Ecological indicators for climate change

By

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Submitted in partial fulfilment of the requirements for the degree - MSc Zoology

In the Faculty of Natural & Agricultural Sciences

University of Pretoria

Pretoria

2015/07/27

Declaration

I, Albé Cobus Bosman declare that the thesis/dissertation, which I hereby submit for the degree – MSc Zoology at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution. Chapters 2 and 3 have been submitted in the paper format. As a result styles and formats may vary between all chapters in the thesis and overlap in content may occur throughout the thesis.

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Abstract:

The evidence of the effects of human mediated climate change is already evident in most ecosystems. The IPCC projects that there could be as much as a 4˚C increase in global average temperatures by the end of this century. In Mpumalanga the average temperature is projected to increase by as much as 2.8˚C, and annual precipitation levels by as much as 60 mm. Climate change, along with other human mediated factors such as land use changes and the over exploitation of natural resources, will lead to increasing pressures on biodiversity. Anthropogenic climate change will have significant impacts on biodiversity. These include impacts on distribution, abundance and ecological interactions. It is important to adopt biodiversity monitoring programs to understand the effects of anthropogenic climate change on the biota, which will enable best practice management and conservation of biodiversity. So far however, very few existing monitoring programs allow for the detection of climate change effects, as shown by the European project EuMon and the South African National Biodiversity Institute. In a cost-constrained world, the efficient use of resources for conservation has become crucial in ensuring the success of mitigating the effects of global change. Two methods of identifying indicators for the assessment of the effects of climate change on biodiversity were developed. The first method included the development of a pragmatic approach to the identification of suitable indicators and was tested in the Mpumalanga province. This approach identifies suitable species and ecosystem indicators, by subjecting candidate indicator candidates through a series of filters. The second method used a combination of climate and biodiversity data to identify indicators in areas of greatest and least climatic change within the Mpumalanga province. It is recommended that a combination of both methods be used, in order to be most useful in informing current and future monitoring programs.

Keywords: Human mediated climate change, biodiversity, monitoring, Mpumalanga province, ecological indicators, pragmatic approach, MTPA.

Acknowledgements

Firstly I would like to thank my supervisors, Professors Mark Robertson and Mathieu Rouget. This thesis would not have been possible without the aid and patience of these two gentlemen.

I would like to thank the Mpumalanga Tourism and Parks Association (MTPA) for providing me with the necessary data to conduct this study; I would also like to give a special mention to Mervyn Lötter from the MTPA for his input throughout the thesis.

To my family and friends, I would like to say thank you for the support and input, especially for all the extra motivation needed to complete the thesis. A special thanks to Paul Trethowan and Joseph Mulders for their comments on previous versions of the thesis.

A very special thanks to those dearest to me for the much needed motivation, Hester Bosman (my mom), Karlien Penning, Stoffel, Woefels and Lifi, thank you for the support.

Lastly I would like to thank the Department of Zoology and Entomology and the University of Pretoria who have provided me with the opportunity to complete the study.

“There are times in life when people must know when not to let go. Balloons are designed to teach small children this” - Terry Pratchett

List of acronyms used throughout the thesis:

Abbreviation	Definition
ARC	Agricultural Research Council
BMP	Biodiversity management plan
CBD	Convention on Biological Diversity
CCI	Climatic Change Index
CITES	The Convention on International Trade in Endangered Species of Wild Fauna and Flora
CO_2	Carbon Dioxide
EuMon	European monitoring
GCM	Global Circulation Model
GIS	Geographic information System
IPCC	International Panel on Climate Change
IUCN	The International Union for the Conservation of Nature
MBCP	Mpumalanga Biodiversity Conservation Plan
MTPA	Mpumalanga Tourism and Parks Agency
NBSAP	National Biodiversity Strategy and Action Plan
NEMBA	National Environmental Management: Biodiversity Act
PPM	Parts per million
SAEON	South African Earth Observation Network
SANBI	South African National Biodiversity Institute
SKEP	Succulent Karoo ecosystem project
SOMD	Self-organizing map based downscaling
UCT	University of Cape Town
UNEP	United Nations Environment Programme
UP	The University of Pretoria

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Chapter 1

Biodiversity and Climate Change in the Mpumalanga Province of South Africa

Introduction

Over the past century the mean global surface temperature has increased by almost 1˚C (Meehl *et al.* 2007) and in the coming century it is projected that the mean global surface temperature could increase by as much as 4˚C (Meehl *et al.* 2007). These rapid shifts in climate have had significant effects on biodiversity (Parmesan 2006), and will continue to do so. Many studies have examined the effects of a rapidly changing climate on biodiversity (Parmesan & Yohe 2003, Parmesan 2006), however there is a need to design and develop long-term monitoring projects to document the changes in biodiversity and the extent to which they match projections. In order to quantify the effects of anthropogenic climate change on biodiversity; suitable long-term monitoring projects that are specifically aimed at monitoring the effects of climate change on biodiversity need to be developed (Niemelä 2000).

In the past the rationale for undertaking most monitoring programs is that additional information about any system will be useful (Nichols & Williams 2006, Pereira & Cooper 2006). This general approach typically does not result in effective management decisions for conservation and has been strongly criticised (e.g. Yoccoz *et al.* 2001, Legg & Nagy 2006). A review done by Lepetz *et al.* (2009) on biodiversity monitoring related to climate change, found that while small scale studies give more insight when compared to large scale studies, these studies show too short time specific responses. Sound monitoring programs should be based on clear justification for acquiring information i.e. “what we strive to know should be driven by what we need to know” (Legg & Nagy 2006, Nichols & Williams 2006).

Monitoring of biodiversity is critically important for assessing trends in biodiversity and forewarning of impending species declines, species extinctions, informing management intervention and quantifying the effectiveness of management practices designed to conserve biodiversity (Lindenmayer *et al.* 2011). The roles of biodiversity monitoring are, in turn, essential for sustaining all levels of biological organization (Scholes *et al*. 2008). Despite its importance, biodiversity monitoring has a somewhat tainted history in conservation management (Kleijn & Sutherland 2003, Bernhardt *et al.* 2005 and Muir 2010). More often than not where biodiversity monitoring is being done it is of a poor quality (Muir

2010, Lindenmayer *et al.* 2011). The biggest problem with biodiversity monitoring is that most development documents typically do not clearly outline, clear-cut statements of relevant, measurable and appropriately sensitive indicators that will provide adequate feedback on the programmes objectives (Lindenmayer *et al.* 2011). All of this leads to poor reporting of trends in biodiversity and there is no clear return on the resources invested in the project which will ultimately lead to poor conservation management decisions (Lindenmayer *et al.* 2011).

Anthropogenic climate change

The Intergovernmental Panel on Climate Change (IPCC) have developed a wide range of climate change scenarios, based on projected emission scenarios. The earth's mean surface temperature is projected to warm between 0.3 and 4.8˚C by the end of the 21st century (IPCC 2014). Projections suggest that terrestrial areas will warm more than the oceans and high latitude regions will warm more than lower latitude tropics (IPCC 2007, IPCC 2014). The associated sea level rise is projected to be between 0.26 and 0.82 m (IPCC 2014). Precipitation is generally projected to increase in low latitude and equatorial areas and decrease in the sub-tropical regions (IPCC 2007). There is good evidence to suggest that these changes are being driven by anthropogenic causes (Crowley 2000, IPCC 2007, Rosenzweig *et al.* 2008). The fourth IPCC, assessment report released in 2007 (IPCC 2007), stated that multiple lines of evidence confirms that the post-industrial rise in greenhouse gases does not stem from natural mechanisms, a statement that was re-iterated in the fifth assessment report, released in 2014 (IPCC 2014). Anthropogenic greenhouse gas (GHG) emissions since the pre-industrial era have driven large increases in the atmospheric concentrations of carbon dioxide, methane and nitrous oxide. The concentration of atmospheric carbon dioxide increased by an estimated 31% between the period of 1750 and 2000 (IPCC 2007). That is an alarming increase of 100 ppm in 250 years, compared to just 20 ppm during the previous 8000 years. For comparison, at the end of the most recent ice age there was a rise in atmospheric CO_2 concentration of approximately 80 ppm. This rise took over 5000 years and higher values than at present have only occurred many millions of years ago. It is estimated that since 1750 about two thirds of anthropogenic mediated CO_2 emissions have come from fossil fuel burning (e.g. coal and petroleum) and about one third from land use change (e.g. deforestation and agricultural). Of the CO_2 released, about 45% has remained in the atmosphere, while about 30% has been taken up by the oceans and the remainder has been absorbed by plants. About half of the carbon dioxide going into the atmosphere is removed over a time scale of 30 years; a further 30% is removed within a few centuries; and the remaining 20% will typically stay in the atmosphere for many thousands of years (IPCC 2007). In the fifth assessment report released in 2014, the IPCC reported that roughly half of the anthropogenic carbon dioxide emissions between 1750 and 2011 have occurred in the last 40 years (IPCC 2014). The changes in atmospheric greenhouse gas concentrations along with land cover change, land use change and natural forces have contributed to changes in the Earth's climate over the 20th century. These changes include: warmer land and ocean surface temperatures, altered spatial and temporal patterns of precipitation, rising sea levels and increased frequency and intensity of El Nino events (IPCC 2007, Hannah *et al.* 2002).

Climate change and biodiversity conservation

Attempts to conserve species and ecosystems in their current state may be futile (Hannah *et al.* 2002). Projections of rapid anthropogenic climate change and evidence of past climatic shifts indicate that current patterns of biodiversity may change at the landscape scale over timeframes as short as decades (Hannah *et al.* 2002, Butchart *et al.* 2010). The changes brought about by anthropogenic climate change are further compounded by other human mediated activities, which include but are not limited to: land use changes, soil, water and air pollution, diversion of water to intensively managed ecosystems and urban systems, habitat fragmentation, selective exploitation of species, introduction of invasive species and stratospheric ozone depletion (Chapin *et al.* 2000). These changes have caused the current rate of biodiversity loss to be greater than the natural background rate of extinction (IPCC 2002). The changes brought about by anthropogenic climate change, particularly in the warmer regions, have affected the timing of reproduction in animals and plants, migration of animals, the length of the growing seasons, species distributions and population sizes and the frequency of pest and disease outbreaks (Parmesan & Yohe 2003, Parmesan 2006). The general effect of projected anthropogenic climate change is that species will migrate poleward or upward in order to track their respective climate envelopes. Individual species responses to anthropogenic climate change will be varied: they will migrate at different rates through fragmented landscapes and ecosystems dominated by long lived species (e.g. long lived trees) which will often be too slow to show evidence of change. The species that make up an ecosystem are unlikely to shift together (Parmesan & Yohe 2003, Chen 2011), and as a result, the composition of most current ecosystems is likely to change.

The most rapid changes are expected to occur in areas where they are accelerated by changes in natural and non-climatic disturbances (Hannah *et al.* 2002). Changes in the frequency, intensity and extent of these disturbances, has caused the most pressing environmental problem of our time, i.e. biodiversity loss (Barnosky *et al.* 2011).

There is now ample evidence that anthropogenic climate change is reshuffling the geographic distributions of plants and animal species worldwide (Parmesan & Yohe 2003). These rapid losses can be ascribed to increased human activities resulting in pollution, habitat destruction, and invasion by alien plant and animal species. These activities are causing changes that threaten the continued existence of many species and the functioning of ecosystems. Even though there is ample evidence to support the fact that anthropogenic climate change is adversely affecting biodiversity, it is important to note and take into consideration other drivers of ecosystem change. These drivers include but are not limited to the following: water availability, drought and fire regime. Furthermore it is also important to note that when monitoring is done, sites are often chosen that represent typical biome or ecosystem types, which could potentially limit the sensitivity of their component species to climate change, thus care should be taken to select sites that include the edge of the biome or ecosystem type (Midgley et al. 2007).

Biodiversity monitoring

Monitoring can be defined as intermittent (regular or irregular) surveillance carried out to ascertain the extent of compliance with a predetermined standard or the degree of deviation from an expected norm (Hellawel 1991). Therefore, a norm has to be defined before the programme can be implemented. The formulation of this norm requires information on the baseline structure of and variation in the system to be monitored (Karr 1987). However the establishment of this natural baseline may be difficult for two reasons; long-term data sets on most taxonomic groups from undisturbed sites are not available to provide information about natural variation in species assemblages, and as anthropogenic influences have mostly homogenised the landscape across the globe it is difficult to find undisturbed sites that can provide baseline information about natural variation (Arcese & Sinclair 1997). Those areas that are still intact i.e. undisturbed, should be set aside to serve as ecological baselines (Angelstam *et al.* 1997). However natural areas still exist in and amongst urban areas, and these could be used to assess the effects of urbanisation on biota by monitoring along a gradient of varying human development (Niemelä *et al.* 2000).

Biological diversity is defined as “the variety and variability among living organisms and the ecological complexes in which they occur” (OTA 1987). However a simple, comprehensive and fully operational definition of biodiversity is unlikely to be found (Noss 1990). Noss (1990) proposed that a characterization of biodiversity that identifies the major components at several levels of organization would be more useful for biodiversity monitoring. This hierarchical approach to defining biodiversity would allow monitoring programs to identify appropriate indicators for assessment at each level of biological organization. Biodiversity monitoring can therefore encompass a variety of biological entities at numerous levels of organisation. Generally, biodiversity monitoring programs use the distribution and abundance of organisms and their associations with the physical environment to determine the status of biodiversity or changes, over time and space for example the savanna ecosystem project (Noble *et al.* 1975). There are three main goals of biodiversity monitoring (Stork *et al.* 1996): assessing the effectiveness of policy or legislation, regulatory function and providing an early warning system (for example of species extinction). These goals can be achieved by conducting biodiversity monitoring at a range of ecological scales using a variety of techniques, including general surveying, cataloguing, quantifying and mapping entities such as genes, individuals, populations, species, habitats and ecosystems (Stork *et al.* 1996), and bringing the resulting information together. Monitoring is a complex task and should be well planned (Niemelä 2000). The objective of the monitoring programme determines the kind of field methods, indicators, and data analysis, required. The monitoring objectives also determine the way the data are synthesized and how the resultant information is communicated to conservation managers and policy makers.

Biodiversity monitoring is an integral part of efforts to stop the loss of biodiversity (Dallmeier 1996, Kremen *et al.* 2010). However, monitoring should not be an end in itself. The aim of biodiversity monitoring should be to provide guidelines for making decisions on how to best manage conservation resources for the effective conservation of biodiversity. Monitoring determines the status of biological diversity at one or more ecological levels and assesses changes over time and space. Monitoring at the global level is needed to compare trends at all levels of biological organization caused by anthropogenic influences. Monitoring is a vital feedback loop between anthropogenic influences and biodiversity. The current status of conservation efforts in South Africa are outlined below.

Conservation in South Africa

The primary objective of the United Nations Centre for Biological Diversity (CBD) is to document and highlight potential and realised global biodiversity losses at all levels of biodiversity (i.e. genes, species and ecosystems). This convention was ratified by South Africa in 1995 and confirmed by the National Environmental Management Act (NEMBA No. 10 of 2004). This act lead to the establishment of the South African National Biodiversity Institute (SANBI), which is charged with monitoring the state of South Africa’s biodiversity, the conservation status of all Red Listed species and the status of all listed invasive species (NEMBA 2004) in South Africa. Other than ratifying the CBD, South Africa is also a signatory to, the RAMSAR Convention on Wetland Conservation and the Convention on International

Trade in Endangered Species (CITES). In 2002 and 2003 South Africa played host to the World Summit on Sustainable Development and the World Parks Congress respectively (IUCN 2013). This enabled South Africa to expand its role as a global participant in furthering the cause for species and ecosystem conservation. All of the above confirm that South Africa's intention is to identify inventories of specimens and conserve the invaluable natural heritage and the right of every individual to a healthy, well protected and ecologically sustainable environment which is enshrined in the Constitution of South Africa (Act 108 of 1996).

Hannah *et al.* (2002) alluded to how conservation strategies should be adapted in the face of anthropogenic climate change. They suggested that conservation strategies should be done at a scale and with objectives that specifically address the potential effects of climate change. More recently in a paper by McGeoch *et al.* (2011), a strategic framework for biodiversity monitoring within South Africa's National Parks was proposed. In their study they chose ten Biodiversity Monitoring Programmes (BMP's) that provide broad coverage of higher level biodiversity objectives of parks. Currently underway is the development of a set of principles which will guide the development of the various biodiversity monitoring programs and data management. These BMP's will give direction to future investment in monitoring programmes in South African protected areas (McGeoch *et al.* 2011).

