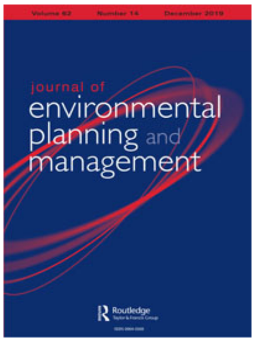

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Prioritizing the protection of climate refugia: designing a climate-ready protected area network

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Protected areas are the primary strategy for maintaining natural landscapes and separating biodiversity features from preventable anthropogenic threats. The Convention on Biological Diversity calls for the coverage of at least 17% of land by protected areas, and the strategic prioritization of important biodiversity areas. Using the spatially explicit reserve design software, Marxan, this study combines climate refugia modelled under future climates in the year 2070 and bioregions to identify priority sites for protected area expansion under climate change in the state of New South Wales (NSW), Australia. Priority sites for new protected areas that meet bioregion and climate refugia targets were identified in central-western, northeast and patches of southeast NSW. Seven existing parks, including Kosciuszko National Park, overlapped with regions identified repeatedly as climate refugia under 12 future climate scenarios. The recommendations from this study support policy-makers in prioritizing the protection of biodiversity under a changing and uncertain climate.

Keywords: conservation planning; protected areas; spatial prioritization; biodiversity; climate change

1. Introduction

Global average temperature has increased by 1.1 °C since 1880 (WMO 2017). Observed impacts of climate change in the twenty-first century include shifting species ranges, changes in population sizes, phenological adjustments, as well as genetic changes (Pecl *et al*. 2017; Scheffers *et al*. 2016). The consequences of climate change will intensify into the future with global temperature expected to increase by 1.5–4.8 °C by 2100 and precipitation patterns predicted to undergo spatial and temporal alterations (IPCC 2014). In periods of intense climate variability, climate refugia can support species' persistence (Keppel *et al*. 2012; Tzedakis *et al*. 2002), and

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therefore, their protection is becoming a commonly prioritized conservation target (Jones *et al*. 2016). Protected areas provide a safe haven for species in a changing environment, buffering them against preventable habitat loss, fragmentation and localized-climate change (UNEP-WCMC and IUCN 2016). By conserving intact vegetation, protected areas also sequester ~20% of all terrestrial carbon, thereby performing an important climate change mitigation function (Melillo *et al*. 2016).

As some species respond to climate change by shifting geographic ranges, the ability of the existing protected area network to conserve species in the longer term may decline (Chen *et al*. 2011; Hughes 2000; Peters and Joan 1985). There is also evidence that novel climates are leading to the establishment of communities for which there is no present-day analogue, and about which we lack a detailed understanding (Williams and Jackson 2007).

In 2010, the parties to the *Convention on Biological Diversity* (CBD) adopted a set of ambitious international targets for expanding and strengthening the protected area network to cover at least 17% of land by 2020 (Aichi Target 11 from the CBD 2011). The targets also call for the strategic prioritization of "areas that are of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas".[1] Priorities for building a more "climate-ready" protected area network to support biodiversity conservation and species adaptation to climate change should focus on expansion in locations that overlap the distributional shifts predicted to occur under climate change (Maggini *et al*. 2013). However, future climates are uncertain, and the impact of climate change on biodiversity is spatially and temporally heterogeneous (Buisson *et al*. 2010; Guisan *et al*. 2013). Forecasting the impacts of climate change on species and habitats under a range of plausible future climate scenarios can reveal high priority locations for protection, where species are most likely to experience tolerable climatic changes and which, therefore, support species survival (Moilanen *et al*. 2006). Conservation decision making under climate change should also adopt a framework that considers economic and resource constraints, as this information can be readily translated into climate adaptation policy (Maggini *et al*. 2013; Wintle *et al*. 2011).

In Australia, the National Reserve System (NRS) is the core instrument for conserving Australia's terrestrial biodiversity. The NRS is guided by the CAR framework of comprehensiveness, adequacy, and representativeness (NRMMC 2009). This framework aims to sample (protect) all biodiversity at multiple spatial scales, including broad-scale bioregions (*comprehensiveness*) and fine-scale subregions (*representativeness*). In this study, we focused on the state of New South Wales (NSW), Australia. Following the federal approach, NSW has adopted the CBD target of protecting at least 17% of terrestrial land by 2020 (State of NSW and OEH 2017), to fill known representation gaps in the protected area network and to prioritize the protection of key habitats for threatened or migratory species, wetlands, refugia, or areas of high connectivity value or importance for climate adaptation (NRMMC 2009).

Climate change will affect the current NSW protected area network by causing some species to move out of protected areas, potentially changing the boundaries of bioregions, reducing the adequacy and representativeness of protected areas and increasing species' exposure to threats. Identifying new sites for protection that make the NSW protected area network "climate-ready" is critical for the protection of species and habitats under a changing climate.

The goals of this study are to: (1) evaluate how the current protected area network of NSW captures predicted sites of climate refugia, and (2) model the optimal placement of new protected areas to meet conservation targets under a changing climate. We use a geographic information system (GIS) to measure the overlap of NSW's protected areas and climate refugia, derived from developed models of the distribution of suitable habitat for NSW biota (Baumgartner, Esperon-Rodriguez, and Beaumont 2018) that revealed climate refugia in the state under 12 equally plausible future climate scenarios, to identify sites that will support species' persistence under climate change. We also use the reserve design software Marxan to identify priority sites for new protected areas that meet national and international targets for biodiversity under climate change, while restricting land acquisition costs. The outputs of our analysis can support the design of a "climate-ready" protected area network.

