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Climate-induced change of environmentally defined floristic domains: A conservation based vulnerability framework

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ABSTRACT

Global climate change is having marked influences on species distributions, phenology and ecosystem composition and raises questions as to the effectiveness of current conservation strategies. Conservation planning has only recently begun to adequately account for dynamic threats such as climate change. We propose a method to incorporate climate-dynamic environmental domains, identified using specific environmental correlates of floristic composition, into conservation strategies, using the province of KwaZulu-Natal, South Africa as a case study. The environmental domains offer an approach to conservation that conserves diversity under current and future climates, recognising that the species constituting diversity may change through time. We mapped current locations of domains by identifying their positions in a multi-dimensional environmental space using a non-hierarchical iterative *k*-means clustering algorithm. Their future locations were explored using an ensemble of future climate scenarios. The HadCM2 and GFDL2.1 models represented the extreme ranges of the models. The magnitude of change in each environmental domain was calculated using Euclidean distances to determine areas of greatest and least stability for each future climate projection. Domains occurring in the savanna biome increase at the expense of domains occurring in the grassland biome, which has significant negative consequences for the species rich grasslands. The magnitude of change maps represents areas of changed climatic conditions or edaphic disjunctions. The HadCM2 model predicted the greatest overall magnitude of change across the province. Species with specific soil requirements may not be able to track changing climatic conditions. A vulnerability framework was developed that incorporated climatic stability and habitat intactness indices. The mean magnitude of change informed the potential speed of transition of domains between the vulnerability quadrants. The framework informs appropriate conservation actions to mitigate climate change impacts on biodiversity. The study explicitly links floristic pattern and climate variability and provides useful insights to facilitate conservation planning for climate change.

1. Introduction

Global climate change is having marked influences on species distributions, phenology and ecosystem composition (Chen, Hill, Ohlemüller, Roy, & Thomas, 2011; Parmesan, 2006). Ecosystems and biodiversity are further impacted by other concurrent stressors such as habitat loss, invasive species, overexploitation, pollution and disease (Mantyka-Pringle, Martin, & Rhodes, 2012). Over the next century, climate change as a result of increasing atmospheric CO_2 levels and other greenhouse gases is expected to become one of

Abbreviations: CCAM, conformal-cubic atmospheric model; CEC, cation exchange capacity; IPCC, Intergovernmental Panel on Climate Change; KZN, KwaZulu-Natal; MAP, mean annual precipitation; MAT, mean annual temperature.

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the greatest drivers of biodiversity loss (Heller & Zavaleta, 2009), especially as climate change progresses towards the extremes.

These changes raise questions as to the effectiveness of current conservation strategies, which tend to focus on static spatial planning based on current conditions (Pressey, Cabeza, Watts, Cowling, & Wilson, 2007). Global change is turning ecosystems into rapidly changing landscapes (Hansen, Hoffman, Drews, & Mielbrecht, 2009). Thus temporal shifts in ecosystems and species need to be incorporated into conservation planning. Sound predictions of future climatic impacts on biodiversity are needed to guide adaptation and conservation planning efforts.

Much research has focussed on understanding climatic impacts on individual species using species distribution models (Erasmus, Van Jaarsveld, Chown, Kshatriya, & Wessels, 2002; Yates et al., 2010). However modelling all species occurring in diverse systems is not feasible and it is suggested instead that models are developed that predict climate effects on the distribution of communities (Yates et al., 2010), ecoregions (Hansen et al., 2009; Watson, Iwamura, & Butt, 2013) or environmental domains (Saxon, Baker, Hargrove, Hoffman, & Zganjar, 2005). Groves et al. (2012) recommend focussing conservation efforts on the geophysical environment (the metaphorical stage with the species as actors), as this maintains species diversity, and similarly, Beier and Brost (2010) recommend the use of land facets. The latter methods offer an approach to conservation that conserves diversity under current and future climates, recognising that the species constituting the diversity may change through time given their capacity to track appropriate conditions, phenological changes or physiological adaptation (Bellard, Bertelsmeier, Leadley, Thuiller, & Courchamp, 2012). Building on these concepts we suggest that by identifying the specific environmental correlates defining current vegetation communities, the environmental domains of these communities may be identified, i.e. the environmental stage is identified. The environmental domains can then be modelled under future climate scenarios to understand how the domains may change and hence how communities are likely to respond, providing useful insights for dynamic conservation planning.

Jewitt, Goodman, Erasmus, O'Connor, and Witkowski (2015) examined the main environmental gradients correlated to floristic composition in KwaZulu-Natal (KZN) based on detailed vegetation sample plot (relevé) inventories. The study identified 23 major floristic communities in the province. The three primary correlates of floristic pattern were found to be temperature, soil base status and precipitation and can be used to define environmental domains. The study focussed on plant community composition because plants underpin trophic structure and functioning, and have been shown to be the most effective predictor of arthropod assemblage composition, a group which comprises almost two-thirds of the world's diversity (Schaffers, Raemakers, Sýkora, & ter Braak, 2008). Vertebrate species are mobile and thus may respond more readily to climate change compared to plants which are sedentary and thus lack motility other than through seed dispersal, as a means of adapting to climate change. Plant communities thus represent a good starting point to investigate dynamic climate changes.

