future climates will coincide with remnant vegetation in extensively cleared regions (Garnett et al., 2013).

In their terrestrial refugia predictions utilising GDMs and Proteales, Fabales, reptiles, and Amphibians as the species of interest, Reside et al.(2013) found that the tips of Eyre and Yorke Peninsulas, the Fleurieu Peninsula, Kangaroo Island, and some of the Flinders Ranges are likely locations of refugia in the future.

5. PREDICTED IMPACTS OF CLIMATE CHANGE ON AGRICULTURE

In addition to the native and exotic species, the expected climate change induced changes in temperature, precipitation, and CO_2 concentrations will also affect agriculture in southwestern and southern Australia (Foster, 2002; Bennett, 2010). As rainfall in southwest Australia is highly seasonal, with 80% of precipitation occurring over the winter months, the growing season of major crops coincides with this rainfall. This decrease in rainfall could then effectively reduce the growing season of crops, despite increased temperatures having the potential to increase the growing season and reduce the incidence of frost (Foster, 2002; Bennett, 2010). Increased CO_2 concentrations in association with slight (~1°C) temperature increases do have the potential to increase plant productivity through CO_2 fertilisation, however this effect will decrease and reverse with increasing temperatures. Another negative aspect of increased growth through CO_2 fertilisation is reduced plant quality through decreased protein content (Ludwig and Asseng, 2006; Bennett, 2010). Increased temperatures can reduce livestock quality through heat stress and reduced pasture quality, and also provide favourable conditions for pest species, both floral and faunal (Foster, 2002; Bennett, 2010).

5.1 PREDICTED IMPACTS OF CLIMATE CHANGE ON THE AGRICULTURE OF SOUTHWESTERN AUSTRALIA

In southwestern Australia, wheat, barley, canola, lupins, and oats are grown as commercial crops, wheat being the dominant crop (van Gool, 2009). Three predictive studies have been performed to assess the potential effects of climate change on crop production in southwestern Australia (Ludwig and Asseng, 2006; van Gool, 2009; Turner et al., 2011), which are summarised below.

The Western Australian Department of Agriculture and Food has published several reports detailing expected futures for crop production in southwestern Australia. These reports were based upon predicted changes in crop productivity from 1995-1999 to 2050, using CSIRO GCMs and climate predictions from Ozclim (van Gool, 2009). A summary of the results concerning expected decreases in production and area suitable for each crop is presented in Figure 5.1. In general, both yield and suitable area are predicted to decrease as a result of climate change. Wheat yield and area reduced in potential by more than 10% are predicted to decrease by 11% and 42% respectively, with the greatest decrease in yield predicted for wheat, with the greatest reductions occurring in the east of the northern agricultural region. Decrease in yield in this region is attributed to the predicted decrease in precipitation and increased temperature resulting in drier soils, increased disease, and reduced crop growth (van Gool, 2009).

The region most likely to exhibit the greatest reductions in potential barley yield (north of Three Springs) is not a major growing region of this crop, therefore overall production of barley is not expected to be greatly impacted (decreased yield of 6%), despite 43% of land presenting more than a 10% decrease in potential. Canola crop yield is expected to decrease by 7%, with 45% of land experiencing greater than 10% reductions in canola crop suitability. Lupins displayed the least decrease in area with greater than 10% potential reduction (27%), possibly due to this crop currently being grown mostly in the north. A 5% reduction in lupin yield was also predicted by 2050. The least affected crop in the predictions, yield wise, is oats with a predicted reduced yield of 4%, and 40% of area predicted to reduce in productivity by more than 10% by 2050 (van Gool, 2009) (Figure 5.1).