Monitoring Biodiversity is not only essential to assess the performance of protected areas but also to assess the state of biodiversity outside of protected areas. For example programs such as the Mpumalanga Biodiversity Conservation Plan (MBCP) (Ferrar & Lötter 2007) and the Succulent Karoo Ecosystem Programme (SKEP) (Driver *et al.* 2003), (the latter of which spans the whole of the succulent Karoo ecosystem), are intended to guide conservation and land use decisions in support of sustainable development. Whilst there are national conservation activities through organisations such as South African National Parks, much of the conservation planning and decision making takes place at the level of provinces in South Africa. Provincial conservation agencies are tasked with biodiversity monitoring.

Numerous studies have been done on improving global biodiversity monitoring systems (Pereira & Cooper 2006). In South Africa the National Biodiversity Strategy and Action Plan is making significant progress towards the development of a national biodiversity monitoring framework (NBSAP 2005). However, both nationally and internationally very few monitoring programs focus on detecting the effects of climate change on biodiversity (SANBI 2007, EuMon 2008). In 2012 the South African National Biodiversity Institute (SANBI) launched a new project to address this issue, the project aims to detect trends in climate change impacts in South Africa (Barnard & De Villiers 2012). Estimates of changes in biodiversity that are accurate enough to detect climate change effects are imperative to diagnose the current state and trends of biodiversity (Lepetz *et al.* 2009). Globally this concern is also being addressed with critical steps being taken to develop suitable ecological monitoring programs (Pereira & Cooper 2006, Nichols & Williams 2006).

Mpumalanga province

The Mpumalanga province (MP) of South Africa is a warm summer rainfall region, with an altitudinal range of 107 to 2400 meters above sea level (m.a.s.l) and an annual rainfall ranging from <500 to >1600 mm per year. The province is represented by three of South Africa's nine biomes, including grassland (Highveld and escarpment hills), savanna (escarpment foothills and lowveld) and forest (south and east facing escarpment valleys).

Mpumalanga's grasslands are mainly found in the Highveld above 1000 m.a.s.l. These are cool, dry open landscapes, with rainfall of over 500 mm/year. The grasslands cover 61% of MP, 44% of which is transformed (Ferrar & Lötter 2007). The savanna regions consist of a combination of trees, shrubs and grass also referred to as bushveld and at lower altitudes (eastern Mpumalanga) known as lowveld. The savannas cover 39% of MP, of which 25% is transformed. In MP, forests occur in small scattered patches, mostly in river valleys in the escarpment region. The forest covers 0.5% of the province of which only 1% is transformed. The province also contains three recognized centres of endemism: Barberton, Sekhukhuneland and Wolkberg, with a fourth being proposed: Lydenburg (Ferrar & Lötter 2007, Knobel & Bredenkamp 2006).

Developing indicators that can be monitored

There are four main categories of biological indicators, these include the following: environmental indicators, ecological indicators, biodiversity indicators and impact indicators (Kremen *et al.* 1994, McGeoch 1998). The first three categories can be classified as biological entities and the fourth one combines biological, physical and geographical indicators. These categories are by no means clear cut as many indicators can overlap between the four categories.

Environmental indicators are those taxa that demonstrate a predictable response to environmental disturbance or change such as pollutants and habitat disturbance (McGeoch 1998). An example of an environmental indicator is shown in a study done by Dallinger *et al.* (1992) where they measured the levels of lead and cadmium in an isopod species *Porcellio scaber*, this was used to assess the levels of heavy metals in a city in Austria. Ecological indicators are those taxa or taxonomic assemblages that are sensitive to environmental stress factors such as climate change and whose response is a representative of at least a subset of other taxa present in the habitat (McGeoch 1998). Ecological indicators differ from environmental indicators in that ecological indicators detect changes in the taxon itself. A biodiversity indicator is a group of taxa or a functional group, the diversity of which reflects some measure of the diversity of other taxa in a habitat or a set of habitats (Kremen *et al.* 1994, McGeoch 1998). Impact indicators focus on both resources and ecological processes that are directly affected by human actions (Kremen *et al.* 1994).

In an ideal situation a monitoring program should comprise an exhaustive survey of all taxa and habitats. However even at a local scale this is not feasible for reasons such as poor taxonomy and high species richness (Niemelä 2000). Therefore it is necessary to select a manageable number of taxa as indicators of the overall change in biological organization.

The use of ecological indicators in conservation management has increased tremendously recently (Noss 1990). Numerous authors have discussed criteria for the selection and use of ecological indicators (Lenhardt & Witter 1977, Holloway 1980, Hellawell 1986, Noss 1990, Brown 1991, Holloway & Stork 1991, Spellerberg 1991, Kremen 1992, Pearson & Cassola 1992, Kremen *et al*. 1993, Hammond 1994, Pearson 1994, Rumpff *et al.* 2010). All of which focussed on indicators at the species level of biological organization, however no single indicator can adequately convey the complex relationships between biota and their environment. Chapter two of this study proposes a pragmatic approach to selecting ecological indicators.

Suitable monitoring sites

Climate plays an important role in determining the geographic ranges of species. With rapid climate change expected in the coming decades, ecologists have projected that species ranges will shift large distances in elevation and latitude (Parmesan 2006). However, most range shift assessments are based on coarse-scale climate models that ignore fine-scale heterogeneity and could fail to capture important range shift dynamics (Ford *et al.* 2013). Moreover, if climate varies dramatically over short distances, some populations of certain species may only need to migrate tens of meters between microhabitats to track their climate as opposed to hundreds of meters upward or hundreds of kilometres pole ward (Parmesan *et al.* 2000). Keeping in mind that there is likely to be variation in the amount of change in different areas of a region, monitoring programs need to take these geographical variations into account.

Apart from the variation in climate across a region, there are other constraints on monitoring programs, which include the following: availability of conservation resources (i.e. resources for conservation are scarce (Niemelä 2000), conservation managers need to be smarter in the way that they assign conservation resources) and feasibility of monitoring the identified site (e.g. accessibility to identified monitoring sites might not always be possible, more so if it falls outside of a protected area). With this in mind it is important to note that most estimates of biodiversity are not based on an appropriate spatial sampling scheme, and thus do not ensure unbiased estimates of biodiversity at larger spatial scales (Yoccoz *et al.* 2001). Subjectively chosen monitoring sites cannot be used to draw inferences about diversity or trends in diversity at regional scales (Yoccoz *et al.* 2001).

Thesis outline

Chapter 1 General Introduction

This chapter briefly introduces the ideas and concepts on which this thesis is based.

Chapter 2 Selecting species and ecosystem indicators for climate change monitoring in Mpumalanga

The evidence of the effects of human mediated climate change is already evident in most ecosystems. The IPCC projects a 4˚C increase by 2050 in global average temperatures. In Mpumalanga the average temperature is said to increase by 2.8˚C, and annual precipitation levels by as much as 60 mm. Climate change, along with other human mediated factors such as land use changes and the over exploitation of natural resources, will lead to increasing pressures on biodiversity. A pragmatic monitoring approach is developed and applied to the Mpumalanga province, in order to assess the effects brought about by anthropogenic climate change. This approach identifies suitable species and ecosystem indicators, by subjecting candidate indicator candidates through a series of filters. This approach will serve as a tool that can be used by conservation agencies to advise future and current climate change monitoring programs.

Chapter 3 Identifying areas for monitoring biodiversity responses to climate change in the Mpumalanga province

Anthropogenic climate change will have significant effects on biodiversity. These include impacts on distribution, abundance and ecological interactions. It is important to adopt biodiversity monitoring programs to understand the effects of anthropogenic climate change on the biota, which will enable best practice management and conservation of biodiversity. So far however, very few existing monitoring programs allow for the detection of climate change effects, as shown by the European project EuMon and the South African National Biodiversity Institute (SANBI). In a cost-constrained world, the efficient use of resources for conservation has become crucial in ensuring the success of mitigating the effects of global change. This study aims to develop a spatial approach to identifying suitable ecological indicators from biodiversity and climate data. Furthermore this approach will be applied to the Mpumalanga province of South Africa.

Chapter 4 Discussion, conclusion and recommendations

This chapter discusses the results and conclusions of each chapter in the broader context of selecting indicators to assess the effects of climate change.

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Chapter 2

Selecting species and ecosystem indicators for monitoring the effects of anthropogenic climate change, in Mpumalanga

Introduction

Global climate change poses major new challenges for biodiversity conservation (Heller & Zavaleta 2009). As the concentration of atmospheric greenhouse gasses increases over the next century, human mediated climate change is expected to become the next great driver of global biodiversity loss (Sala *et al.* 2000). Over the past century average global temperatures have increased by almost 1˚C (Meehl *et al.* 2007). Changes in precipitation levels have also increased globally, in the mid and high latitudes of the northern hemisphere, a decadal increase of 0.5%-1% has been observed mostly in autumn and winter, whereas in the sub-tropics, precipitation has generally increased by about 0.3% per decade (Walther *et al.* 2002). Shifting climatic conditions are expected to adversely affect biodiversity (Dlamini 2010) and numerous examples of this have already been documented (Pauli *et al.* 1996, Rutherford *et al.* 1999, Parmesan *et al.* 1999, Dunn & Winkler 1999, Sparks 1999). Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise (IPCC 2014).

In southern Africa the impact of climate change has begun to be revealed on the region's biodiversity (Meadows *et al.* 2006). Thomas *et al.* (2005), predict that at the current rate of climate change, 37% of plant taxa in a selection of species rich areas are already committed to extinction and predictions are similar for animal taxa (van Jaarsveld *et al.* 2000). Erasmus *et al.* (2002), predict significant range contractions in almost 80% of the 179 species in their study, these included 34 bird, 19 mammal, 50 reptile, 15 butterfly, and 57 other invertebrate species. These losses are projected across the diverse array of landscapes present in southern Africa, and three specific biomes that dominate southern Africa; grasslands, savannas and forests (Low & Rebelo 1996).

The Mpumalanga province of South Africa, presents a unique conservation challenge in southern Africa, as it has a diverse landscape encompassing three of the seven South African terrestrial biomes, of which the grassland is severely threatened (Rutherford *et al.* 1999). The region faces the threats of local extinctions and changes in community function with the projected effects of climate change (Dlamini 2010). Monitoring and managing these changes in an efficient, cost effective way presents a major challenge for managers in the Mpumalanga province. This has led to a recent call from the Mpumalanga Tourism and Parks Agency (MTPA) for a more comprehensive climate change monitoring program.

Responsible conservation decision making, and thus natural resource management is entirely dependent on the information provided by appropriate and proper resource monitoring (Yoccoz *et al.* 2001). Long-term data are crucial for assessing the severity of the impacts of anthropogenic climate change, as biotic responses may exhibit threshold effects and nonlinear dynamics (Andersen *et al.* 2009), furthermore natural variability such as floods might be critical factors controlling the distribution and functioning of biological organization (Woodley 1992). In summary long-term data are important to distinguish between signals of anthropogenic change (for example anthropogenic climate change) and natural variability. The development and application of monitoring techniques plays a critical role in the ongoing process of balancing economic development, human welfare and ecological protection. The use and application of ecological indicators provide the means by which proper resource monitoring can be undertaken (e.g. Kremen *et al.* 1994, Pearson 1994). The use of ecological indicators in conservation management has increased tremendously over the past decade (Noss 1990). Numerous authors have discussed criteria for the selection and use of ecological indicators (Lenhardt & Witter 1977, Holloway 1980, Hellawell 1986, Noss 1990, Brown 1991, Holloway & Stork 1991, Spellerberg 1991, Kremen 1992, Pearson & Cassola 1992, Kremen *et al.* 1993, Hammond 1994, Pearson 1994, Rumpff *et al.* 2010), all of which have focussed on indicators at the species level of biological organization. However, no single indicator can adequately convey the complex relationships between biota and their environment. In order to adequately assess the state of biodiversity in a changing climate a more comprehensive monitoring strategy needs to be implemented.

Therefore, this study aims to develop an approach for identifying a manageable number of ecological indicators at various levels of biological organization, which can be used to assess the effects of anthropogenic climate change on biodiversity. Furthermore this approach will be applied to the Mpumalanga province of South Africa, where a set of suitable indicators will be identified at the species and ecosystem level of biological organization.

Methods

Approach

The approach proposed in this study is based on the three components of biodiversity, these include: composition, function, and structure. These components are nested into a hierarchy that incorporates each attribute of biodiversity at four levels of biological organization, which include: genetic, species, ecosystem and regional landscape level (Noss 1990). The current study however only focused on identifying ecological indicators for the species and ecosystem levels of biological organization.

The approach was developed prior to the workshops held in conjunction with the Mpumalanga Tourism and Parks Agency (MTPA) and other research institutes, which included the Agricultural Research Council (ARC), South African Earth Observation Network

(SAEON) and the University of Pretoria (UP). The pragmatic approach was developed in order to inform current and future biodiversity monitoring programs, specifically aimed at assessing the effects of anthropogenic climate change.

The first step involves the identification of the monitoring approach's objective. Step two involves the identification of attribute lists for the potential indicators, which can be organized into three hierarchical categories, which include: feasibility, climate change sensitivity and importance. Step three involves the identification of what aspect to monitor of each suitable indicator (Figure 1).

In this study the pragmatic approach was applied to the Mpumalanga province of South Africa. The chosen objective was based on the needs of the MTPA, and a need to understand anthropogenic climate change and its effects on biodiversity in the Mpumalanga province. The application of the proposed approach required the development of set of potential attributes prior to the workshops. These attributes were then scrutinized and further developed during the workshops (Table 1). Along with the set of attributes, a set of possible candidate indicators were also identified at the workshops. The set of attributes were organized in hierarchical groups (these include the following: feasibility, climate change sensitivity and importance), which serve as filters in the identification of suitable ecological indicators (Figure 1). The first filter, which is called Feasibility, includes those attributes that determine whether a candidate indicator is realistic and practical to monitor from a management perspective. The second filter, which is called Climate Change Sensitivity, includes those attributes that determine whether a candidate indicator is acutely sensitive in its response to climatic change. The third filter, which is called Importance, includes those attributes that determine whether a candidate is important to the Mpumalanga province, for example an endemic or a keystone species. It is important to note that the filters are arranged in order of importance, for example if a candidate does not possess 50% of the attributes in each filter it will be deemed not suitable. When a candidate possesses the required attributes, it will then progress to the next filter. In the case of the Mpumalanga province the last filter (importance) will not eliminate candidates as it is not important in achieving the objective set in step one. This filter is intended to aid the MTPA in further prioritizing resources for monitoring. If a candidate does not pass through the first filter i.e. fulfils 50% or more of the attributes it is discarded. If a candidate meets all of the requirements of the first two filters (i.e. Feasibility and Climate Change Sensitivity) it will be regarded as a suitable candidate for the monitoring program.

In order to determine the suitability of the identified indicators (Table 2), each indicator was evaluated and was assigned a score of suitability by applying the three filters; the score was a measure of how many of the criteria are fulfilled by the proposed indicators. This was done as the attributes in the first two filters (Feasibility and Climate change sensitivity) were considered to be more important than the last filter (Importance) and were thus assigned a higher weight. The reason for this is that it is considered more important for a candidate to be able to give insights into the impacts caused by anthropogenic climate change, than it is to be an important biodiversity feature for the Mpumalanga province.

The study further identified existing datasets that could be suitable to use as baseline data to quantify changes in biodiversity that have resulted from anthropogenic climate change in the Mpumalanga province (Table 3). These datasets were identified by the same panel of experts that attended the workshop. The following information was obtained as far as possible for each data set: terrestrial or aquatic data (Domain/system), name of program/dataset, purpose of dataset, species or group focussed on (indicator(s)), type of data collected (measurements), date of data collection, frequency of data collection, geographic area covered by the dataset, organization that the dataset belongs to, contact person i.e. dataset curator, number of sites/records i.e. type of survey (once off/repeated), status of site, quality of data, access to data and general notes on the dataset (Table 3). However, in order to determine the suitability of the datasets only a few attributes were regarded as being critical, these included: time period, type of measurement and number of sites/records. A suitable baseline dataset was considered to be one for which at least five years of data had been collected, where presence-absence records had been collected for at least four sites or for which at least 40 records were available.