The ability of species to track changing environmental domains will be hampered by habitat loss and land-cover change, which are recognised as major drivers of biodiversity loss (Jetz, Wilcove, & Dobson, 2007; Millenium Ecosystem Assessment, 2005; Vitousek, 1994). Indeed, in KZN an average of 1.2% per annum of natural habitat was transformed between 1994 and 2011, and it was estimated that by 2011 only 53% of the province remained in a natural state (Jewitt et al., in press). Climate change and habitat loss negatively interact contributing to the loss of biodiversity (Mantyka-Pringle et al., 2012). By considering the degree of habitat loss as well as climate stability (Watson et al., 2013), the vulnerability of environmental domains can be determined. By further considering the mean magnitude of change expected in each domain, the rate of change in each domain can be determined. We present a spatially explicit vulnerability framework using the environmental domains that can inform appropriate conservation actions and indicate where they are most appropriate.

We present an approach for understanding climatic impacts on vegetation communities by using the specific environmental correlates of these communities to define current environmental domains. Using edaphic factors assumed not to change significantly by 2050 and an ensemble of modelled future climates, future environmental domains are tracked and used to identify areas of climatic stability (potential macro-refugia) and instability (potential novel communities). We present a vulnerability framework that incorporates climatic stability, habitat intactness and the potential rate of climate change. These climate-dynamic environmental domains and the vulnerability framework will facilitate conservation planning for climate change. In particular we address the following questions: 1) What and where are the major environmental domains in KZN, determined using the three primary climatic and edaphic correlates of floristic composition in KZN? 2) How will the environmental domains change in KZN by 2050, determined using an ensemble of climatic models based on the A2 emission scenario? 3) Which areas of the province are expected to experience the least and greatest magnitude of change? 4) Which domains are the most vulnerable in terms of climate change, habitat loss and mean magnitude of change?

2. Materials and methods

2.1. Study area

KZN is a province of South Africa occurring on the eastern seaboard of the country (Fig. 1). It has a complex landscape, in terms of both biological and physical diversity. It is species rich having more than 6000 vascular plant species in an area of 93 307 km^2 and endemism levels of 16% (Scott-Shaw, 1999). It contains portions of the Maputaland-Pondoland-Albany biodiversity hotspot and the Drakensberg Alpine, Midlands, Pondoland and Maputaland centres of endemism (Mucina & Rutherford, 2006). KZN has a steep temperature gradient with mean annual temperatures (MAT) ranging between 7.9 °C and 22.9 °C, owing largely to an altitudinal gradient of over 3000 m from the Indian Ocean to the top of the Drakensberg escarpment. Similarly the province has a strong precipitation gradient with mean annual precipitation (MAP) ranging between approximately 450 mm–1900 mm. Cation exchange capacity (CEC) varies between 3 and 112 cmol kg^{-1} (ISRIC, 2013).

2.2. Analysis

The current climatic variables of MAT and MAP were derived from Schulze (2007) at a one arc minute resolution, averaged over a 30 year period (1961–1990). Using a multi-decadal range incorporates the inter-annual variability of the variables. The soil CEC data was obtained from ISRIC (International Soil Reference and Information Centre, 2013) at a 1 km resolution and averaged to a depth of 1 m. The current and future data were standardised to the same projection, resolution (1.8 km × 1.8 km) and normalised to a consistent range. All mapping work was done in ArcMap 10.2 (ArcGIS, 2013).

Future MAT and MAP data specific to KZN was calculated from climate models projected to 2050, averaged over a 20 year period (2041–2060). The future climate data were developed by the

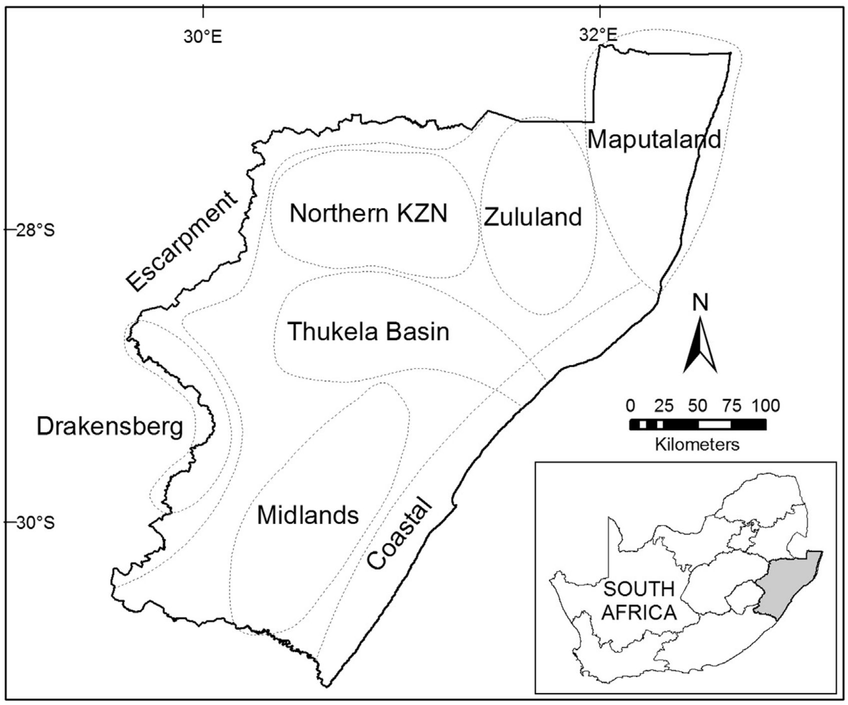

Fig. 1. The province of KwaZulu-Natal (KZN), South Africa with the regions referred to in the text.

