

Assessment of potential climate change impacts on Namibia's floristic diversity, ecosystem structure and function

**Guy Midgley, Greg Hughes, Wilfried Thuiller
Gill Drew, Wendy Foden**

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Climate Change Research Group
South African National Biodiversity Institute
Kirstenbosch Botanical Garden, Rhodes Drive
Cape Town



For :
Namibian National Biodiversity Programme
Directorate of Environmental Affairs
Private Bag 13306
Windhoek
Namibia



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Executive Summary

We present here a first assessment of the potential impacts of anthropogenic climate change on the structure, function and biodiversity of the Namibian flora and vegetation, projected for 2050 and 2080 according to leading climate change scenarios and climate models (Hadley Center's HADCM3 General Circulation Model (Gordon *et al.*, 2000) using the A2 and B2 IPCC SRES socio-economic development scenarios (Nakicenovic & Swart 2000). In relation to projections for southern Africa of six other respected GCMs, the HADCM3 warming projections are close to or somewhat higher than their mean, and projections of rainfall tend to be near the dry extreme for both 2050 and 2080 (Ruosteenoja *et al.*, 2003).

We used dynamic global vegetation modeling (DGVM) approaches to simulate changes in vegetation structure and function (Woodward *et al.*, 2001), and statistical modeling approaches to develop bioclimatic niche models (BNM) (Peterson 2001; Guisan *et al.* 2002; Thuiller 2003) for over 800 plant species from knowledge of their distribution. This modeling effort represents one of the most comprehensive assessments of impacts of climate change on plant diversity in any southern Hemisphere country.

Significant changes in vegetation structure and function are projected in several areas of Namibia by 2080. The dominant vegetation type simulated in Namibia under current climate conditions, which we term Grassy Savanna, is projected to lose its spatial dominance to Desert and Arid Shrubland vegetation types. Vegetation is projected to suffer some reductions in cover and reduced Net Primary Productivity (NPP) throughout much of the country by 2050 (exacerbated by 2080), with important implications for the faunal component of Namibia's ecosystems, and the agricultural sector.

However, the impacts of rising atmospheric CO₂ that may directly increase plant primary productivity and therefore ameliorate vegetation response to climate change, introduce substantial uncertainty in projections in some parts of the country, mainly in the savanna woodland ecosystems of the northern Kalahari and northeastern Kalahari woodland regions. For example, elevated CO₂ exacerbates the reduced dominance of Grassy Savanna by 2080, by facilitating the increase of currently relatively scarce C3-dominated vegetation types, Woody Savanna, Mixed Grassland, and C3 Grassland/Shrubland. These currently uncommon types become widespread in the northeastern quadrant of the country with elevated CO₂, suggesting the strong potential for bush encroachment problems in these regions. In addition, fire is predicted to increase somewhat in either frequency or intensity in this north-east region under the elevated CO₂ scenarios only. Arid vegetation types increase in cover by almost 20% by 2050, and up to 43% by 2080 in the absence of a CO₂ fertilization effect, but with CO₂ fertilization modeled, the expansion of Desert in 2080 is reduced from 43% to just under 30%.

Changes in species richness and community composition are projected to be substantial in Namibia (based on modeling of over 800 species), but are strongly dependent on the migration capability of the species modeled. This is because BNM for individual species suggest that spatial shifts in the ranges of species often result from climate change – species are projected to become locally extinct in areas that become climatically unsuitable, and are required to migrate (or be translocated) to occupy new areas of potential geographic range in which they do not currently occur. We use two extreme assumptions to quantify this uncertainty, namely zero and perfect migration capability. Assuming a pessimistic zero migration ability, over 40% of the plants modeled are projected to become Critically Endangered or Extinct in Namibia

by 2080, but with optimistic full migration the proportion of species in these IUCN Red Data Book categories is approximately 30% by 2080. Importantly, results for endemic species only (161 of the total 834 modeled) showed lower susceptibility to climate change (19% and 12% classified Extinct and Critically Endangered respectively by 2080), probably because endemics are both arid-adapted and located in regions of lower projected climate change. These tend to be associated with topographic diversity which have probably buffered endemics against past climate change by reducing the need for past range shifts, and led to their persistence in evolutionary time.

We examined temperature and rainfall records from all available long-term weather stations (only 15 stations with durations of between 25 and 60 years) in Namibia and the northern Cape. Roughly half the stations showed significant increases in temperature over their recording period, while none showed a significant decline. The mean decadal increase across all stations during this interval was 0.2°C (s.d. = 0.1°C). This increase is roughly three times the global mean temperature increase reported for the 20th century. Water balance, a composite measure of temperature and rainfall reflecting the water available to plants, showed a significant decline at a third of stations. No stations showed a significant increase in water balance over this period. It is important to point out that the small number of long term climate stations from which to detect these potentially damaging trends is likely to be a significant limitation for any Namibian representation in international negotiations on climate change issues.

An early warning sign of climate change is indicated by the response of populations of *Aloe dichotoma* to apparent trends in recent climate, which indicate warming and drying trends in Namibia and northern South Africa over the past 15 to

30 years. This response is typical of that expected for species of the arid west under the expected climate change scenarios, and comprises a loss of species range in the northern and central parts of Namibia.

Significant uncertainties relating to the results presented must be acknowledged, however, and include those relating firstly to the climate projections, and those relating to the problems of modeling vegetation response to the projected changes. Uncertainties in climate projections have been extensively discussed, and are greater for rainfall than temperature projections (IPCC, 2001). It is important to point out that a scenario of no change in climate is highly unlikely, that some degree of warming is virtually assured, and this is supported by empirically measured trends in Namibia and northern South Africa. However, given that HADCM3 projections for southern Africa tend to be drier than several currently accepted GCMs, these results may present a somewhat pessimistic (though far from a worst-case) scenario for vegetation change in Namibia.

With respect to modeling vegetation structural and functional response, the DGVM approach has been widely used to project changes worldwide, and the highest degree of uncertainty relates to the impact of the CO₂ fertilization effect. In the absence of published results for southern African savanna shrub species and ecosystem feedbacks to elevated CO₂, it is not yet possible to gauge the relative credibility of “no CO₂ fertilization” and “+CO₂ fertilization” scenarios.

With respect to results for biodiversity changes, it is well known that bioclimatic niche models have many shortcomings, and furthermore that the projected changes are those that would be expected with an instantaneous species response to climate change. These scenarios also do not take into account any CO₂ fertilization effect. Combined with the scale of the study that conceals species persistence in small

areas buffered from climate change impacts by topographic relief, these results should therefore be seen as pessimistic (though not worst-case) projections. Nevertheless, the results are of sufficient concern to warrant further effort to confirm or refute them, and at least to begin addressing conservation strategies that might assist in protecting species diversity from this threat.

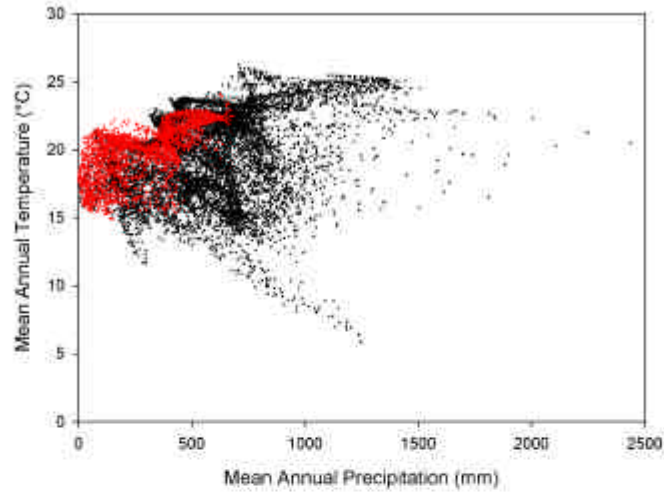
Taken together, these results indicate an appreciable vulnerability of Namibian biodiversity as a whole to projected anthropogenic climate change, and an increase in pressure on the adaptive capacity of conservation planning in this country over the next few decades. However, the geographic location and concentration of many Namibian plant species endemics affords some level of resilience in endemic biodiversity and could form the basis for developing effective adaptation strategies to climate change. Ongoing monitoring of climatic trends at a far higher spatial resolution than is currently the case will be critical in assessing the rate of climate change in this region, and its potential future evolution.

Introduction

Namibia is one of southern Africa's most arid countries, named as it is after the world-renowned Namib Desert, and situated on the Atlantic coast roughly between 29°S (Orange River) and 17°S (Cunene and Kavango Rivers), bounded in the east by the 20°E and 21°E longitudinal lines south and north of 22°S respectively, and including the east-trending Caprivi strip north of the Okavango Delta which extends to 25°E. This region is under the strong aridifying influence of the cold Benguela current and is positioned in the latitudinal zone of stable descending air of the Hadley Cell, limiting convective rainfall throughout much of the country's interior. Namibian climate ranges from arid and semi-arid in the west, with a temperate, regionally fog-bound coastal desert, to more subtropical summer-rainfall conditions in the north-east. The central, southern and coastal areas are among the most arid landscapes south of the Sahara. In relation to the rest of southern Africa, Namibia represents a low rainfall extreme and experiences intermediate to warm temperatures and high potential evapotranspiration (Figure 1).

Regardless of these climatic constraints, Namibia is home to a remarkable biodiversity, notably among its plant species. Within its borders, more than 4500 plant taxa have been recorded, almost 700 of which are endemic to the country, and a further 275 of which are Namib Desert endemics shared with southern Angola (Maggs *et al.* 1998). Plant species endemism is concentrated in five centers (Maggs *et al.* 1994), the Kaokoveld in the north, The Otavi highland in the Kalahari basin in the east, the Okavango region in the northeast, the Auas mountains on the western edge of the central plateau, and the succulent-rich southern Namib.

Current Namibian climate relative to southern African climate



Namibian climate relative to southern African climate

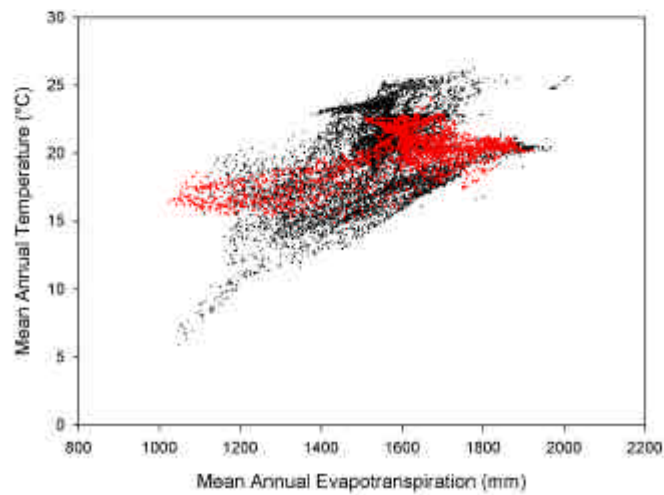


Figure 1: Scatterplots of the Namibian climate (red dots) relative to that of southern Africa south of 19°S (black dots, each point represents annual means for 10x10 pixel). A: Scatterplot of Mean Annual Temperature and Mean Annual Precipitation. B: Scatterplot of Mean Annual Temperature and Mean Annual Potential Evapotranspiration.

This variety of plant species in Namibia makes up a broad range of ecosystem types ranging from desert landscapes with sparse plant cover on the western coastal belt with high succulent dominance in the south-west, through arid shrubland and sparse woodland with C4 grasses along the escarpment, to tree-grass mixed savanna and woodland vegetation in areas of higher rainfall in the northeastern Kalahari basin. Various categorizations of Namibian vegetation types have been proposed. These can be summarized most simply as a set of four biomes based on plant life form dominance (Irish 1994), namely the ephemeral therophyte-dominated Desert, succulent-shrub dominated Succulent Karoo, C4 grass and shrub co-dominated Nama-Karoo, and tree and grass co-dominated Savanna. Using a finer definition of vegetation types based on both vegetation structure and floristic attributes, fourteen relatively homogenous vegetation zones can be defined (Giess 1971), which subdivide the Desert Biome into three zones on a north-south axis, the Nama-Karoo Biome into three zones, and the Savanna Biome into eight zones.

The economy of much of the region depends on extensive ranching activities, both commercial and communal/subsistence, which are underpinned by the productivity of its grassland-, savanna- and shrub-dominated ecosystems. The economic output of Namibia, and subsistence livelihoods which sustain up to 70% of the population, are therefore sensitive to climatic variability (Barnard & Taskforce 1998). Food self-sufficiency by 2020 is a stated policy goal, and this will be highly dependent on at least the maintenance of current levels of net primary productivity (NPP). Tourism and ecotourism are also likely influenced by the natural beauty and biodiversity in Namibia, and although it is more difficult to link ecosystem integrity and tourism potential, it is possible that climate warming and aridification will threaten this lucrative sector.

Because Namibia represents an arid extreme for southern Africa, it seems feasible that the country will be vulnerable to the impacts of anthropogenic climate change, which is predicted to raise global air temperatures by between roughly 2° and 5°C, and alter regional rainfall patterns, by the end of this century (IPCC 2001). For example, if a mainstream scenario of climate change for 2080 (see Methods, pp. 59,60) is projected onto the axes given in Figure 1, it can be seen that new climate extremes emerge for the subcontinent, mainly in Namibia (Figure 2).

The antiquity and persistence of desert conditions in Namibia is thought to be the basis of high species endemism in the more arid parts of the country, though recent work has begun to show that for much of the Pleistocene (the past two million years) cool glacial conditions may have been accompanied by higher rainfall in especially the southern parts of this zone, as it fell under the influence of rain-bearing westerly frontal systems (Midgley *et al.* 2001). It is likely that warming will exacerbate the extreme climates of the hyper-arid Namib and its surrounds, and possibly increase the temperature and rainfall gradients currently present in the country.

At least some level of vulnerability to climate change of Namibia's natural ecosystems is likely, given that the biodiversity of neighboring South Africa has been found to be vulnerable to climate change (Rutherford *et al.* 1999), shares similar bioclimates with the southern regions of Namibia, and possesses similar biome types. A full assessment of vulnerability to climate change in the biodiversity sector requires knowledge of the interaction between potential impacts of climate change on biodiversity, and the ability of conservation efforts to adapt to or mitigate these. In terms of simple impacts of higher temperatures and a more arid regime, these may

Future Namibian climate relative to southern African climate

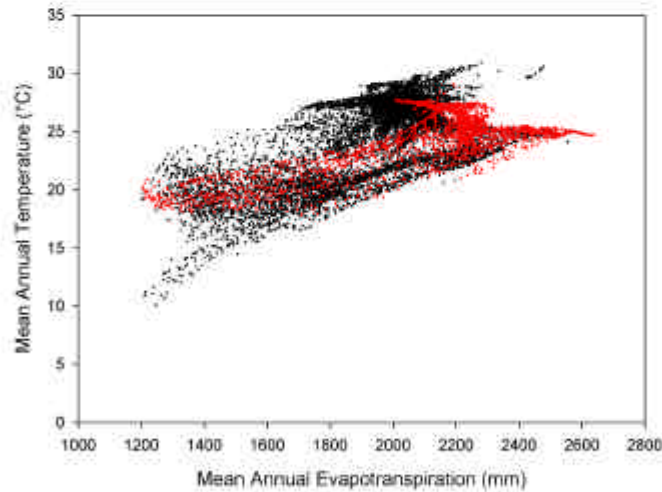
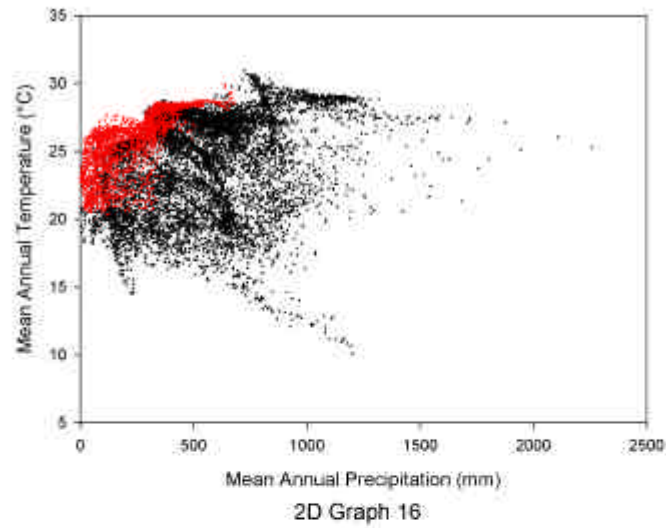


Figure 2: Scatterplots of the Namibian climate projected for ~2080 by the GCM HADCM3 (red dots, see Methods) relative to that projected for southern Africa south of 19°S (black dots, each point represents annual means for 10°x10° pixel). A: Scatterplot of Mean Annual Temperature and Mean Annual Precipitation. B: Scatterplot of Mean Annual Temperature and Mean Annual Potential Evapotranspiration.

exceed the current tolerance extremes for at least some elements of the Namibian flora. Adaptive capacity by conservation is limited by the extensive areal extent of these impacts, and the high cost of some active adaptive interventions, such as *ex situ* conservation or species translocation. This is not to say that lower cost options for adaptive management of conservation areas, such as assessment of the placement of expanded protected areas may not represent effective strategies (Hannah *et al.*, 2002). This study does not assess adaptation options, but merely provides a first assessment of potential impacts and the vulnerability of plant biodiversity to projected climate change.