2. Methods

We used the geographic information system ArcGIS version 10.2 (ESRI 2013) to measure the overlap between the current protected area network and predicted sites of climate refugia, and to prepare the input files required for the Marxan analysis. All raster data were projected to the NSW Lambert Conformal Conical projection using the GDA94 datum (i.e. EPSG:3308). The term "coverage" indicates the proportion of the Interim Biogeographic Regionalization for Australia (IBRA) subregions and the 12 climate refugia that are included in the protected area network. We measured the total overlap of subregions and climate refugia with protected areas in NSW (Figure 1) and

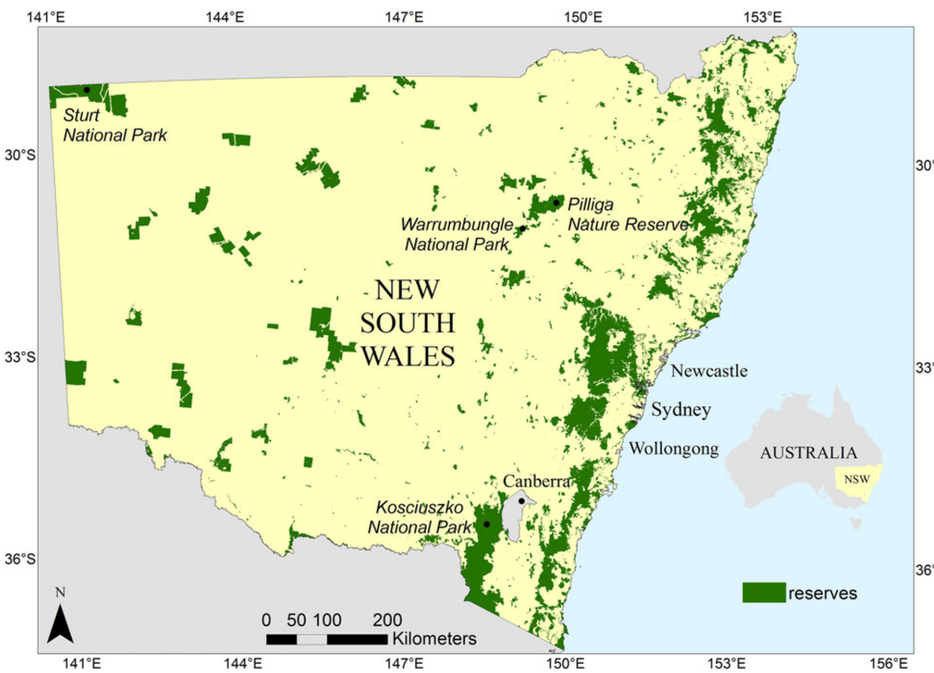

Figure 1. Location of 1,010 protected areas covering ~76,000 km^2 in New South Wales, Australia (CAPAD 2014).

compared this to Aichi Target 11 of 17% coverage of subregions (CBD 2011). We used the conservation planning software Marxan version 2.1.1 (Ball, Possingham, and Watts 2009; Watts *et al*. 2009) to identify optimal locations for future protected area expansion in NSW. Details of this analysis are given below.

2.1. Study region

Our study region included the mainland of NSW, Australia, which spans a total area of ~800,000 km^2 of which ~75,000 km^2 is covered by protected areas (~9%; Figure 1; CAPAD 2014). This region excludes the Commonwealth (Australian) Jervis Bay Territory and the Australian Capital Territory (ACT), and the Pacific Subtropical

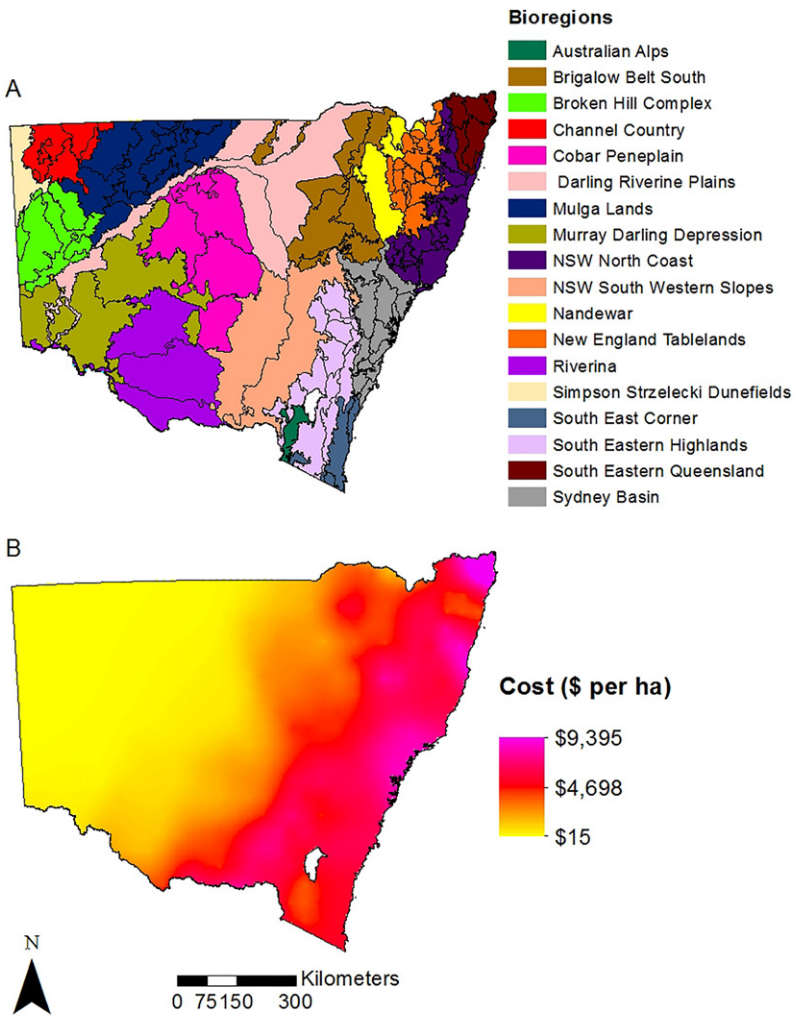

Figure 2. (A) The 18 bioregions in New South Wales (Department of the Environment 2012a, 2012b) delineated into 131 subregions based on climate, geology, landform, native vegetation and species information. (B) 2013 land value used in the Marxan analyses ($\$ha^{-1}$; ABARES).