Council for Scientific and Industrial Research (CSIR) (Engelbrecht, McGregor, & Engelbrecht, 2009; Engelbrecht et al., 2011). They used the conformal-cubic atmospheric model (CCAM), a variable-resolution global model, of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) to perform dynamic downscaling which is suited to regional climate modelling. The model is good at simulating the present-day characteristics over Africa (Engelbrecht et al., 2009). The downscaling procedure forces the lower-boundary of the CCAM simulations (Engelbrecht et al., 2011) with the bias-corrected sea-surface temperature and sea-ice output of six different Coupled Global Climate Models that simulate the coupled ocean, atmosphere and land-surface processes, used in the Assessment Report Four (IPCC, 2007) of the Intergovernmental Panel on Climate Change (IPCC). The six models are CSIRO Mk 3.5, GFDL2.1 (GFDL cm2.1), GFDL2.0 (GFDL cm2.0), HadCM2, ECHAM5 and Miroc-Medres (Engelbrecht et al., 2011). All the projections are based on the A2 emission scenario of the Special Report on Emission Scenarios (SRES) (IPCC, 2000). The authors of the downscaled models recognise the need for more regional climate-change modelling studies including the use of different SRES (Engelbrecht et al., 2009; Engelbrecht et al., 2011), but at the time of this study such ensembles were not yet available. The horizontal resolution of the data is about 0.5° (approximately 60 km over southern Africa). The CCAM is problematic in that it generally overestimates rainfall totals over southern Africa, especially over and to the east of the eastern escarpment of South Africa, but this is also a problem of other Regional Climate Models (Engelbrecht et al., 2009). This modelling suite was specifically chosen rather than the later Assessment Report 5 models because they are dynamically downscaled, correlate well with current conditions and are specifically bias-corrected.

Data for each 1.8 km grid cell and environmental variable combination was written to a table. A multivariate geographic, non-hierarchical, iterative *k*-means clustering algorithm based on Euclidean distance was used to allocate each data point, including current and future variables, to an environmental domain (Hargrove & Hoffman, 2004; Saxon et al., 2005). The *k*-means clustering partitions *n* observations (grid cells) into *k* clusters (domains). The algorithm was coded in C and is dynamically load-balancing and fault-tolerant, and it performs both initial seed-finding and iterative cluster assignment in parallel. Domain seeds began initially with the most dissimilar seeds and each data point was assigned to the closest seed. After each iteration, the domain centroids were recalculated and each cell re-assigned to the new centroid until an acceptable convergence to an equilibrium classification or local optimum was obtained (<0.5% of cells changing). The final number of domains selected (23) was based on the number of floristic hierarchical clusters identified in KZN in the Jewitt, Goodman, O'Connor, and Witkowski (2015) analysis which identified the environmental correlates of floristic composition in the province using 2155 vegetation sample plots. The coordinates of the final domain centroids represent the domain's position in environmental space (Saxon et al., 2005) and is an index of their environmental similarity (Faith & Walker, 1996). The environmental domains were mapped back into geographic space.

The magnitude of predicted environmental change associated with the expansion or contraction of environmental domains was calculated by multiplying each individual current environmental domain reclassified to 0 and 1, by each predicted future domain for each climate model, to determine the nature of the environment changes over time. Since the domain centroids are located in environmental space, Euclidean distances can be used to calculate the magnitude of change associated with a grid cell changing from a current environmental domain type to a different future environmental domain. The Euclidean distances between current and future domain centroids were used to generate a dissimilarity matrix (Appendix A) which was used to generate a magnitude of change map for each future projection.

2.3. Development of the vulnerability framework

Other vulnerability frameworks consider exposure, sensitivity, adaptive capacity (Dawson, Jackson, House, Prentice, & Mace, 2011) or landscape conservation capacity and vulnerability to climate change (Gillson, Dawson, Jack, & McGeoch, 2013; Mazziotta et al., 2015). Our framework plots the Climate Stability Index against the Habitat Intactness Index thus representing two major agents of biodiversity loss, whilst also considering the mean magnitude of change expected in each domain, which is an indication of the potential speed of transition expected in each domain. The Climate Stability Index identifies the proportions of current domains that remain stable in future climate scenarios, i.e. where the magnitude of change is zero. The more stable an environmental domain is, the more robust it will be to climate change. The Habitat Intactness Index identifies the current levels of remaining natural vegetation in each domain based on the accumulated transformation as at 2011 (Jewitt et al., in press). The more natural habitat that remains in an environmental domain, the more likely it is that species will be able to naturally respond to changing climate.

The vulnerability framework places the environmental domains into quadrants that can inform appropriate conservation action (Fig. 2). Studies have shown that once 50% of the landscape is transformed a persistence threshold is reached, where after there is a rapid decline in the probability of landscapes supporting viable populations of organisms (Flather & Bevers, 2002). Hence a threshold of 50% of habitat intactness is applied. Similarly, a threshold of 50% is applied to the climate stability index. The conservation actions are climate adaptation strategies appropriate for biodiversity conservation (Gillson et al., 2013; Mawdsley, O'Malley, & Ojima, 2009). The least conservation effort is required in the top right quadrant which has sufficient remaining natural habitat and relatively large proportions of climatically stable areas, with conservation effort, resources and risk increasing towards the bottom left quadrant, which is high risk in that it is both climatically unstable and there is little natural habitat remaining. Quadrants are labelled 'Robust', 'Susceptible', 'Constrained' and 'Vulnerable' according to the degree of climatic stability and habitat intactness. Vulnerable domains require concerted conservation effort and resources if the species occurring in them are to persist into the future, a central tenet of conservation planning (Pressey et al., 2007). The likely speed of transition of domains between quadrants is indicated by overlaying the mean magnitude of change in each domain on the framework and serves to further prioritise domains requiring conservation effort.