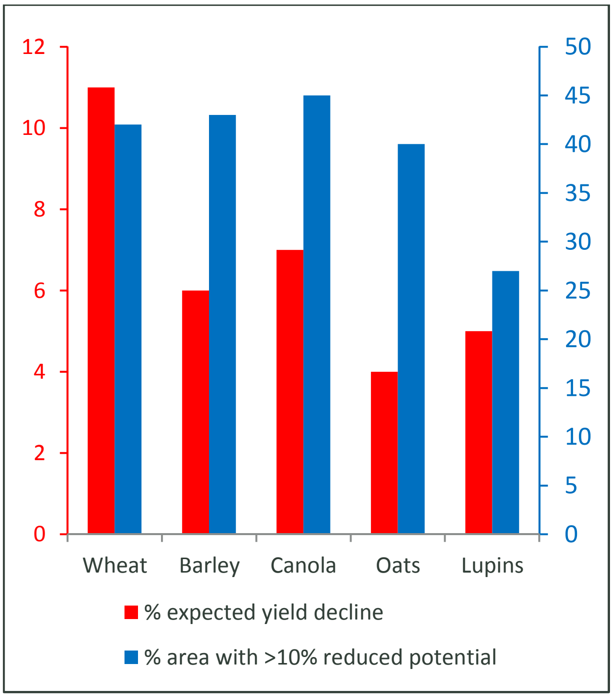

Figure 5.1 Expected decreases in crop yield and suitable cropping area as a result of climate change(Data from van Gool (2009))

Ludwig and Asseng (2006) investigated the effect of altered temperature, rainfall, and atmospheric CO_2 concentration on the crop production of wheat (Triticum aestivum). This study utilised a crop simulation model, Agricultural Production Systems Simulator (APSIM), to determine changes in wheat crop yield and protein content based on altered climatic conditions across soil types at three locations in southwestern Australia (Binnu, Kellerberrin, and Kojonup). A range of potential future conditions were modelled, but results presented were based upon two likely scenarios – 15% reduction in rainfall, 2°C increase in temperature, and 525 ppm CO_2 concentrations by 2050, and 30% reduction in rainfall, 4°C increase in temperature, and 700 ppm CO_2 concentrations by 2100. It was found that predicted responses to changes in temperature and rainfall were not linear, and that these variables interact with increased levels of CO_2. It was expected that the negative effects of increased temperatures will be offset by the increased production resulting from increased CO_2 concentrations, thus Ludwig and Asseng (2006) predicted that reduced rainfall is likely to be the climatic variable of most concern for crop production in southwestern Australia. Furthermore, soil type and location were found to influence the magnitude and direction of climate change related impacts. Relative to the baseline (1954–2003) production, under the 2050 conditions little change was expected at Binnu and Kellerberrin over sandy loam and duplex soil, but decreased production was predicted over clay soils. Increased production was predicted at Kojonup, with decreasing magnitude of increase over sandy loam, duplex soil, and then clay soil. Similar patterns of change in production were predicted for the 2100 scenario, with decreased production across all soil types at Binnu and Kellerberrin, again the greatest decrease being over clay soils. Increased production was forecast at Kojonup over sandy loam and duplex soils, with little change relative to current production levels over clay soils.

Predicted changes in temperature and rainfall for the crop growing regions of southwestern Australia and Loess Plateau in China were considered by Turner et al. (2011), recommendations for future crop growing practices were then made, taking the altered climate into consideration. Suggested practices for southwestern Australia include – selection of deep rooting wheat varieties to take advantage of early vigour, addition of nutrients and micronutrients which increase plant heat tolerance, taking advantage of the decrease in the incidence of frost and plant longer season crops earlier to provide higher yield through longer growing season, crop rotations with the use of genetically modified crops to limit the impact of weeds and pests, the use of fertilisers (particularly nitrogen), conversion of species better suited to the new climate (i.e. oats to wheat as climate dries), and conservation of and increased efficiency in water use (Turner et al., 2011).

5.2 PREDICTED IMPACTS OF CLIMATE CHANGE ON THE AGRICULTURE OF SOUTH AUSTRALIA

Within the NRM regions of South Australia that this program addresses, agricultural industries are largely dominated by dryland cereal cropping and sheep and beef cattle grazing. These two agricultural pursuits are often undertaken on the same paddocks, rotated on annual or longer cycles. Other important agricultural industries in this region are horticulture (particularly grapes and stonefruit), although these tend to be restricted to particular physical environments (e.g. southern and central Mt Lofty Ranges).