Islands. In accordance with the CBD (CBD 2011), Australia has adopted a target whereby 17% of the continent, including all of the country's bioregions (Figure 2A) is to be in protected areas (Australian Government Department of Energy and Environment 2018). This target has been endorsed by all states and territories of Australia. The dedication of land for conservation began in NSW with the establishment of the Royal National Park in Sydney's south in 1879 (the world's second official national park). Since then, the NSW protected area network has expanded and now includes 1,010 protected areas, with significant additions along the east coast and mountainous regions in the 1970s and 1980s (OEH 2014). The framework for adding new land to the reserve system in NSW includes the transfer of public land, the voluntary sale or transfer of private land, bequests and donations, and biodiversity offsets (OEH 2018). The state of NSW is home to 1,622 described native vertebrates and 7,788 plant species, of which 900 species (∼10%) and 100 ecological communities are listed under the state government legislation as being at risk of extinction (OEH 2017).

2.2. Data inputs

2.2.1. Protected areas

We used the Collaborative Australian Protected Areas Database (CAPAD 2014; Figure 1) to extract information on the spatial distribution of 1,010 government, Indigenous and privately protected areas in NSW. There are 63 different types of protected areas included in CAPAD. The majority (% of protected areas) are classified as National Parks (72%), followed by Nature Reserves (13%), State Conservation Areas (8%), and Indigenous Protected Areas/Aboriginal Areas (<1%) with the remaining types together representing less than 5% of the NSW protected area network (CAPAD 2014; OEH 2014). Protected areas in this database have the following governance arrangements: government (48%); community (40%); joint (7%); and private (5%). We used two different approaches for treating protected areas in this analysis. Firstly, to identify existing protected areas that overlapped with climate refugia, we classified protected areas by name so that they were easily identifiable. Secondly, we dissolved all protected areas into a single feature to calculate the coverage of subregions and to identify new areas to add to the current reserve network.

2.2.2. Subregions

The IBRA framework is the national and regional planning tool that supports the planning and monitoring of the protected area network against the conservation targets developed to meet the CAR principles. Within this framework, the continent has been classified into 89 bioregions, which are geographically distinct land areas characterized by broad, landscape-scale natural features and environmental processes. As the bioregions are linked to species assemblages, they provide a useful means for reporting on complex biodiversity patterns (Commonwealth of Australia 2017). In NSW, 18 discrete IBRA bioregions have been classified, and further refined into 131 subregions. Our analysis used subregional data (Department of the Environment 2012a, 2012b; Figure 2A), because broad-scale bioregion targets are met when fine-scale subregion targets are met. We included all subregions that extended into NSW that might be shared by another state or territory.

2.2.3. Land value

We used 2013 land value data (\$ha^{-1}; ABARES 2013; Figure 2B) derived from farmers' estimates of their properties to reflect the cost of purchasing land for the protected area network. Economic data on management and transaction costs were not used in the analysis because these were not available at an appropriate spatial scale.

2.2.4. Climate refugia

We used 12 maps of *internal* climate refugia (Figure 3) that were modeled by Baumgartner, Esperon-Rodriguez, and Beaumont (2018) as predictions of important areas for the protection of flora and fauna, both inside and outside protected areas. We

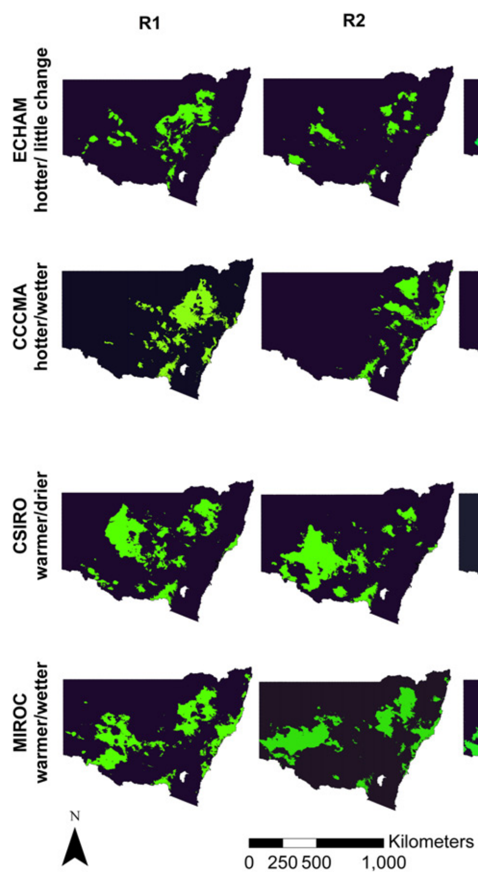

Figure 3. Climate refugia corresponding to 12 alternative future climate scenarios for 2070 (Baumgartner, Esperon-Rodriguez, and Beaumont 2018), in order from top left to right: ECHAM R1; ECHAM R2; ECHAM R3; CCCMA R1; CCCMA R2; CCCMA R3; CSIRO R1; CSIRO R2; CSIRO R3; MIROC R1; MIROC R2; MIROC R3. R1, R2, and R3 indicate whether the climate scenario corresponds to the first, second or third configuration of the WRF RCM. Each scenario describes a future reflecting different changes in mean annual temperature and annual precipitation relative to the baseline period (1990–2009). MIROC projects a warmer and wetter future. CCCMA projects a hotter future than MIROC, and one that is also wetter across most of the state. CSIRO projects a warmer future and is generally the driest of the four models. ECHAM projects the greatest increase in temperature, with changes in precipitation varying across the State. See full methodology in Baumgartner, Esperon-Rodriguez, and Beaumont (2018).