3. Results

3.1. Climate models

The predicted change in MAP and MAT by 2050 compared to current conditions were graphed to determine which models predicted the greatest and least climate change in the province by 2050 (Fig. 3). The GFDL2.1 model predicted the lowest average temperature increase of 1.5 °C and was the only model to predict a slightly increased MAP (29 mm) in KZN. The HadCM2 model predicted an average 2.1 °C increase in MAT and a decrease of 90 mm in MAP in KZN. Since these two models represent the extremes of the predicted changes, only their results are presented for brevity. The GFDL2.1 model is good at representing large-scale current climate, including El-Niño, the drying of the African Sahel and seasonal predictions but is biased in the simulation of tropical climate and variability (www.gfdl.noaa.gov/model-development). The HadCM2 model overcomes difficulties associated with equilibrium and cold-start transient climate change experiments and captures the

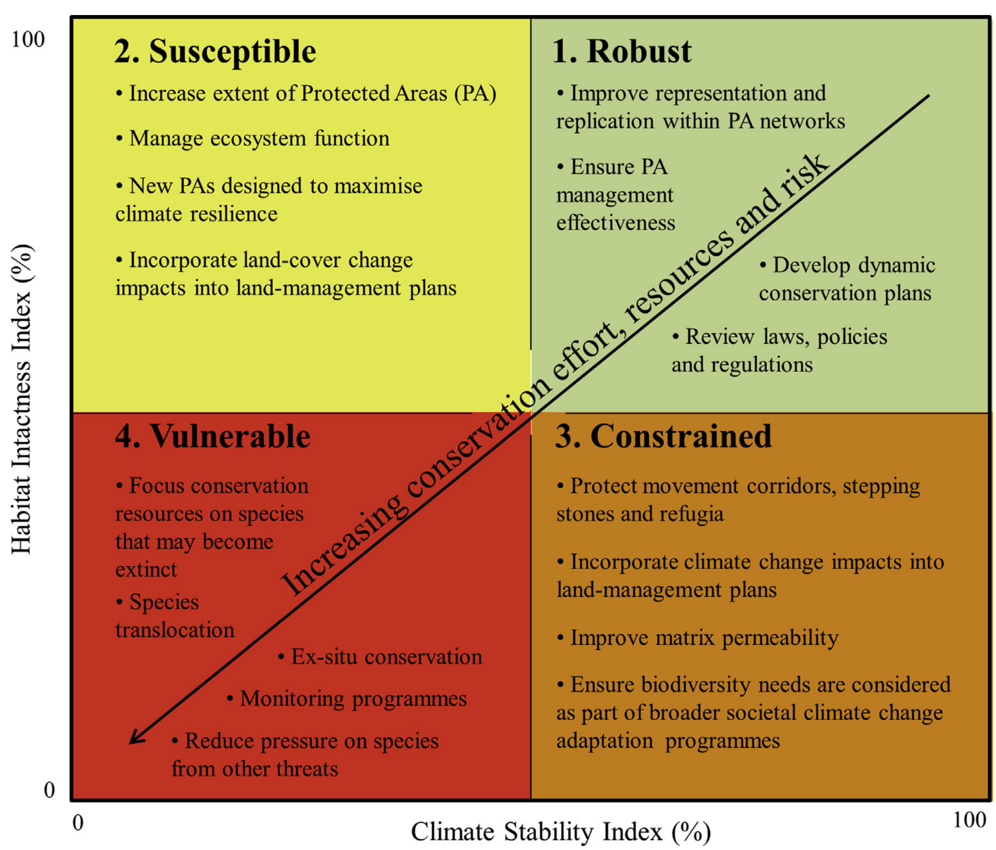

Fig. 2. The vulnerability framework with adaptation strategies appropriate for biodiversity conservation (Mawdsley et al., 2009).

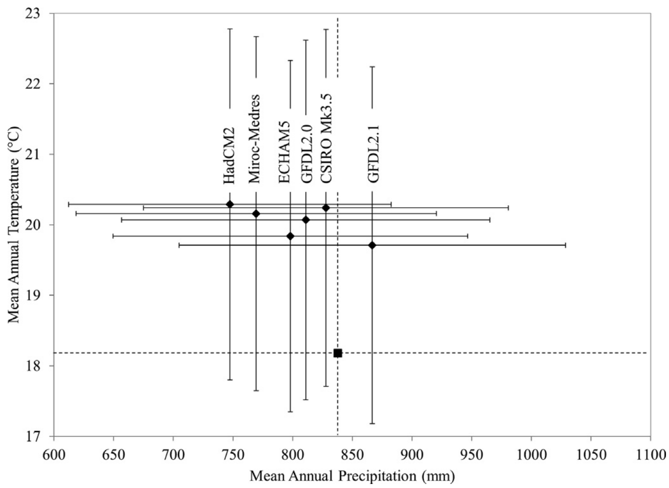

Fig. 3. The predicted change in mean annual precipitation (MAP) and mean annual temperature (MAT), with Standard Deviation bars (2041–2060), compared to current mean annual conditions, indicated by the dashed line and square symbol. Only the extremes of the models *viz.* HadCM2 and GFDL 2.1, are presented in this analysis.

observed signals of global-mean temperature changes well (www.ipcc-data.org).