Results

Pragmatic approach

The approach outlined in this study is given below in Figure 1. This pragmatic approach is the first of two methods developed in this study to identify indicators to assess the effects of anthropogenic climate change on biodiversity. The approach consists of three steps, identification of objective, determining attributes and finally identifying indicators.

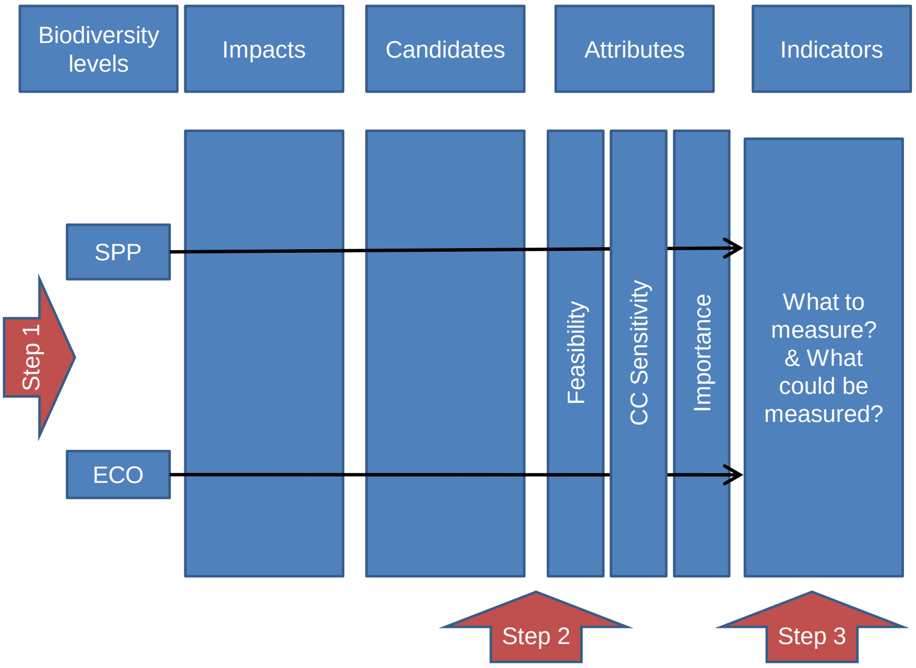

Figure 1: The pragmatic approach: identifying suitable indicators at the species (SPP) and ecosystem (ECO) level of biological organization for the assessment of anthropogenic climate change impacts on biodiversity. Step one involved the identification of the monitoring approach's objective. Step two involved the identification of attribute lists, these include: "feasibility", "climate change sensitivity" and "importance". These act as filters for the identification of ecological indicators (Step 3).

The second step in the approach (Figure 1) involved developing a set of attributes that can be used as filters to determine the suitability of candidate indicators (Table 1). Three filters where develop, these include: A - Feasibility (five attributes), B - Climate change sensitivity (14 attributes) and C - Importance (four attributes). Of these only 20 are applicable to determining suitability at the species level of biological organization and 13 are applicable for determining suitability at the ecosystem level of biological organization.

Table 1: Set of attributes identified for selecting suitable ecological indicators at the species and ecosystem level. The list consists of three categories; A = feasibility (i.e. whether it is viable to use as an indicator from a management and logistic perspective), B = climate change sensitivity (i.e. must be able to give insights into climate change impacts), and C = importance (i.e. whether it is important for the Mpumalanga province). For each attribute a reference that supports it as an important attribute of an indicator is given as far as possible. The attributes that can be applied to both the species- and ecosystem level where identified in the last two columns.

A – Feasibility

Attributes	Description/Rationale	Species	Ecosystem
Easy to find	In order for a species to be easily and routinely monitored it must be easy to find, so as to not waste conservation resources (Holloway & Stork 1991).	x	
Sufficient population size	In order for a species to be easily and routinely monitored a sufficiently large population size is needed, so as to not waste conservation resources if one cannot find individuals of the species being monitored (Jenkins 1971).	x	
Sound taxonomy & easily identified	Because conservation resources are scarce, monitoring will not always be undertaken by experts. Thus the taxonomy of an indicator must be stable and sound, in order for non-experts to accurately monitor trends (Stork 1994). However even if the monitoring is undertaken by experts it is still preferable to work with a group that has a sound taxonomy so as to not avoid confusion in the field.	x	x
Areas where land use change is minimal.	Monitoring should be focused but not limited to areas where land use change is minimal (Thuiller 2007), in order to isolate the effects of climate change from other factors that influence species distributions and abundance (e.g. land use change). An example of an area where land use change is minimal would be a protected area.	x	x
Concentrate monitoring in areas of highest projected climate change	Monitoring should be focussed in areas of highest projected climate change. This is important as it will give valuable information on how biodiversity responds to climate change and the observed changes are most likely due to climate change.	x	x

B - Climate change sensitivity

Attributes	Description/Rationale	Species	Ecosystem

Clearly defined altitudinal range	Species distribution patterns are largely determined by altitude. If a species altitudinal range has not been clearly defined it will be difficult to track its response to climatic changes (e.g. certain Protea species occur in clearly defined altitudinal bands) (New 1995).	x	
Short lived species	Mobile organisms or organisms with short generation times (Curnutt *et al.* 1998) adjust more rapidly to altered disturbance regimes than less mobile or long-lived species (Platt *et al.* 2000). Even though short lived species will give valuable insights into the effects of climate change; they tend to be to variable in their response to climate change effects.	x	
CO_2 sensitive species	Woody plants (regarded as CO_2 sensitive species) typically possess the C3 photosynthetic pathway, whereas the grasses they have replaced in tropical regions are primarily C4. Historic increases in atmospheric CO_2 have conferred a significant advantage to C3 species relative to C4 species with respect to physiological activity, growth and competitive ability, and invasion of woody plants into C4 grasslands has been accompanied by a 30% increase in atmospheric CO_2 over the past 200 years (Archer *et al.* 1995). A better understanding of how woody plants respond to atmospheric CO_2 changes will ultimately report on the severity of climatic changes.	x	
Easily dispersed species	Species that can easily disperse will respond to the effects of climate change much faster than those that dot disperse easily, thus one will see a response much more quickly, by allowing one to adequately assess the effects of climate change without having to have hundreds of years of data (Foden *et al.* 2007).	x	
Migratory species	Changes in the timing of arrival and departure of migratory species can indicate changes in climate. Some migratory species specifically time their departure and arrival in accordance with temperature (Both *et al.* 2006). Thus observing the behaviour of these species is a very easy and cost effective way of measuring the effects of climate change.	x	
Sex ratio (or breeding success) is temperature dependent	In contrast to other amniote vertebrates, whose gender is determined genetically at conception, the sex of offspring in many reptiles is irreversibly determined by the surrounding temperatures. The sex ratio of offspring in these taxa may be radically altered by as little as a 1°C shift in incubation temperature. Hence, sex ratio, a critical demographic parameter, is subject to the vagaries of the thermal environment in species with temperature-dependent sex determination, even though offspring sex ratio is under strong frequency-dependent selection to be balanced. Monitoring the population dynamics of reptiles may give insights into temperature changes (Janzen 1994).	x	
Habitat specialist	Species that are habitat specialists are very sensitive to any change in their physical and chemical surroundings caused by anthropogenic climate change. These species are most likely to respond faster to the effects of anthropogenic climate change, thus these species will provide vital information in a relatively short period of time (Noss 1990).	x	
Transition zones	Climatic warming will have adverse effects on biodiversity. These effects should be most evident at biome transitions zones (Ecotones) (Loehle 2000).		x

Fire dependent ecosystems	The fire regime has been regarded as a global control agent for ecosystems (Bond *et al.* 2005), changes in the fire regime could greatly influence ecosystems. Thus monitoring fire dependent ecosystems will provide insights into changes in the fire regime (Staver *et al.* 2009). Changes in climate have the potential to significantly affect the fire regimes, especially in areas where climate and not fuel, tends to be the limiting factor.		x
Known climate change response/climate change sensitive ecosystems	Monitoring species or ecosystems which have a known climatic response will save time because we know which attribute to monitor for a specific species or ecosystem (Noss 1990).	x	x
High altitude species or ecosystems	It is suggested that global warming is driving species ranges poleward and toward higher elevations. Thus species/ecosystems that are already at their geographical range limit will most likely not be able to adapt to a changing climate, as they are already at their geographical range limit. Thus to fully assess the severity of climate change one has to monitor in those areas where the greatest changes are expected to occur (New 1995). A species or ecosystem is regarded as being a high altitude species or ecosystem if it occurs above 1500 m.a.s.l. (Colwell *et al.* 2008).	x	x
Range restricted species or ecosystem	Species/Ecosystems that have restricted geographic ranges may be more vulnerable to extinction, sensitive to climate change, important to Mpumalanga and easier to monitor once its exact geographic range has been determined.	x	x
End of range	It is expected that the effects of climate change may have stronger effects at the margins. Individuals living at the edge of their species' physiological tolerances and thus are more likely than those living in the interior to experience stressful, harmful or lethal weather events (Parmesan 2000, Davis & Shaw 2001, Foden *et al.* 2007).	x	x
Pronounced seasonal change	Phenological responses to climate change differ across trophic levels, which for example may lead to birds failing to breed at the time of maximal food abundance, plants flowering at a later stage causing a mismatch between plant and pollinator (Both *et al.* 2006). Phenological changes are one of the most commonly measured forms of biological responses to climatic changes, because it is easy and cost effective way of monitoring biological responses to climatic changes (Parmesan 2003).	x	x

C – Importance

Attributes	**Description/Rationale**	**Species**	**Ecosystem**
Keystone species	Species that play an important role in the ecosystem are regarded as keystone species (e.g. pests & pathogens) (Hellawell 1986).	x	
Importance for ecosystem services	Ecosystem services play a major role in the lives and wellbeing of humans.		x

Endemic to Mpumalanga	Species/Ecosystems that are unique to Mpumalanga are important to conserve as they do not occur elsewhere, and is thus under greater risk of extinction (Hellawell 1986).	x	x
Threatened	Species/Ecosystems that are already classified as vulnerable, threatened and near threatened by the IUCN are under increased risk of extinction (Hellawell 1986).	x	x

Suitable indicators for Mpumalanga

Nine suitable indicators were identified at the species level of biological organization for the Mpumalanga province (Table 2), which included: plants (six) (indicator to be measured include the following: phenology, changes in distribution and change in growth), reptiles (one) (indicator to be measured include the following: changes in distribution), amphibians (one) (indicator to be measured include the following: changes in distribution) and birds (one) (indicator to be measured include the following: changes in distribution). At the ecosystem level three indicators were identified. The three represent the major biomes that are found in Mpumalanga (savanna, grassland and forest). The proposed indicator that will be assessed at the ecosystem level is changes in species composition.

Table 2: Suitable indicators for Mpumalanga. For each candidate species an appropriate indicator was determined. The candidates were given a suitability score, determined by the number of criteria they met for all categories. In order to be regarded as suitable each individual candidate must at least fulfil half (50%) of the criteria specified by each filter. Cat. A = Category A (Feasibility), Cat. B = Category B (Climate change sensitivity) and Cat C. = Category C (Importance).

Candidate	**Indicator**	**Rationale**		**Score**	
Species level candidates			**Cat. A**	**Cat. B**	**Cat. C**
Plants					
Morea galpinii (Fabaceae)	Phenology (flowering time)	Sensitive to temperature changes	4/5	6/12	0/3
Rapanea melanophloeos (Myrsinaceae)	Phenology	High altitude species, and temperature triggers flowering	5/5	2/12	0/3
Gladioulus longicaulus (Iridaceae)	Phenology		5/5	5/12	0/3
Protea comptonii (Proteaceae)	Phenology and distribution	Clearly defined altitudinal range	3/5	4/12	1/3

Strelitzia caudate (Strelitziaceae)	Distribution changes	Species with end of range in Mpumalanga	3/5	5/12	0/3
Boophane disticha (Amaryllidaceae)	Growth rate of bulb	Bulb very sensitive to temperature changes	3/5	2/12	0/3
Reptiles					
Pseudocordylus melanotus (Cordylidae)	Distribution changes	High altitude species	3/5	2/12	0/3
Amphibians					
Hadromophryne natalensis (tadpole) (Heleophrynidae)	Distribution changes	High altitude species, tadpole easier to find than adults	3/5	6/12	1/3
Birds					
Halycyon albiventris (Dacelonidae)	Distribution changes	Easy to find (large population)	4/5	2/12	1/3
Ecosystem level candidates					
Forest site	Change in species composition	Presence absence data for a number of plots at various sites in the Mpumlanga province	3/3	5/7	1/3
Savanna site	Change in species composition	Savannah ecosystem project was initiated in 1973 to examine the semi-arid savanna region of southern Africa. This database contains a considerable amount of data points that fall within the boundaries of the Mpumalanga province.	3/3	1/7	1/3
Grassland site	Change in species composition	Most threatened biome in Mpumalanga (Ferrar & Lötter 2007)	3/3	7/7	2/3

Existing Mpumalanga datasets

There are currently 18 datasets that contain biodiversity data for the Mpumalanga province; these are outlined in Table 3 below. All of these datasets were not intended to assess the effects of climate change on biodiversity, but could serve as a baseline for future monitoring projects. The majority (ten) of the datasets only exist as species inventories, with only one recording phenological changes (Table 3). There is however a wide taxonomic spread throughout the datasets, which includes: plants, birds, large mammals and some reptiles.

Table 3: Existing Mpumalanga monitoring datasets. Along with the dataset name, species or group of interest (Indicators), the time period over which the data were collected (Time period), where the data were collected (coverage), the type of survey (i.e. whether it done once off or was repeated), the type of measurements taken is given, these include abundance, distribution, population demographics, inventory, phenological change. MP = Mpumalanga, ARC = Agricultural Research Council, MTPA = Mpumalanga Tourism and Parks Agency, SANPARKS = South African National Parks.

Dataset name	Indicator(s)	Time period	Coverage	Type of survey	Abundance	Distribution	Population dynamics	Inventory	Phenological changes
River biomonitoring	Fish, crocodiles	1987-2002	Olifants river, Loskop dam	Monthly	**x**	**x**			
SANPARKS	Hippo, crocodiles		Lakes & rivers in MP	Monthly			**x**	**x**	
Small mammals	Rodents, bats, insectivores						**x**	**x**	
Large mammals	Oribi, leopards							**x**	
ARC large mammals	Range of large mammals			Annual		**x**	**x**		
Carnivores program	Honey badger						**x**	**x**	
MTPA birds	Blue swallow, bald ibis, flamingos			Monthly			**x**		

Lowveld bird club	Range of bird species				**x**			
Aloe photo data	Aloes	1980	One site in MP	Once off			**x**	
Phenology study	Range of tree species		Loskop dam					**x**
Savannah ecosystem project plants	Range of species	1989		Annual		**x**	**x**	
Savannah-ecosystem project-birds		1989		Annual				
ARC tree	Range of tree species			Annual		**x**		
Provincial protected areas program	Range of plant species		MP protected areas			**x**		
Herpetology program	Plated lizards						**x**	
Priority species plan	Rhino, zebra, buffalo					**x**		
Manyaleti biodiversity inventory	Invertebrates, birds, mammals, woody plants		Manyaleti Game Reserve	Annually except woody plants every 5 years		**x**	**x**	
MTPA vegetation survey	Trees, grass, forbs	1989	Kruger National Park			**x**		

Discussion

The pragmatic approach (Figure 1) outlined in this study is aimed at informing current and future biodiversity monitoring programs. The pragmatic approach is intended to be developed as a tool which can be used by any conservation agency to assess any impact by using appropriate attributes of biodiversity features to be used as ecological indicators, in any region. The approach can be taken one step further by looking at the effects of the impact of interest, by identifying indicators for all levels of biological diversity, which could be designed to include the genetic, species, ecosystem and regional landscape level. This approach outlines a workflow that can be used to inform current monitoring strategies or for developing new monitoring strategies.