define internal refugia (hereafter "refugia") for a given species as areas that are currently suitable and occupied by that species and are projected to remain suitable until at least 2070 (the NARCliM "far future" scenario), under 12 climate scenarios projected for the state. Refugia were identified using species distribution models (SDMs). These models can be used to identify refuge areas for development and implementation of conservation plans that incorporate climate change (Araújo *et al*. 2004). However, there is a high level of uncertainty about both projections of species distributions and optimal reserve design. SDM limitations include the relationship between projected habitat suitability and species abundance in a particular area and uncertainty in the approach selected for fitting predictive models (Carvalho *et al*. 2011; Guisan *et al*. 2013; Moilanen *et al*. 2006).

SDMs were fitted for 228 individual species using Maxent version 3.3.3k (Elith *et al*. 2006; Phillips, Anderson, and Schapire 2006), a presence-background machine learning approach, and subsequently projected to NSW under future climate scenarios. The 228 species included 117 plant species representative of ecoregions within NSW, and that are likely to play key roles in the functioning of ecosystems (Grime 1998). The remaining 111 species were mostly threatened animals placed within the "landscape-managed" or "iconic" streams of the NSW's Saving our Species Program, a state-wide program that aims to secure threatened species in the wild (OEH 2013) and some were nominated by OEH scientists.

We used *baseline* (hereafter "current") and *far future* (hereafter "future") climate data created as part of the NSW and ACT Regional Climate Modeling (NARCliM) project (Evans *et al*. 2014). These data included the states of standard bioclimatic variables (BIOCLIM; Busby 1991) at 2000 (i.e. current, 1990–2009) and 2070 (i.e. future, 2060–2079; for details, see Hutchinson and Xu 2014). Future climate data were derived by NARCliM from the projections of four Global Climate Models (GCMs): (1) CSIRO-Mk3.0 (hereafter CSIRO); (2) ECHAM5 (hereafter ECHAM); (3) MIROC3.2 (hereafter MIROC); and (4) CCCMA3.1 (hereafter CCCMA). These projections were spatially downscaled to 0.1 degree resolution using three alternative configurations of the Weather and Research Forecasting (WRF version 3; Skamarock *et al*. 2008) Regional Climate Model (RCM) for 2070 (Evans *et al*. 2014). This resulted in a total of 12 equally plausible, alternate climate scenarios for south-eastern Australia, with contrasting projections of precipitation and temperature. The GCMs assumed the SRES A2 emissions scenario (Nakicenovic *et al*. 2000), which roughly follows the trajectories of the newer RCP 8.5 scenario in terms of projected radiative forcing and global mean temperature (i.e. high emissions; IPCC 2013). All modeling and calculation of statistics were performed in R version 3.1.2 (R Development Core Team 2014). See full methodology in Baumgartner, Esperon-Rodriguez, and Beaumont (2018).

2.3. Analysis of protected area expansion under climate change

We used the conservation planning software Marxan version 2.1.1 (Ball, Possingham, and Watts 2009; Watts *et al*. 2009) to identify optimal locations for future protected area expansion in NSW. Marxan, a frequently used tool to support conservation planning, uses a simulated annealing algorithm to support the strategic design of protected area networks by selecting different combinations of areas that meet conservation objectives at minimum cost (Possingham *et al*. 1993). Marxan enabled us to specify multiple biodiversity targets simultaneously, including prioritizing climate refugia and achieving broad coverage across subregions for the lowest land acquisition cost. We focus here on land acquisition as the primary mechanism for reserve establishment, as the State encompasses only a small area of public land that could be upgraded to protected areas, and Indigenous held land that could be declared Indigenous Protected Areas. Other mechanisms, such as conservation covenants, have had limited implementation in NSW, with only 1,300 km^2 currently declared (Craigie *et al*. 2014). It also allows for objectives to be set for total boundary length (boundary length modifier; hereafter "BLM"), with penalties for failing to meet conservation targets (species penalty factor; hereafter "SPF"). We created a "planning unit" layer of 200,152 grid cells (resolution 4 km^2) spanning the NSW mainland. We converted spatial data on biodiversity features (i.e. subregions, climate refugia), land purchase price and protected areas into 4 km^2 grid cells that were masked to the NSW planning unit layer to ensure consistent extent and overlap. We dissolved all protected areas into a single feature for this analysis.

We performed 100 runs of 1 billion iterations. The outcome of each run represents an alternate optimal protected area network that achieves the conservation targets at the lowest cost. We assessed the frequency of each planning unit and the feature(s) it contained being selected in 100 runs (Lombard *et al*. 2003). This approach prevented the influence of idiosyncrasies of individual Marxan solutions on our results. We did not impose any configuration constraints on the design (BLM set at 0). We determined the SPF by running calibrations in Zonae Cogito version 1.74 (Segan *et al*. 2011) to find the SPF with the lowest cost and the highest number of biodiversity features. These values differed between models based on the number of biodiversity features.