No previous quantified assessment of risk of climate change to plant biodiversity has been undertaken for Namibia – this is an urgent need, given that projections for warming and drying are harsh for central and western parts of southern Africa, with most extreme projected warming centered on Botswana (IPCC 2001).

Climate trends in southern Africa during the 20th century reveal a rate of warming which is comparable with that of the global average, and on the order of about 0.05°C per decade (Hulme *et al.* 2001), though the sparse coverage of weather stations in this region strongly constrains definitive conclusions. Rainfall patterns over southern Africa during the past century reveal a high degree of year-to-year variability, of the order of 30%, and have shown a sharp reduction from the century average during the decades of the 1980's and 1990's (Hulme *et al.* 2001). To some extent, drought incidence in southern Africa can be linked to the El Nino-Southern Oscillation (ENSO) index, with severe water deficits occurring in 1991/1992 and 1994/1995 and during the intervening years. However, ENSO-linked rainfall anomalies in Namibia are somewhat discordant with those of central and east southern Africa, with northwestern Namibia and neighboring parts of Angola showing only

weak or even positive rainfall anomalies in three of four significant drought events in the subcontinent this century (Hulme *et al.* 2001).

General approach

In this study we modeled the potential impacts on plant biodiversity and ecosystem structure and function. There are many approaches to modeling climate change impacts on vegetation, all of which are subject to significant uncertainty. By using complementary approaches we have attempted to present a diverse view of these impacts.

We first used a mechanistic modeling approach, termed a dynamic global vegetation model (DGVM, Prentice *et al.* 1992, Woodward *et al.* 1995) to explore impacts of change on ecosystem structure, function and plant functional type dominance throughout the country. Because it is a general global modeling approach, the elements of vegetation modeled are relevant to the entire planet, and are termed Plant Functional Types (PFTs, Smith *et al.* 1997). These include a small number of broad categories such as C₄ grasses, deciduous trees and C₃ herbaceous and shrub types. Such an approach has been used worldwide and its generality is underpinned by being based on a fundamental understanding of plant physiology, growth form, biogeochemical cycling of water, nutrients and carbon, and ecosystem disturbance by fire. While the approach provides a prediction of ecosystem structural change (e.g. grassland transformed to savanna), it uses robust assumptions that allow the determination of impacts on important ecosystem functional properties such as soil carbon storage, soil nitrogen content and net primary productivity (NPP), the basis of land utilization efforts such as livestock ranching. The modeling approach is

advantageous in being dynamic, in the sense that the time scale over which ecosystem-level responses and feedbacks occur is simulated annually, allowing non-equilibrium conditions to exist. In other words, lags in ecosystem response such as occur via slow changes in soil quality through vegetation shifts and changing fire regimes are simulated. A final major advantage of using this approach is that it provides a first approximation of how the direct impacts of rising atmospheric CO₂ may alter the direct impact of climate alone on vegetation, a consideration that has previously been shown to be critical in moderating the impacts of climate change (Hulme *et al.* 2001). Elevated CO₂ potentially increases the water- and nutrient-use efficiency of plants that use the C3 photosynthetic pathway (Drake *et al.* 1997), and favors woody plants with a high degree of investment in carbon-rich support tissue (such as trees) relative to herbaceous species (such as grasses) (Bond & Midgley 2000; Bond *et al.* 2003). These effects may be significant, and potentially ameliorate the worst effects of warming and drying on vegetation.

In order to assess climate change impacts on plant biodiversity through changing species geographic range, we used statistical modeling approaches to develop bioclimatic niche models (Peterson 2001; Guisan *et al.* 2002; Thuiller 2003) for almost one thousand plant species from knowledge of their distribution. This modeling effort alone represents by far the most comprehensive assessment of climate change impacts on plant diversity in any developing country.

The bioclimatic niche models are used to project the future geographic ranges of all species modeled, given certain assumptions (see Methods p. 65), to derive an index of risk for biodiversity and community compositional modification. These projections are necessarily limited by a lack of knowledge concerning individual species' CO₂ responses, but remain a useful index of threat of species loss and

community modification, especially in more arid regions where the CO₂ effect on plant growth may be less significant (because the perennial vegetation of arid regions is dominated by succulent plants with CAM photosynthesis which is not as responsive to rising atmospheric CO₂ as the more common C₃ photosynthesis, and because CO₂ effects on soil water through reduced stomatal conductance is negated largely by the low vegetation cover and LAI).

Species range change projections are strongly affected by assumptions relating to the migration rates of species concerned (Higgins & Richardson 1999). Migration rate remains one of the most significant uncertainties in species range projections (Midgley *et al.*, submitted), and because of this we assume both of two migration scenarios, “zero” and “perfect” migration, to express the uncertainty relating to this constraint in understanding. Finally, we further analyze these results in terms of IUCN red list categories (IUCN 2001) to assess the potential change in numbers of threatened species in Namibia.

Global temperature increases in the latter three decades of the 20th century are attributable to anthropogenic greenhouse gas emissions (IPCC 2001). We assessed whether climate changes concordant with the projected change may already be evident, by analysing temperature and water balance changes of rainfall stations with an extensive historical record to justify long-time scale analysis. We carried out, in a related project, a field study of a flagship Namibian desert species *Aloe dichotoma* in order to explore if early climate change is impacting this species, and report the results here due to their relevance to the credibility of our modeling approaches.

We finally discuss relationships between the results derived from the different approaches and attempt to refine our projections in terms of their uncertainties, given the impacts of elevated CO₂ and fire regime change in the region.

It is important to stress the fact that among the many assumptions and simplifications inherent in developing these risk assessments (see Methods section for further discussion), the models are developed on the scale of approximately 10' (roughly 15 x 18 km at these latitudes), and therefore may conceal topographic details and their impacts on species persistence, such as through the existence of micro-sites (such as shaded kloofs).

Results

Climate change scenarios

Baseline climate data for Namibia, at 10' resolution, were obtained from the Climate Research Group at the University of East Anglia (New *et al.* 2000). We present here changes projected by the General Circulation Model (GCM) HadCM3 (Gordon *et al.* 2000) for three key bioclimatic aspects of Namibia's climate, for ~2050 and ~2080, according to the SRES A2 and B2 global economic and social development scenarios (see Methods p34 for a brief description of SRES).

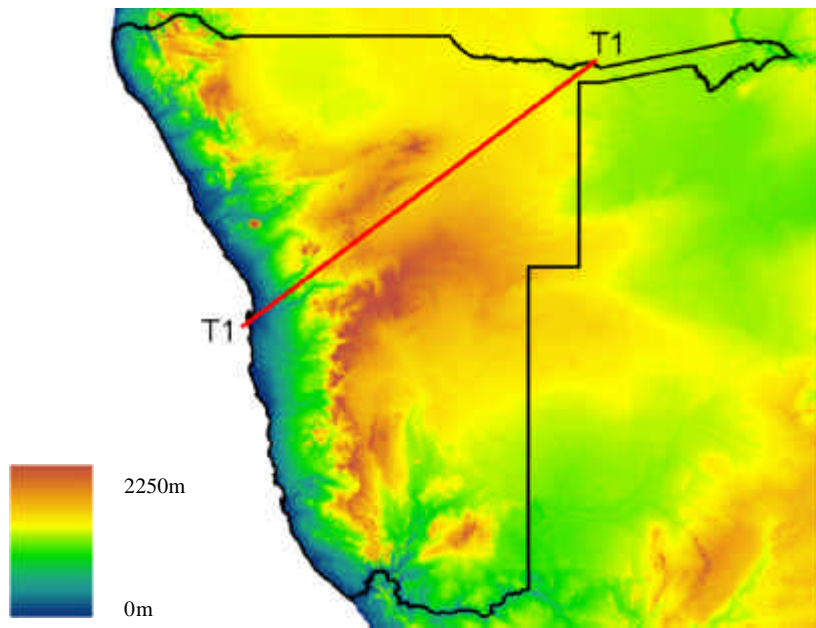
According to a comprehensive General Circulation Model inter-comparison (Ruosteenoja *et al.*, 2003), the temperature projections for the southern African region by HADCM3 for 2050 and 2080 tend to be close to or somewhat higher than the mean for six other GCMs. Projections of rainfall reductions by HADCM3 tend to be near the extreme projected by the six other GCMs for spring, autumn and summer quarters (between a 10% and 30% reduction relative to the present), but more extreme than any other GCM for the winter quarter (~40% reduction relative to the present).

Temperature changes projected for Namibia itself are significant, but have a strong longitudinal spatial structure that is relevant for assessing risk to Namibian biodiversity. Simply put, warming by 2050 is more limited in the coastal regions than eastward on the escarpment and inland regions, and this temperature gradient steepens by 2080 (Figure 3). This spatial pattern is credible in the light of the ameliorating influence of the cold Atlantic on coastal temperatures. Warming is also in general higher for the A2 than the B2 scenario, but only noticeably so by 2080.

The spatial pattern of change for potential evaporation is broadly similar to that of minimum temperature with a strongly steepening inland-coastal gradient by 2080 (Figure 4). Unfortunately, GCMs are currently unable to simulate details of regional climates, particularly the incidence of coastal fog that is known to be an important influence on marine-influenced ecosystems of the coastal strip. In a sense, then, these scenarios represent a conservative change for coastal regions in central and southern Namibia, because we are forced to assume that current patterns of fog incidence are not affected by climate change.

Mean annual rainfall projections have a higher associated uncertainty than do temperature projections. HADCM3-derived projections reveal both a latitudinal and longitudinal pattern of change, with rainfall reductions projected for the entire country (Figure 5), but more severe in the north-west and central regions than in the southwest and northeast. For these projections, the B2 scenario generates the most extreme rainfall reductions (generally more than 20% in least affected parts, and as high as 80-100% in the central Namib coastal region). Particularly strong rainfall reductions are noted in the area of Windhoek and the surrounding highland region.

Elevation map and position of transect (T1)



Annual Temperature along Transect T1

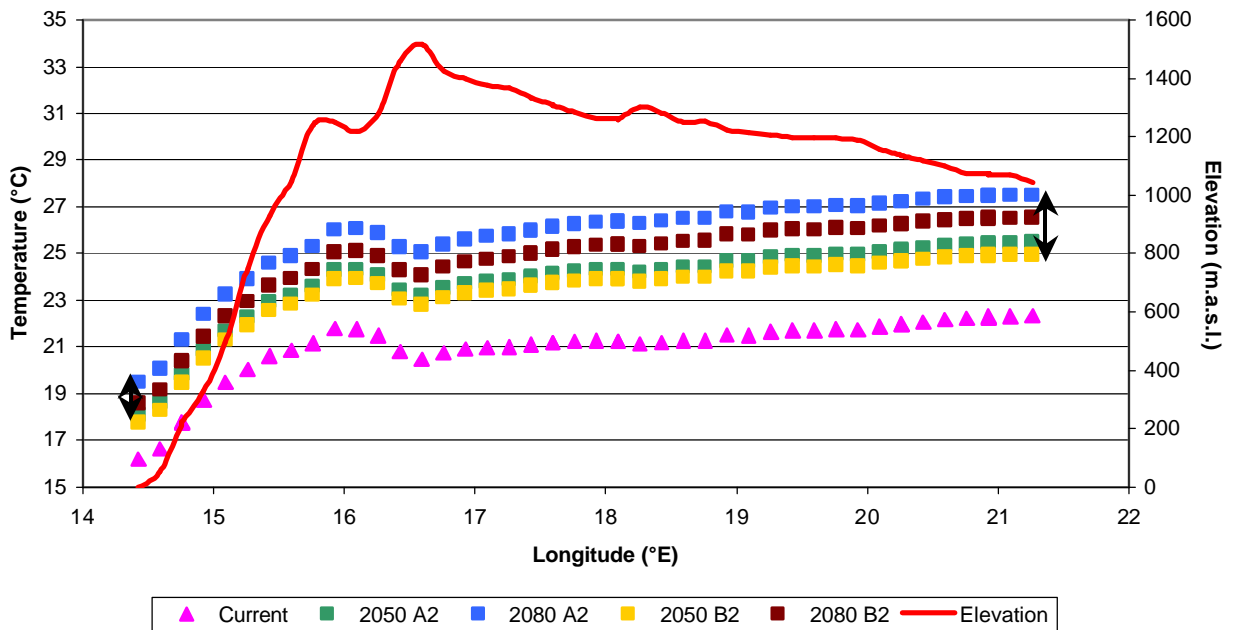


Figure 3: Changes in elevation along a southeast/northwest transect (T1) in Namibia (see upper panel). The lower panel shows projected changes in mean annual temperature (MAT) in relation to position on this transect, and altitude. Note the moderating effect of the Atlantic ocean on the projected temperature increases.

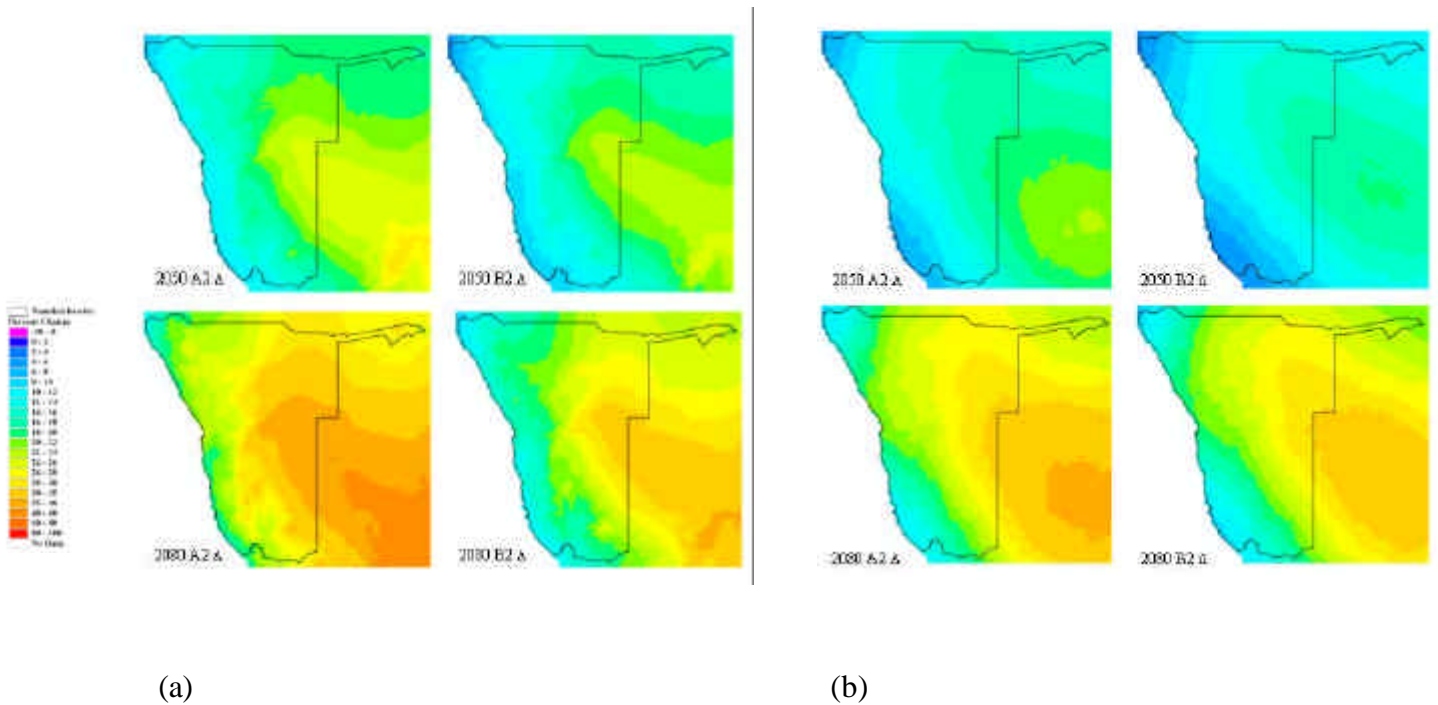


Figure 4: Changes in (a) Winter mean temperature and (b) Potential evapotranspiration as projected for 2050 and 2080 according to the GCM HadCM3, driven by atmospheric changes projected according to the A2 and B2 scenarios.