In this study however the pragmatic approach was applied to the Mpumalanga province of South Africa in conjunction with the MTPA. The objective of which was to assess the effects of climate change on biodiversity in the Mpumalanga province of South Africa. It was decided that only the species and ecosystem level of biological organization would be used in this study, because of the available resources for conservation within the MTPA (i.e. expertise, money etc.). The third filter was regarded as being important for the MTPA to further prioritise the allocation of resources for monitoring programs, in the case of the Mpumalanga province as it speaks to ecosystem health rather than the effects of climate change. Climate plays a pivotal role in the understanding of biodiversity patterns and ecosystem processes (Lepetz *et al.* 2009). In order to adequately assess the state of biodiversity in a changing climate a comprehensive biodiversity monitoring strategy needs to be implemented. Numerous studies have given recommendations on what a comprehensive biodiversity monitoring program needs to comprise of. It needs to be done over longer time frames across larger scales, in order to increase detectability of indicators identified and account for the spatial variation in climate across an area (Yoccoz *et al.* 2001, Lepetz *et al.* 2009, Lindenmayer *et al.* 2011). The approach outlined in this study provides such a solution. Several indicators were identified at the species and ecosystem level of biological organization using attributes specifically aimed at monitoring the effects of climate change on biodiversity. The next chapter of this study explores the spatial component of biodiversity monitoring.

Of the three categories/filters identified in the approach all indicators score low in category C (i.e. Importance, Figure 1), however this is not of particular concern here as category C is only regarded as an extra means of informing the allocation of resources in this study, in order to incentivise managers to carry out monitoring protocols. If a candidate is deemed important to Mpumalanga it will aid in the justification of resource allocation on its monitoring. For example *Protea comptonii* is seen as a good indicator based on the following attributes identified by the pragmatic approach: it has sound taxonomy, it occurs in areas where land use change is minimal, it has a clearly defined altitudinal range, it is regarded as a high altitude species and it is listed as threatened under the latest IUCN Red list. It is important to note that a good indicator must have two attributes; it must be a good indicator of climate change effects, and it must be convenient and cost effective for management to monitor (i.e. it should be easy to find, and easy to identify). The third filter (Importance) as mentioned earlier is seen as an extra source of information for the managers, and speaks more to the importance of the chosen indicator for the Mpumalanga province than the direct effects of climate change on biodiversity. As justifying the allocation of scarce resources is an already difficult task. Furthermore such biodiversity features could potentially already have a baseline dataset and maybe even a monitoring programme that focuses on these biodiversity features. This means that managers can combine climate change monitoring with the monitoring of general ecosystem health (that may be threatened by factors other than climate change in the short-term). A candidate that is feasible to monitor, gives a good indication of the severity of the changes brought about by anthropogenic climate change and is important for the conservation of biodiversity within the Mpumalanga province, would be best suited for the monitoring program (Table 2). Most notable is the fact that most of the proposed candidate indicators scored a zero out of three at the third filter (category C), with the exception of *Protea comptonii* (1/3), *Hadromophryne natalensis* (1/3), *Halycyon albiventris* (1/3), Forest site (1/3), Savanna site (1/3) and the Grassland site (2/3). It is important to note that even though these aforementioned candidate indicators met an attribute in the third filter, this filter is most important for the purposes of the MTPA in allocating resources for monitoring, thus when only looking at the objective of the monitoring programme: assess the effects of climate change on biodiversity, those candidates that did not score high in the last filter might still be suitable for use (Figure 1). At the species level of biological organization *Hadromophryne natalensis* scored highest overall on all three filters, thus making it most suitable for use as an indicator. When looking at an indicator it is important to decide what to measure in order for it to provide the information needed to achieve the objective of the monitoring program, in this case it would be measuring phenological changes, distributional shifts and growth rate. These measurements will provide valuable insights into the effects of climate change on biodiversity. At the ecosystem level of biological organization the Grassland ecosystem scored highest overall on all three filters, thus making it most suitable for use as an indicator.

The biggest problem with biodiversity monitoring is that at the beginning of a new monitoring program it is usually not clearly stated which indicators are to be measured to achieve the objective (Lindenmayer *et al.* 2011). This in turn leads to poor reporting of trends in biodiversity and there is no clear return on the resources invested in the project which will ultimately lead to poor conservation management decisions (Lindenmayer *et al.* 2011). The approach outlined in this study addresses this problem by making the definition of an objective central to the functioning and application of the pragmatic approach (Figure 1).

The importance of long-term data sets that could potentially give valuable insights into the effects of climate change on biodiversity must not be overlooked. Various datasets exist within the MTPA (Table 3), however an urgent synthesis of these data sets is needed in order to highlight key gaps in our knowledge of the impacts of climate change (Magurran 2010). Even though the majority of these data sets were not aimed at climate change monitoring, they could still serve as a baseline on which further programmes can be built in order to accurately assess climate change impacts and also serve as a baseline for measuring the impact of current conservation efforts. As we continue to feel the effects of climate change, it is important that we have monitoring in place that has been specifically designed to monitor climate change impact on biodiversity.

By monitoring biodiversity patterns and processes we are able to obtain valuable baseline data for other monitoring programs, for example monitoring alien and invasive taxa. Global climate change has significant implications for human wellbeing and biodiversity conservation. The approach outlined in this study should be seen as a starting point for the development of an integrated working climate change monitoring programme within the MTPA.

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Chapter 3

Identifying areas for monitoring biodiversity responses to climate change in the Mpumalanga province

Introduction

Human mediated environmental changes have resulted in a global concern for the conservation of ecological systems (Chapin *et al.* 2000). Of these changes, it is said that anthropogenic climate change could be the next great driver of extinction events (Chapin *et al.* 2000). Over the past century the mean global surface temperature has increased by almost 1˚C (Meehl *et al.* 2007) and in the coming century it is projected that it could increase by as much as 4˚C (Meehl *et al.* 2007). Along with the prediction of increased average temperatures, an increase in extreme events, such as heat waves and storms are also projected (Mckee *et al.* 1993, Meehl *et al.* 2007). Over the past few decades, the effects of these changes have become particularly obvious in the trends observed at all levels of biological organization (Kerr 2007a, Kerr 2007b). These effects include changes in behaviour, changes in phenology (seasonal activities) (Chmielewski *et al.* 2004), changes in species distributions (Parmesan 2006) and changes in ecological interactions, such as competition, predation, symbiosis, parasitism and mutualistic associations (Davis *et al.* 1998, Bosch *et al.* 2007). These changes are further compounded by disturbance, habitat loss and fragmentation (Walther *et al.* 2002, Parmesan 2006, Skelly *et al.* 2007). It is expected that certain areas in any region are likely to experience greater changes in climate than others (Ackerly *et al.* 2010). Therefore the impacts of anthropogenic climate change largely depends on the relationship between temporal change and the spatial variation of the climate (Ackerly *et al*. 2010). For example the impacts on biodiversity, brought about by climate change will be greater where the rate and/or magnitude of climate change is greater (Ackerly *et al.* 2010). The lack of knowledge especially concerning lag-times between a given effect and its related response makes it difficult to predict long-term biological responses to climatic change (Lepetz *et al.* 2009). Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise (IPCC 2014).

Global declines in biodiversity have triggered national and international agreements to reduce or halt these trends (Reyers & McGeoch 2007). Several commitments were made of which most notably was that of the Convention on Biological Diversity (CBD) to significantly reduce the rate of current biodiversity loss by 2010 (UNEP 2003a, UNEP 2003b). These commitments have led to the need for biodiversity monitoring systems at a global scale, with which to measure progress towards the commitments and other policy targets (Balmford *et al.* 2005a, Balmford *et al.* 2005b).

How biodiversity will respond to a rapidly changing climate is widely recognized as one of the most pressing questions for biologists today (McCarty 2001, Walther *et al.* 2002, Thomas *et al.* 2005). To fully understand climate change and its effects on biodiversity, it is essential to monitor species or populations over a long period of time (Yoccoz *et al.* 2001, Walther *et al.* 2002) and at several different sites (Ackerly *et al.* 2010). These sites must not be chosen subjectively, as one cannot draw inferences about diversity or trends thereof (Yoccoz *et al.* 2001). However research progress is often hampered by the lack of long-term data sets from which patterns can be extracted and predictions can be tested. Even when robust monitoring strategies are based on good management objectives and have a subset of indicators for measurement, there is still a need to review these strategies on a regular basis (Lindenmayer *et al.* 2011). This will allow the continuous improvement as new research is done or when management objectives change. This approach has been dubbed “adaptive monitoring” by Lindenmayer and colleagues (2011). However in order to ensure the long-term integrity of the data, it is essential that the biodiversity monitoring protocols be set up in such a way that the data can be used as a long-term ecological monitoring dataset (Lindenmayer *et al.* 2011). Proper biodiversity monitoring has become ever important as conservationists face a continuing struggle to demonstrate progress made toward protecting earth’s biological resources (Stem *et al.* 2005).

Bearing in mind that resources for conservation are relatively scarce (Nichols & Williams 2006, McDonald-Madden *et al.* 2011), it is important to note that it is impossible to effectively monitor all components of biological organization everywhere that they occur. This is why some selection of biodiversity features and areas of interest is always required as a matter of good survey design (Nichols & Williams 2006). The selection of which variables to monitor and where, are determined largely by the objectives of the monitoring program (McGeoch *et al.* 2011).

Selecting sites to monitor the effects of climate change on biodiversity is complicated by the spatial variation of climate across an area. It is further complicated by the fact that future climate values are only projected values, which are usually forecast by using values of predefined climate parameters, for example annual temperature or precipitation, which are obtained from general circulation model outputs, which are usually downscaled to spatial resolutions finer than the coarse cell size of the raw climate model data. These climate surfaces are interpolated, gridded representations of historical or future climate data. With this in mind it is important that monitoring sites be chosen in both areas of greatest and least projected climatic change, due to the variability of generalized global circulation models (GCM) (Hewitson & Crane 1996, Hewitson & Crane 2006). It is often difficult to decide on which model to use as they all have their strengths and weaknesses, some are better at reflecting extremes, and others at reflecting means or information from thoroughly-data-rich parts of the globe. GCM's are complex and based on many assumptions. Thus most studies use an ensemble approach to using GCM's in their studies.

This study aims to develop a spatial approach to identifying suitable indicators for monitoring the effects of anthropogenic climate change on biodiversity. Furthermore this study will be applied to the Mpumalanga province of South Africa, where suitable ecological indicators from biodiversity data in areas of greatest and least projected climatic change will be identified. This study also aims to identify the biodiversity features that should be monitored at specific sites, which in turn will inform the planning of monitoring programs within the Mpumalanga province.

Methods

Study area

The Mpumalanga (MP) province of South Africa is the focus of this study (depicted in the top left corner, highlighted in blue in Figure 1). The MP province is a warm summer rainfall region, with an altitudinal range of 107 to 2400 meters above sea level (m.a.s.l) and an annual rainfall ranging from <500 to >1600 mm per year. The province is represented by three of South Africa's nine biomes, these include grassland (Highveld and escarpment hills), savanna (escarpment foothills and lowveld) and forest (south and east facing escarpment valleys). Mpumalanga's grasslands are mainly found in the Highveld above 1000 m.a.s.l. These are cool, dry open landscapes, with rainfall of over 500 mm/year. The grasslands cover 61% of MP of which 44% are transformed (Ferrar & Lötter 2007). The savanna regions consist of a combination of trees, shrubs and grass also referred to as bushveld and occur at lower altitudes (eastern MP) it is known as lowveld. The savannas cover 39% of MP of which 25% are transformed. In MP, forests occur in small scattered patches, mostly in river valleys in the escarpment region. The forest covers 0.5% of the province of which only 1% is transformed. The province also contains three recognized centres of endemism: Barberton, Sekhukhuneland and Wolkberg, with a fourth being proposed: Lydenburg (Ferrar & Lötter 2007, Knobel & Bredenkamp 2006).

Identifying areas of greatest and least climatic change

Climate Data

Climate data are widely available either as interpolated climate surfaces or as point data. Interpolated climate surfaces are useful when working at a broad scale (e.g. continental) but when working at a fine scale (e.g. provincial scale) point data are more useful. For example topography and water bodies play a major role in the micro-climate, but these elements are often missed by interpolation as it is usually done in 10 km x 10 km grids, or coarser (Kriticos *et al*. 2011).

In this study it was decided to use point data, because of the fine scale at which the biodiversity features were recorded and the fact that data from seven global circulation models (GCM's) were available for each weather station. For a full list of these GCM's please refer to Appendix Table 4.

Climate data used in this study were empirically downscaled by using a method called self-organizing map based downscaling (SOMD) which was developed at the University of Cape Town (UCT) (Hewitson & Crane 2006). This method recognizes that the regional response is both stochastic as well as a function of the large scale synoptic. As such it generates a statistical distribution of observed responses to past large scale observed synoptic states. These distributions are then sampled based on the generated synoptic in order to produce a time series of GCM downscaled daily values for the variable in question (typically temperature and rainfall) (Hewitson & Crane 2006).

A total of 43 weather stations are located within Mpumalanga. The climate was assumed to be relatively homogenous within a five kilometre radius around each station. Where two stations occurred within a five kilometre radius of one another only one was chosen for this study, preference was given to stations that are outside of a town. As a result, data from only 31 of the 43 weather stations were used (Figure 1).

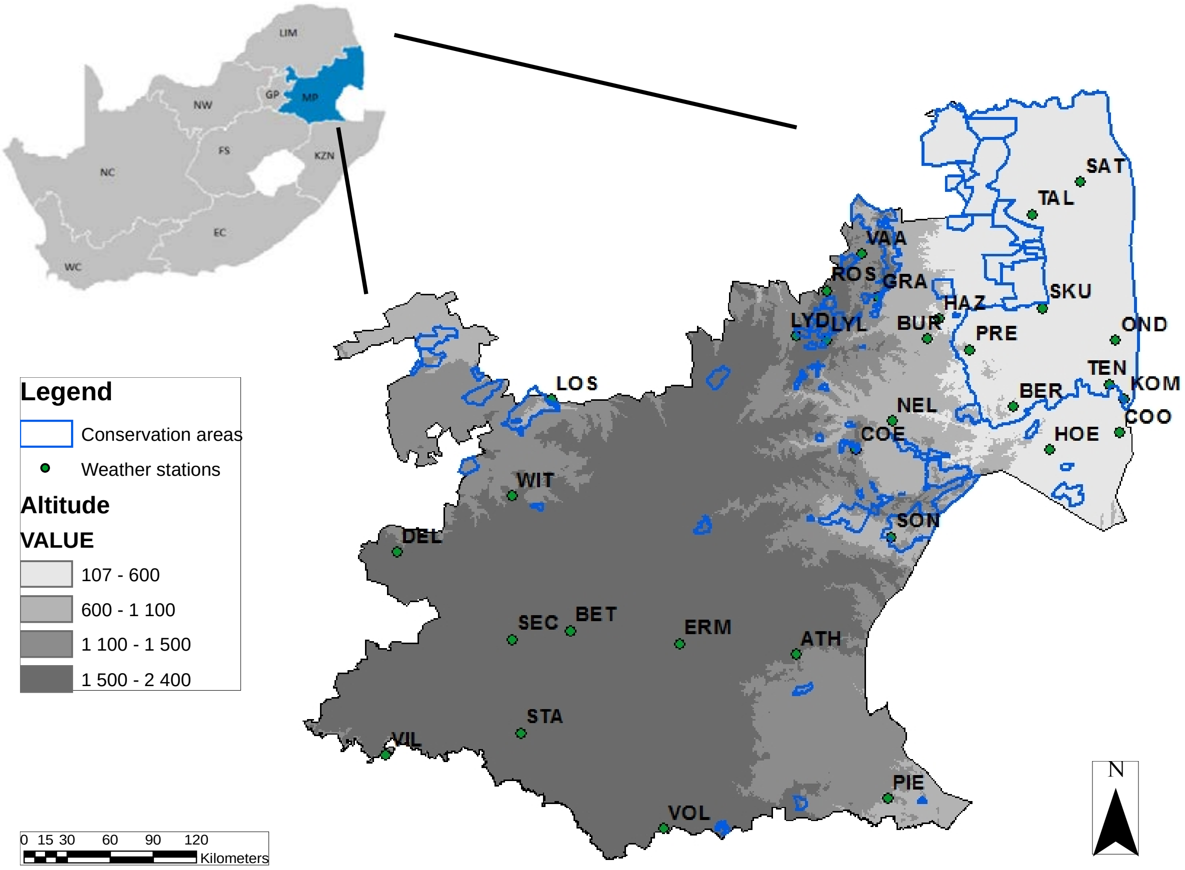

Figure 1: The locations of the 31 selected weather stations within the Mpumalanga (MP) province of South Africa in relation to the conservation areas (in blue) and altitude ranging from 107 m.a.s.l. to 2400 m.a.s.l. Weather stations: VIL - Villiers, VOL - Volksrus, PIE - Piet Retief, STA - Standerton, ERM - Ermelo, DEL - Delmas, SEC - Secunda, BET - Bethal, SON - Songimvelo, WIT - Witbank, COE - Coetzeestroom, HOE - Hoechst, COO - Coopersdal, LOS - Loskopdam, LYD - Lydenburg, LYL - Lydenburg Longtom, NEL - Nelspruit, BUR - Burgershall, HAZ - Hazyview, PRE - Pretoriuskop, BER - Berg-en-Dal, TEN - Tenbosch, OND - Onder sabie, KOM - Komatipoort, ROS - Rosenkrans, VAA - Vaalhoek, GRA - Graskop, TAL - Talamati, SKU - Skukuza, SAT - Satara.