We developed two Marxan scenarios to model the optimal placement of new protected areas under the future climate scenarios that would meet the targets of 17% coverage of all subregions and varying targets of climate refugia (30, 50, and 70%). In Scenario 1 (S1), existing protected areas were "locked-in", requiring Marxan to identify the placement of additional protected areas necessary to achieve the required portions of all conservation targets at minimal cost. In Scenario 2 (S2), existing protected areas were not included in the analysis, so that the optimal placement of protected areas would not be influenced by the location of existing protected areas.

3. Results

The mainland protected area network of NSW spans 75,822 km^2 (9%), with individual protected areas ranging in size from 11 km^2 to 6,891 km^2 (mean = 81 km^2; SD = 381 km^2, $n = 1{,}010$). Larger protected areas are generally located along the east coast (Figure 1). The average coverage of the 131 subregions was 18% (SD = 23%), which exceeds the CBD target of 17%. However, a spatial bias towards the east coast of NSW occurs where the majority of protected areas are located. The coverage of subregions by the protected area network was heterogeneous. For example, the north coast subregion of "Washpool" located in the "NSW North Coast" bioregion had the highest coverage (88%; Figure 4). Nine western subregions and one in north-central NSW had no coverage by protected areas and the majority of subregions (69%) had less than 17% coverage. Of the 131 subregions, 42 had at least 17% coverage, and 89 subregions had less than 17% coverage.

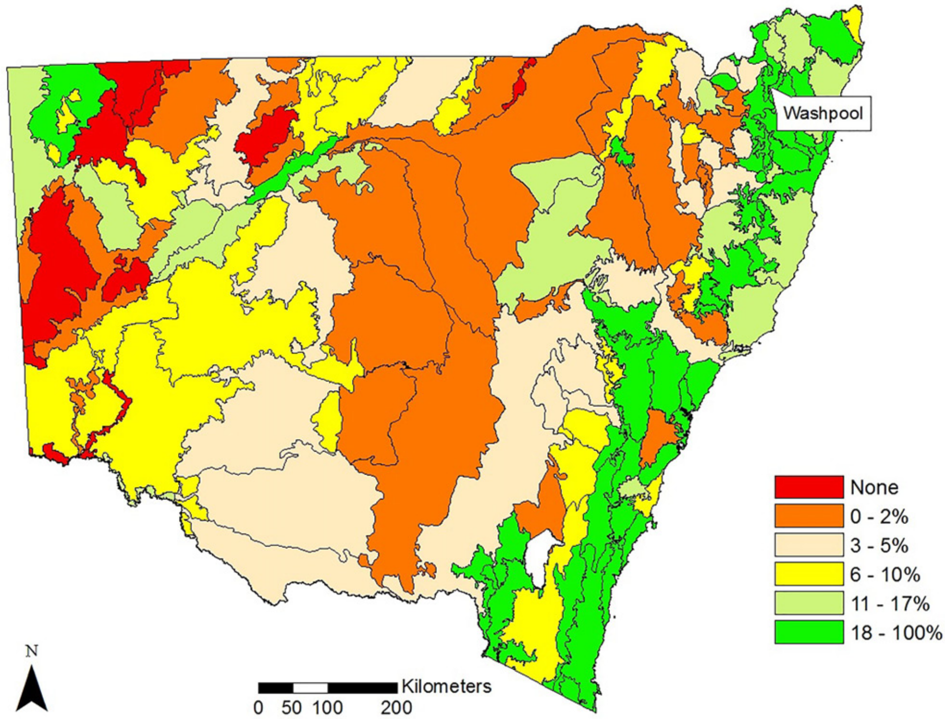

Figure 4. Percent (%) of each of the 131 IBRA subregions covered by the New South Wales (NSW) protected area network. The best-protected subregions are along the east coast (bright green). The north coast subregion of "Washpool" found in the "NSW North Coast" bioregion had the highest coverage (88%). Nine western subregions and one in north-central NSW had no coverage by protected areas (red), and the majority of NSW subregions (69%) had less than 17% coverage.

Table 1. Percent (%) of climate refugia covered by protected areas in New South Wales according to 12 plausible future climate scenarios for 2070.

Climate scenario	Total area of refugia (km^2)	Area of refugia protected (km^2)	Percent (%) of refugia protected
ECHAM R1	72,280	5,444	8
ECHAM R2	40,068	4,504	11
ECHAM R3	33,084	1,764	5
CCCMA R1	88,488	8,416	10
CCCMA R2	67,204	9,484	14
CCCMA R3	35,432	6,480	18
CSIRO R1	126,120	8,548	7
CSIRO R2	126,472	8,644	7
CSIRO R3	64,712	3,768	6
MIROC R1	136,736	15,072	11
MIROC R2	133,756	13,440	10
MIROC R3	115,712	12,936	11
Average	**86,672**	**8,208**	**9.5**

Note: Scenarios represent different Global Circulation Models (GCMs; refer to details of GCMs in Figure 3).

