

Assessing the vulnerability of South Africa's national protected areas to climate change
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Abstract

Protected areas should be reviewed under expected future climate conditions so that conservation and expansion strategies can be developed appropriately. An assessment of the vulnerability of protected areas to climate change is a necessary step in developing such strategies. Indeed, a vulnerability assessment is an important step in developing adaptation strategies for conservation. This is important as substantial climate change has already been experienced at a park level in South Africa. The aim of this study was to develop a method for assessing the relative vulnerability of protected areas to climate change and to apply this to South Africa's 19 national parks. The method includes identifying and quantifying potential impacts of climate change on each focal protected area, carried out by developing and/or using projections for species, ecosystems, infrastructure, tourism and neighbouring communities. Potential impacts were combined with measures of each park's adaptive capacity to develop an overall park vulnerability score. This study has taken vulnerability assessment at a protected area level further than has been attempted before by assessing not only the biophysical but also the socioeconomic impacts of climate change on a protected area, quantifying the potential changes (potential impacts) and developing a relative index. The results indicate that climate change has the potential to contribute significantly to the threats faced by South Africa's national parks. Apart from a potentially devastating impact on species and ecosystems, the effects on tourism demand, community relations and infrastructure are of concern. Not surprisingly, the most vulnerable parks are largely coastal, where tourist infrastructure is at risk of both flooding and sea-level rise, and there are higher population densities. Furthermore, coastal ecosystems are expected to transform significantly which will have consequences for range-restricted species. Management strategies need to take heed of the magnitude of potential impacts identified in this study and work towards developing adaptation pathways.

Contents

Abstract	iii
Introduction.....	1
Aim and objectives.....	4
Literature review	5
Vulnerability assessments at a protected area level	5
Potential impacts on the biophysical and socioeconomic aspects of protected areas	7
Species.....	7
Ecosystems	8
Infrastructure.....	8
Neighbouring communities	9
Tourism.....	10
Adaptive capacity.....	11
Indicator approach to vulnerability assessments	11
Methods	13
Study area.....	13
Data analysis.....	13
Climate data and projections.....	14
Indicators developed.....	19
Potential impacts	19
Adaptive capacity.....	25
Results	27
Potential impacts	27
Species.....	27
Ecosystems	28
Infrastructure.....	30
Neighbouring communities	31
Tourism.....	31
Adaptive capacity.....	36
Vulnerability index	37
Discussion.....	42
Acknowledgements	45
References.....	46

Introduction

Protected areas should be reviewed under expected future climate conditions so that conservation and expansion strategies can be developed appropriately (Hannah *et al.* 2002; Hansen *et al.* 2010; Araujo *et al.* 2011). An assessment of the vulnerability of protected areas to climate change is a necessary step in developing such strategies. Indeed, a vulnerability assessment is an important step in developing adaptation strategies for conservation (Glick *et al.* 2011; Figure 1). The following two quotes further highlight the importance of assessing the vulnerability of protected areas to climate change.

“We cannot fulfill our duties as stewards of the Earth’s last natural ecosystems if we plan and manage for a world that no longer exists.” IUCN

“The placement and management of reserves and protected areas will need to take into account potential climate change if the reserve systems are to continue to achieve their full potential.” IPCC



Figure 1. The steps for developing climate change adaptation strategies. Source: Glick *et al.* 2011.

Vulnerability to climate change, as defined by the IPCC, is a function of a system’s exposure and sensitivity to climate hazards and its capacity to adapt to their adverse effects (IPCC 2007). Early studies focused on potential impacts and considered only the exposure and sensitivity of a system to climate change (Füssel and Klein 2006). This then progressed to undertaking vulnerability assessments, by including the adaptive capacity of the system (Figure 2).

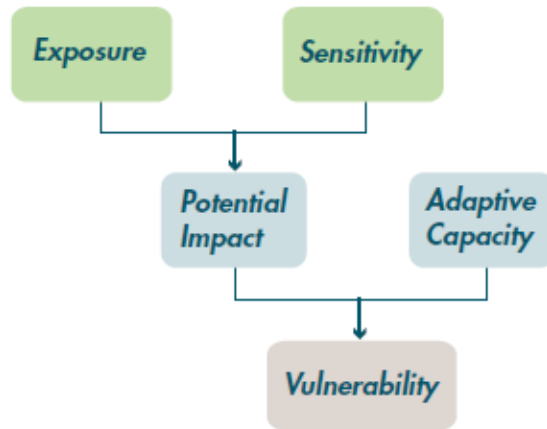


Figure 2. The components of vulnerability. Source: Glick *et al.* 2011.

The potential impact on protected areas is defined in this paper as any potential climate change-related impact that hampers a protected area's ability to meet its conservation mandate. Climate change will have a profound impact on species and ecosystems globally (IPCC 2001) but the vulnerability of a protected area to climate change is generally understood to be a function of both biophysical and socioeconomic factors (O'Brien *et al.* 2004). The potential impact on a protected area is therefore a function of the direct impact on biodiversity as a result of the climate impact on species and ecosystems, as well as the indirect impact on the functioning of the protected area as a result of the climate impact on infrastructure, neighbouring communities and tourism. The adaptive capacity of a protected area acts to suppress the potential impacts and thereby supports a protected area to meet its conservation mandate.