Description of available data for each weather station

The Coupled Modelled Intercomparison Project (CMIP3) archive GCM's were used (Meehl *et al.* 2007). The downscaling methodology requires daily archive fields which limited the number of suitable GCM's to a total of seven. Each GCM has a number of simulations. The first is a simulation of the 20th Century climate (1961 to 2000) forced by observed greenhouse gas (GHG) concentrations. This simulation is the GCMs' representation of the observed climate period (current data). It is important to note that there is no correspondence between real years (observed records) and the years of the 20th Century simulations. This means one can expect a slight deviation between a particular year in the 20th Century simulation and that year in the observational record.

A number of simulations of future periods and greenhouse gas concentration scenarios were also done. The future period of 2046 - 2065 was selected and the future development scenario A2. This scenario assumes that there will be relatively slow population growth, relatively slow per capita growth; relatively slow energy efficiency improvements, delayed development of renewable energy and no barriers to the use of nuclear energy (http://www.ipcc.ch/ipccreports/tar/wg1/029.htm). This scenario was chosen as it did not represent the two extremes of projected development scenarios (i.e. not too extreme yet not too conservative). A total of three GCM simulations, one 20th Century period and one future period were therefore analysed for each particular GCM. Each GCM simulation was downscaled to the station location and various climatological summary statistics were produced.

Future and current downscaled climate data were downloaded from the University of Cape Town's climate portal (www.cip.csag.uct.ac.za/webclient/map/South Africa (stations)).

Weather station climate change values

The downloaded downscaled climate data, for the 31 weather stations, included both future and current annual precipitation, maximum and minimum temperature. For the maximum temperature data set only the warmest month of the year was used (i.e. January) and for the minimum temperature data set only the coldest month of the year was used i.e. July (Figure 3).

In order to improve the accuracy of projected climatic changes, the data from seven GCM's were combined by applying a consensus method based on the average function (Marmion *et al.* 2009). The future climate values were subtracted from the current climate values for each climatic variable (precipitation, minimum temperature and maximum temperature); this was done in order to obtain the value of change for each climatic variable (this we refer to as the climate change value). A climatic change index (CCI) was developed by rescaling the climate change values of each climatic variable to between zero and one. Rescaling was done by dividing the climate change value by the range of climate change values, which we call the range-adjusted climate change value. The range-adjusted climate change values were divided by the minimum of these values, to yield the rescaled climate change value. An average of the rescaled climate change values of the three climatic variables was taken to give a CCI score per weather station. This allowed the identification of areas of greatest and least projected climatic change.

Identifying a subset of weather stations

A subset of 10 weather stations was identified based on the CCI scores. The top five weather stations of greatest (red labels, Figure 6) and least (green labels, Figure 6) projected climatic change were chosen respectively. It was decided that due to the lack of resources for conservation a subset of weather stations needed to be chosen in order to make the proposals in this study feasible.

Biodiversity data

The biodiversity data were obtained from the Mpumalanga Tourism and Parks Agency (MTPA). This is the same dataset that was used to compile the Mpumalanga biodiversity conservation plan (Ferrar & Lötter 2007). It is important to note that the data used in the conservation plan was focussed on assessing only those biodiversity features that were either deemed as important or currently ranked as threatened on the International Union for the Conservation of Natures' (IUCN) Red list. In this study ecological processes (Table 1) were excluded from the analysis, as the study focuses on identifying individual biodiversity features that occur in areas of greatest and least climatic change. A total of 287 biodiversity features were used for the current analysis. This terrestrial biodiversity data, or surrogates for biodiversity features, were captured in a geographical information system (GIS) and allocated to 65000 hexagon planning units spanning the whole province, with each hexagon covering 118 hectares. The feature list was compiled by using the following data sources: the MTPA's threatened species databases, expert biologists, non-governmental organizations for example Highland Crane Working Group, and museum databases. The species list was based on the conservation importance of the species. This generally included all Red Data Listed or threatened taxa for which sufficiently precise locality data were available. Priority was given to local endemics and the MTPA responsibility for protecting these endemics. Not all of the data available are actual known point localities, the database includes modelled distributions, buffered nest sites (i.e. known nesting sites were buffered to accommodate dispersal and vicinity of other close by nesting sites (i.e. one nesting site was assumed to be in the vicinity of other possible nesting sites), buffered know localities and known point localities.

Table 1: Descriptions of the groups of biodiversity features used in this study (Ferrar & Lötter 2007).

Biodiversity features	**Description**	**Extent/Size**
Vegetation types	68 Vegetation types: National vegetation types other than forests (biodiversity surrogates)	68 types: 9 forest, 28 grassland, 31 savanna
Amphibians	Modelled distributions of important species	3 species
Birds	16 threatened species (known, modelled and/or nesting sites – 24 features in total)	Feeding and known sites – 19 species Nesting sites – 7 species
Invertebrates	Buffered known localities and point locations	17 species
Mammals	Modelled distributions, actual distributions and buffered sites	13 species
Plants	Known point localities	187 species

Biodiversity data analysis

The data obtained were used to develop a biodiversity list for each of the selected weather stations. This was done by first determining which planning units occur within five kilometres of the selected weather stations. A five kilometre buffer was chosen based on the assumption that climatic conditions will generally be uniform in this area. The hexagons that occurred within the five kilometre buffer where identified. Their respective biodiversity features were compiled in two tables (Table 2 and 3). It is important to note that if a hexagon was not fully within the five kilometre boundary those biodiversity features associated with it were still incorporated into the biodiversity lists. The analysis was conducted using R ver. 2.14.1 (R development core team 2011) and ArcGIS ver. 10.1 (ESRI inc. 2011).

Those biodiversity features identified in the areas of greatest climatic change were subjected to the pragmatic approach identified in chapter 2, in order to test the suitability of the biodiversity elements identified from this study in the areas of greatest climatic change. Furthermore an example of each group of biodiversity features from the areas of least change were also assessed (Table 4).

Statistical analyses

The data were subjected to the following statistical analyses: 1-Principal component analyses (PCA) and 2-Multidimensional scaling (MDS) ordination plot.

Principal Component Analyses (PCA) plot:

The PCA plot was used to understand the differences in the values of variables that describe the characteristics of the weather stations in terms of the abiotic environment and biodiversity.The variables used in the PCA, included: climatic change index (CCI), percent transformed (perc_trans) refers to the percentage area covered by transformed land within the five km buffer zone around each weather station, percent protected (perc_prot) refers to the percentage area covered by protected areas within the five km buffer zone around each weather station, altitude (alt), irreplaceability (irrep), refers to a value given by the Mpumalanga Biodiversity Conservation Plan, which gives a score of irreplaceability (Ferrar & Lötter 2007), and species richness (spprich), this value is based on the number of species found within the five kilometer buffer zone around each weather station.

Multidimensional scaling (MDS) ordination plot:

The MDS plot was used to show similarity among the weather stations based on biodiversity feature composition within the 5 km buffer. Weather stations that are placed closer together in the plot are more similar in terms of the biodiversity feature composition within the 5 km buffer than those that are placed further apart.

Results

Areas of projected climatic change

Projected future precipitation values are projected to increase in the western region of the province, with a slight projected decrease in the eastern region of the province (Figure 2). When compared to current values one can see that the current low precipitation areas (eastern side of the province) are projected to become drier, whereas the current high precipitation areas (central and western side of the province) are projected to become wetter (Figure 2). Projected future maximum temperature values are projected to increase across the whole of the province, with the greatest increase occurring in the western region of the province (Figure 3). When compared to current values one can see that the current warm areas (eastern side of province) will have less of an increase in maximum temperature values than that of the current cooler areas (western side of the country) (Figure 3). Projected future minimum temperature values are projected to increase across the whole of the province, with the greatest increase occurring in the western region of the province (Figure 4). When compared to current values one can see that the current warm areas (eastern side of province) will have less of an increase in minimum temperature values than that of the current cooler areas (western side of the country) (Figure 4). It is evident that the areas of greatest change are projected to be on the western side of the province, and the areas of least change occur in the eastern side of the province (Figure 2, 3 and 4). Furthermore a clear trend can be observed in that as the altitude increases the projected climatic change increases (Figure 6). However it is also important to note that maximum and minimum temperature values have less variation (smaller standard deviation) among the various GCM’s than precipitation (Figure 2, 3 and 4). Although the variation of the precipitation values is relatively high, a clear trend of the generally colder areas of the province (west of the escarpment) experience the greatest projected climatic change (Figure 6). Those weather stations that represent areas of least change are displayed in green and those representing the areas of greatest change are displayed in red (Figure 5 and 6).

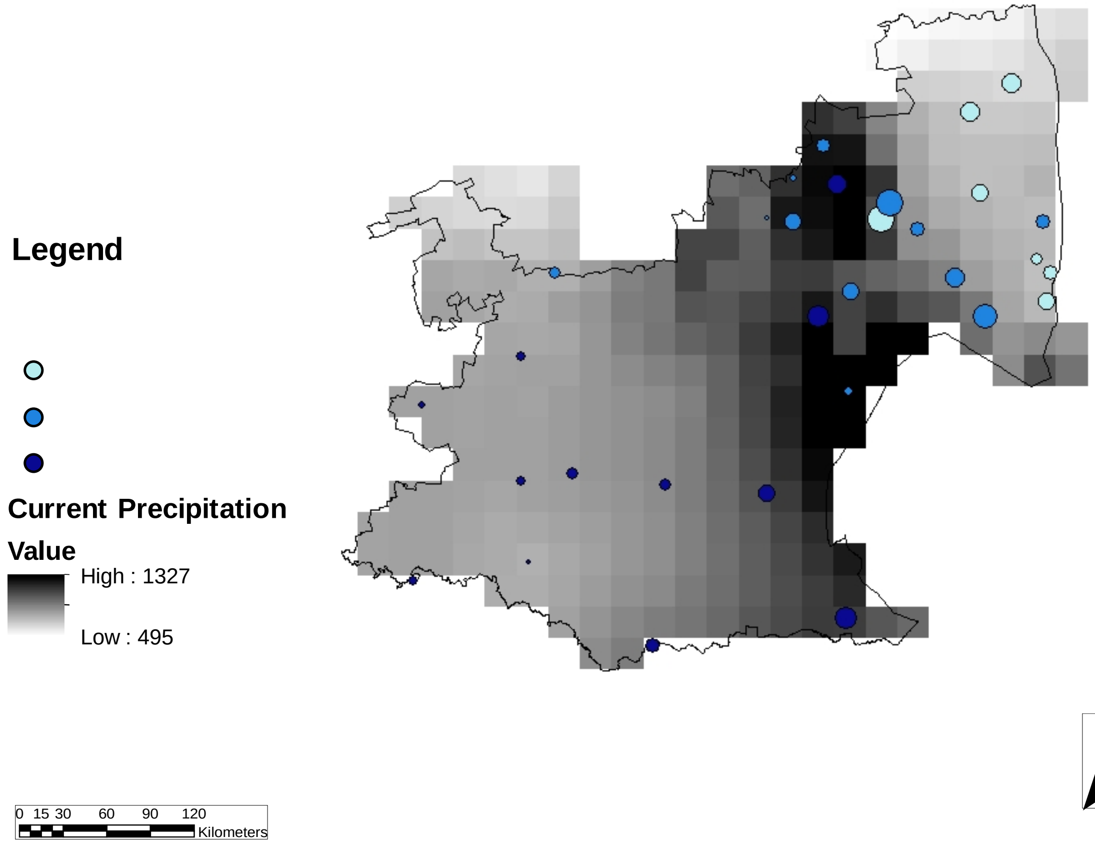

Figure 2: Map showing the projected change in precipitation for 31 weather stations (dots) in relation to that of the current precipitation levels (background) within MP, where the colour of the dots represents the magnitude of change and the size of the dots represent the variation (standard deviation) between the seven GCM's.

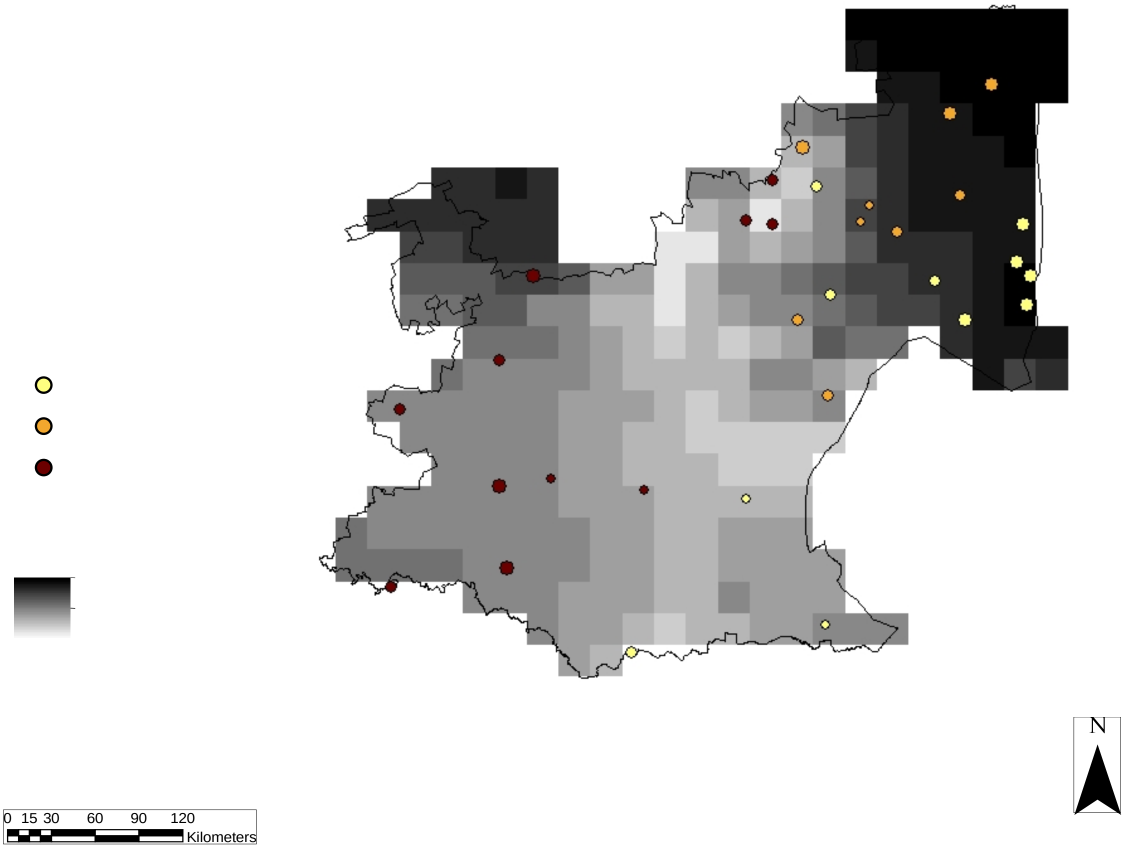

Figure 3: Map showing the projected change in maximum temperature for the month of January for 31 weather stations (dots) in relation to that of the current maximum temperature levels (background) within MP, where the colour of the dots represents the magnitude of change and the size of the dots represent the variation (standard deviation) between the seven GCM’s.