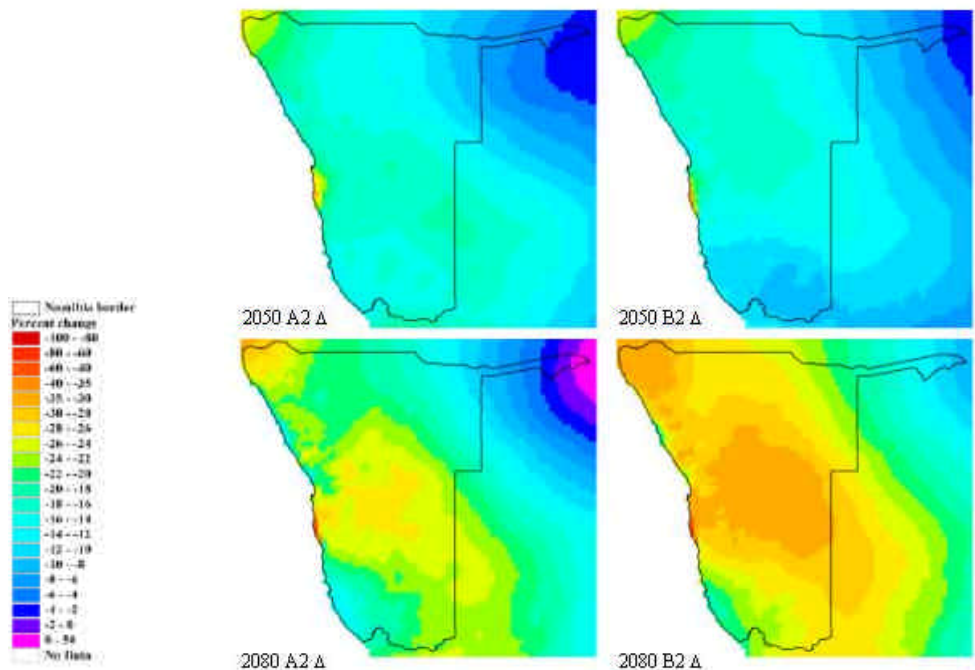


Figure 5: Changes in Mean Annual Precipitation (MAP) as projected for 2050 and 2080 according to the GCM HadCM3, driven by atmospheric changes projected according to the A2 and B2 scenarios.

Dynamic Global Vegetation Model (DGVM)

The DGVM results encompass simulations of the present day vegetation state as well as that for the future – results for the present allow an assessment of the success of the DGVM in simulating real patterns that exist in Namibia. Future results are presented for multiple atmospheric CO₂ concentrations.

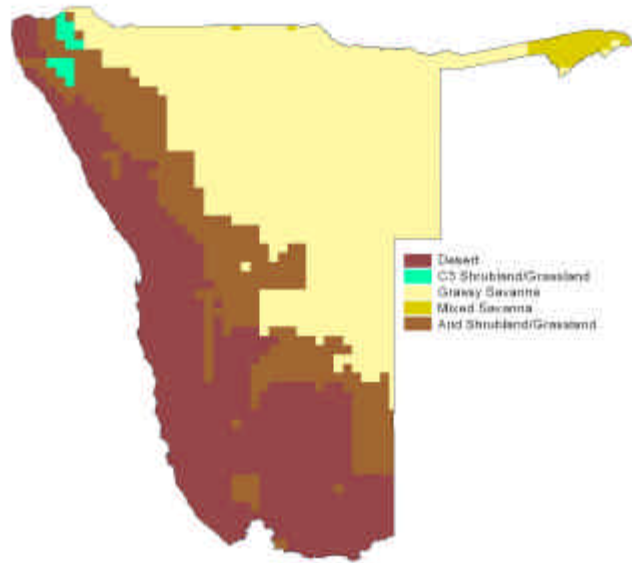
Current PFT and structural distribution patterns

Seven vegetation structural classes are defined as occurring in Namibia under current and future conditions by the DGVM output (see Table 1, after Drew 2004).

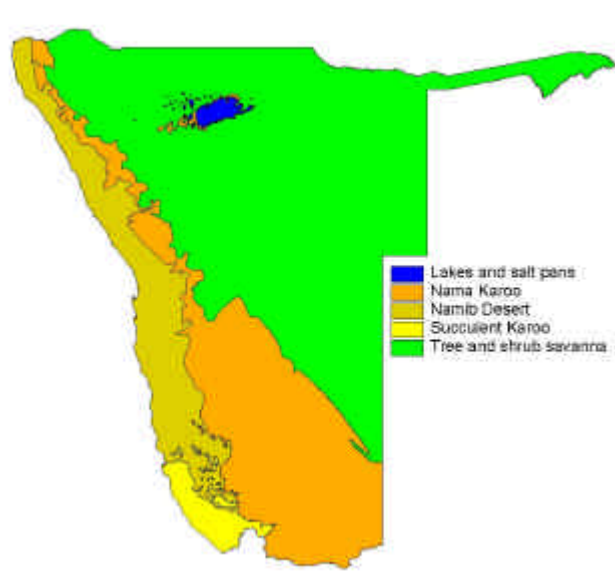
Structural class	Definition i.t.o. PFT proportional cover
Desert	Bare ground > 80%
Arid shrubland/grassland	Bare ground 20% to 80% cover, C3 or C4 > 20% to 60% cover
C3 shrubland/grassland	C3 > 60% cover
Grassy savanna	C4 > 60% cover, Deciduous trees 0 to 30% cover
Mixed savanna	C4 30% to 60% cover, Deciduous trees 30% to 60% cover
Woody savanna	C4 and C3 20% to 60% cover, Deciduous trees 30% to 60% cover
Mixed shrubland/grassland	C4 and C3 30% to 60% cover, above conditions for other PFT not met

Table 1: Vegetation structural classes as defined by the cover of bare ground and proportional cover of plant functional types (PFT's), namely C3 grasses/shrubs, C4 grasses, and deciduous trees (a subset of the 6 PFT's as originally defined (Woodward *et al.*, 1995)).

The vegetation structural classes simulated under current climate conditions reproduce the distribution of vegetation structural types with relatively satisfying detail in Namibia (Figure 6), revealing the expected gradients in vegetation cover, structural change and productivity from the arid west and south-west through to the more mesic north-east. Desert vegetation is projected along the entire western coastal strip, broadly congruent with the mapping of northern, central and southern Namib by Giess (1971) (Desert Biome of Irish (1994)), Desert and Succulent Steppe (Succulent Karoo Biome of Irish (1994)), the Semi-desert and Savanna transition of the escarpment, and the Dwarf Shrub Savanna of the southern central interior. Inland of



(a)



(b)

Figure 6: Main vegetation structural types (a) simulated by the mechanistic Sheffield Dynamic Global Vegetation Model (SDGVM), driven by climate conditions for 1960 to 1990 as projected by CRU. In (b) vegetation biomes are mapped according to Irish (1994).

the Desert, the SDGVM simulates a continuous strip of Arid Shrubland/Grassland inland of the escarpment, essentially defining a mixed C4/grass and shrub assemblage which is transitional to the north-eastern region – defined as Grassy Savanna – which represents a grass-dominated savanna with an increasing representation of deciduous trees towards the Okavango and the Caprivi strip. The distribution of cover of deciduous trees shows a zone roughly congruent with the Arid Shrubland/Grassland with up to 10% tree cover, increasing in the north-east to between 10 and 20%, and up to 40% on the northern border, and up to 50% in the eastern reaches of the Caprivi strip (Figure 7). C4 grass cover (Figure 8) is distributed more widely than that of deciduous trees, increasing from 10% in the coastal desert belt to roughly 30% on the escarpment, and up to 90% in the interior north-east. C3 grass and shrub vegetation is sparsely distributed except for a minor concentration of this PFT in the northern Kaokoveld region, south of Angola (Figure 9). This anomaly is likely due to anomalies in the base climate data in this region that has a sparse coverage of climate stations and limited accuracy of climate interpolations.

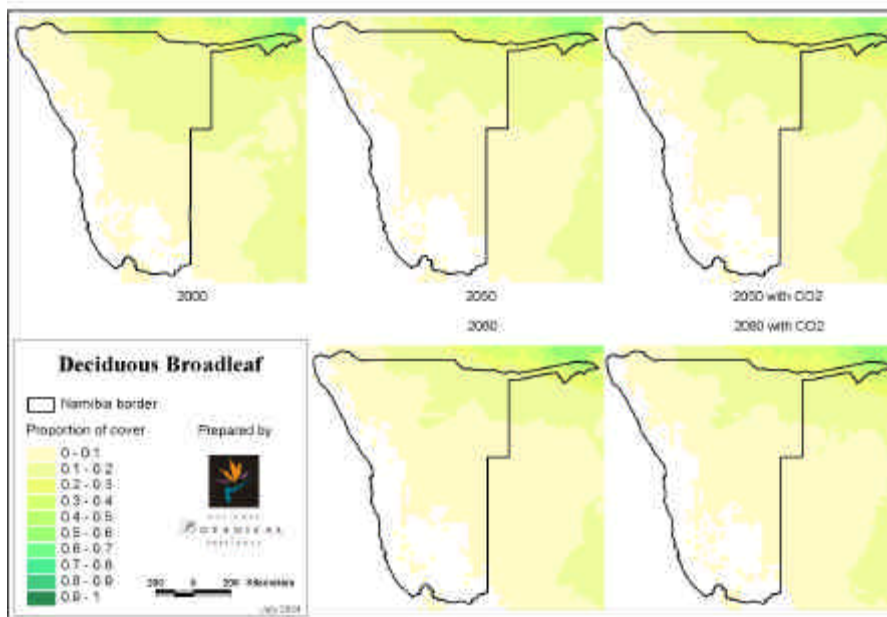


Figure 7: Proportion of land surface covered by deciduous trees simulated by SDGVM under current climate conditions, and those driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled.

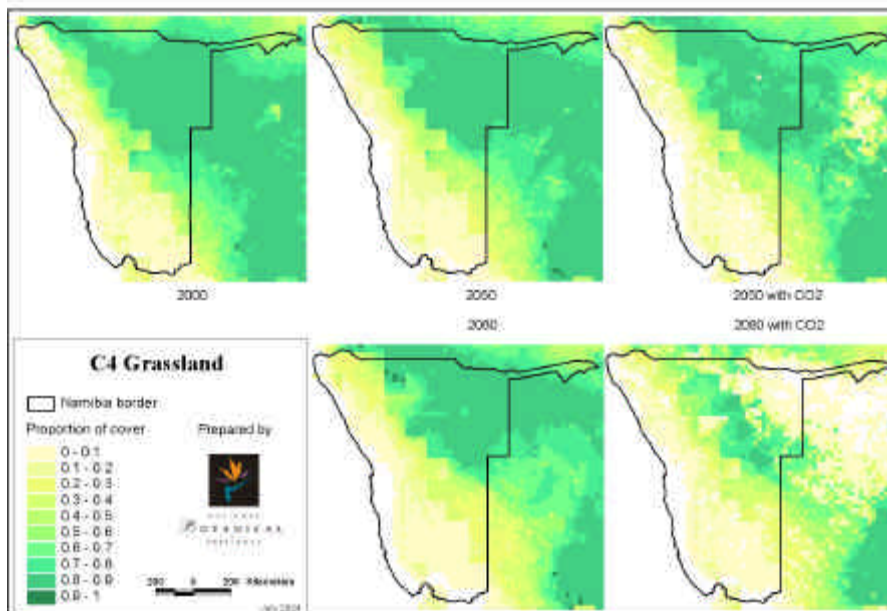


Figure 8: Proportion of land surface covered by C4 grasses simulated by SDGVM under current climate conditions, and those driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled.

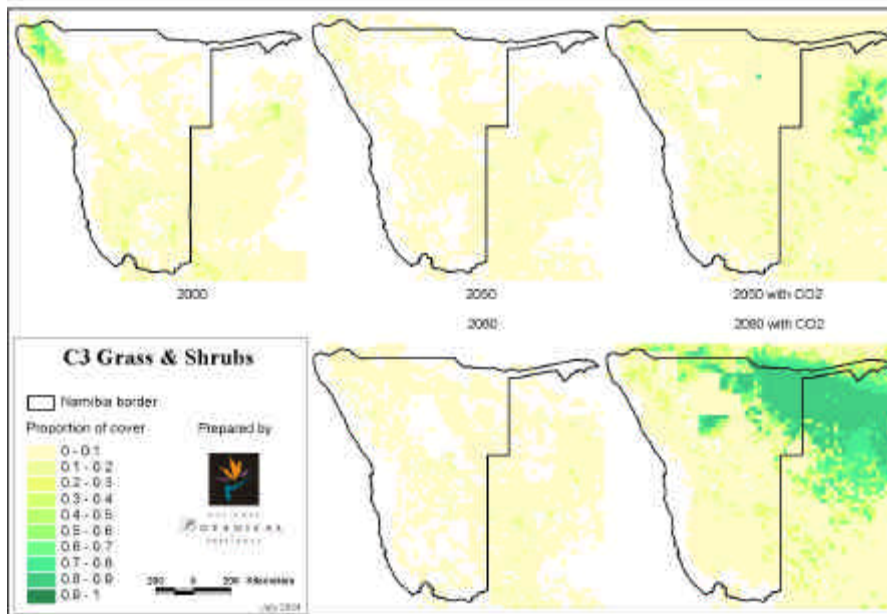


Figure 9: Proportion of land surface covered by C3 grasses and shrubs simulated by SDGVM under current climate conditions, and those driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled.

In terms of total biomass, deciduous trees are projected not to exceed 250 g m⁻² for most of the country, which is an underestimate for the central/northern region (Rutherford, 1978). However, on the northern Angolan border and eastern Caprivi, biomass is projected more realistically at up to 2000 g m⁻² (Figure 10). C4 grass biomass (Figure 11) peaks in the north-east at up to 400 g m⁻². Net Primary Productivity (NPP) is projected to range between 0 and 5 tons ha⁻¹, following the spatial pattern of increasing biomass trends in C4 grasses and deciduous trees towards the north-east. Leaf area index (LAI) is projected to range between 0 and 5 (Figure 12), peaking in a zone broadly congruent with Giess' (1971) Forest Savanna and Woodland vegetation.

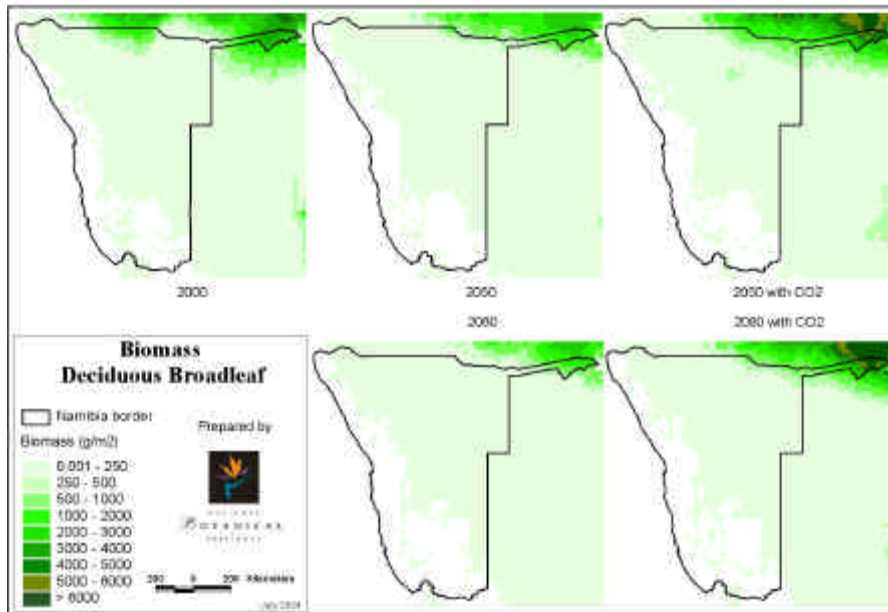


Figure 10: Biomass of deciduous trees simulated by SDGVM under current climate conditions, and those driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled.