3.2. Environmental domains

The mapped environmental domains (Fig. 4) showed marked changes by 2050. Domains 3, 12, 16, 17, 21 and 22 decrease in extent at the expense of domains 1, 4, 6, 7, 9, 10, 11, 13, 18, 19, which increase in extent (Table 1; Appendix B) in both models. The decreasing domains occur in the Midlands, low Drakensberg, Escarpment and northern KZN regions and all occur in the grassland biome (Appendix C). The increasing domains occur in Maputaland, Zululand and the Thukela basin regions and occur primarily in the savanna biome with the exception of domain 9 which occurs in grassland and domain 13 which occurs in the Indian Ocean Coastal Belt. Domains 2 and 8 remain stable across time. They represent the high altitude, cool and moist grassland domains of the high Drakensberg and are limited in extent. They remain stable given the high altitudinal range occurring in this region. Domains 5, 14, 15, 20 and 23 have variable responses across the models but occur along the coastal and south western (only domain 14) regions of the province. These differences arise due to the significantly drier conditions predicted along the coastal regions by the HadCM2 model. Temperature increases are ameliorated along the coast compared to inland areas. No domains disappear entirely during this analysis period and similarly no novel domains appear.

3.3. Magnitude of change

The magnitude of change maps indicate areas that will experience the greatest (darker shaded areas) or least stress (white coloured areas) from climate induced environmental change and thus where ecosystems and biodiversity will be at greater or lesser risk (Fig. 5). The HadCM2 model predicts the greater overall magnitude of change across KZN with large regions in south-western KZN and central Maputaland remaining stable but with large coastal changes. Both models predict changes in the western Thukela Basin and Northern KZN regions, and concur in part on changes in the Midlands and Zululand.

3.4. Vulnerability framework

In our case study (Fig. 6), domains 2, 3, 6, 8, 10, 18, and 19 consistently occur in quadrant one. They occur broadly in the Drakensberg, Midlands, parts of Zululand and western Maputaland. The size of the domain circles indicate the mean magnitude of change expected for each domain. For example, the mean magnitude of change for domain 8 in the HadCM2 model is large, thus it could potentially rapidly move to quadrant two. Consistent domains in quadrant two include 1, 4 and 21. They occur in the western Thukela Basin, northern KZN and eastern Zululand. There are no consistent domains in quadrant three as the HadCM2 model does not predict any domains in this quadrant given the large climatic changes predicted by this model. Domains 13, 15 and 20 occur in quadrant three in the GFDL2.1 model. Similarly domains 15, 20 and 23 also occur in the highly transformed, fragmented coastal parts of the province, although the models differ on the predictions of domain expansion and contraction. The most vulnerable domains are 17 and 23. These occur along the escarpment, Midlands and southern coastal regions. Species occurring in these domains are at high risk of local extirpation. The vulnerability framework results are represented spatially (Fig. 7).

4. Discussion

Our study gives an indication of the nature and extent of climate impacts in KZN using environmental domains. The current environmental domains were identified by specifically using previously identified environmental correlates of floristic community composition in KZN (Jewitt, Goodman, O'Connor et al., 2015). The nature of climate change was investigated by modelling the two extremes of an ensemble of future climate change scenarios. This provided an insight into how the environment is predicted to change, acknowledging that species will respond to climate change individualistically (Midgley, Hannah, Millar, Thuiller, & Booth, 2003). The study explicitly links floristic pattern and climate variability and provides useful insights to facilitate conservation planning for a changing climate.

The spatial distribution of the environmental domains shows where species with good dispersal ability would be able to disperse to in the increasing domains, assuming no barriers to species movements. Species restricted to diminishing domains may become stranded and would require a targeted conservation effort (Saxon et al., 2005). The models predicted conditions suiting savanna species would increase at the expense of current grassland areas. The grasslands in the province are both ancient and diverse in their suites of plant and animal species (Bond & Parr, 2010). Thus, predicted declines of grassland domains pose a significant risk to their unique biodiversity.

The magnitude of change maps highlight areas of greatest or least stress. This could be due to changed climatic conditions or a soil type disjunction. Geological formations in the province are broadly orientated in a north-south direction and are thus confounded with the east-west temperature gradient which decreases from the coast to the top of the Drakensberg Mountains. Thus species with specific soil requirements may not be able to track changing climatic conditions. The areas of stability (least stress) represent potential broad-scale macro-refugia areas. Refugia are areas that components of biodiversity can retreat to, persist in and potentially expand from in a changing climatic world (Keppel et al., 2011). Micro-refugia will exist in all domains based on the local topography, cold air drainage, prevailing wind directions and aspect (Ashcroft, 2010). The identification of broad-scale stable areas may guide the location of future protected areas which would limit climate change impacts on biodiversity. By incorporating