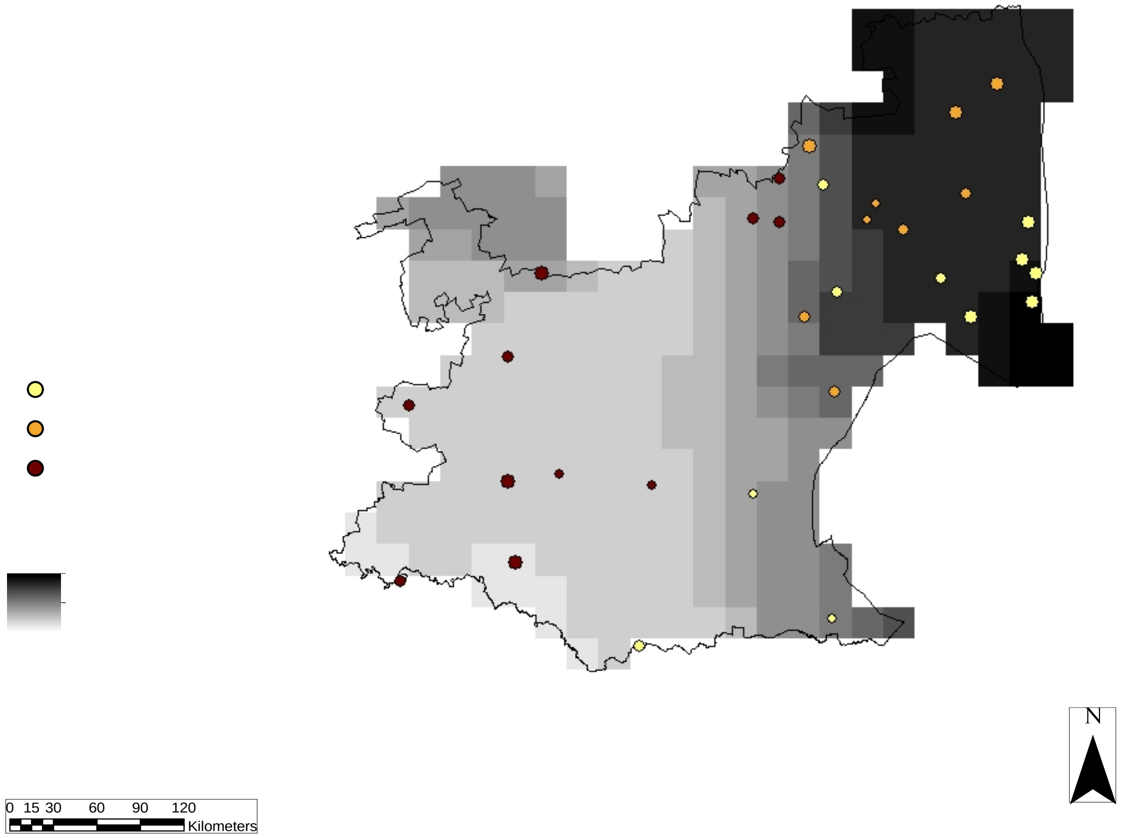

Figure 4: Map showing the projected change in minimum temperature for the month of July for 31 weather stations (dots) in relation to that of the current minimum temperature levels (background) within Mpumalanga, where the colour of the dots represents the magnitude of change and the size of the dots represent the variation (standard deviation) between the seven GCM's.

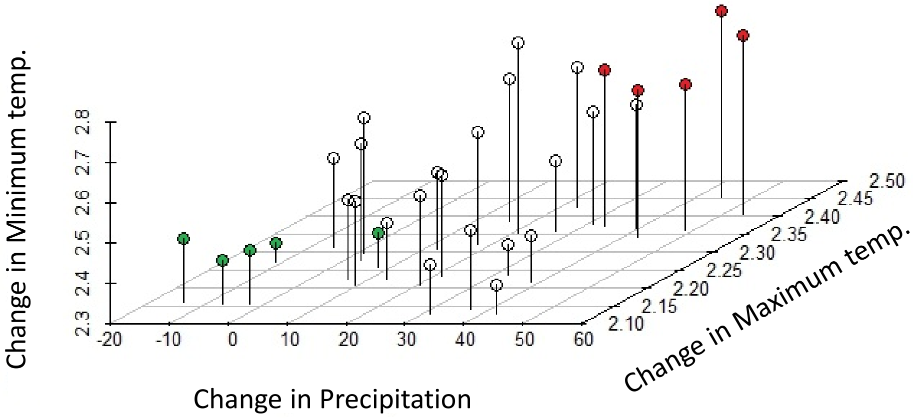

Figure 5: A three-dimensional plot showing the position of each weather station in relation to one another based on the elements (change in Minimum temperature, change in Precipitation and change in Maximum temperature) of the Climatic Change Index (CCI). Bethal, Delmas, Standerton, Villiers and Secunda represent those stations in the areas of greatest change (red dots). Burgershall, Coopersdal, Komatipoort, Pretoriuskop and Tenbosch represent those stations in areas of least change (green dots).

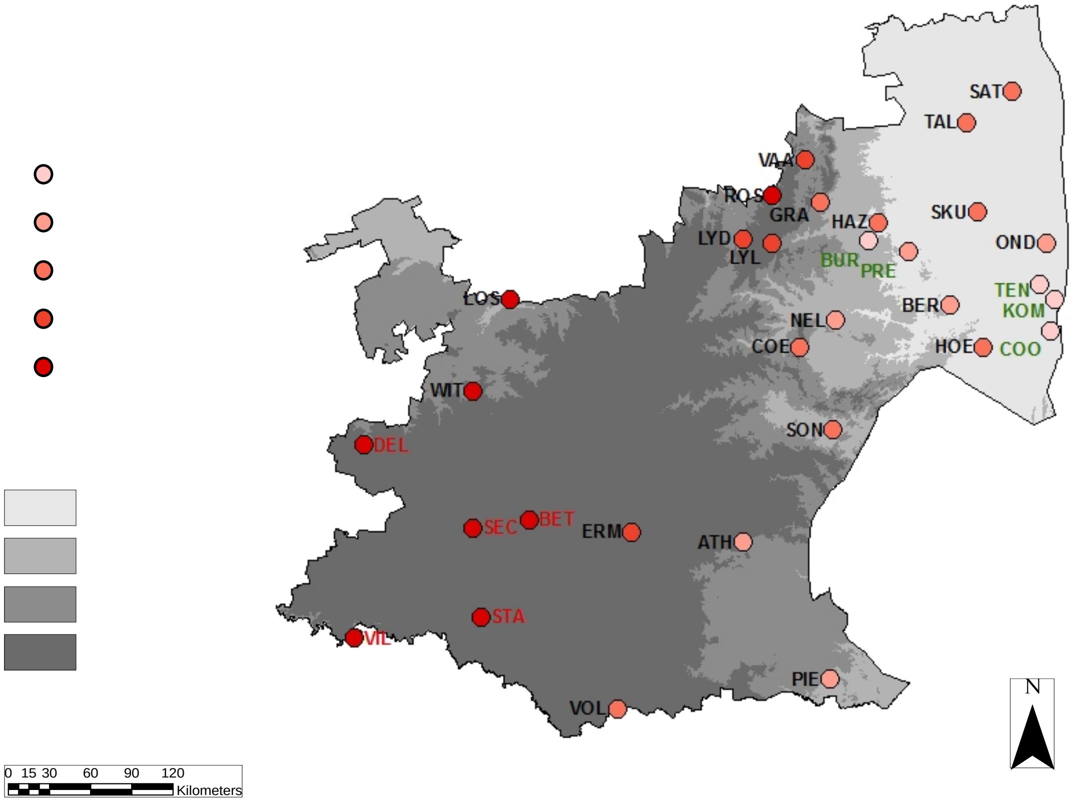

Figure 6: Map showing the climatic change index (CCI) values for each of the 31 weather stations. The colour of the dots represent the magnitude of change, i.e. dark red represents greatest projected change and light pink represents least projected change. Those weather stations that represent the areas of greatest climatic change are labelled in red and the weather stations representing the areas of least change are labelled in green. Weather stations: VIL - Villiers, VOL - Volksrus, PIE - Piet Retief, STA - Standerton, ERM - Ermelo, DEL - Delmas, SEC - Secunda, BET - Bethal, SON - Songimvelo, WIT - Witbank, COE - Coetzeestroom, HOE - Hoechst, COO - Coopersdal, LOS - Loskopdam, LYD - Lydenburg, LYL - Lydenburg Longtom, NEL - Nelspruit, BUR - Burgershall, HAZ - Hazyview, PRE - Pretoriuskop, BER - Berg-en-Dal, TEN - Tenbosch, OND - Onder sabie, KOM - Komatipoort, ROS - Rosenkrans, VAA - Vaalhoek, GRA - Graskop, TAL - Talamati, SKU - Skukuza, SAT – Satara, ATH – Athole.

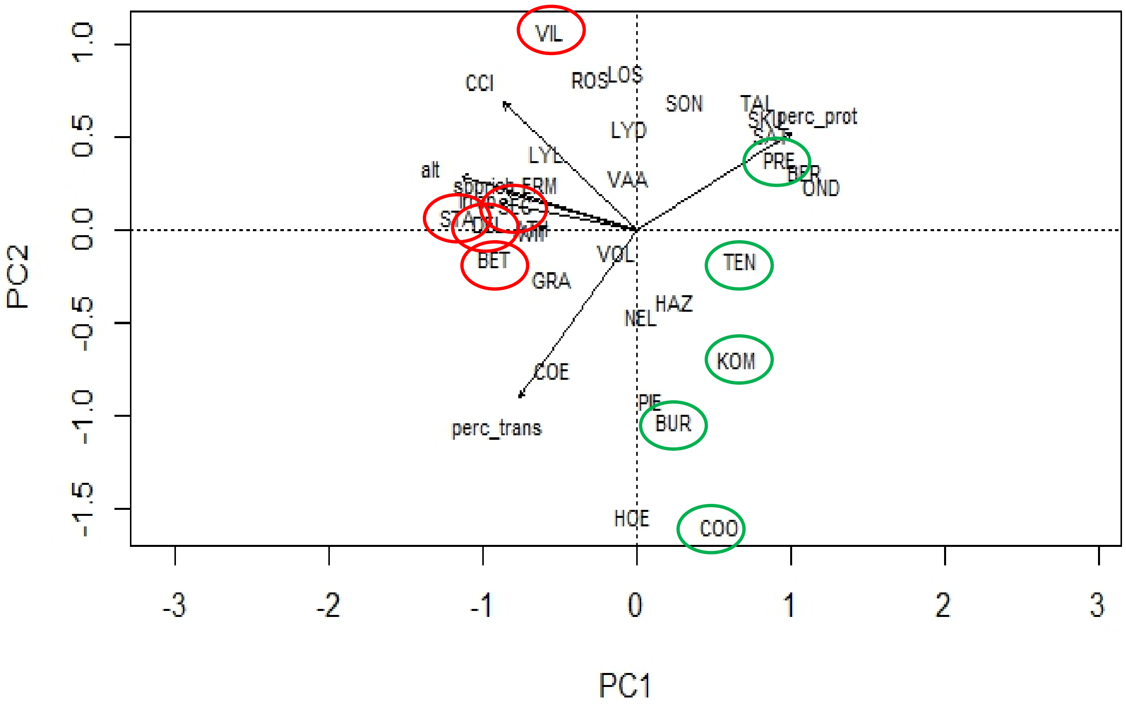

Figure 7: Principal component analysis results, above are the results of analyses done on 31 weather stations. The weather stations representing the areas of least climatic change are highlighted in green (COO = Coopersdal, TEN = Tenbosch, KOM = Komatipoort, PRE = Pretoriuskop, BUR = Burgershall) and those representing the areas of greatest climatic change are highlighted in red (BET = Bethal, STA = Standerton, SEC = Secunda, DEL = Delmas, VIL = Villiers). The arrows represent the variables used in the PCA analysis. The variables used include the following: climatic change index (CCI), percent transformed (perc_trans) refers to the percentage area covered by transformed land within the five km buffer zone around each weather station, percent protected (perc_prot) refers to the percentage area covered by protected areas within the five km buffer zone around each weather station, altitude (alt), irreplaceability (irrep), refers to a value given by the Mpumalanga Biodiversity Conservation Plan (MBCP), which gives a score of irreplaceability (Ferrar & Lötter 2007), and species richness (spprich), this value is based on the number of species found within the five km buffer zone around each weather station.

Biodiversity features

Only twelve biodiversity features were identified in the buffers around the five weather stations representing areas of greatest projected climatic change. These include one amphibian species, six bird species and five vegetation types (Table 2). Whereas in the areas of least projected climatic change 24 biodiversity features where identified, these include two amphibian species, two bird species, four mammal species, four plant species, six reptile species and six vegetation types where identified (Table 3). Only one biodiversity feature was identified at both areas of greatest - and least projected change; the African bullfrog (*Pyxicephalus adspersus*) (Table 2 and 3). Not all of the identified biodiversity features occurred at all five weather stations in the areas of greatest and least projected climatic change respectively (Table 2 and 3). Only two biodiversity features occurred at all five weather stations in the areas of least projected change (least concern) , these included: African bullfrog (*Pyxicephalus adspersus*) and blue korhaan (*Eupodotis caerulescens*) (Table 2). Only two biodiversity features occurred at all five weather stations in areas of greatest change, these included: saddle bill stork (*Ephippiorhynchus senegalensis*) and southern ground hornbill (*Bucorvus leadbeateri*) (Table 3).

Six biodiversity features one of each group identified from areas of least change were assessed by using the pragmatic approach developed in the previous chapter (Chapter 2), in order to assess the suitability of the identified biodiversity elements. These include one amphibian, one bird, one plant, one mammal, one reptile and one vegetation type (Table 4).

Areas of greatest projected change

All 12 of the biodiversity features identified in this study in areas of greatest projected change, passed through the first two filters (Feasibility and Climate change sensitivity) of the pragmatic approach developed in chapter 2, all of which scored high. All 12 of the biodiversity features only fulfilled one of the attributes in the Importance filter (Table 4). Based on this the following biodiversity features were identified as possible ecological indicators: one amphibian: *Pyxicephalus adspersus* (African Bullfrog), six birds: *Anthropoides paradiseus* (Blue crane), *Eupodotis caerulescens* (Blue Korhaan), *Spizocorys fringillaris* (Botha's Lark), *Balearica regulorum* (Blue crowned crane), *Bugeranus carunculatus* (Wattled crane), *Anthus chloris* (Yellowbreasted pipit) and five vegetation types: Eastern Highveld Grassland, Eastern Temperate Freshwater Wetlands, Frankfort Highveld Grassland, Rand Highveld Grassland and Soweto Highveld Grassland.

Areas of least projected change

All six of the biodiversity features identified in this study in the areas of least projected change, passed through the first two filters (feasibility and climate change sensitivity) of the pragmatic approach developed in chapter 2 of this thesis. All of the biodiversity features identified in this study in the areas of least projected change, only fulfilled one of the attributes of the third filter (Importance) with exception of one, Pretoriuskop sour Bushveld, which fulfilled two of the three attributes (Table 4). The following biodiversity features where identified as possible ecological indicators: two amphibians: *Breviceps sopranus* (Whistling rain frog), *Pyxicephalus adspersus* (African bullfrog), two birds: *Ephippiorhynchus senegalensis* (saddle-billed Stork), *Bucorvus leadbeateri* (southern ground hornbill), four mammals: *Amblysomus hottentotus meesteri* (Hottentot golden mole), *Amblysomus robustus* (robust golden mole), *Cloeotis percivali australia* (Percival's trident bat), *Miniopterus natalensis* (natal long-fingered bat), four plants: *Adenium swazicum* (impala lily (modelled)), *Eriosema naviculare* (sand pea), *Hypoxis hemerocallidea* (African wild potato), *Siphonochilus aethiopicus* (wild ginger), six reptiles: *Afroedura haacke* (Haacke's flat gecko), *Aspedilaps scutatus intermedius* (giant horned lizard), *Cordylus giganteus* (giant girdled lizard), *Cordylus warreni barbertonensis* (Barberton girdled lizard), *Cordylus warreni warreni* (Warrens spiny-tail lizard), *Platysaurus wilhelmi* (common flat lizard) and six vegetation types: Delagoa Lowveld, Gabbro Grassy Bushveld, Legogote Sour Bushveld, Northern Lebombo Bushveld, Pretoriuskop Sour Bushveld, Sweet Arid Basalt Lowveld.