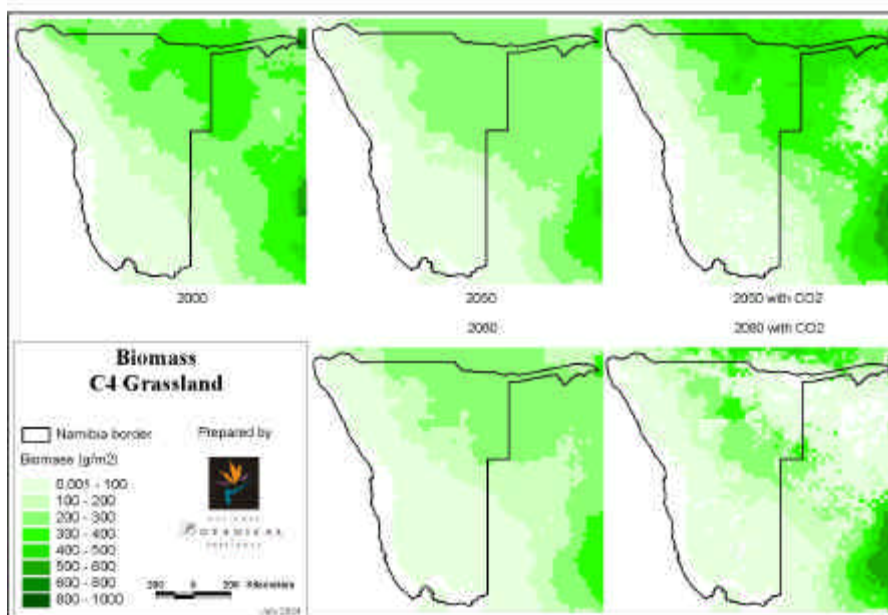
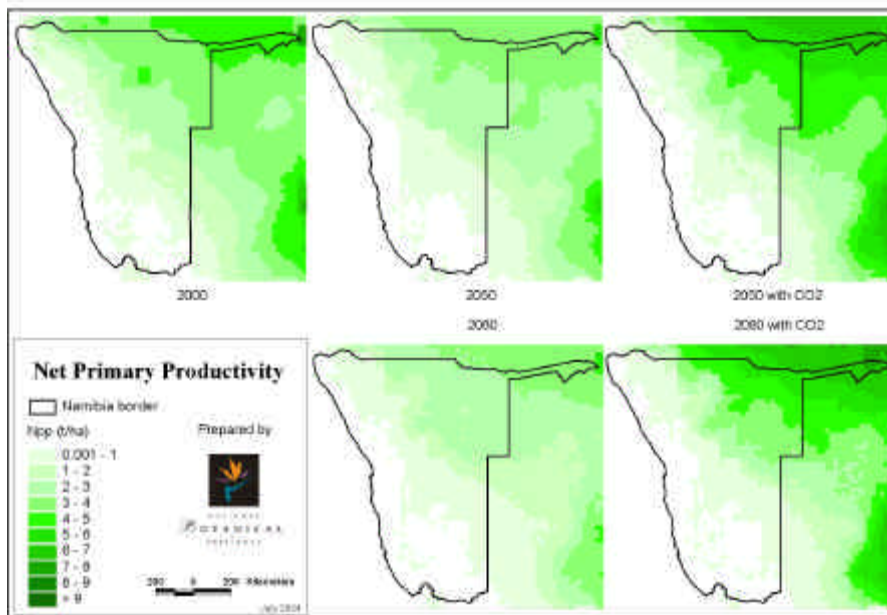


Figure 11: Biomass of C4 grasses simulated by SDGVM under current climate conditions, and those driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled.

a)



b)

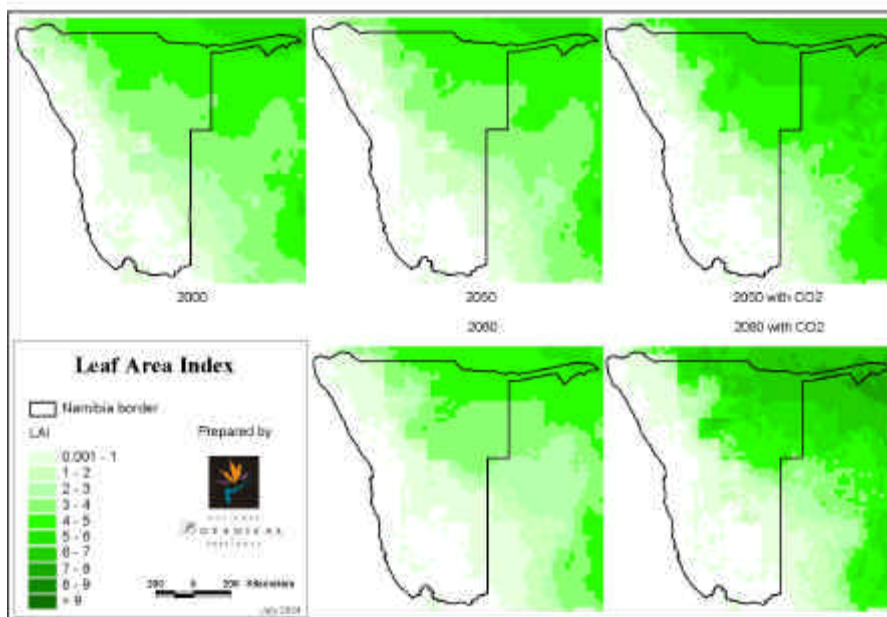


Figure 12: Key ecosystem characteristics simulated by the mechanistic Sheffield Dynamic Global Vegetation Model (SDGVM), under current climate conditions, and those driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled. (a) Net Primary Productivity (NPP) (b) Leaf Area Index (LAI)

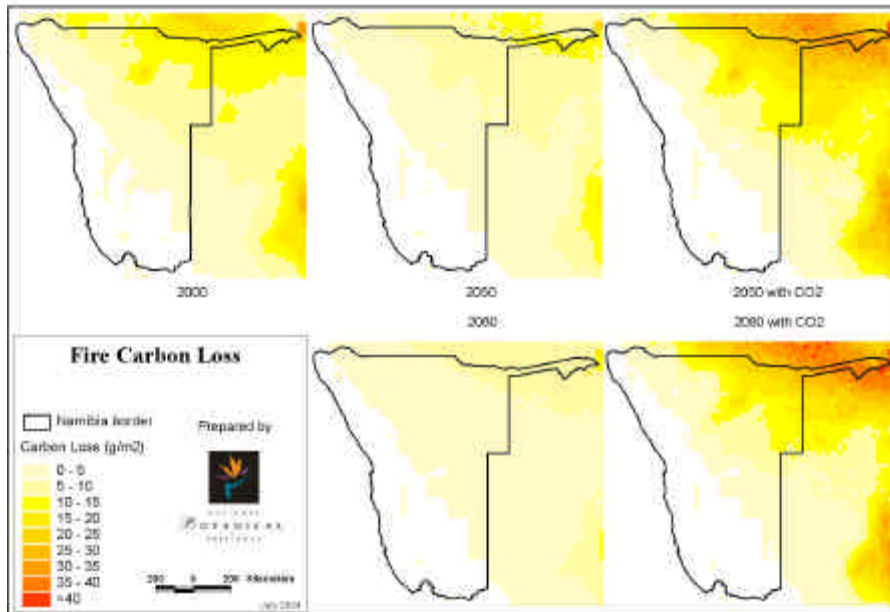


Figure 13: Losses of carbon to fire simulated by SDGVM under current climate conditions, and those driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled.

The incidence of fire (Figure 13) is quantified by mass of carbon burned per annum, and is simulated in all vegetation classes bar Desert, increasing to up to a peak value of ~20 g m⁻² carbon loss in areas of highest biomass.

Future PFT distribution and ecosystem structure and function

Future projections of total vegetation cover provide a first-cut assessment of climate change impacts on vegetation structure, and are indicated by changes in bare ground prevalence and leaf area index. These projections indicate vegetation cover reduction over the central highlands by 2050, with further reductions to 2080 (Figure 14). The greatest absolute cover reductions are mapped in the Kaokoland region in the extreme northwest, and in the Kalahari basin in the southeast, with less significant

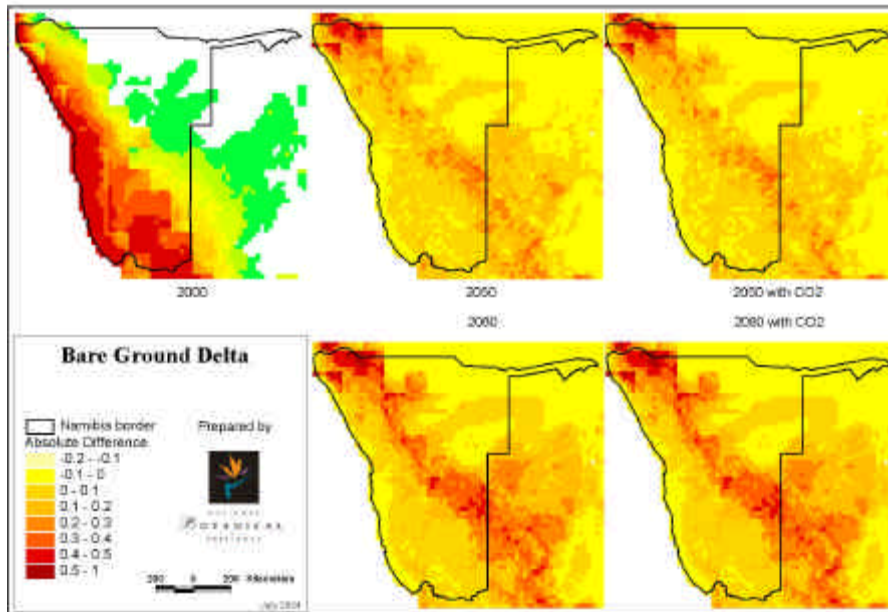


Figure 14: Cover of bare ground, simulated by SDGVM under current climate conditions, and changes in bare ground driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled.

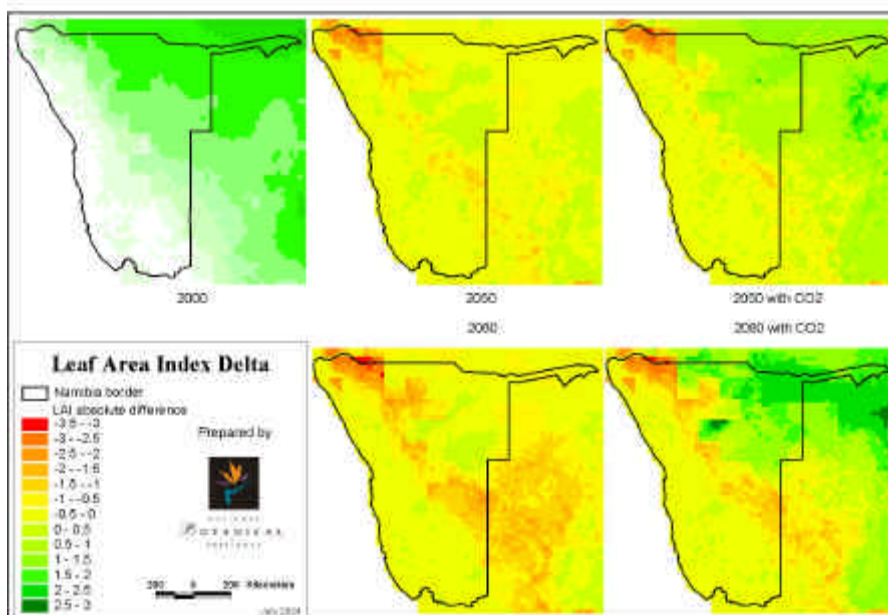


Figure 15: Leaf Area Index (LAI) simulated by SDGVM under current climate conditions, and changes in LAI driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled.

reductions noted at higher altitudes in the central highlands. Some geographically limited increases in cover (Figure 14) not projected to exceed 10%, are thus barely significant. The direct effects of rising atmospheric CO₂ on total cover are not significant. Projected changes in LAI are more diverse, indicating significant reductions in areas of highest decrease in vegetation cover (Figure 15). However, these regions are of limited spatial extent, and much of the country is projected to experience LAI changes of between +10% and -10%. Of further interest is the strong ameliorating effect of rising atmospheric CO₂ on LAI responses to climate change in the mesic northeastern Kalahari, which is projected to benefit significantly from CO₂ fertilization in terms of LAI. This finding is an important indication of the uncertainty in projection introduced by the CO₂ fertilization effect.

The future climate scenarios (without CO₂ fertilization) cause significant changes in PFT distribution and PFT success throughout the country (Figure 16, 17 and Table 2), especially in the central escarpment and southern central regions. A primary finding is the expansion of the two most arid vegetation types, Desert and Arid Shrubland/Grassland, mainly at the expense of Grassy Savanna and Mixed Savanna classes. The arid vegetation types increase by almost 20% by 2050, and up to 43% by 2080, in the absence of a CO₂ fertilization effect, but with CO₂ amelioration, the expansion of Desert in 2080 is reduced from 43% to just under 30%. The current dominance of Namibian vegetation by Grassy Savanna vegetation under current climatic conditions is projected to diminish substantially by 2050, with significant cover and biomass reductions evident in the central highlands and northeastern plains. Including the effects of elevated CO₂ exacerbates this effect in 2080, by facilitating the increase of currently relatively scarce C3-dominated vegetation types, Woody Savanna, Mixed Grassland, and C3 Grassland/Shrubland.

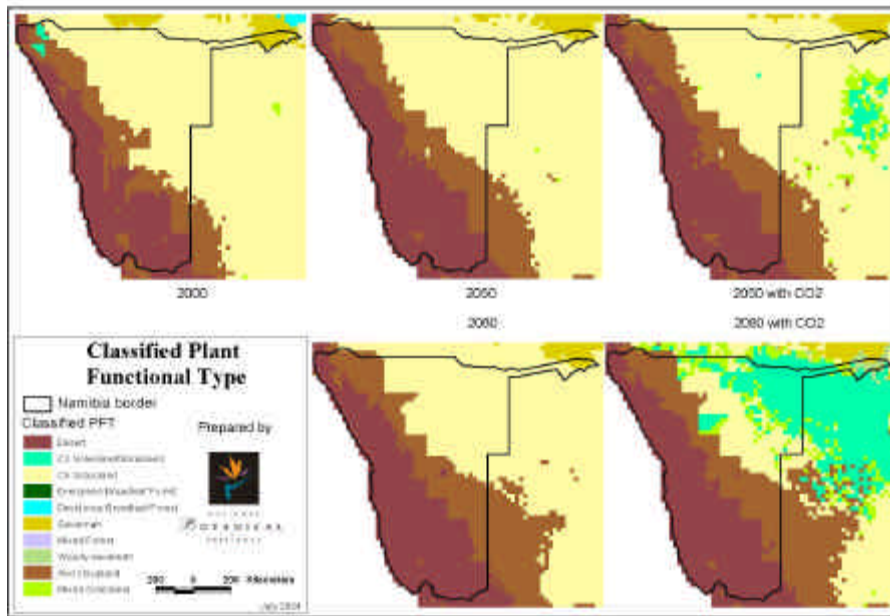


Figure 16: Vegetation structural classes simulated by SDGVM under current climate conditions, and those driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled.

Structural class	Current	2050	2050 +CO ₂	2080	2080 +CO ₂
Desert	650	766 +18%	753 +16%	931 +43%	825 +27%
Arid shrubland/grassland	351	407 +16%	419 +19%	403 +15%	413 +18%
Grassy savanna	889	749 -16%	743 -16%	691 -22%	296 -67%
Mixed savanna	40	21 -48%	24 -40%	18 -55%	10 -75%
Woody savanna	0	0	0	0	20
Mixed shrubland/grassland	0	0	3	0	113
C3 shrubland/grassland	13	0	1	0	266

Table 2: Cover of SDGVM-generated vegetation classes (number of 12''x12'' pixels) under current and projected future climate and atmospheric CO₂ conditions.

These currently uncommon types become widespread in the northeastern quadrant of the country, suggesting the strong potential for bush or woodland encroachment problems in these regions. This effect also appears to involve an ecosystem function feedback via the nitrogen and carbon cycle, in which soil nitrogen and carbon is projected to increase in the northeast, thus favoring the success of C3 growth forms (presumably shrubs) relative to C4s. In addition, the potential fire frequency is predicted to increase somewhat in this north-east region under the elevated CO₂ scenarios only.

The distribution of the second-most dominant PFT, namely deciduous trees, is also reduced in extent by climate change, and this impact is not ameliorated by elevated CO₂ (Figure 16). Deciduous trees suffer a reduction in both biomass and cover throughout their current range, showing a general retreat towards the northeastern Kalahari.

Finally, the C3 PFT, which is currently correctly predicted to be a minor component of Namibian vegetation, shows an interesting positive response to a combination of climate change and elevated CO₂ throughout much of the current range of deciduous trees. While it is possible that the C3 form may benefit from greater available soil moisture due to increased water-use efficiency of vegetation at elevated CO₂ (Drake *et al.* 1997), it seems more likely that this success is explained at least partly by the ecosystem feedback of increased soil nitrogen availability in the northeastern quadrant of the country. This effect should be considered as a preliminary finding and worthy of future deeper investigation, due to its complex nature.