Liddicoat et al. (2012) investigated predicted changes in wheat yields and soil erosion risks for the South Australian agricultural zone, using a combination of mapped soil features and future climate models. The authors found that, across the agricultural zone, the exposure of wheat crop yields to drying climates varied among soil types and climatic zones. For example, sandy soils tended to be more resilient than clay soils in lower rainfall cropping areas. However, the lower rainfall cropping areas are also likely to be the least viable for cropping under future climates, particularly under the more extreme emission scenarios. For the regions within the scope of this project, the northern Eyre Peninsula (Eyre Peninsula NRM region) and southern Flinders Ranges (Northern and Yorke NRM region) appear to be most susceptible, while the northern Yorke Peninsula is also predicted to have significantly reduced yields. However, wetter parts of the state, where water is less limiting (and growing season becomes more limiting), may benefit with respect to wheat yields (Liddicoat et al., 2012). Furthermore, a future drying climate in these marginal landscapes is also likely to increase the risk of soil erosion, which will further limit the viability of cropping industries in these landscapes.

The impact of future climates on other agricultural industries is less well understood. Preliminary investigations are underway to predict the response of South Australian viticulture to future climates, based on some generally well understood responses of grape quality and volume to climatic variables (Hayman et al., 2009).

Appendix A Additional Tables

A1. Summary of the possible methods for making ecological predictions.

Method	Approach	Strengths	Weaknesses	Main uses
Extrapolation	Assume existing trends persist.	Requires little data. Easy. Reveals issues.	Assumes current trends persist, but this is often unlikely, for example density dependence may intervene.	Predicting population change. Extrapolation of changes in distribution in relation to predicted climate change.
Experiments	Experimentally introduce environmental change of interest.	Excellent as shows real response. Reveals unexpected interactions.	Usually impossible. Replicated, long-term large scale experiments are expensive.	Could be used for most issues but usually too slow and expensive. Routine experimental assessment of response to conservation management could revolutionize conservation.
Phenomenological models	Combine the quantified demographic components.	Superb for unravelling mechanisms and making predictions within existing parameter values.	Can be difficult to quantify density dependence. Difficult to extrapolate to novel conditions. In practice many models are based on flimsy science so warranting little faith in their conclusions.	The backbone of ecology.
Game-theory population models	Determine density-dependent processes (depletion, interference, territoriality or social rank) and assess population consequences assuming optimal settlement decisions.	Can consider responses to novel conditions. Individuals behave in a sensible manner.	Often assumes individuals have perfect knowledge of environment. Some parameters may be unknown.	Combined with phenomenological models to predict distribution or population response of vertebrates to habitat change.
Expert opinion	Experts asked to predict response. May be feedback on response to produce a consensus (Delphi technique	Only possible approach when no other information.	No guarantee that linked to reality. Opinion can be confused with	Informal expert opinion underpins most conservation decisions. Formal use of expert opinion could usefully

	and nominal group technique) or ranking of experts.		knowledge.	assess the policy response to the available information. Delphi technique could be used for converting evidence into practice
Outcome-driven modelling	Consider limited range of outcomes for complex problems. Estimate probability of each outcome.	Can use a wide range of information and readily update. Easier to examine and challenge. Can be made more rigorous as more information available so in theory eventually becomes mechanistic model.	Less rigorous than mechanistic models.	Could be used for complex problems where limited responses.
Scenarios	Response to a range of possible future states considered.	Can consider complex problems. Useful for assessing decisions against possible changes.	Not predictive. Subjective.	Used widely in business. Has been used to assess whether GM crops should be grown in UK. Could be used to consider possible responses to complex ecological problems.

Source: Sutherland (2006)

A2. Summary of studies using SDMs to predict future ranges of species in southwestern and southern Australia.