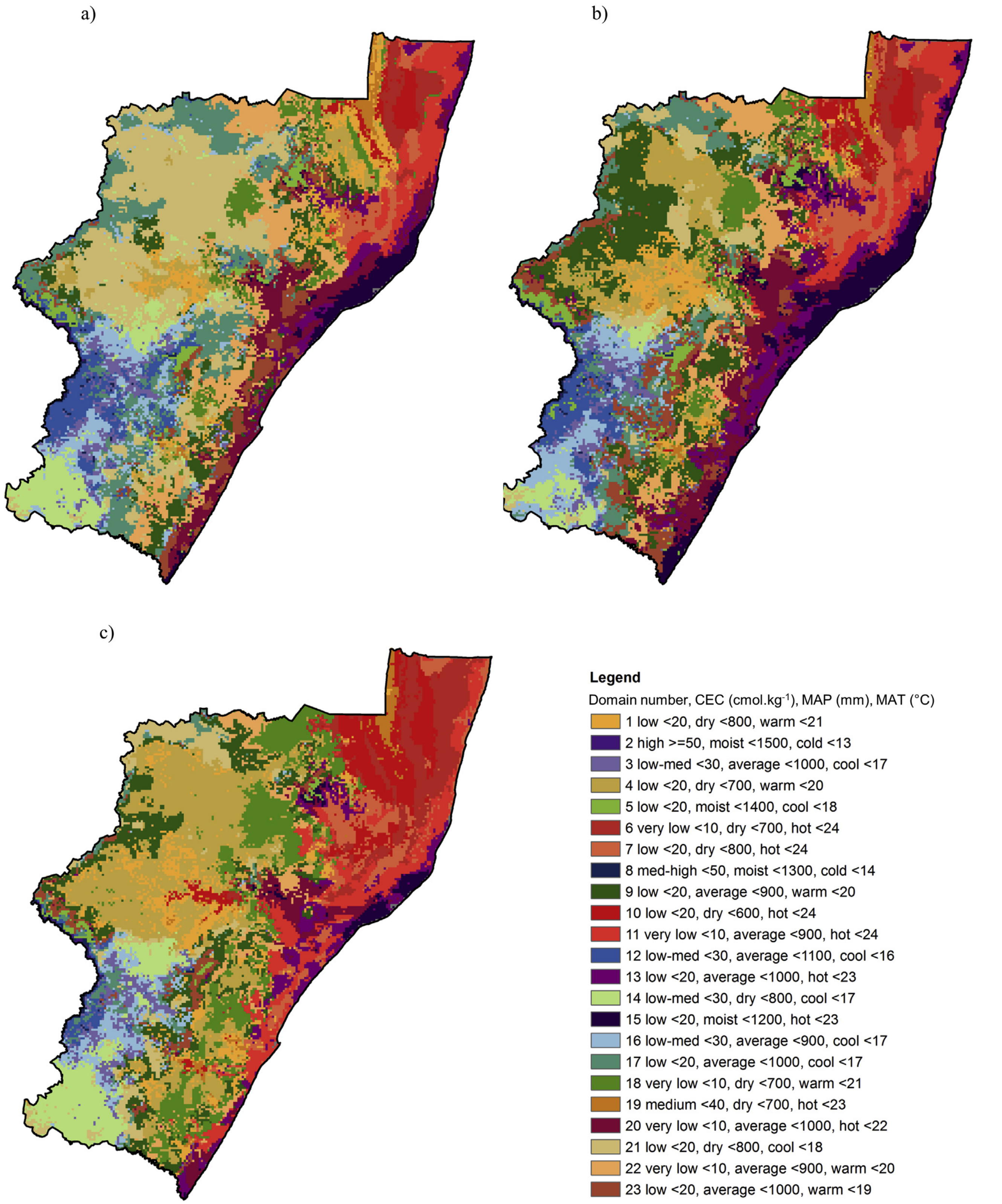

Fig. 4. The environmental domains of KwaZulu-Natal (KZN): a) Current (1961–1990) domains b) GFDL2.1 projected 2050 (2041–2060) domains c) HadCM2 projected 2050 (2041–2060) domains.

micro-refugia, climatically suitable areas for conservation corridors may be identified which could link existing protected areas, proposed protected areas and critical biodiversity areas identified through systematic conservation plans. These areas thus represent the most climate change resilient areas of the province.

The vulnerability framework informs appropriate conservation measures (Mawdsley et al., 2009). The suggested adaptation strategies are neither exhaustive nor exclusive to each quadrant, but

Table 1
Domain descriptions, current biome, spatial extent (ha) and percentage of surface area of KwaZulu-Natal, where IOCB refers to the Indian Ocean Coastal Belt.

Domain	Description (CEC (cmol kg^{-1}), MAP (mm), MAT (°C))	Current biome	Current		GFDL2.1		HadCM2	
			Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
1	Low <20, dry <800, warm <21	Savanna	372,694	3.9	403,153	4.3	563,662	6.0
2	High ≥50, moist <1500, cold <13	Grassland	16,085	0.2	16,427	0.2	14,716	0.2
3	Low-med <30, average <1000, cool <17	Grassland	250,859	2.7	247,094	2.6	217,320	2.3
4	Low <20, dry <700, warm <20	Savanna	303,221	3.2	663,595	7.0	1,725,209	18.3
5	Low <20, moist <1400, cool <18	Grassland	121,494	1.3	160,166	1.7	50,651	0.5
6	Very low <10, dry <700, hot <24	Savanna	178,305	1.9	236,827	2.5	634,847	6.7
7	Low <20, dry <800, hot <24	Savanna	213,897	2.3	398,020	4.2	466,809	4.9
8	Med-high <50, moist <1300, cold <14	Grassland	38,673	0.4	35,935	0.4	28,748	0.3
9	Low <20, average <900, warm <20	Grass/Savanna	499,322	5.3	1,213,225	12.9	821,365	8.7
10	Low <20, dry <600, hot <24	Savanna	151,610	1.6	249,147	2.6	584,196	6.2
11	Very low <10, average <900, hot <24	IOCB/Savanna	394,598	4.2	524,989	5.6	655,723	6.9
12	Low-med <30, average <1100, cool <16	Grassland	382,277	4.1	287,820	3.0	72,212	0.8
13	Low <20, average <1000, hot <23	IOCB/Savanna	256,334	2.7	511,984	5.4	328,546	3.5
14	Low-med <30, dry <800, cool <17	Grassland	462,702	4.9	196,443	2.1	518,829	5.5
15	Low <20, moist <1200, hot <23	IOCB	206,710	2.2	491,792	5.2	107,804	1.1
16	Low-med <30, average <900, cool <17	Grassland	497,953	5.3	437,377	4.6	302,878	3.2
17	Low <20, average <1000, cool <17	Grassland	1,068,801	11.3	561,608	6.0	188,230	2.0
18	Very low <10, dry <700, warm <21	Grass/Savanna	338,129	3.6	339,155	3.6	889,128	9.4
19	Medium <40, dry <700, hot <23	Savanna	77,687	0.8	99,933	1.1	118,071	1.3
20	Very low <10, average <1000, hot <22	Grass/IOCB/Savanna	540,732	5.7	657,777	7.0	236,485	2.5
21	Low <20, dry <800, cool <18	Grass/Savanna	1,836,093	19.5	417,527	4.4	423,003	4.5
22	Very low <10, average <900, warm <20	Grass/Savanna	818,970	8.7	645,114	6.8	299,798	3.2
23	Low <20, average <1100, warm <19	Grass/IOCB/Savanna	409,998	4.3	642,034	6.8	188,914	2.0