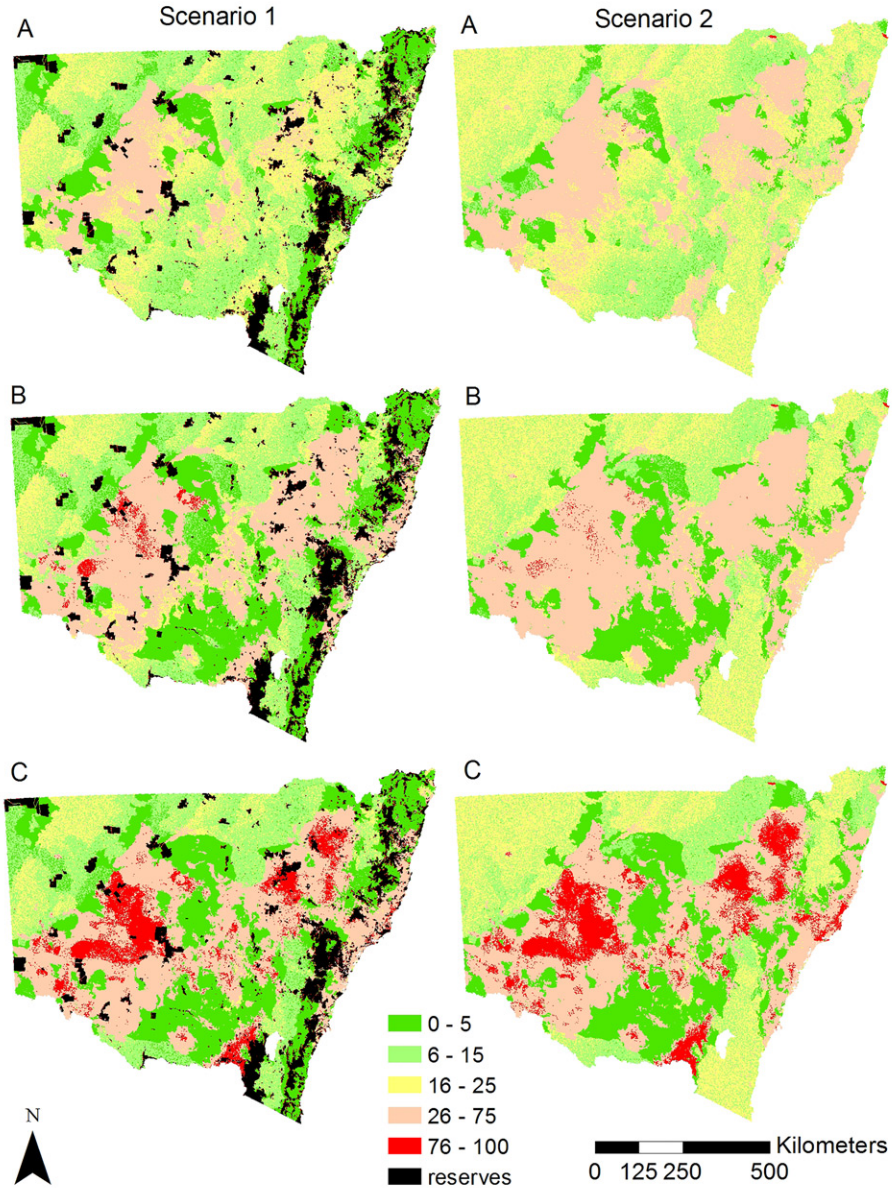

Figure 5. The selection frequency of grid cells for Scenario 1: reservation based on maps of climate refugia, IBRA subregions, land cost and the existing protected area network (shown in black). Scenario 2: reservation based on maps of climate refugia, IBRA subregions and land cost. Selection frequency (0 to 100) of planning units was determined by Marxan using 100 runs and targets of 17% coverage of IBRA subregions and (A) 30%, (B) 50%, and (C) 70% coverage of climate refugia for both scenarios. Regions in red represent the highest priority areas for additional reservation, followed by tan, yellow, light green and bright green.

The coverage of the climate refugia under the 12 future climate scenarios ranged from 5% (ECHAM, R3) to 18% (CCCMA, R3), with an average of 9.5% (Table 1). Refugia projected by CCCMA R3 are located in the eastern (Figure 3), which is where most protected areas are located. This result might be influenced by the small total

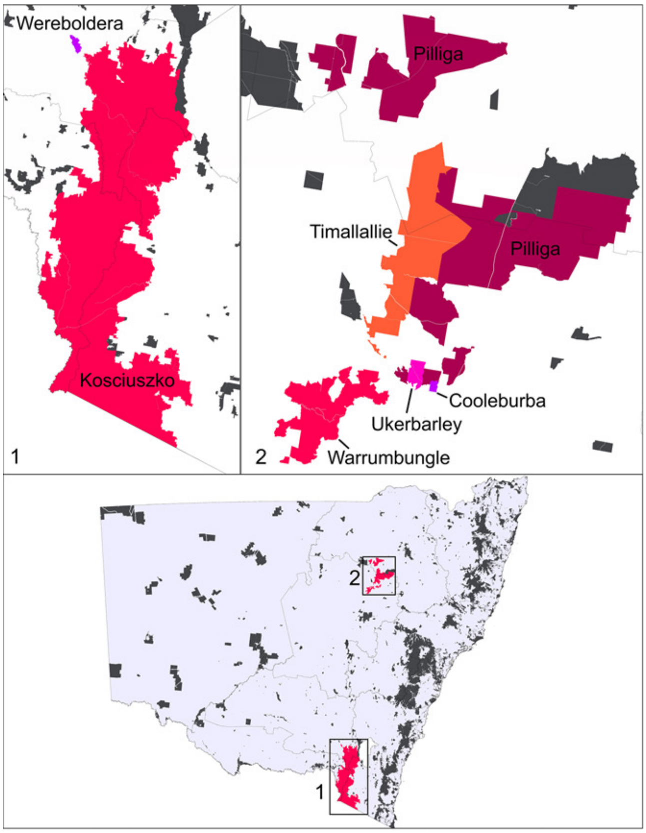

Figure 6. Location of the seven protected areas that are predicted to be climate refugia in New South Wales, Australia, under all twelve future climate scenarios for 2070: Warrumbungle National Park, Pilliga Nature Reserve, Timallallie CCA Zone 1 National Park, Cooleburba State Conservation Area, Ukerbarley State Conservation Area, Kosciuszko National Park and Wereboldera State Conservation Area.