Author(s)	Year	Species/Group	Modelling Program	GCM(s)	Emission Scenario(s)	Timeframe	Region
Fitzpatrick et al.	2008	Banksia	Maxent	CGCM1, CSIRO2, HadCM3	B1, A1B, A1F	decadal 2000 - 2080	SW
Gibson et al.	2010	Quokka	Maxent	MIROC-H, MIROC-M, CSIRO Mk 3.5	B1, A1B, A1FI	2030, 2050, 2070	SW
Yates et al.	2010	Banksia	Maxent	MIROC-H, MIROC-M, CSIRO Mk 3.5	B1, A1B, A1FI	2030, 2050, 2070	SW
Hill et al.	2012	Mites	Maxent	23 GCM ensemble	A1FI	2030, 2050, 2070	Aust.
O'Donnell et al.	2012	WoNS	Maxent	BCCR:BCM v. 2.0, CSIRO Mk 3.5, INMCM3, MIROC-M	A2	2020, 2050	Aust.
Gallagher et al.	2012	Exotic grasses	Maxent	BCCR:BCM v. 2.0, CSIRO Mk 3.0, CNRM CM3, MIROC-M	A2a	2050	Aust.
Davies	unpub.	Frogs	Maxent	CCCMA-CGCM2, CSIRO Mk2, HCCPR-HadCM3	A1B, A2a, B2a	2020, 2080	SW
Davies	unpub.	Freshwater Fishes	Maxent	CCCMA-CGCM2, CSIRO Mk2, HCCPR-HadCM3	A1B, A2a, B2a	2020, 2080	SW
Davies	unpub.	Aquatic Invertebrates	Maxent	CCCMA-CGCM2, CSIRO Mk2, HCCPR-HadCM3	A1B, A2a, B2a	2020, 2080	SW
Molloy et al.	2014	Western Ringtail Possum	Maxent & Domain	CSIRO Mk 3.5, MIROC-M and ECHO-G	A2a	2050	SW
Molloy et al.	2014	Possum arboreal habitat	Maxent	CSIRO Mk 3.5, MIROC-M and ECHO-G	A2a	2050	SW

Prober et al.	2012	Great Western Woodlands	Maxent	23 GCM ensemble	B1, A1B, A1FI	2030, 2050, 2070	SW
Crossman et al.	2008, 2011	Mt Lofty Ranges native plants	Maxent, Logistic Regression, GRASP	Maximum change from mixed model of Suppiahet al. (2006)	SRES	2030	MLR (SA)
Fordham et al.	2012	Pygmy Blue Tongue, key habitat grass species	BRTs	MRI-CGCM2.3.2, UKMO-HadCM3, MIROC3.2 (medres), CSIRO-Mk3.0, GFDL-CM2.0, ECHAM5/MPI-OM, UKMO-HadGEM1	MiniCam (ref), MiniCam (Level 1)	Annual 2015-2080	Northern MLR (SA)
Guerin et al.	2013	20 native shrub species	GAM, Maxent	“various climate change scenarios and models”		2030, 2070	Adelaide Geosyncline (SA)
Harris et al.	2012	Glossy Black Cockatoo	Ensemble of 7 models: BIOCLIM, Euclidian and Mahalanobis distances, GLMs, Random Forest, Genetic Algorithm for Rule Set Production, and Maxent	9 GCMs	LEV1 (450ppm), WRE750 (750ppm)	Annual 2011-2100	Kangaroo Island (SA)
McCallum et al.	2013	Needle Bottlebrush	Maxent	Minimum and maximum change from mixed model of Suppiah et al. (2006)	SRES, 450ppm	2030, 2070	Adelaide Geosyncline (SA)
James et al.	2013	Freshwater fish, crayfish, and turtles	Maxent	18 GCMs	RCP 8.5	2085	Aust.
Reside et al.	2013	Mammals, birds, amphibians, and reptiles	Maxent	18 GCMs	RCP 8.5	2085	Aust.

A3. Summary of SDM predicted effects of climate change on species found in southwestern and southern Australia.

Species (Common name)	Range contraction	Range expansion	Extinction possible	Southward migration	Westward migration	Increased impact with increased severity
Setonix brachyurus (Quokka)	✓		✓	✓		✓
Banksia burdettii (Burdett's Banksia)	0 dispersal	∞ dispersal	✓	✓		✓
Banksia candolleana (Propeller Banksia)	0 dispersal	∞ dispersal		✓		✓
Banksia hookeriana (Hooker's Banksia)	0 dispersal	∞ dispersal		✓		✓
Banksia laricina (Rose Banksia)	0 dispersal	∞ dispersal		✓		✓
Banksia leptophylla (Slender-leaved Banksia)	0 dispersal	∞ dispersal		✓		✓
Banksia baueri (Woolly Banksia)	✓			✓	✓	✓
Banksia baxteri (Baxter's Banksia)	✓			✓	✓	✓
Banksia coccinea (Scarlet Banksia)	✓			✓	✓	✓
Banksia dryandroides	✓			✓	✓	✓