In terms of ecosystem function, results suggest that NPP is significantly reduced in the central-northwestern regions, by between 0.5 and 1 t/ha, and by up to

0.5 t/ha in the northeastern Kalahari. The reduction in the northeast is projected to reverse with rising atmospheric CO₂, also a likely result of the increased nitrogen availability. The result of these changes is reflected in similar changes in fire occurrence, which is reduced in a similar pattern by climate change alone, but increases in the northeastern quadrant with rising atmospheric CO₂.

Overall, the SDGVM projections reveal a significant negative impact of climate change on ecosystem NPP, vegetation structure and cover, and the distribution of dominant PFTs. These effects are strongest in the central/northwest regions and the northeast quadrant, but in a tentative finding, are strongly ameliorated in the northeastern quadrant by rising atmospheric CO₂. In general, and according to a broad vegetation-type classification, the SDGVM projects a substantial expansion under climate change of Desert at the expense of Arid Shrubland/Grassland, Arid Shrubland/Grassland expansion at the expense of Grassy Savanna by both 2050 and 2080 (Figure 17). With the effect of elevated CO₂, Grassy Savanna is severely transformed into a C3 Shrubland/Grassland in the northeastern Kalahari.

The direct impacts of elevated CO₂ bear further investigation, as these have the potential to significantly modify climate change impacts in the northeastern quadrant of the country, in particular. Future change with CO₂ fertilization suggests a weak CO₂ impact in the arid coastal belt central escarpment and southern central regions. However, significant CO₂ fertilization appears to permit expansion of novel woody C₃ vegetation types in the north-east regions of the country. This is almost certainly due to a CO₂ stimulation of woody C3 shrubs in regions where sufficient moisture is available to support an appreciable leaf area index, and there is an increase in soil nitrogen availability due to ecosystem feedbacks. This fertilization supports a slight increase in NPP relative to the constant-CO₂ simulation, and in turn appears to

support a relatively unchanged, or even slightly enhanced fire regime. This change in fire regime occurs in spite of a reduction in C₄ grass success in the region.

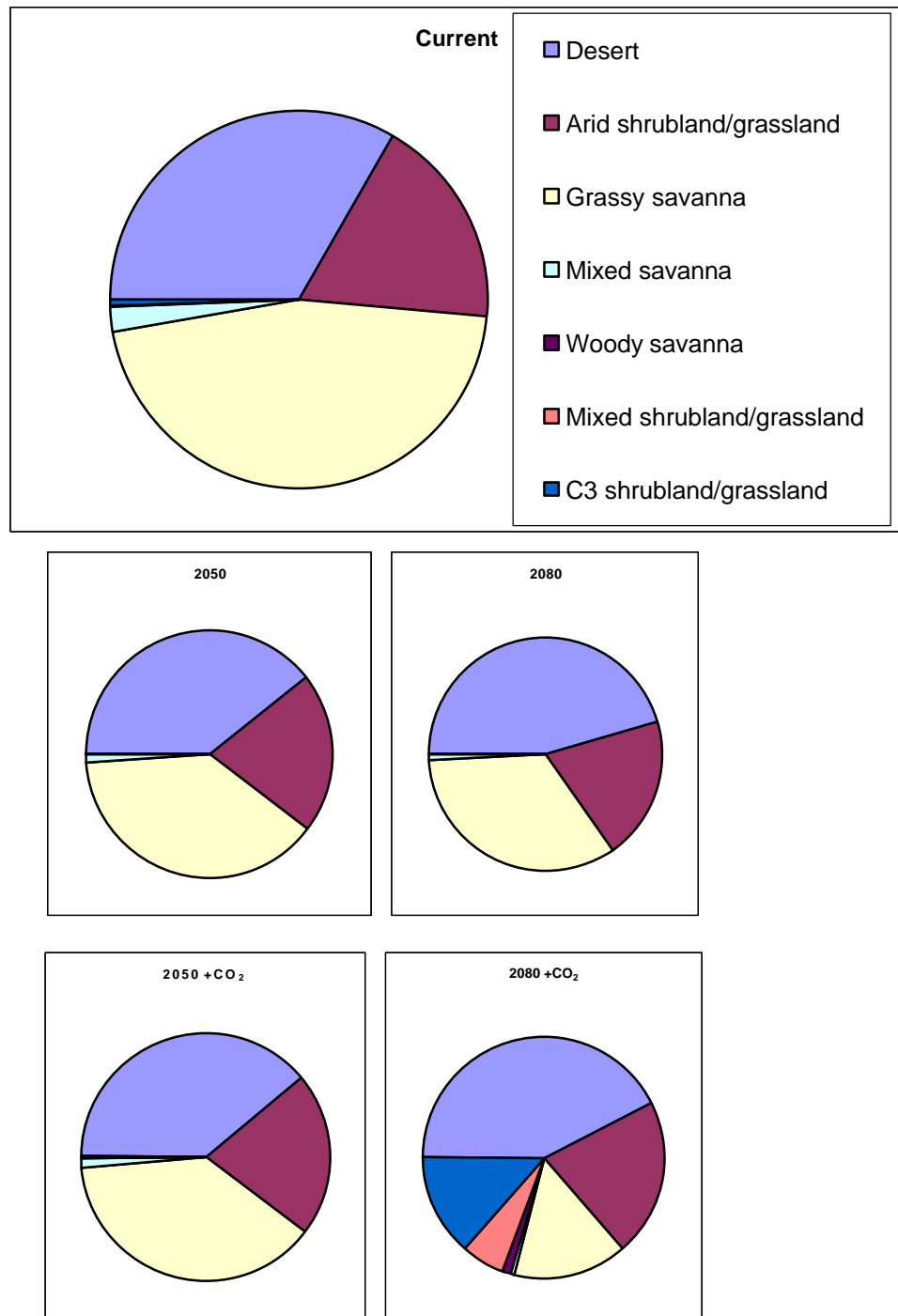


Figure 17: Pie charts showing changes in the relative cover of Namibia by vegetation structural classes simulated by SDGVM under current climate conditions, and those driven by climate changes projected for 2050 and 2080 according to the GCM HadCM3 and atmospheric changes projected according to the A2 scenarios. Simulations include those with and without the CO₂ fertilization effect, as labelled.

Biodiversity results

These results are based on the modeling of the geographic ranges of individual species (numbering 834 from an original >1000 species investigated), and their potential changes. These results have been synthesized into various biodiversity measures in order for a holistic assessment to be undertaken.

Bioclimatic model results for all modeled species

Spatial patterns

The current pattern of plant species diversity in Namibia seems well simulated by the bioclimatic niche models. When the niche models are overlaid to generate a map of modeled overall species richness, those regions identified as species-rich accord well with mapped levels of endemic species richness (Barnard & Taskforce 1998). These areas include the Kaokoland region in the northwest, the escarpment and the central mountain chain. The Succulent Karoo region in the south is underrepresented almost certainly due to low representation in the input species data.

As discussed in the Methods section (pp. 64,65), we assess the impacts of climate change using two assumptions relating to plant migration, namely zero or perfect migration ability (the migration process comprises four sub-processes, namely, fecundity, dispersal, recruitment and population growth). These two assumptions provide upper and lower bounds on expected species range changes. While neither assumption is correct, it is likely that the migration median lies closer to zero than perfect migration (e.g. Schurr et al. *accepted*). It is also important to stress that results reported here in terms of species loss or turnover should be treated with some caution, and we advise that these be seen as identifying areas of relative risk, rather than as predictors of absolute species loss or turnover.

Overall risk of community compositional change can be estimated using an index of species turnover and species loss at the pixel scale (i.e. the latter representing a local, but not regional, extinction of a species). Species turnover summarises both local extinctions and potential in-migrations, representing an index of potential modification of community composition. When viewed on a relative scale, and even assuming perfect migration, it is clear that risk of local species loss per modeled cells in the landscape as a proportion of current species richness is disturbingly high, with projected mean species loss for 2050 between 40 and 50% at the pixel scale, and between 50 and 60% by 2080 (Figure 18). It is important to note that this does not refer to species extinction *per se*, but more certainly a loss of reproductive success and recruitment in the given pixel.

Species turnover results indicate significant changes in community composition resulting from species extinction and influxes (Figure 19). Turnover ranges between 40 and 70%, with much of the change committed to occur under climate regimes projected for 2050. Migration significantly increases turnover, indicating very rapid potential shifts in community composition in cases where floristic elements have high migration potential.

Spatially, the patterns of species loss and turnover vary quite markedly. Projected local extinctions at the pixel scale, assuming zero migration, are in excess of 80% in the northeastern and northern Kalahari, dropping to below 20% from the edge of the escarpment into the coastal desert zone. These patterns are highlighted in projections of species loss by biome (Figure 20). The Desert Biome is projected to suffer less from climate change than any other biome, while Savanna types show a large variability in response.

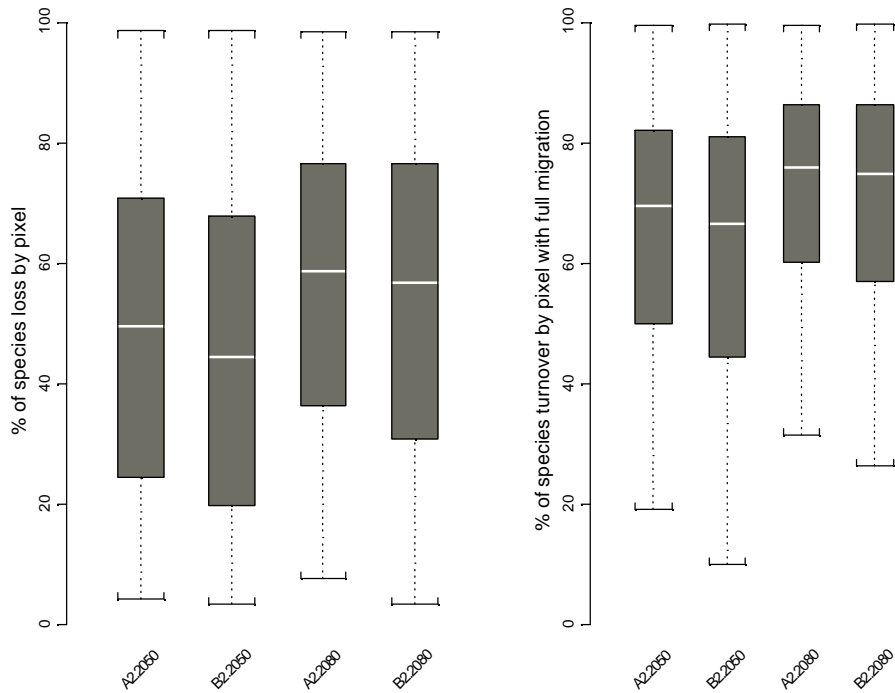
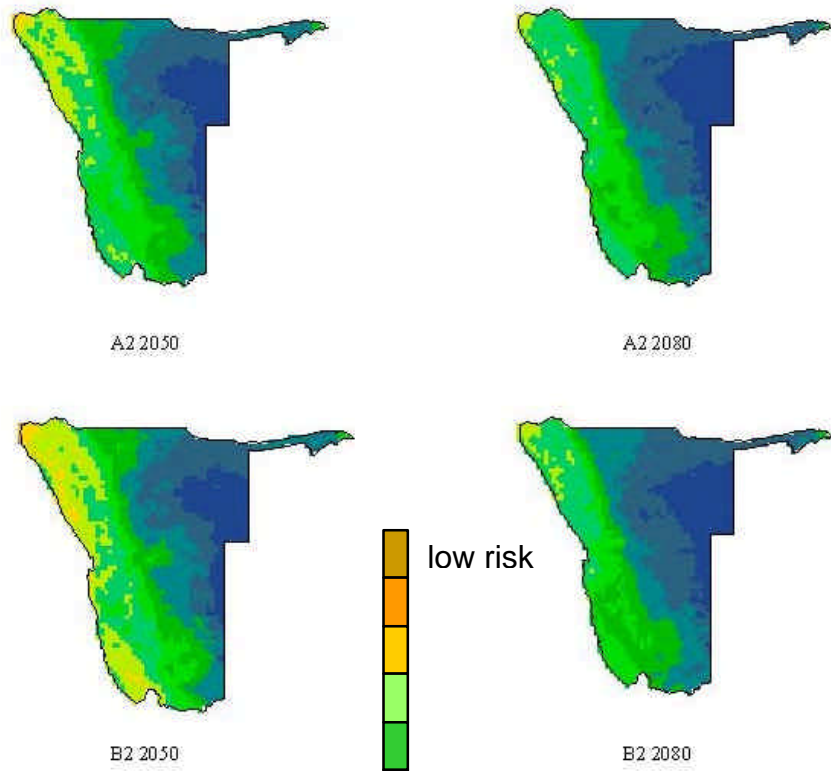


Figure 18: Summary of percentage of species loss (left figure) and turnover (right figure) per modelled pixel, with full dispersal assumptions, at two future times under two SRES scenarios

Under assumptions of full migration, significant changes in potential species richness can be seen for the climate scenarios, with the highest risk of species loss centered on the northeastern Kalahari. Absolute richness changes are reduced in extent relative to the zero migration assumption. Significant gains in species resulting from extensive potential migration occur in the coastal desert and southern inland

(a)



(b)

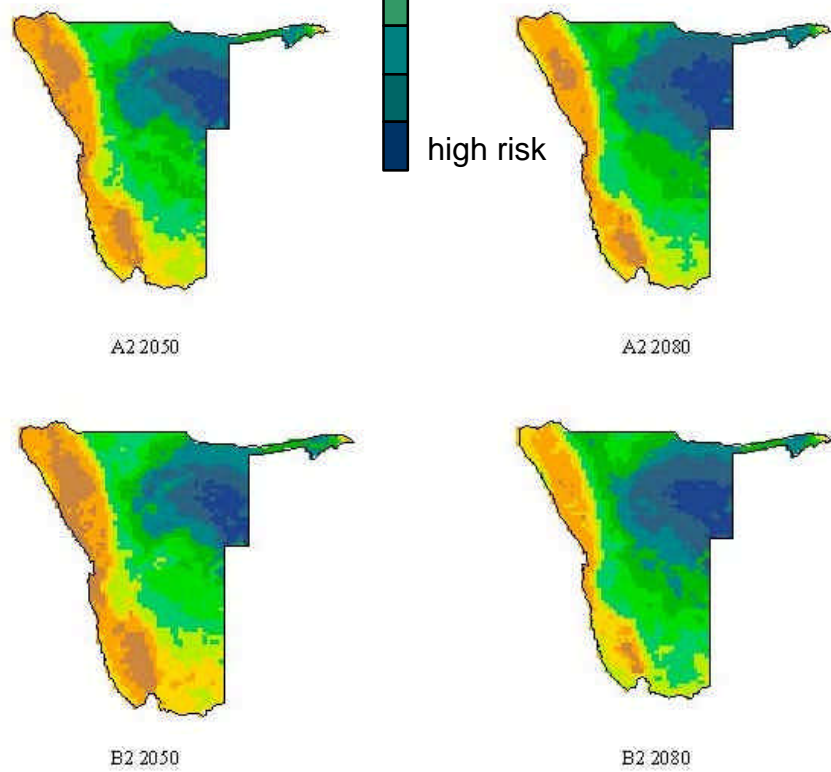


Figure 19: Species turnover per modelled pixel for full migration (a) and null migration (b) assumptions at two future times under two SRES scenarios

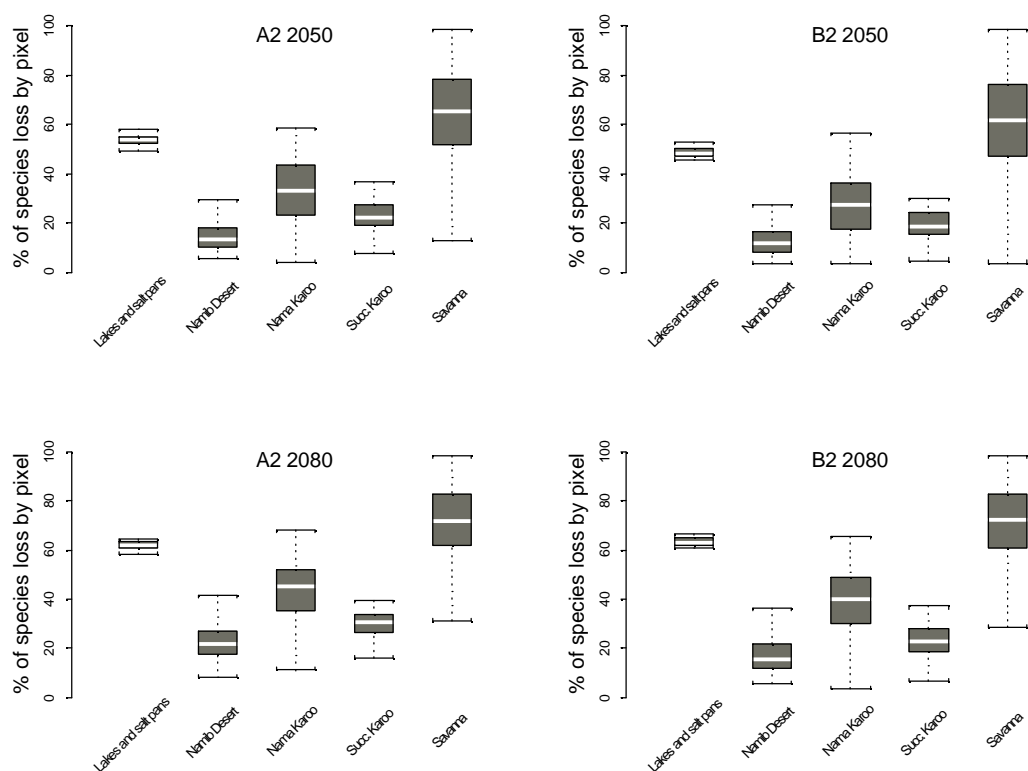


Figure 20: Percentage of species loss per modelled pixel grouped by biome (*sensu* Irish 1994) at two future times under two SRES scenarios.

regions. Taken together, these patterns suggest that the optimum conditions for supporting high levels of species richness are spatially shifted, but with the escarpment showing the highest potential stability in species richness, regardless of migration assumptions.