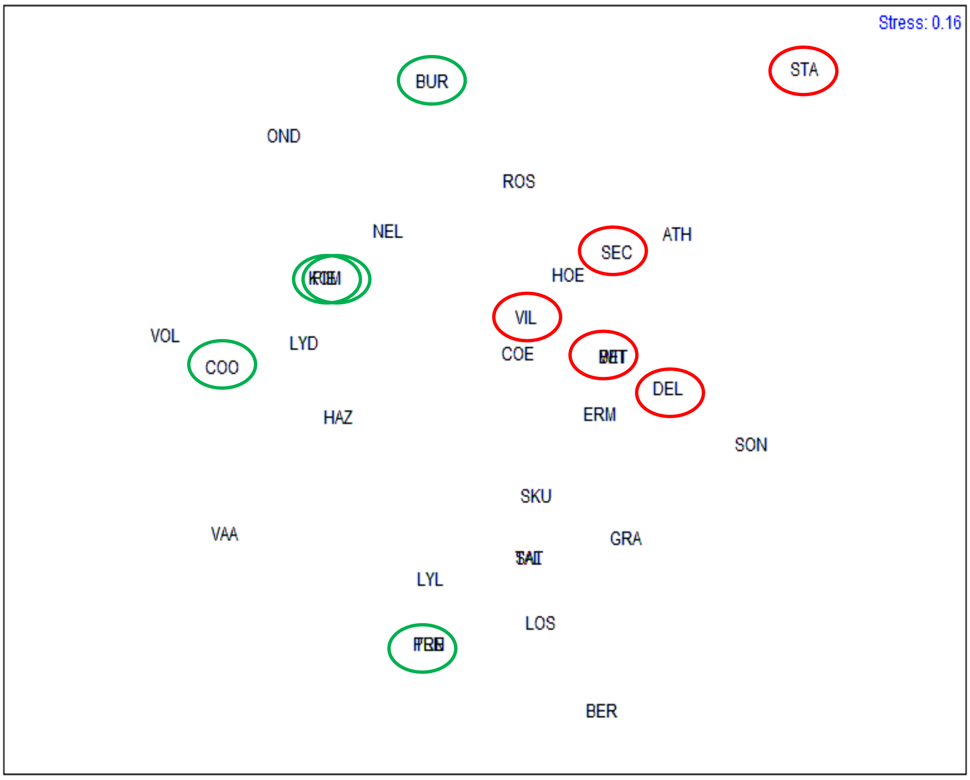

Figure 8: Species ordination plot showing the relatedness of the 31 weather stations with regards to species composition. A presence absence transformation was used to derive the MDS plot. The weather stations representing the areas of least projected climatic change are highlighted in green (COO = Coopersdal, TEN = Tenbosch, KOM = Komatipoort, PRE = Pretoriuskop, BUR = Burgershall) and those representing the areas of greatest projected climatic change are highlighted in red (BET = Bethal, STA = Standerton, SEC = Secunda, DEL = Delmas, VIL = Villiers).

Table 2: Biodiversity features/ecological indicators that occur within a five kilometre buffer around those weather stations that occur in areas of greatest projected climatic change (Figure 5). Where: BET – Bethal, DEL – Delmas, SEC – Secunda, STA – Standerton, VIL – Villiers. Coverage refers to the percentage of a specific biodiversity feature's distribution within Mpumalanga that occurs in the areas of greatest projected climatic change.

		Weather stations					
Scientific name	**Common name**	**BET**	**DEL**	**SEC**	**STA**	**VIL**	**Coverage (%)**
Amphibian							
Pyxicephalus adspersus	African bullfrog	X	X	X	X	X	1.01
Bird							
Anthropoides paradiseus	Blue Crane (foraging)	X		X			0.46
Eupodotis caerulescens	Blue Korhaan (modelled)	X	X	X	X	X	0.80
Spizocorys fringillaris	Botha's Lark	X		X	X	X	1.42
Balearica regulorum	Grey Crowned Crane (foraging)	X	X	X	X		0.54
Bugeranus carunculatus	Wattled Crane (feeding)	X		X			0.38
Anthus chloris	Yellowbreasted pipit (foraging)	X					0.02
Vegetation							
Eastern Highveld Grassland		X	X				2.79
Eastern Temperate Freshwater Wetlands		X	X			X	0.99
Frankfort Highveld Grassland					X	X	2.61
Rand Highveld Grassland			X				1.17
Soweto Highveld Grassland		X		X	X	X	2.58

Table 3: Biodiversity features that occur within a five kilometre buffer around those weather stations occurring in areas of least projected climatic change (Figure 5). Where: BUR – Burgershall, COO – Coopersdal, KOM – Komatipoort, PRE – Pretoriuskop, TEN – Tenbosch. Coverage refers to the percentage of a specific biodiversity feature's distribution within Mpumalanga that occurs in the areas of least change.

		Weather stations					
Scientific name	**Common name**	**BUR**	**COO**	**KOM**	**PRE**	**TEN**	**Coverage (%)**
Amphibian							
Breviceps sopranus	Whistling rain frog		X	X			4.84
Pyxicephalus adspersus	African bullfrog			X		X	0.05
Bird							
Ephippiorhynchus senegalensis	Saddle-billed Stork	X	X	X	X	X	2.22
Bucorvus leadbeateri	Southern Ground Hornbill	X	X	X	X	X	1.20
Mammal							
Amblysomus hottentotus meesteri	Hottentot golden mole	X					0.22
Amblysomus robustus	Robust golden mole				X		3.28
Cloeotis percivali Australia	Percival's Trident Bat			X			84.51
Miniopterus natalensis	Natal Long-Fingered Bat				X		25.58
Plant							
Adenium swazicum	Impala Lily (modelled)		X	X		X	0.70
Eriosema naviculare	Sand pea				X		60

Hypoxis hemerocallidea	African wild potato				X		57.14
Siphonochilus aethiopicus	Wild ginger				X		27.27
Reptile							
Afroedura haacke	Haacke’s Flat Gecko				X		5.94
Aspedilaps scutatus intermedius	Giant Horned Lizard	X	X				0.31
Cordylus giganteus	Giant Girdled Lizard				X		0.12
Cordylus warreni barbertonensis	Barberton Girdled Lizard	X		X			3.17
Cordylus warreni warren	Warrens spiny-tail lizard		X	X			1.22
Platysaurus wilhelmi	Common flat lizard	X		X	X		1.85
Vegetation							
Delagoa Lowveld						X	3.78
Gabbro Grassy Bushveld					X		0.02
Legogote Sour Bushveld		X					2.80
Northern Lebombo Bushveld				X			3.75
Pretoriuskop Sour Bushveld		X			X		15.14
Sweet Arid Basalt Lowveld			X	X		X	5.28

Table 4: Assessment of biodiversity features suitability in areas of greatest and least climatic change, by using the pragmatic approach identified in chapter 2 (Figure 1). The list consists of three categories; A = feasibility (i.e. whether it is viable to use as an indicator from a management and logistic perspective), B = climate change sensitivity (i.e. must be able to give insights into climate change impacts), and C = importance (i.e. whether it is important for the Mpumalanga province). See attribute lists in chapter two for a more comprehensive list of descriptions of each criterion.

	Biodiversity features																	
	Areas of greatest change												**Areas of least change**					
	Pyxicephalus adspersus	*Anthropoides paradiseus*	*Eupodotis caerulescens*	*Spizocorys fringillaris*	*Balearica regulorum*	*Bugeranus carunculatus*	*Anthus chloris*	Eastern Highveld Grassland	Eastern Temperate Freshwater Wetlands	Frankfort Highveld Grassland	Rand Highveld Grassland	Soweto Highveld Grassland	*Breviceps sopranus*	*Bucorvus leadbeateri*	*Amblysomus hottentotus meesteri*	*Siphonochilus aethiopicus*	*Afroedura haacke*	Pretoriuskop Sour Bushveld
A – Feasibility																		
Attributes																		
Easy to find	X	X	X	X	X	X								X	X	X		
Sufficient population size			X										X	X	X	X	X	
Sound taxonomy & easily identified	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Areas where land use change is minimal													X	X	X	X	X	X
Concentrate monitoring in areas of highest projected climate change	X	X	X	X	X	X	X	X	X	X	X	X						
B - Climate change sensitivity																		
Attributes																		
Clearly defined altitudinal range.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
Short lived species.																		

CO_2 sensitive species.																	X
Easily dispersed species.																	
Migratory species.		X					X										
Sex ratio (or breeding success) is temperature dependent.																X	
Habitat specialist.	X						X								X		
Transition zone.								X	X		X						X
Fire dependent ecosystems.								X		X	X	X					
Known climate change response/climate change sensitive ecosystems.								X	X	X	X	X					
High altitude species or ecosystems.							X	X	X	X	X	X					
Range restricted species or ecosystem.				X													X
End of range.														X			
Pronounced seasonal change.		X				X											
C – Importance																	
Attributes																	
Keystone species.																	
Importance for ecosystem services.																	
Endemic to Mpumalanga.																	X
Threatened.	X	X	X	X	X	X	X	X	X	X	X	X	X		X		X

Discussion

The need for and selection of suitable indicators and monitoring sites for the assessment of the effects of anthropogenic influences on biodiversity has been discussed at length (Yoccoz *et al.* 2001, Lepetz *et al.* 2009, Lindenmayer *et al.* 2011). This study outlines a spatial approach to identifying suitable indicators and sites, for monitoring the effects of climate change on biodiversity. Biodiversity data was used alongside several future climate models to select certain biodiversity elements as indicators for the monitoring of climate change impacts (Balmford *et al.* 2005a, Mace *et al.* 2005 and Balmford *et al.* 2005b). Climate models will not only aid conservation managers in selecting future reserves for conservation, but also aid in the selection of where to focus monitoring efforts (Carnaval *et al.* 2009).

The approach outlined in this study explores the use of spatial analyses, to identify possible biodiversity features at various sites within an area of interest, for monitoring the effects of anthropogenic influences. In the case of the Mpumalanga province it can be said that the eastern part of the province is projected to become warmer and drier whereas the western region is said to become warmer and wetter (Figure 2, 3 and 4). Further analyses shows that that the variation between sites (weather stations) found within the areas of greatest projected climatic change and those found in areas of least projected climatic change are largely driven by the following components: percent protected (perc_prot) and percent transformed (perc_trans) (Figure 7). Very little variation occurs amongst the sites in areas of greatest projected climatic change. In contrast there is a marked variation amongst the sites found within the areas of least climatic change, which can be ascribed to the fact that two of the five are found within the boundaries of the Kruger national park (Tenbosch and Komatipoort), which will therefore have the same biodiversity features, whereas the others are outside of the park and might not have been adequately sampled (Figure 8).

Twelve biodiversity features from the 31 weather stations where identified as possible indicators for monitoring in both areas of greatest and least projected climatic change (Table 2 & 3). The suitability of these biodiversity features were assessed by running them through the filters identified in the pragmatic approach (Table 4). A list of suitable indicators are given in the results of this study. Only three biodiversity features were identified in both approaches used in this thesis. These include the following; at the species level of biological organization: *Protea comptonii*, *Gladioulus* (this includes all species within this genus) and at the ecosystem level: forest and grassland (montane and Highveld patch). The poor overlap between the two approaches could be ascribed to the following: limited amount of biodiversity data available for the approach used in this study and the subjective list of candidate biodiversity features identified by expert opinion in chapter 2. The limited amount of biodiversity data can be ascribed to the fact that few protected areas occur in the western regions, thus it can be said that past monitoring efforts are biased towards the regions where most of the protected areas are located (eastern side of the province) (Figure 2) or it may just be that there are few biodiversity features in these regions (areas of least change). Furthermore no plant species were recorded in the areas of greatest change, which is highly unlikely, as this would mean that there were no plant species within the MBCP dataset for this region. This problem could largely be overcome by collating all existing historic data sets within the MTPA. These existing data sets could potentially show an existing trend of the state of biodiversity in the province, in light of the changing climate.

Both the approach outlined in this chapter and the previous chapter (chapter 2), have their respective advantages and disadvantages for informing future monitoring programs. The approach outlined in chapter 2 can be applied to any region and can be used by conservation agencies to inform current or future biodiversity monitoring programs. A disadvantage of this study is that it is sensitive to the group of experts that are available to assist in the identification of the biodiversity features. The advantages of the approach outlined in this chapter include that it can be used to spatially identify suitable indicators, to monitor and in which areas to monitor these indicators. The disadvantages of the approach outlined in this chapter include that it is reliant on the spread of available point climate data (i.e. spread of weather stations) within the area of interest and also larger more detailed biodiversity data sets than were available for the Mpumalanga province (i.e. compiled from widespread long-term recording of biodiversity features in the area of interest). This approach is useful when working at a fine scale where global interpolated climate data is too coarse to draw useful inferences at a provincial scale.

Conclusion

The increasing need for more comprehensive and advanced conservation efforts, in a cost-constrained world has forced conservationists to find a balance between science and management (Heller & Zavaleta 2009). Although there is little doubt that more information can improve management of biodiversity, a more useful and cost effective approach in gathering information is needed. This can be achieved by clearly specifying the objectives of a monitoring program (Yoccoz *et al.* 2001). It is clear that we need more biodiversity monitoring programs for more effective biodiversity conservation not only in Mpumalanga but in the whole of South Africa. For additional monitoring programs to work, a well-conceived, robust and understandable means of conducting the monitoring is needed (Nichols & Williams 2006). The approach outlined in this study will give more insight into the development of climate change monitoring programs. Through informed decision making the projected impacts of climate change on biodiversity could be mitigated.

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Appendix

Table 2: Weather stations that occur in areas of greatest change and the biodiversity features that is associated within the five kilometre buffer. Where Total PU = total area in hectares covered by specific biodiversity feature across all planning units (PU) associated with the specified weather station. Total MP = total area in hectares covered by specific biodiversity feature in the whole of the Mpumalanga (MP) province. Percentage within PU = percentage coverage of specific biodiversity feature, that occurs within the various weather stations planning units.

Biodiversity features per station	Total_PU (ha)	Total_MP (ha)	Percentage within PU (%)
BETHAL			
Pyxicephalus adspersus	6.8	561377.9	0.00121
Wattled Crane (feeding)	3035.5	1179560.1	0.25734
Botha's Lark	3151.5	618821.8	0.50928
Blue Korhaan (modelled)	2621.1	1227941.3	0.21346
Blue Crane (foraging)	3849.7	1530449.6	0.25154
Grey Crowned Crane (foraging)	3847.6	1504265.7	0.25578
Yellowbreasted pipit (foraging)	119.2	698359.2	0.01708
Eastern Highveld Grassland	1919.2	541093.3	0.35468
Eastern Temperate Freshwater Wetlands	68.9	13783.6	0.50045
Soweto Highveld Grassland	1908.5	492692.6	0.38736
DELMAS			
Pyxicephalus adspersus	4069.7	561377.9	0.72494
Blue Korhaan (modelled)	4091.9	1227941.3	0.33324
Grey Crowned Crane (foraging)	60.3	1504265.7	0.00401
Rand Highveld Grassland	3656.1	311688.6	1.17299
Eastern Highveld Grassland	550.7	541093.3	0.10177
Eastern Temperate Freshwater Wetlands	22.4	13783.6	0.16258
SECUNDA			
Pyxicephalus adspersus	717.4	561377.9	0.12780
Wattled Crane (feeding)	1459.7	1179560.1	0.12375
Botha's Lark	2586.3	618821.8	0.41794
Blue Korhaan (modelled)	2777.6	1227941.3	0.22620
Blue Crane (foraging)	3254.8	1530449.6	0.21267
Grey Crowned Crane (foraging)	3955.7	1504265.7	0.26297
Soweto Highveld Grassland	4388.2	492692.6	0.89067
STANDERTON			
Pyxicephalus adspersus	897.6	561377.9	0.15989

Botha's Lark	2332.3	618821.8	0.37689
Blue Korhaan (modelled)	173.4	1227941.3	0.01412
Grey Crowned Crane (foraging)	290.3	1504265.7	0.01930
Frankfort Highveld Grassland	73.5	28421.9	0.25867
Soweto Highveld Grassland	4843.6	492692.6	0.98309
VILLIERS			
Pyxicephalus adspersus	0.6	561377.9	0.00011
Botha's Lark	739.1	618821.8	0.11943
Blue Korhaan (modelled)	107.1	1227941.3	0.00872
Frankfort Highveld Grassland	666.9	28421.9	2.34676
Eastern Temperate Freshwater Wetlands	45.31	13783.6	0.32872
Soweto Highveld Grassland	1559.03	492692.6	0.31643

Table 3: Weather stations that occur in areas of least change and the biodiversity features that is associated within the five kilometre buffer. Where Total PU = total area in hectares **(* with exception of a few features that are represented by a number of observational records rather than a coverage area)** covered by specific biodiversity feature across all planning units (PU) associated with the specified weather station. Total MP = total area in hectares covered by specific biodiversity feature in the whole of the Mpumalanga (MP) province. Percentage within PU = percentage coverage of specific biodiversity feature, that occurs within the various weather stations planning units.