(Dryandra-leaved Banksia)						
Banksia gardneri (Prostrate Banksia)	✓			✓	✓	✓
Banksia media (Southern Plains Banksia)	✓			✓	✓	✓
Banksia nutans (Nodding Banksia)	✓			✓	✓	✓
Banksia repens (Creeping Banksia)	✓			✓	✓	✓
Banksia attenuata (Candle Banksia)	0 dispersal	∞ dispersal		✓		✓
Banksia grandis (Bull Banksia)	0 dispersal		✓	✓		✓
Banksia ilicifolia (Holly-leaved Banksia)	0 dispersal			✓		✓
Banksia menziesii (Firewood Banksia)	0 dispersal	∞ dispersal		✓		✓
Banksia prionotes (Acorn Banksia)	0 dispersal			✓		✓
Penthaleus major (Blue Oat Mite)	✓			✓	✓	
Penthaleus falcatus (Blue Oat Mite)	✓			✓		
Penthaleus tectus (Blue Oat Mite)	✓					
Banksia (100 spp.)	85%	6%	Up to 24%			

Cortaderia selloana (Pampas Grass)	✓			✓		
Eragrostis curvula (African Lovegrass)	✓			✓		
Nassella hyalina (Cane Needle Grass)		New		✓	✓	
Pennisetum polystachion (MissionGrass)		New		✓		
Piptochaetium montevidense (Uruguayan Rice Grass)		New			✓	
Sporobolus africanus (Rat's Tail Grass)	✓			✓		
Nasella neesiana (Chilean Needle Grass)	✓			✓		
Nasella trichotoma (Serrated tussock)		New		✓		
Callistemon teretifolius (Needle Bottlebrush)	✓					
Calyptorhynchus lathami halmaturinus (South Australian glossy black-cockatoo)			✓			
Tiliqua adelaidensis (Pygmy Blue Tongue)			✓			
Acacia lineata (Narrow Lined-leaved Acacia)	✓					✓
Acacia pinguifolia (Fat-leaved Wattle)	✓					✓

Acacia rhigiophylla (Dagger-leaved Wattle)	✓	✓				
Allocasuarina robusta (Mount Compass Oak-bush)	✓					✓
Austrostipa mollis group (Soft Spear-grass)	✓					✓
Carpobrotus rossii (Karkalla)	✓					✓
Correa aemula (Hairy Correa)	✓					✓
Correa pulchella	✓					✓
Prostanthera eurybioides (Monarto Mintbush)	✓					✓
Carpobrotus modestus (Inland Pigface)	✓					✓
Dodonaea humilis	✓					✓
Helichrysum rutidolepis (Button Everlasting)	✓					✓
Olearia picridifolia (Daisy-bush)	✓					✓
Podolepis rugata var. rugata (Pleated Podolepis)	✓					✓
Acacia menzelii (Mezel’s Wattle)	✓					✓

Acacia triquetra	✓					✓
Acaena echinata (Sheep's Burr)		✓				
Acrotriche cordata (Coast Ground Berry)	✓					✓
Allocasuarina mackliniana ssp. Mackliniana (Western Sheoak)		✓				
Beyeria opaca (Dark Turpentine Bush)	✓					✓
Caladenia rigida (Spider Orchid)	✓					✓
Eragrostis eriopoda (Love Grass)		✓				
Eucalyptus diversifolia (Coast Gum)	✓					✓
Eucalyptus yalatensis (Yalata mallee)	✓					✓
Gahnia ancistrophylla (Donkey Saw-sedge)		✓				
Gahnia deusta (Heathy Saw-sedge)	✓					✓
Hypericum japonicum (Matted St John's Wort)	✓					✓
Lomandra juncea (Desert Mat-rush)	✓					✓

Olearia lepidophylla (Club-moss Daisy-bush)	✓					✓
Pomaderris obcordata (Pimelea Pomaderris)		✓				
Prostanthera aspalathoides (Pixie Caps)	✓					✓
Pseudanthus micranthus (Fringed Pseudanthus)		✓				
Pterostylis dolichochila (Long-tongued Shell Greenhood)	✓					✓
Pultenaea kraehenbuehlii (Tothill Bush-pea)	✓					✓
Rhagodia ulicina (Spiny Goosefoot)	✓					✓
Schizaea bifida (Forked Comb Fern)	✓					✓
Schoenus laevigatus (Short-leaf Bog-sedge)	✓					✓
Sclerolaena patenticuspis (Spear-fruit Saltbush)	✓					✓
Stackhousia aspericocca (Rough-nut Stackhousia)	✓					✓
Utricularia dichotoma (Aprons)	✓					✓
Veronica hillebrandii (Coast Speedwell)	✓					✓