The species turnover index reveals a region of high turnover in the northeast quadrant of the country, regardless of migration assumption. Both zero and perfect migration assumptions show a reduction in turnover from north-east to west and south-west. The migration assumption used leads to significant uncertainty in estimating species turnover towards the escarpment and the west coast.

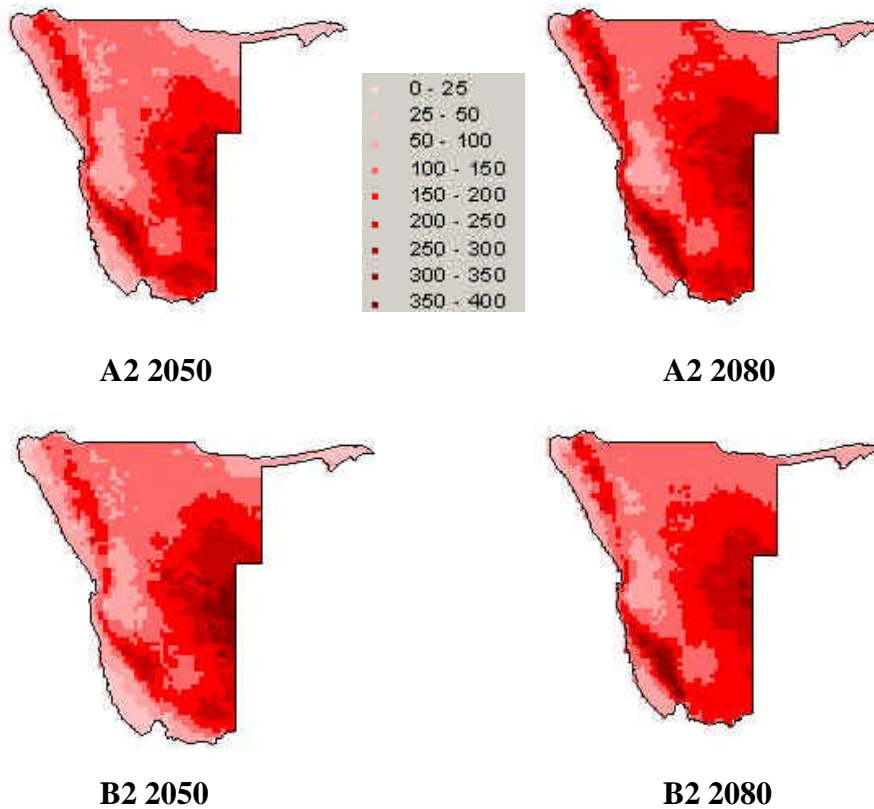


Figure 21: Expected absolute number of species gained per modelled pixel assuming full migration at two future times under two SRES scenarios.

A map of absolute species gain per pixel (Figure 21) reveals a potential migration of species into the northeast/central quadrant and the escarpment. Therefore, these results suggest relatively small changes in species richness in the northern, central and southern Namib, and large changes in the north-east. This can be seen in the percentage of species turnover on a biome basis, where the Namib Desert is expected to less perturbed than the other biomes, while Savanna is projected to experience a high species turnover, mainly due to an in-migration of species (Figure 22).

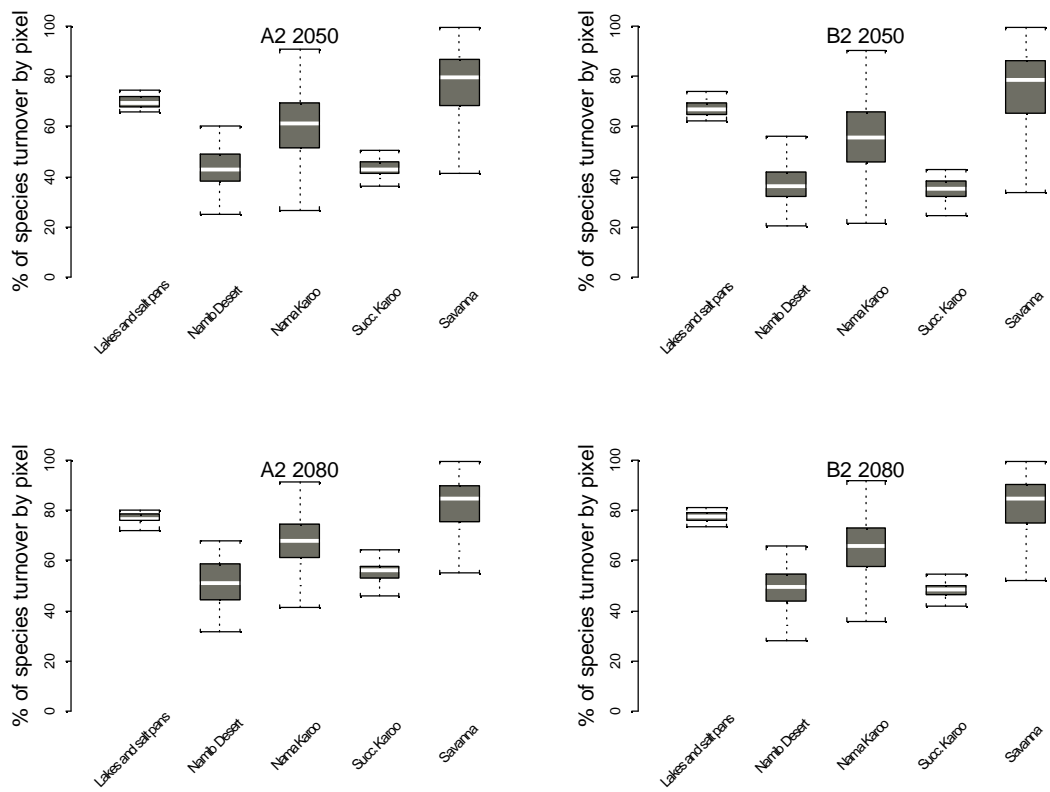


Figure 22: Percentage of species turnover per modeled pixel grouped by biome (*sensu* Irish 1994) at two future times under two SRES scenarios.

Taken together, maps of species richness as a whole projected both with (Figure 23) and without dispersal assumptions (Figure 24), show a future concentration of species on the escarpment, rather than the central highlands.

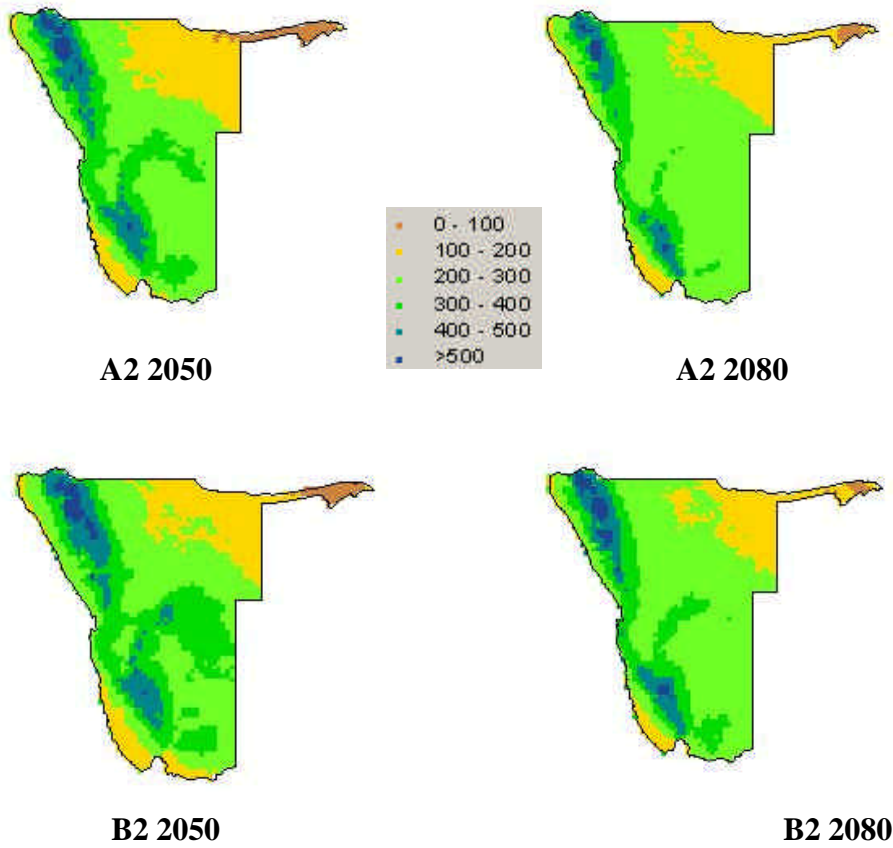


Figure 23: Expected absolute future species richness assuming full migration of species at two future times under two SRES scenarios

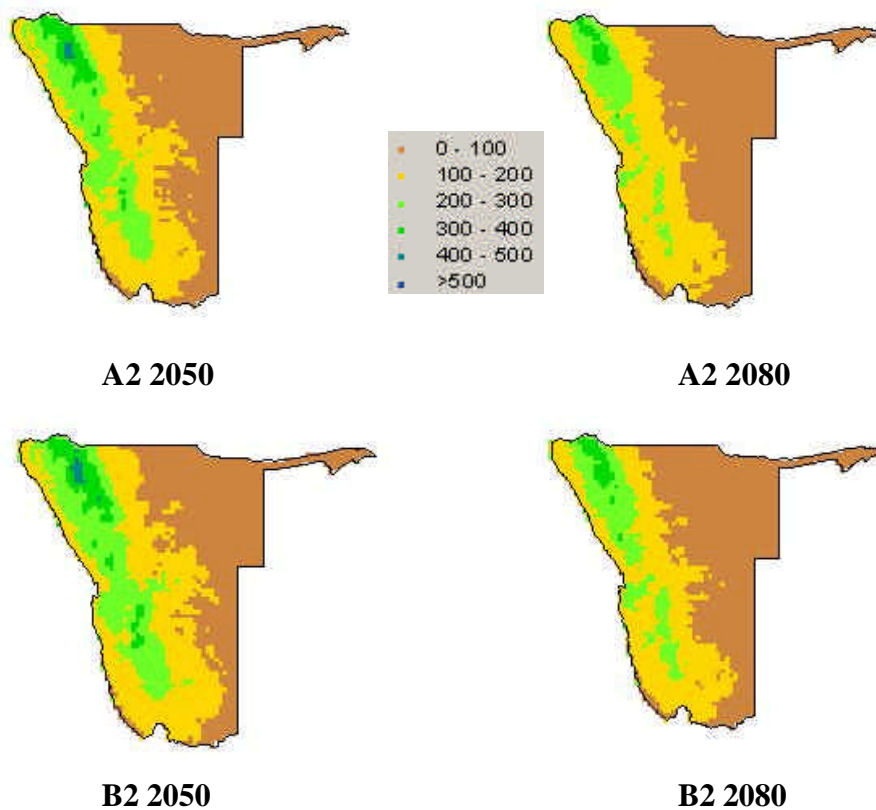


Figure 24: Expected absolute future species richness assuming no migration of species

Species-specific sensitivity

Species range change. Individual species range size changes vary widely, with the majority of species suffering range losses (Figure 25), but with a minority experiencing a significant increase in range. This finding suggests that future climate change may be an advantage to a small subset of species that might be able to capitalize on the novel climatic conditions in this country, but that this will depend strongly on their migration capacity.

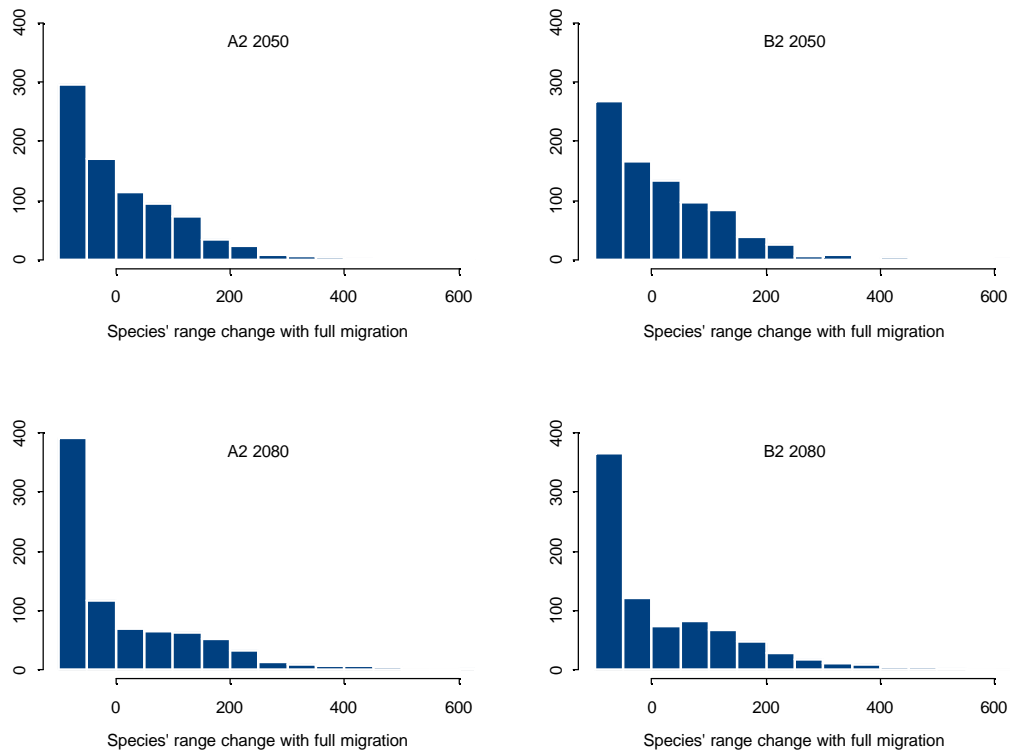


Figure 25: Modelled species range change according to the different time-slices and SRES scenarios

Impacts on species Red List Status The Red List criteria have been developed by the IUCN in order to provide a consistent and objective means of categorizing the vulnerability of species to extinction (IUCN 2001). A range of fundamental criteria are used to classify species into vulnerability classes ranging from Lower Risk (LR) to Extinct (EX). The most appropriate classification criterion for assessing climate change threats to species is the assessment of potential geographic range change, a statistic that is projected by bioclimatic niche-based models.

We assigned each species to a threat category ((IUCN, 2001)), or classified it as Lower Risk (LR), depending on the projected reduction in range size from present to 2050 or 2080. Present and future range size (area of occupancy) was estimated from the number of pixels where a species occurs. Loss in range size was calculated

by subtracting future range size from present range size. In line with IUCN Red List criterion A3(c), the following thresholds were then used to assign a species to a threat category (IUCN 2001). Extinct (EX): species with a projected range loss of 100% in 50 or 80 years; Critically Endangered (CR): projected range loss of > 80%; Endangered (EN): projected range loss of > 50%; and Vulnerable (VU): projected range loss of > 30%. It is important to note that our Red Listing approach is simplistic, general and considers only the future effects of rapid anthropogenic climate change.