Fig. 5. The magnitude of change expected in a) the GFDL 2.1 climate model and b) the HadCM2 climate model. White areas indicate more stable areas, whereas darker areas indicate a greater magnitude of change.

rather represent a hierarchical scale of increasing conservation effort, risk and resources. For instance, appropriate legislation would benefit domains in all quadrants but if required, a monitoring programme may be developed for a threatened species even if the environmental domain occurs in the 'Robust' quadrant. The most appropriate conservation measure would depend on the conditions associated with each domain. For instance, domains 2 and 8 are considered 'Robust'. They occur in the Maloti Drakensberg Park World Heritage Site at high altitude. Thus they require effective protected area management in order to maximise resilience. Domain 13 is predicted to increase in extent in the future in both models. However this is one of the coastal domains, an area of the province that is highly transformed (Jewitt et al., in press). Thus whilst the environmental variables may permit a domain range

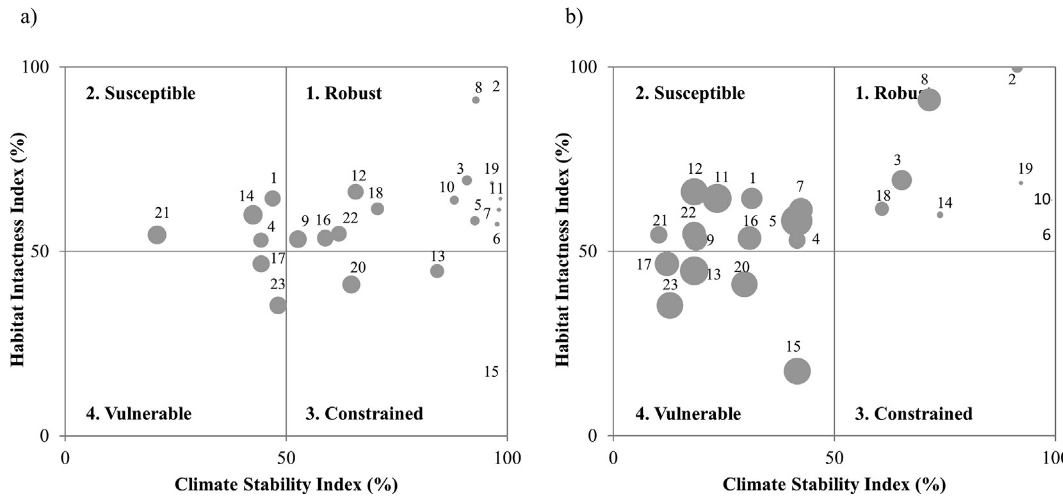

Fig. 6. The vulnerability framework for: a) the GFDL2.1 climate model, and b) the HadCM2 climate model. The Climate Stability Index reflects the percentage of the domains that remain stable in the future. The Habitat Intactness Index identifies the current levels of natural habitat remaining. The size of the circles indicates the relative mean magnitude of change expected in each domain.