area predicted to be a refuge under this model (35,432 km^2) compared to the other models (mean = 86,672 km^2; SD = 39,826 km^2). A total of 363 protected areas included sites that are predicted to become climate refugia under one or more scenarios. Seven existing protected areas included sites that are predicted to be climate refugia under all twelve scenarios; Warrumbungle National Park, Pilliga Nature Reserve, Timallallie CCA Zone 1 National Park, Cooleburba State Conservation Area and Ukerbarley State Conservation Area in northeast NSW, and Kosciuszko National Park and Wereboldera State Conservation Area in southeast NSW (Figure 6). This finding highlights the importance of these regions for providing refuge from climate change for species already distributed there and potentially for new species migrating from surrounding areas.

In our first Marxan prioritization Scenario 1 (S1), we identified regions that could potentially be added to the existing protected area network to improve the coverage of subregions and climate refugia (towards the 17% target) at the lowest cost. These sites were located in central-western NSW, northeast NSW, south of Pilliga Nature Reserve, and patches of the southeast (shown in red in Figure 5C). Selection frequencies in S1 were low along the north-east and south-east coasts, which are already highly covered by the existing protected area network. In Scenario 2 (S2), we identified sites that represent subregions and refugia at the lowest cost (existing protected areas were not included in this scenario; Figure 5). Importantly, sites identified as high priorities by S2 were similar to the optimal locations for protection identified in S1 (Figure 5). Selection frequencies along the north-east and south-east coasts were higher under S2 than Scenario 1, because S2 did not account for the contribution of the existing protected area network towards achieving the coverage targets of subregions and refugia. Scenario 2 favored the selection of low-cost areas that covered multiple refugia as there were numerous combinations of sites available to meet the 17% target for subregions. In both scenarios, selection frequencies were highest where refugia were identified repeatedly under 12 future climate scenarios. Refugia sites had higher selection frequencies as the weighting was increased from 30% to 70%. Under both S1 and S2, selection frequencies were high in western NSW; bound in the north by Paroo-Darling State Conservation Area, in the east by Yathong Nature Reserve, south by Mungo National Park and west by Kajuligah Nature Reserve.

4. Discussion

Protecting biodiversity into the future requires adaptive management and modifications to management plans in response to current and predicted impacts of climate change. Evaluating the capacity of protected area networks to support species persistence under climate change, and prioritizing the protection of climate refugia is crucial to building a more "climate-ready" protected area network. Using a spatial prioritization approach, we were able to leverage the growing body of evidence on local climate impacts to identify a range of options for protected area expansion in NSW that will support species survival in a changing climate. Our approach also optimizes the allocation of resources under the economic constraint of land acquisition.

Our analysis reiterated a known weakness of the NSW protected area network: its inadequate representation and protection of biological features in the west (Pressey *et al*. 2000; Pressey and Taffs 2001; Craigie *et al*. 2014). Spatial priorities to strengthen the resilience of the protected area network for conserving biodiversity should focus on working towards filling gaps in under-represented ecological features and targeting climate refugia. Our analysis identified priority locations for protection that are predicted to support species survival under climate change, but which lack current protection: the Riverina and Murray Darling Depression bioregions in central-western NSW; the Nandewar and Brigalow Belt South bioregions in northeast NSW; and pockets of the South Eastern Highlands and NSW South Western Slopes in eastern NSW (Figures 2A and 5). Within these priority locations, planners will need to consider the logistics of implementation by consolidating and improving the efficiency and effectiveness of existing protected area boundaries. For example, the addition of protected areas that improve management access and the overall shape of the protected area network, and which buffer threats from surrounding land use (OEH 2014).

Although significant efforts have been made to expand and improve the protected area network in NSW over the last century, many biodiversity features are poorly represented due to a long history of reserving "residual" land (places with low commercial value; Joppa and Pfaff 2009; Pressey *et al*. 2000). For example, many protected areas in NSW are located in the mountainous region in the east of the state that is unsuitable for agriculture. However, the seven protected areas that captured refugia identified repeatedly under 12 future climate scenarios were all located in the east of the state (Figure 6). The protected area network in NSW has been shaped by selective opportunities for capturing land, which has historically been mostly from Crown land transfers. A further limitation to the identification and designation of protected areas in NSW has historically been imposed by the availability of landscapes in their natural state, with some landscapes being heavily cleared of native vegetation. For example, by the end of the last century, over 80%–90% of the Lowland Grassy Woodland in the South East Corner bioregion had been cleared (Keith and Bedward 1999).

The existing NSW protected area network has been designed to protect areas of natural beauty and recreational potential, capture the present-day ranges of species and ecosystems and habitats of threatened species, reduce threats from wildfires and invasive species, and support the regeneration of degraded vegetation. A relatively recent objective of this network is to buffer against the impacts of climate change by prioritizing the protection of climate refugia and places that mitigate the impacts of ongoing climatic changes (NRMMC 2009). The success of refugia in providing a safe haven from climate change is influenced by a number of factors. A species must either already inhabit the location or be able to disperse there for a site to be realized as refugia (Pecl *et al*. 2017). Knowledge of the dispersal capabilities of many species is limited, although there is clear evidence that shifts in species' ranges have already occurred in response to anthropogenic climate change (Chen *et al*. 2011; VanDerWal *et al*. 2012). This migration towards more suitable habitat exposes the native vegetation to further stress, as native plants have to compete for space with invasive species (Dainese *et al*. 2017). Climate-driven invasions can cause conditions to become intolerable due to novel biological interactions (Aronson *et al*. 2015; Dukes and Mooney 1999). However, if the species already inhabits an area (as per the definition of internal refugia used in this study), biotic interactions are likely to be more tolerable than in external refugia (areas that will become climatically suitable, but are not currently occupied by the species). Thus, although thermal tolerance and dispersal ability play a key role in the establishment and survival of species (Ferrier and Guisan 2006; Heller and Zavaleta 2009), it is also critically important to consider the effect of biological interactions on species' future distributions (Berg *et al*. 2010).