RDB calculations for the Namibian species modeled highlight that most could be strongly threatened by climate change (Figure 26). For both time-slices, species are less threatened by climate change under the assumption of perfect migration, because of the potential for species to move across the landscape. More importantly, this simple application of IUCN criteria shows that more than half of the total number of species could at least be classified as vulnerable by 2050 and 2080.

For 2050 and under the zero migration assumption, 25% of the species were classified as Critically Endangered (range contraction >80%) and 5% as Extinct. These percentages are increased for the 2080 time slice, with 30% of critically endangered and 13% extinct respectively.

Individual species reveal contrasting responses - for instance, one of the dominant tree species in the northeastern quadrant, *Baikiaea plurijuga*, was expected to lose 100% of its current range in Namibia, and gained few new habitats assuming perfect migration. This species was therefore categorized as potentially Extinct or Critically Endangered in Namibia in the future, depending on the migration ability assumption. However, the species is very likely to persist in neighbouring countries that retain a bioclimate suitable for this widespread southern African species, and

would not be classified as globally extinct. Conversely, *Colophospermum mopane*, a dominant species of the western highlands was expected to be very stable (0% loss) and gain substantial habitats under the full migration assumption. This species was classified at Lower Risk in Namibia, regardless of the migration assumption.



Figure 26: Barplots representing the percentage of species classified according to our IUCN Red Data Book assessment for each time-slice and under both assumption on species' migration. Null Migr, Full Migr represent no migration and full migration abilities. EX=Extinct; CR=Critically Endangered; EN=Endangered; VU=Vulnerable; LR=Lower Risk.

The results show the decisive role of migration in impacting on species threat status. With an assumption of zero migration, almost half of the 834 species modeled are classified as Extinct or Critically Endangered in Namibia by 2080, but with perfect migration assumed, only a third are Extinct or Critically Endangered, and almost half are classified as Less Threatened, even by 2080.

Bioclimatic model results only for endemic species

Spatial patterns

Patterns are somewhat different for endemic species, which appear less affected by climate change than the species complement modeled as a whole (Figure 27). Endemic richness, currently modeled as being associated with the escarpment and highlands of the northwest, is retained in escarpment regions, but projected to increase in more southerly escarpment settings. Highest endemic species losses are projected to occur in the central highland regions, concurring with areal projections of vegetation cover reduction by the SDGVM approach.

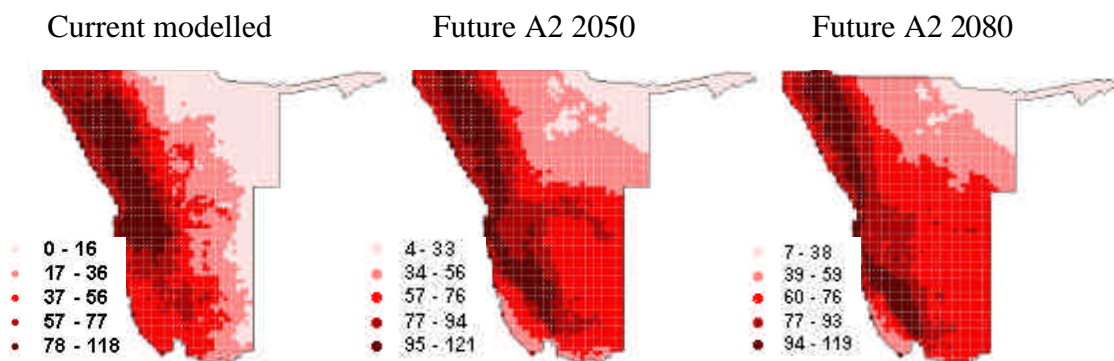


Figure 27 Current and future endemic species richness according to the different climate change scenarios and assuming full migration of species

Species-specific sensitivity

Species range change. Individual range size for endemic species changes vary widely, with around 40% of species suffering range losses (Figure 28), but with the remaining experiencing a significant increase in range. This finding suggests that future climate change may be an advantage for a majority of Namibian endemic species that might be able to capitalize on the novel climatic conditions in this country, but that this will depend strongly on their migration capacity. However, climate change remains a great threat for less than half of the modeled endemic species.

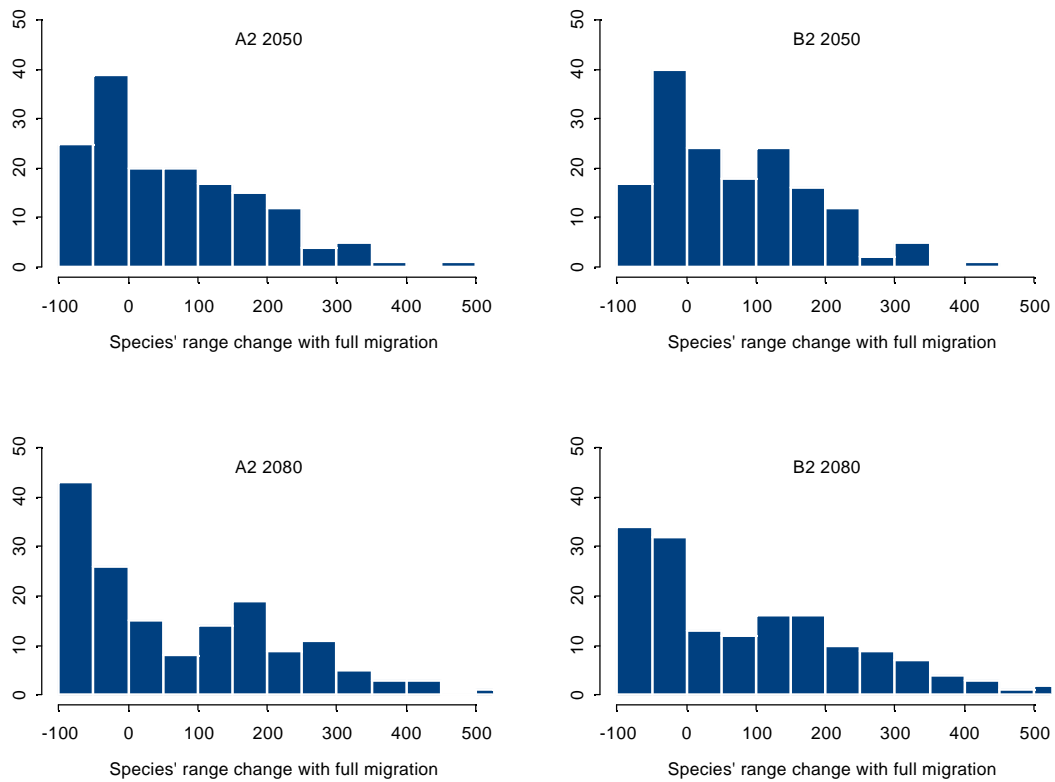


Figure 28: Modeled range change for endemic species according to the different time-slices and SRES scenarios

Impacts on species Red List Status. Red Results for the 161 endemic species modeled present a far less gloomy picture than for all species. Endemics reveal no potential extinctions due to climate change even by 2080, and more than 60% of species to be “Less Threatened” with full migration, and about half “Less Threatened” with zero migration assumptions by 2080 (Figure 29).



Figure 29: Barplots representing the percentage of endemic species classified according to our IUCN Red Data Book assessment for each time-slice and under both assumption on species' migration. Null Migr, Full Migr represent no migration and full migration abilities. EX=Extinct; CR=Critically Endangered; EN=Endangered; VU=Vulnerable; LR=Lower Risk.

Importantly, results for endemic species only (161 of the total 834 modeled) showed overall lower susceptibility to climate change (19% and 12% classified Extinct and Critically Endangered respectively by 2080) than non-endemic species, probably because endemics are both arid-adapted and located in regions of lower projected climate change. These species tend to be associated with topographic diversity which have probably buffered endemics against past climate change by reducing the need for past range shifts, and led to their persistence in evolutionary time. However, the greater susceptibility of non-endemics may also be partly because the modeling of non-endemics is not complete due to exclusion of their ranges outside of Namibia in model construction (an unavoidable consequence of incomplete distribution data of pandemic species).

Empirical evidence of climate change

Climate data

We examined temperature and rainfall records from all available long-term weather stations (only 15 stations with durations of between 25 and 60 years) in Namibia and the northern Cape (see methods). Fifty three percent of stations showed significant increases in temperature over their recording period, while none showed a significant decline. The mean decadal increase across all stations during this interval was 0.2°C (s.d. = 0.1°C). This increase is three times the global mean temperature increase reported for the 20th century (IPCC, 2001). Water balance, a composite measure of temperature and rainfall reflecting the water available to plants (see methods), showed a significant decline at 33% of stations over the last 25-60 years. No stations showed a significant increase in water balance over this period. It is important to point out that the small number of long term climate stations from which to detect these potentially damaging trends is likely to be a significant limitation for any Namibian representation in international negotiations on climate change issues.

Trends in population level mortality in *Aloe dichotoma* (Kokerboom)

It is extremely difficult to show unequivocally that anthropogenic climate change is the cause of a decline in the success of a wild species, yet several authors have begun to show that a typical response (fingerprint of climate change, Root *et al.* (2003)) includes a shift in geographic range towards the Pole, and upwards in elevation. In order to show such a response, it is necessary to study a species with a substantial geographic range, especially in terms of latitudinal extent. The flagship stem and leaf-succulent tree species *Aloe dichotoma* represents a charismatic and

highly visible element of the desert landscape, and has a large geographic range stretching from a southerly limit some 200km north of Cape Town, to its northernmost outpost on the Brandberg Mountain massif north of Windhoek (and due north of Swakopmund) in Namibia (range extent 21°-31° South, ~200 000 km²).

Aloe dichotoma's giant, stem-succulent growth form, succulent leaves and shallow root system are adaptations for rapid absorption of moisture from sporadic rainfall events and storage of water during subsequent droughts (Jacobsen 1960; Barkhuisen 1978). Individuals grow up to 10m in height and usually occur in dense populations of up to 10 000 trees. *Aloe dichotoma's* long life span (approximately 200 years (Vogel 1974)) makes it a reliable species for studying long-term climate trends, as signs of imminent population extinction through climate-related stress would indicate a climate signal which exceeds the tolerance range of the species as experienced over the past two centuries, at least.

Bioclimatic models for *Aloe dichotoma* project that climatic warming will cause localised extinction of populations within the equator-ward part of its distribution range (when some aspect of climate becomes lethal to the species), and range expansion into regions that change to become suitable, including at the high latitude and high altitude edges of *Aloe dichotoma's* range.

We examined 54 populations of *Aloe dichotoma* throughout its range (see methods, p. 63) and found that population mortality at individual sites ranged between 2% and 71% (Figure 30). Population mortality decreases along latitudinal and altitudinal clines. We observed a significant trend of decreasing mortality from the equatorial to the poleward regions of *Aloe dichotoma's* range ($R=0.393$, $n=53$, $p<0.004$; Figure 31). A regression of the residuals from this analysis and the altitude of each population also produced a significant trend ($R=0.331$, $n=53$, $p<0.016$). In

other words, populations at low altitudes on the equator-ward range edges appear to be approaching localised extinction, but where these populations are at high altitude there is lower mortality. Populations at poleward and high altitude extremes tend to experience only minimal mortality. The relative severity of *Aloe dichotoma* cumulative water stress is reflected by the percentage of months during the past decade in which water balance fell below -90 mm (see methods). Population mortality at study sites within 100km of the weather stations is positively correlated with cumulative water stress ($R=0.491$; $n=22$; $p<0.021$). This strongly suggests that a combination of water and heat stress is the cause of mortality in declining *Aloe dichotoma* populations.

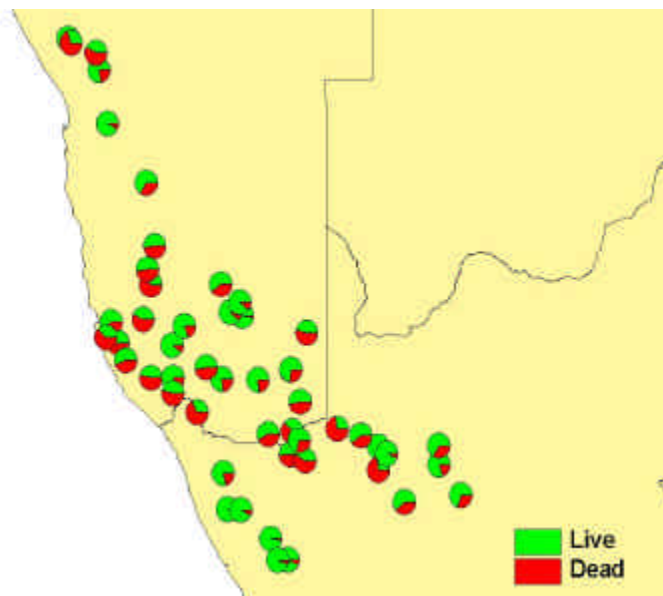
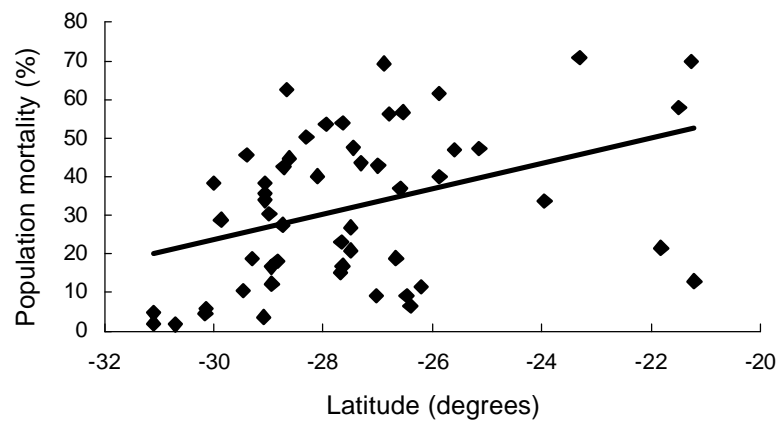


Figure 30: The geographical location of 54 sampling sites of *Aloe dichotoma* population status, with measured mortality indicated by the pie charts (mortality is proportional to the red portion of the pie charts).

(a)



(b)

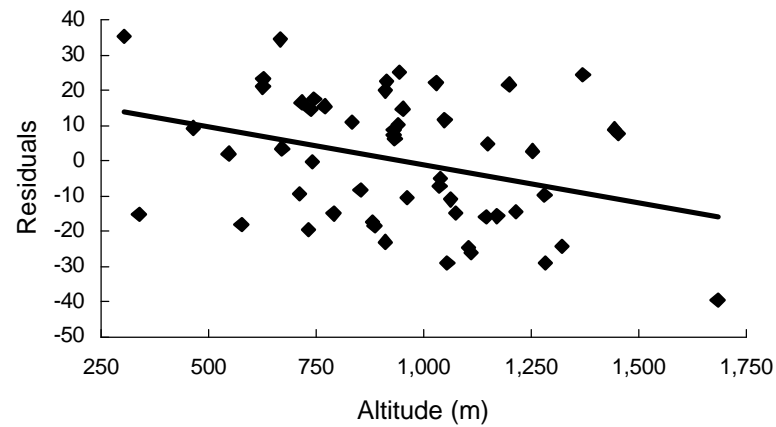


Figure 31: Plots of the *Aloe dichotoma* mortality versus latitude (a) and the residuals from this regression plotted against altitude (b) indicating that where latitude does not explain the mortality, elevation plays a critical role.

Discussion

This study has used a range of approaches to project the potential impacts of climate change on the structure, function and biodiversity of the Namibian flora and vegetation. While there are significant uncertainties associated with each of the approaches, we have attempted to quantify important uncertainties through the use of a range of climate scenarios (associated with different scenarios of human societal development), and assumptions relating to significant uncertainties in the biological response of species and ecosystems. Even using the most conservative scenarios (e.g. projections for 2050 under low human rate of development) and optimistic assumptions relating to biological responses (such as perfect abilities of species to migrate in response to climate change, and the effect of rising atmospheric CO₂), results suggest that substantial changes in ecosystem structure, ecosystem function and biodiversity can be expected in many biomes and vegetation types of Namibia.

It is notable that projections of ecosystem structure suggest a negative response of vegetation to the warming and drying trends generated by the climate scenarios. Reductions in vegetation cover, increases in proportion of bare ground, and overall reductions in NPP all point to reduced potential of vegetation to support rangeland activities, be they on a commercial or subsistence model. This finding is in general accord with the findings for South African rangelands (Scholes *et al.*, 1999), but differs in that rising atmospheric CO₂ does not appear to ameliorate the negative effects of drying and warming as was found in more mesic South African rangeland sites. This is almost certainly because the CO₂ effect on stomatal control of evapotranspiration is not effective where low vegetation cover and leaf area index imply low control of soil water by canopy transpiration. This is especially true in the

arid regions of the western and especially southwestern regions of Namibia. By contrast, where LAI is high, in woodland vegetation types of the northeast quadrant, rising atmospheric CO₂ could potentially cause significant changes in ecosystem structure and function, and results assuming CO₂ fertilization effects suggest increasing success by woody elements, and potential increases in NPP.