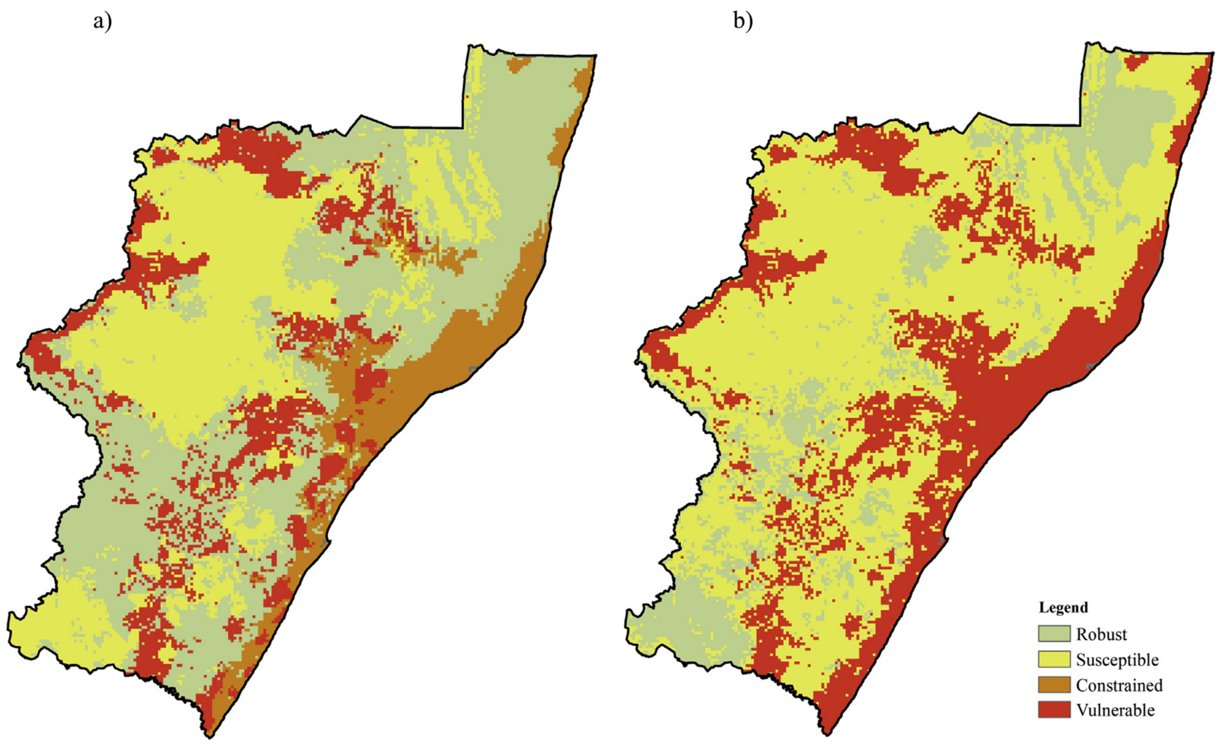

Fig. 7. The environmental domains ranked according to the vulnerability framework for: a) the GFDL2.1 climate model, and b) the HadCM2 climate model.

expansion, species occurring in this area occur in fragmented patches and so in reality would not easily be able to track these increasing domain ranges. Conservation measures that protect movement corridors and improve matrix permeability would be appropriate. The matrix surrounding protected areas consist of land-use practices that are often hostile to the survival of many species (Heller & Zavaleta, 2009), thus initiatives that mitigate these threats are beneficial to the species occurring there.

Species occurring in the 'Vulnerable' quadrant are at the most risk. Suggested conservation interventions include species translocations and *ex-situ* conservation. Assisted colonization is risky because of a lack of knowledge of the species biology of all species that may need to be translocated, an increased risk of the spread of pests and diseases, prohibitive costs (Hancock & Gallagher, 2014) and unknown consequences of introducing new species into communities (McLachlan, Hellman, & Schwartz, 2007). Reducing pressure on species from other threats may be more appropriate. *Ex-situ* conservation is a long-term activity, also with prohibitive costs (Cohen, Williams, Plucknett, & Shands, 1991). In future there may be no suitable habitat within which to re-establish species conserved through *ex-situ* conservation. Habitat loss is currently considered more significant than climate stability (Jetz et al., 2007) to biodiversity conservation, and it is also the threat that may be more easily influenced by conservation action locally (Watson et al., 2013), so securing habitat intactness should be prioritised.

Depending on the configuration of landscape transformation, an expanding domain could theoretically improve its habitat intactness index in future, but given the rapid rate of landscape transformation in the province this is unlikely, especially by 2050. If the current rates of habitat loss are not curtailed in line with the Convention on Biological Diversity (CBD) target of bringing the rate of habitat loss to zero by 2020, then the domains will move downwards in the framework.

The projections of climate change are uncertain and the models differ in their future predictions. By using an ensemble of climate models a range of possible responses to future climate change scenarios are produced. Where models concur, the uncertainty of the response is reduced and can increase the efficacy of proposed conservation adaptation strategies (Jones-Farrand, Fearer, Thogmartin, Thompson, Nelson, & Tirpak, 2011). Using adaptive management, the uncertainty associated with the effectiveness of the adaptation strategy may be evaluated (West et al., 2009) and fed back into conservation planning and management.

The future climate predictions made here are only until 2050. Far more extreme climatic change is expected by 2100 (Dawson et al., 2011; Mantyka-Pringle et al., 2012), hence diminishing domains may disappear entirely and novel domains may appear. The macro-refugia identified may not persist to the end of the century. Further research should be directed towards identifying and incorporating micro-refugia into conservation plans, and developing a network of potential conservation corridors using climatically stable areas that link protected areas and critical biodiversity areas. Should finer-scaled climatic models become available, the domains should be refined to better distinguish fine-scale heterogeneity in climate change.

5. Conclusion

By identifying climate-dynamic environmental domains that are explicitly linked to current floristic communities, the potential impacts of climate change on the biodiversity may be explored. This objective, coarse-filter approach facilitates conservation planning for common matrix plant species, and should be complemented by targeted fine-scale conservation plans for rare or threatened species. Beier et al. (2015) reviewed the use of abiotic surrogates for species representation in conservation planning and found them effective, particularly for plants and where the variables that most influence species turnover are used. Our technique may be successfully applied in regions where the environmental correlates of floristic communities are well known, or in areas where species information is scarce but the environmental gradients can be determined. The ensemble of future climate scenarios promotes an understanding of the range and degree of climate change impacts. Incorporating habitat loss, climate stability and magnitude of change into a vulnerability framework informs appropriate conservation actions to mitigate climate change impacts on biodiversity, facilitates dynamic conservation planning and highlights regions at most risk.

Author contributions

Debbie Jewitt: primary researcher and lead author,
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Peter Goodman: PhD supervisor, statistical and project advice,
Tim O'Connor: PhD supervisor, statistical and project advice,
William Hargrove: assisted with running the *k*-means clustering algorithm,
Damian Maddalena: assisted with running the *k*-means clustering algorithm,
Ed Witkowski: PhD supervisor and project advice.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2015.06.004.

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