Biodiversity features per station	**Total_PU (ha)**	**Total_MP (ha)**	**Percentage within PU (%)**
BURGERSHALL			
Saddle-billed Stork	4435.8	1467668.9	0.30224
Southern Ground Hornbill	4936.1	2637509.2	0.18715
Amblysomus hottentotus meesteri	15.9	7211.8	0.21992
Aspedilaps scutatus intermedius	247.9	113549.1	0.21832
Cordylus warreni barbertonensis	1957.3	98763.2	1.98184
Platysaurus wilhelmi	1849.2	501468.4	0.36876
Legogote Sour Bushveld	4278.8	152538.5	2.80510
Pretoriuskop Sour Bushveld	868.2	70332.7	1.23444
COOPERSDAL			
Breviceps sopranus	2179.9	50138.1	4.34793
Saddle-billed Stork	4666.7	1467668.9	0.31797
Southern Ground Hornbill	4260.8	2637509.1	0.16155
Adenium swazicum (modelled)	592.1	123227.4	0.48052
Aspedilaps scutatus intermedius	106.1	113549.1	0.09346
Cordylus warreni warreni	204.8	17457.2	1.17343

Sweet Arid Basalt Lowveld	4877.2	252402.4	1.93230
KOMATIPOORT			
Breviceps sopranus	244.6	50138.1	0.48779
Pyxicephalus adspersus	266.6	561377.9	0.04750
Saddle-billed Stork	5608.8	1467668.9	0.38216
Southern Ground Hornbill	4471.9	2637509.2	0.16955
Cloeotis percivali Australias	942.2	1114.9	84.5117
Adenium swazicum (modelled)	6.2	123227.4	0.00500
Cordylus warreni barbertonensis	1169.2	98763.2	1.18380
Cordylus warreni warreni	8.6	17457.2	0.04944
Platysaurus wilhelmi	349.6	501468.4	0.06972
Northern Lebombo Bushveld	3322.2	88642.9	3.74789
Sweet Arid Basalt Lowveld	2479.2	252402.4	0.98222
PRETORIUSKOP			
Saddle-billed Stork	9792.5	1467668.9	0.66721
Southern Ground Hornbill	9792.5	2637509.2	0.37128
Miniopterus natalensis	3187.3	12459.5	25.58155
Amblysomus robustus	3422.2	104343.7	3.27977
Eriosema naviculare	3*	5*	60.00000
Hypoxis hemerocallidea	4*	7*	57.14286
Siphonochilus aethiopicus	6*	22*	27.27273
Cordylus giganteus	70.6	58239.4	0.12124
Platysaurus wilhelmi	7098.2	501468.5	1.41549
Afroedura haackei	1608.2	27089.7	5.93674
Gabbro Grassy Bushveld	11.1	74158.1	0.01502
Pretoriuskop Sour Bushveld	9781.3	70332.7	13.90723
TENBOSCH			
Pyxicephalus adspersus	34.4	561377.9	0.00613
Saddle-billed Stork	8096.1	1467668.9	0.55163
Southern Ground Hornbill	8096.1	2637509.2	0.30696
Adenium swazicum (modelled)	260.1	123227.4	0.21107
Delagoa Lowveld	2339.1	61959.7	3.77522
Sweet Arid Basalt Lowveld	5968.8	252402.4	2.36479

Table 4: Full list of the seven CMIP3 archive GCM's used in this study. Additional information is available on the Coupled Modelled Intercomparison Project (CMIP) website at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php. CMIP3 ID - represents the unique code assigned to each GCM in the CMIP3 database.

Originating groups	**Country**	**CMIP3 ID**
Canadian Centre for Climate Modelling & Analysis	Canada	CGCM 3.1
Météo-France / Centre National de Recherches Météorologiques	France	CNRM-CM3
Max Planck Institute for Meteorology	Germany	ECHM 5
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM 2.1
Institut Pierre Simon Laplace	France	IPSL-CM4
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group.	Germany/Korea	ECHO-G
Max Planck Institute for Meteorology	Germany	ECHAM 5

Chapter 4
General Discussion

Many studies in recent years have investigated the effects of climate change on the future of biodiversity (Bellard *et al.* 2012). Despite this climate change ecology is still in its infancy, however tremendous improvements are made rapidly in virtually all aspects of this emerging field (Bellard *et al.* 2012).

Critical requirements to be able to predict future trends in biodiversity include the need to know where and to what extent climate change is occurring. However due to the large variation in the responses of different species and ecosystem indicators to climate change, there is a need to use and integrate multiple approaches for assessing climate change impact (Dawson *et al.* 2011).

To determine how conservation efforts can be improved and to guide new strategies, it is critical that our progress towards limiting species extinctions, as a result of climate change, is monitored (Pereira & Cooper 2006). Foden and colleagues (2013), developed a framework which can be used to assess the vulnerability of species to climate change based on specific traits of the taxa. This approach coupled with that given in Chapter 2 in this study could be a possible step forward in assessing and refining the suitability of the chosen indicators even further. A review by Balmford *et al.* (2003), suggested that monitoring should be focussed on trends in the abundance and distribution of populations and habitat extent. Scholes and Biggs (2005) proposed the Biodiversity Intactness Index (BII), as a means to assess the progress made towards reducing the rate of biodiversity loss by 2010. They found that in 2000 that across all plant and vertebrate species in southern Africa had declined to 84% of their presumed pre-modern levels. The taxonomic group with the greatest loss was mammals (71%), and the ecosystem type with the greatest loss was grassland (74%) (Scholes & Biggs 2005). Pereira & Cooper (2006) further proposed a global biodiversity monitoring network. Until such time that an adequate global monitoring program is functional and in place, management authorities of respective conservation areas should do what they can to improve monitoring. More recently in a paper by McGeoch *et al.* (2011), a strategic framework for biodiversity monitoring within South Africa's National Parks was proposed. In their study they chose ten biodiversity monitoring programmes (BMP's) that provide broad coverage of higher level biodiversity objectives of parks. Currently underway is the development of a set of principles which will guide the development of the various biodiversity monitoring programs and data management. These BMP's will give direction to future investment in monitoring programmes in South African protected areas (McGeoch *et al.* 2011).

In this thesis two potential methods for monitoring the effects of climate change on biodiversity are presented and tested. This case study is used to evaluate the usefulness of these methods in monitoring the effects of climate change on biodiversity and provide broad guidelines and recommendations for the monitoring of climate change effects in other areas, based on this study. Studies such as the ones outlined above by Scholes and Biggs (2005), McGeoch and colleagues (2011), and the current study, addresses the shortfall in current monitoring programs, in that they provide the necessary tools to inform and develop new monitoring strategies which will aid conservationists in their struggle to mitigate the effects of anthropogenic climate change.

Selecting species and ecosystem indicators for climate change monitoring

The pragmatic approach identified in this study, I feel has resulted in the identification of useful indicators in Mpumalanga for two reasons. Firstly the species indicators cover a broad range of taxa that are likely to be vulnerable to climate related impacts. And, secondly I managed to identify ecosystem level indicators that are representative of the Mpumalanga province. I was also able to carry out this method in a relatively short space of time and in a cost effective manner. For these reasons, the pragmatic approach could be used in other areas that are facing an urgent need for climate change monitoring and lack the resources to sustain large budgets.

However, there are a number of disadvantages with this method. The candidate ecological indicators were identified subjectively by a group of experts at the various workshops, i.e. these experts already had an idea of what a good indicator would be. This study focussed solely on developing an approach to identify indicators at the species and ecosystem level of biological organization, if the approach is used to develop indicators at the genetic level of biological organization, specialist skills and equipment will be needed and might be too costly for conservation agencies.

Using climate and biodiversity data in a spatial approach to identify suitable areas to act as ecological indicators of climate change

The spatial approach used in this study, I feel has resulted in the identification of suitable monitoring sites along with their respective biodiversity features, within Mpumalanga for two reasons. Firstly the identified sites occur in both areas of least and greatest climatic change and secondly they also occur both in and outside of protected areas. These areas were identified by using simple cost effective spatial analyses of the available climate and biodiversity data, which can easily be replicated in other areas.

Advantages and disadvantages of the approaches used in this study

Both approaches identified in this study yielded useful results. The first approach, using a pragmatic method to identify ecological indicators, can be used to identify ecological indicators specifically aimed at monitoring the effects of climate change on biodiversity and is thus most useful in areas or under circumstances in which biodiversity is the primary concern. Approach two however, identifies appropriate ecological indicators based on their geographical position rather than their attributes. Both approaches have their respective strengths and weaknesses and are therefore most effective when used in combination. The first method had the following advantages: it identified several indicators in a cost effective timely manner and outlines a simple workflow that can be used and adapted relatively easily by any conservation organisation. However, the first method had the following disadvantages: it was difficult to develop it for other levels of biological organization, such as at the genetic level, due to a lack of a comprehensive data set. This approach is best suited to be used where there is a need to further develop existing monitoring programs that will assess the effects of anthropogenic climate change on biodiversity.

Method two on the other hand allows the user to make use of existing biodiversity data sets, thus allowing the user to see a trend of the effects of anthropogenic climate change in the region. This approach is best suited, where there are sufficient point climate data and biodiversity data sets available. This method however is largely dependent on the availability and the quality of the point climate data and biodiversity data in the area of interest.

Both these approaches will result in a set of suitable indicators to monitor the effects of anthropogenic influences on biodiversity, but where the one (the first method) is largely focussed on identifying a list of indicators, method two identifies where best to monitor the identified indicators in the area of interest. Both these approaches whether used separately or in tandem allows the user to improve existing monitoring programs or inform new biodiversity monitoring programs.

In this case study the MTPA would also be best suited to adopt a combination of the two approaches. When comparing the lists of the identified biodiversity features of each approach it was found that there were only three overlapping biodiversity features, these include at the species level: *Protea comptonii*, *Gladioulus* (this includes all species within this genus) and at the ecosystem level: forest and grassland (montane and Highveld patch). The poor overlap between the two methods could be ascribed to the biodiversity data set used in method two, where there were very few biodiversity features identified and in some cases there were no plant species identified in certain regions, which are highly unlikely. It could also be that the candidate list of biodiversity features used in the first method was not comprehensive enough.

Comparison of results found in this study with that of two other monitoring and scoring systems

As alluded to earlier a number of other monitoring and scoring systems exist (Balmford *et al.* 2003, Scholes & Biggs 2005, Pereira & Cooper 2006 & McGeoch *et al.* 2011). All of these approaches aim to develop and/or improve biodiversity monitoring strategies. In comparison the approaches outlined in this thesis differ from that of Scholes & Biggs (2005) and McGeoch *et al.* (2011), in that this thesis aims to provide specific information on how to improve or develop monitoring strategies aimed at assessing the state of biodiversity based on the impacts of climate change. Whereas Scholes & Biggs (2005) provide an index which gives the average richness- and area-weighted impact of a set of activities on the population of a given group of organisms in a specific area. McGeogh *et al.* (2011), aims to provide a strategic framework which will inform future monitoring strategies within the South African national parks (SANParks). More specifically it is aimed at: 1 – assessing and improving the efficiency and effectiveness of conservation action, 2 – informing management action and policy at both local and national levels, 3 – providing evidence of conservation success and 4 – strengthening the case for conservation among policy makers. In short the framework presented represents part of the scoping and design phase of a monitoring system for SANParks.

The pragmatic approach outlined in this thesis differs from these in that it specifically aims to inform and aid in the development of monitoring strategies that assess the state of biodiversity based on the impacts of climate change.

Recommendations for the selection of methods of identifying indicators

I recommend that a combination of both approaches will be most useful in informing future and current monitoring programs. Therefore in order to be certain that one will observe biodiversity changes in response to a shift in climate, monitoring efforts should be focussed in the areas where projected climatic changes will be greatest, it is also important to note that monitoring should not be restricted to these areas, as these are only projected changes and should be taken as such. Therefore it is also necessary to monitor in areas of least projected climatic change, in order to have a holistic picture of how biodiversity responds to climatic changes.

Recommendations for the MTPA

Though this study focused on an assessment of methods for identifying indicators to assess the effects of climate change on biodiversity, in this instance they have also applied them to one specific example – the Mpumalanga province of South Africa. Based on this study it is recommended that monitoring efforts should be focused in both areas of least and greatest projected climate change. By focussing monitoring efforts in these areas and on their associated biodiversity features (Table 2 & 3), one will get a better understanding of the effects of the impacts brought about by anthropogenic climate change within the Mpumalanga Province. These sites were recommended based on the needs of the MTPA, to have an all-encompassing monitoring strategy for the effects of climate change on biodiversity. The number of sites to be monitored is deemed as feasible as resources for conservation are scarce, thus the majority of the sites (3/5) occur within protected areas. Furthermore these sites represent both areas of greatest and least climatic change and cover a broad range of taxa (these include: amphibians, birds, mammals, plants, reptiles and vegetation types).

It is recommended that the Mpumalanga Tourism and Parks Agency (MTPA) consider adopting a combination of both approaches outlined in this study, in order to not necessarily develop new monitoring programs but to further develop and improve the monitoring programs already in place in the MTPA. The pragmatic approach will allow the MTPA to further identify more ecological indicators if needed, which will specifically be used to monitor the impacts of anthropogenic climate change on biodiversity. The further development of ecological indicators will allow the MTPA to add another tier to the existing monitoring programs. Both approaches can be strengthened by collating and curating biodiversity data within the MTPA. By doing this the MTPA will have a baseline from which they can assess the changes that have already taken place within the province. In order to fully understand the responses of biodiversity to anthropogenic influences such as recent climatic change, the indicators should be rigorously tested in order to adequately understand how they will respond to rapid climatic change. The latter of which can be done by working in conjunction with external partners.

Conclusion

There are problems with applying a strict set of methods for the identification and selection of ecological indicators, such as those outlined in this study. First, the primary advantage of using ecological indicators is to provide a cost- and time-effective route to mitigating the effects of anthropogenic climate change (Botkin *et al.* 2010) and many methods are exhaustive and time consuming, quickly surpassing the point of diminishing returns. Second, given that many conservation managers faced with conservation concerns are also tightly constrained by small budgets, expensive monitoring methods are generally prohibited by cost.

The selection and testing of biota as indicators remains difficult, difficulties in establishing operational indicators of biodiversity stem from three main sources: these include: 1 – the data are not fit for purpose i.e. both historical data and newly collected data needs to be fit to answer the specific objectives of monitoring programs, 2 – a loss of information occurs when a complex and multidimensional concept is reduced to a one dimensional indicator, and 3 – we have a very rudimentary understanding of the causal links between biodiversity and ecosystem functioning (Flather *et al*. 1997, Scholes & Biggs 2005).

There are few cases where ecologists can provide decision-makers with ecological indicators that have gone through a series of tests, to fully understand its suitability as an indicator, as tools for conservation assessment and planning (McGeoch, 1998). To avoid the indefinite continuation of this dilemma we should not allow the urgency of conservation crises to dishearten or blind us to the importance of medium- to long-term research investments and a rigorous research approach to support (or refute) the utility and application of ecological indicators in the fight against anthropogenic climate change.

Future work should include the following: data should be collected with the purpose in mind, i.e. we need to collect fit for purpose data. In order to make sound management decisions we need the correct information. Using biota as indicators is still in its infancy, once indicators have been identified through theoretical approaches such as the ones outlined in chapter 2, they should be subjected to thorough tests in order to ensure their effectiveness in assessing the state of biodiversity.

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