Projections of biodiversity change seem more extreme than those suggested by the changes in ecosystem structure and function, even if assumptions of “perfect migration” are accepted. The bioclimatic niche models used to develop these projections have been criticized (e.g. Pearson & Dawson 2003; Thuiller *et al.* 2004), but remain the most pragmatic approach for assessing climate change effects on large numbers of species, and have been used in many influential assessments (e.g. Peterson *et al.* 2002; Thomas *et al.* 2004; Thuiller 2004). The species turnover and species loss found in this broad analysis are somewhat more extreme than those projected for Europe and Mexico under similar climate change scenarios (Peterson *et al.*, 2002; Thuiller, 2004). Thuiller (2004) projected between 27-42% species loss from individual modeled pixels, and 45-63% of species turnover in Europe according to 7 climate change scenarios for 2080. In Mexico, (Peterson *et al.*, 2002) projected up to 2.4% global extinction of animal species modelled under the most stringent migration assumptions, but species turnover rates as high as 45%. The expected impacts of climate change on species richness *per se* appear more extreme in Namibia, an arid country, than in Mexico or Europe where a larger range of climates is encountered even in the future.

The greatest degree of incongruity between the results for the two approaches used in this study (namely the species-specific approach and dynamic vegetation approach) is seen in the northeast quadrant of Namibia, and assuming a CO₂

fertilization effect for the mechanistic modeling approach. Species turnover and species loss is projected to be extremely high in this region, but the structure and NPP of vegetation does not appear strongly negatively impacted. Such potential disagreement is extremely interesting as it suggests that despite high species turnover and species loss by pixel in some regions, this may have only a moderate impact on vegetation structure and ecosystem functioning. This has important policy implications, as from a conservation point of view, climate change could strongly affect species richness and vulnerability, and more than 50% of Namibian species could be classed at Least Vulnerable according to our application of Red List criteria. Protected areas and reserve networks would require an assessment of their capacity to retain species in the long term. Conversely, from an ecosystem services point of view, climate change could affect ecosystem processes moderately, though in the central regions of the country structural change, NPP loss and change in biodiversity are projected to be high. It is of concern that the most species-rich regions of the country are projected to suffer both the highest level of biodiversity loss and structural change. By contrast, species loss and turnover for arid coastal and southern regions are low, and the Succulent Karoo Biome is not projected to experience significant losses of species – however, it is possible that this is the result of the low numbers of species modeled in these regions.

Our analysis of temperature and rainfall records from all available long-term weather stations (only 15 stations with durations of between 25 and 60 years) in Namibia and the northern Cape reveal that half the stations showed significant increases in temperature over their recording period, while none showed a significant decline. The mean decadal increase across all stations during this interval was 0.2°C (s.d. = 0.1°C). This increase is roughly three times the global mean temperature

increase reported for the 20th century (IPCC, 2001). Water balance, a composite measure of temperature and rainfall reflecting the water available to plants, showed a significant decline at a third of stations. No stations showed a significant increase in water balance over this period. Tied in with these observations, an early warning sign of climate change is indicated by the response of populations of *Aloe dichotoma* to apparent trends in recent climate, which indicate warming and drying trends in Namibia and northern South Africa over the past 15 to 30 years. This response is typical of that expected for species of the arid west under the expected climate change scenarios, and comprises a loss of species range in the northern and central parts of Namibia.

Significant uncertainties relating to the results presented must be acknowledged, however, and include those relating firstly to the climate projections, and those relating to the problems of modeling vegetation response to the projected changes. Uncertainties in climate projections have been extensively discussed, and are greater for rainfall than temperature projections (IPCC, 2001). It is important to point out that a scenario of no change in climate is highly unlikely, that some degree of warming is virtually assured, and this is supported by empirically measured trends in Namibia and northern South Africa. However, given that HADCM3 projections for southern Africa tend to be drier than several currently accepted GCMs, these results may present a somewhat pessimistic (though far from a worst-case) scenario for vegetation change in Namibia.

Taken together, these results indicate an appreciable vulnerability of Namibian biodiversity as a whole to projected anthropogenic climate change, and an increase in pressure on the adaptive capacity of conservation planning in this country over the next few decades. However, the geographic location and concentration of many

Namibian plant species endemics affords some level of resilience in endemic biodiversity and could form the basis for developing effective adaptation strategies to climate change. Ongoing monitoring of climatic trends at a far higher spatial resolution that is currently the case will be critical in assessing the rate of climate change in this region, and its potential future evolution.

Methods

Climate change and emissions scenarios

We used climate change scenarios driven by global greenhouse gas emissions projections that flow from socio-economic development scenarios generated by the IPCC (IPCC-TGCI, 1999). These development scenarios (also called “storylines”) provided the basis for the Special Report on Emissions Scenarios (SRES) (Nakicenovic & Swart, 2000) and describe the projected development path of human civilization on the planet. Four primary storylines have been explored, and are termed A1, A2, B1 and B2. They envisage socio-economic development as follows:

A1 – Very rapid economic growth, low population growth (global population peaks mid-century) and rapid introduction of new and more efficient technology. Economic and cultural convergence and capacity building occurs, with substantial reduction in regional differences in per capita income. Pursuit of personal wealth takes precedence over environmental quality. This storyline is subdivided into three based on energy technology as follows: A1F1 fossil fuel-intensive, A1T non-fossil fuel-intensive, A1B Balanced fossil and non-fossil fuel energy sources.

A2 – A differentiated world. Regional cultural identities are strengthened, with emphasis on family values and local traditions. Continuously rising population is realized, together with less concern for rapid economic development or technological change.

B1 – A convergent world with rapid changes in economic structures, lower emphasis on material wealth and introduction of environmentally-friendly technologies. Low population growth is realized (global population peaks mid-century

as in A1), and there is an emphasis on global solutions for achieving environmental and social sustainability, including concerted effort in technology development, dematerialization of economies and improving equity.

B2 – A world in which local solutions to achieving economic, social and environmental sustainability is emphasized. Global population rises continuously. This is a heterogeneous world with less rapid, and more diverse change in technology implementation, but a strong emphasis on community initiative and social innovation to solving environmental problems.

The A2 and B2 scenarios have been most extensively applied in General Circulation Models, and were selected for use in this study as representing a higher end and an intermediate greenhouse gas emission scenario, respectively. The scenarios can be ranked in order of their impacts on global temperatures through radiative forcing as follows: A1F1 > A2 > A1B > B2 > A1T > B1.

Vegetation type and ecosystem model

Climate datasets

The CRU CL 2.0 dataset (New *et al.* 2000) downscaled from 30 minutes to a resolution of 10 minutes was chosen to represent current climate, and was used as the baseline for both DGVM and species-level modeling. Future (~2050 and ~2080) climate predictions were produced by perturbing the current climatic data with anomalies derived from climatic simulations produced by the HADCM3 General Circulation Model (Gordon *et al.* 2000) using only the A2 IPCC SRES scenario (Nakicenovic & Swart 2000) in accordance with globally accepted guidelines for climate impact assessment (IPCC-TGCIA 1999) and using a technique described by Hewitson (2003). The atmospheric CO₂ input data were also provided by the Hadley

Centre and consist of an average for each year from 1830 to 2100, given as a partial pressure.

SDGVM background

The Sheffield Dynamic Global Vegetation Model (SDGVM) of Woodward *et al.* (1995) and Woodward *et al.* (2001) was designed to simulate vegetation responses to climate change, using simple climate inputs (temperature, precipitation, relative humidity and CO₂) and edaphic data. The model includes subroutines for biomass, phenology, hydrology, carbon and nitrogen cycling, and vegetation dynamics. Vegetation is predicted in terms of plant functional types (PFTs) as opposed to species. SDGVM models six PFTs, namely C3 Grassland/Shrubland (C3), C4 grass, evergreen broadleaved trees (EvBl), evergreen needle-leaved trees (EvNl), deciduous needle-leaved trees (DcNl) and deciduous broadleaved trees (DcBl), with sites that do not support any vegetation labelled as Bare Ground (BG). Only four of the six PFTs occur in southern Africa, as the climate is generally unsuitable for naturally occurring needle-leaved trees. The vegetation modelled by SDGVM is the potential natural vegetation based on the conditions provided as inputs and does not take into account processes such as anthropogenic modifications of the land surface. The incorporation of a disturbance generator, which is used to simulate fire events, improves the accuracy with which SDGVM predicts the vegetation of Africa (Bond *et al.* 2003).

SDGVM Simulations

Five model integrations were performed and are identified by the time period they represent, these being:

- 1) 2000: A control run representing current condition (1971-2000);
- 2) 2050clm: Medium range (2040-2069) forecast with no change in CO₂;

- 3) 2050CO₂: Medium range (2040-2069) forecast with a change in CO₂;
- 4) 2080clm: Long range (2070-2099) forecast with no change in CO₂;
- 5) 2080CO₂: Long range (2070-2099) forecast with a change in CO₂;

All other parameters were set to the default, and the model was run with annual results recorded for each simulation. The control experiment was used as a baseline for comparing responses to the climatic perturbations.

Model validation is a key step in assessing the fidelity of simulation results, especially as an understanding of successful and unsuccessful simulation of current conditions enhances our understanding of model simulation of future changes (Giorgi *et al.* 2001). The Sheffield Dynamic Global Vegetation Model (SDGVM) has been extensively tested at a global scale (Woodward *et al.* 1995; Beerling & Woodward 2001; Cramer *et al.* 2001; Woodward *et al.* 2001). While Drew (2004) has tested the model at a sub-continental scale in Africa it was necessary to test the robustness of the model at the Namibian scale. This was achieved by comparing the model vegetation distribution (cover) output with two vegetation databases, namely a SPOT-VGT classification and the ISLSCP vegetation dataset (Defries *et al.* 2000). While this comparison process is difficult owing to the impacts of land transformation, in both cases SDGVM was found on the whole to reproduce observed vegetation patterns with sufficient accuracy as to prove useful.

Modeling biodiversity using species-level bioclimatic models

Climate datasets

The CRU CL 2.0 dataset (New *et al.* 2000) downscaled from 30 minutes to a resolution of 10 minutes was chosen to represent current climate. Future (~2050 and ~2080) climate predictions were produced by perturbing the current climatic data with anomalies derived from climatic simulations produced by the HADCM3 General Circulation Model (Gordon *et al.*, 2002) using both the A2 and B2 IPCC SRES scenarios (Nakicenovic & Swart 2000) in accordance with globally accepted guidelines for climate impact assessment (IPCC-TGCIA 1999), using a technique described by Hewitson (2003). Seven variables were selected based on their known effects on plant survival and growth (Midgley *et al.* 2002; Midgley *et al.* 2003): Annual and winter temperature, annual, winter and summer precipitation and annual and winter potential evapotranspiration. Potential evapotranspiration estimates were calculated using the FAO 56 Penman Monteith combination equation (Allen *et al.* 1998).

Plant species distributional data

Plant species distribution data were extracted from the Namibian National Botanical Research Institute herbarium database (WIND 2004) that forms part of the Southern African Botanical Diversity Network (SABONET). While many of the recent herbarium records have locality information recorded utilising GPS, the bulk of the records are best described as being at quarter degree scale (QDS). Consequently, this was chosen as the scale at which the statistical models would be derived. The database contains records detailing 213 Families, 1196 Genera and more than 4500 species and infra-specific taxa covering 95% of the country. These records were

checked for taxonomic correctness (Mannheimer, 2004 – pers comm.) as well as for anomalous spatial locality information. A subset of 1020 species each with more than 20 unique QDS occurrences was selected for modeling.

Bioclimatic niche-based models

Models relating species distributions to the seven bioclimatic variables were fitted using the BIOMOD framework (see details in Thuiller 2003, 2004) on a random sample of the initial data (70%). For each species, Generalised Linear Models (GLM), Generalised Additive Models (GAM), Classification Tree Analysis (CTA) and Artificial Neural Networks (ANN) were calibrated. Then each model for each species was evaluated on the remaining 30% of the initial dataset using the values obtained for the area under the curve (AUC) of a received operating characteristic (ROC) plot of sensitivity against (1-specificity) (Swets 1988). Sensitivity is defined as the proportion of true positives correctly predicted, whereas specificity is the proportion of true negatives correctly predicted. For each species, the model with the highest AUC was retained to project future distribution (Thuiller 2003). We transformed the probability of occurrence from models using a threshold maximising the percentage of presence and absence correctly predicted (Pearce & Ferrier 2000; Thuiller *et al.* 2003).

For species turnover/gain/loss by pixel, we removed species for which model accuracy (AUC) was lower than 0.8 (i.e. fair model) to make sure that species used for the risk assessment were well modelled by NBM. Species were predicted to lose or gain suitable habitat or have a stable distribution in the future. To evaluate the percentage of extinction (similar to species turnover without dispersal), we summed the number of species lost (L) by pixel (opposed to stable species) and related it to current species richness by pixel. The procedure was the same to assess the

percentage of species gained (assuming full dispersal) (G) by pixel (under assumptions that species could reach new habitat). Percentage of species turnover by pixel under the assumption of dispersal has been estimated by: $T = 100 \times (L+G)/(SR+G)$; where SR is the current species richness for a given pixel.

Bioclimatic modelling of species ranges is underpinned by a number of assumptions, chief among them that some aspect of climate controls the limits of the species geographic range, and that the species range reflects that control (in other words, the species range is in equilibrium with current climate conditions). It is conceivable that several plant species have ranges that are controlled by aspects of ecosystem disturbance, strong interactions with other species (such as competitive interactions, or interactions with pollinator species), or that stochastic changes in population dynamics underpin the absence of species from parts of its range due to local extinction. Unfortunately, bioclimatic modelling is currently the only efficient means to generate multiple species response projections under climate change scenarios, and combined results should be used as a guide to infer the realised species responses with climate change.

In terms of species range responses themselves, assumptions must be made about both the persistence of species after bioclimates have become unsuitable, and about the rate at which species are able to migrate to occupy novel ranges that become available with changing climates. These dynamics cannot be inferred without careful species-specific study, but as a first-cut estimate it is common to assume two extreme options: zero migration (species is unable to disperse and establish in new range) and perfect or full migration (species is able to migrate immediately in response to climate change). These two assumptions allow the possible responses to be bracketed and uncertainty to be assessed. Species do not persist in unsuitable bioclimates under

either assumption, leading to an overestimate of the potential rate of range loss, but estimating the total range loss that would ultimately result from the climate change scenario.

Red data list status

To communicate our findings through a common conservation tool, we assigned each species to a threat category (IUCN 2001), or classified it as Lower Risk (LR), depending on the projected reduction in range size from present to 2050 or 2080. Present and future range size (area of occupancy) was estimated from the number of pixels (each 320 km²) where a species occurs. Loss in range size was calculated by subtracting future range size from present range size. In line with IUCN Red List criterion A3(c), the following thresholds were then used to assign a species to a threat category (IUCN 2001). Extinct (EXT): species with a projected range loss of 100% in 50 or 80 years; Critically Endangered (CR): projected range loss of > 80%; Endangered (EN): projected range loss of > 50%; and Vulnerable (VU): projected range loss of > 30%. It is important to note that our Red Listing approach is very simplistic, generalised and considers only the extra effects of rapid anthropogenic climate change.

Climate station data analysis

We used data from all stations in Namibia and north-western South Africa from which temperature records of 24 or more years are available (15 stations). We tested for stationarity by visually assessing deviance from a straight line when cumulative temperature and rainfall values for neighbouring stations were plotted against each other (Gordon *et al.* 1992). Water Balance was calculated as the difference between precipitation and potential evapotranspiration (Thornthwaite

1948) based on monthly means of mean daily temperature and total monthly precipitation (Wells 2002). Annual trends (calculated from April to March in order to represent a growth year) were analysed using Robust MM Regression (Rosseeuw & Yohai 1984).

***Aloe dichotoma* empirical data collection**

We selected large, discrete populations and measured 100 live individuals in the densest part of each. We measured smaller populations where no larger ones could be found and where they made an important contribution to describing the species' range. In these cases we measured the entire population. Estimates for each individual included degree of fungal pathogen infection of leaves and trunk (scores); extent of animal damage to the stem or trunk (score); the percentage of the total potential canopy removed and the percentage of the total potential canopy in which leaf abscission occurred.

The number of dead trees within the area covered by the 100 sampled live trees was used to derive the percentage of each population's mortality. We used a 1,000 x 3 metre transect through the population to derive an estimate of population density. This also provided a second estimate of relative mortality and this was generally in agreement with the first estimate.

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