Vittadinia australasica (Coast New Holland Daisy)	✓					✓
Freshwater fish richness	✓			✓		
Crayfish richness	Stable (no Engaewa spp.)					
Turtle richness	Stable					
Mammals (239 spp.)	✓			✓		
Birds (599 spp.)	✓			✓		
Amphibians (218 spp.)	✓			✓		
Reptiles (625 spp.)	✓			✓		
Frogs	✓			✓	✓	✓
Freshwater fishes	✓			✓	✓	✓
Aquatic invertebrates	✓			✓	✓	✓
Great Western Woodland	✓		✓		✓	✓

A4. Summary of studies using alternative methods to predict future conditions in southwestern and southern Australia.

Author(s)	Year	Species/Group	Method	Predicted future climate	Location
Klausmeyer & Shaw	2009	Mediterranean ecosystems	Averaged future climate simulations to determine future Mediterranean climate extent	23 AOGCMs & B1, A1b, and A2 scenarios for 2070-2099.	Global
Catford et al.	2012	Riparian ecosystems	Used process models, functional groups, analogue systems, and migration/dispersal/adaptive potential to hypothesise novel ecosystems	Aust. Av. = 0.6-1.5°C increase by 2030, 2.2-5°C by 2070. Decreased rainfall.	Aust.
Hughes et al.	1996	Eucalyptus	Frequency distributions of climate amplitudes	Warming of 0-2°C by 2030, 0-5°C by 2070. Northern increase in rainfall by up to 20% (2030) to 40% (2070), southern decreases of between 0% - 20%.	Aust.
Chambers et al.	2005	Birds	Literature review	0.4-2°C increase by 2030, 1-6°C increase by 2070. Decreased rainfall and increased climatic variability.	Aust.
Ludwig & Asseng	2006	Wheat	Full factorial design	Used historic and 2, 4, and 6°C increase in temp. Historic and -15%, -30%,-60% and +10% rainfall. 350, 525, 700 ppm CO_2 concentration.	SW
Turner et al.	2011	Crops	Predicted future regional climates	CSIRO GCM with A2a scenario for 2050 & 2080.	SW & China
Guerin et al.	2013	Ecological communities	Predicted distribution of species turnover using GDM (current and future climates)	0.4-3.8°C increase in mean annual temp.; up to 30% decrease in mean annual rainfall (minimum and maximum change from Suppiah et al. (2006) mixed model)	Adelaide Geosyncline
Fordham et al.	2012	Pygmy Blue Tongue	Coupled climate envelopes, habitat suitability models and stochastic demographic models, along with predicted responses to alternative management strategies	see Appendix 1, Table A2	Northern MLR (SA)
Harris et al.	2012	Glossy Black Cockatoo	Coupled habitat suitability and population models to predict response to climate, fire, disease and	see Appendix 1, Table A2	Kangaroo Island (SA)

			management		
McCallum et al.	2013	Needle Bottlebrush	Coupled SDMs with population genetic analysis to identify genetic refugia	see Appendix 1, Table A2	Adelaide Geosyncline
Reside et al.	2013	Terrestrial refugia	GDM	GFDL-CM2 & MIROC-M with RCP 6.0 & RCP 8.5	Aust.
Reside et al.	2013	Tingle mosaic	GDM	GFDL-CM2 & MIROC-M with RCP 6.0 & RCP 8.5	SW

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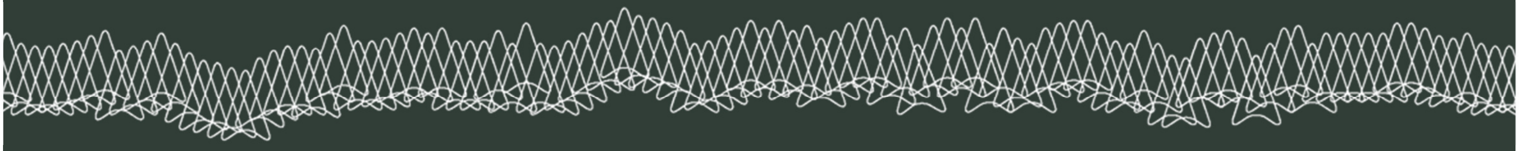

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