Climate-driven changes in the characteristics and distribution of ecosystems, triggered by large-scale changes in vegetation communities, can be severe enough to alter biomes and changes of this scale alter the measurement unit with which we evaluate conservation success (Bellard *et al*. 2012; Leadley *et al*. 2010). For example, the Millennium Ecosystem Assessment forecasts alterations in up to 20% of terrestrial ecosystems (Sala *et al*. 2005).

The appropriate management of refugia is complex and dependent on a number of factors. Firstly, a combination of protecting and restoring habitat at refugia sites will provide the best opportunity for conserving biodiversity, factoring in the availability of intact vegetation (Maggini *et al*. 2013). The potential for changes in species assemblages, driven by the variable response rates of species' to changing climates, will have important implications for how protected areas are managed (Gallagher *et al*. 2014; Urban, Tewksbury, and Sheldon 2012). In Australia, protection targets are underpinned by the IBRA classification framework. If species reassemble into communities that are distinct from the IBRA classifications, then the monitoring of protection targets will be a challenge. Another management concern is the movement of species across administrative boundaries, which calls for strong planning and communication between agencies across boundaries (e.g. new and former ranges). Planners will need to develop objectives that prioritize areas where suitable habitat is highly likely to exist in the future, ensure appropriate threat management in locations with suitable habitat that have potential to be colonized, and promote the presence of corridors for species movement (Pecl *et al*. 2017). In cases where species are unable to naturally disperse to refugia, or there is no overlap between a species' current and predicted future range (external climate refugia), assisted colonization has been proposed to avoid localized extinction (Burbidge *et al*. 2011; Loss, Terwilliger, and Peterson 2011). Generally, acceptable initiatives to support adaptation are those targeting improved connection of vegetation across landscapes to support species' dispersal (Hannah *et al*. 2007). Initiatives to connect habitat in NSW include the Great Eastern Ranges initiative, a 33 million hectare conservation corridor stretching from the Wet Tropics in the north to the Grampians in the south (Pulsford, Fitzsimons, and Wescott 2013).

We recognize that decisions about which species to protect, and where, need to be guided by additional finer-scale information on populations of threatened and migratory species, which was not used in our analysis. Here, climate refugia were identified using a combination of threatened and dominant species, based on the assumption that retaining suitable habitat of species representative of their respective communities and ecoregions will minimize the disruption of ecosystem function (Grime 1998; Baumgartner, Esperon-Rodriguez, and Beaumont 2018). Nevertheless, further research into the capacity of protected areas to capture specific groups or taxa that are more vulnerable to climate change would be valuable. These groups include species that have narrow ranges of physiological tolerance to variation in temperature and water availability, are sensitive to fire, have low genetic variability, narrow geographic ranges, long generation times and long times to sexual maturity are keystone species (e.g. dispersers or pollinators), or are poor dispersers. Species-specific data would provide additional information on the position of the protected area network to capture climate-sensitive species and should be considered in conjunction with broader-scale regional analysis. Our results should be interpreted with information on vegetation condition, as this was not considered in our analysis.

Additionally, our analysis is limited in scope to reserves listed in the CAPAD database. Land that is privately-managed for conservation, provides an important supplementary role to the National Reserve System, covering around 4% of NSW (EPA 2015). Access to a central database that collates locations of privately managed conservation areas would strengthen this analysis. Deliberately, we did not include dispersal capacity in our definition of refugia (Baumgartner, Esperon-Rodriguez, and Beaumont 2018), therefore, we only considered the management of internal refugia. An extended approach would also consider external refugia, although this would require greater knowledge of species' dispersal abilities, which for many species is still limited. The question of how best to manage and monitor refugia using a mix of actions is pertinent to address in more detail (Morelli *et al*. 2016). For example, how large an area of climate refugia should be managed? Should refugia be prioritized by their potential to provide refuge for species already threatened? We recommend that future research endeavor to explore these questions further.

4.1. Conclusions

This study evaluates the status of the NSW protected area network and identifies priority areas for protecting predicted sites of climate refugia using a systematic approach, combining spatial analysis and the reserve design software Marxan. Our analysis provides novel information on where bioregions and climate refugia are adequately protected under CAPAD, and where they need greater coverage. Identifying and protecting predicted sites of climate refugia is a strategic priority listed by government agencies to support the adaptation of biodiversity to future environments by reducing exposure to climate change. The recommendations from this study are designed to support policy-makers in developing management strategies that are best positioned to protect biodiversity under a changing and uncertain climate, spanning distinct combinations of temperature increase and precipitation change. Widespread climate adaptation initiatives are already underway in NSW and elsewhere, however, until now, there was no cross-examination of existing protected areas with adaptation priorities. Our statewide prioritization of bioregions and refugia provides guidance for decision makers around biodiversity conservation in the context of climate uncertainty, under a range of contrasting, but equally plausible climate futures.

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Note

1. https://www.cbd.int/sp/targets/

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