The threat of biodiversity loss as a result of climate change is expected to become more severe as global warming accelerates (Willis *et al.* 2015). Most predictions indicate that species' distributions will change and that more species will become threatened with extinction (Midgley *et al.* 2002). Much work has been done on assessing the impact of climate change on biodiversity (Williams and Jackson 2007; Dawson *et al.* 2011; Foden *et al.* 2013; Moritz and Agudo 2013; Scheffers *et al.* 2016) as well as the impact of climate change on the tourism sector (de Freitas 2003; Kajan and Saarinen 2013; Markham *et al.* 2016), the susceptibility of infrastructure to climate hazards (Nicholls 2014; Markham *et al.* 2016; Davis-Reddy and Vincent 2017), and the impact of climate change on communities (Lemieux *et al.* 2010; Belle 2016). Adaptive capacity at the protected area-level, although not explicitly defined in prior studies, includes financial capacity (budget), technology, education, information, skills, access to resources, and management capabilities (O'Brien *et al.* 2004). There have, however, been few attempts to assess the vulnerability of a protected area where all these potential impacts, as well as adaptive capacity, have been considered and quantified.

In South Africa, substantial climate change and related impacts are predicted. A study by van Wilgen *et al.* (2016) on the change in climate experienced at the protected area-level in South Africa over the past few decades indicates significant temperature increases have already been experienced in most parks.

Furthermore, the observed temperature changes over the last 20 - 50 years have, in several instances, already reached those predicted for near future scenarios. It is clear from the study that substantial climate change has already been experienced at a park level in South Africa (Figure 3).

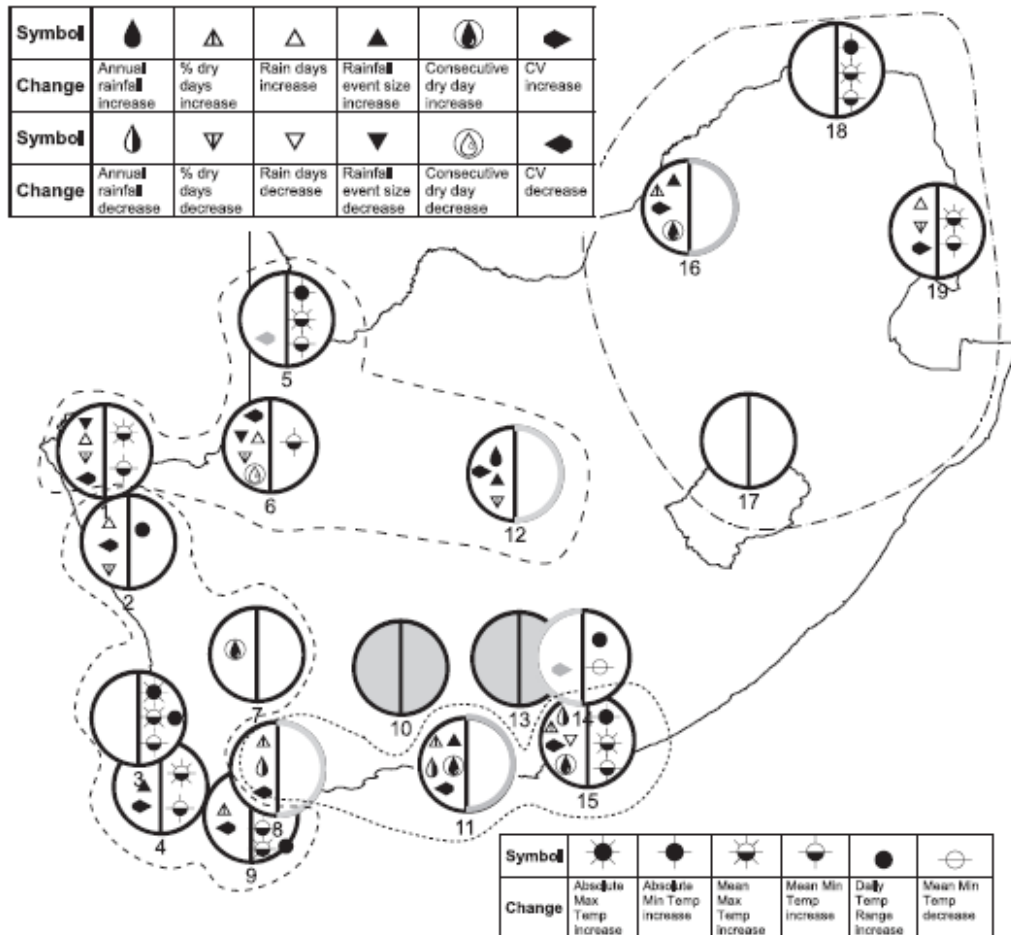


Figure 3. Spatial distribution of significant annual trends in rainfall (left of circles) and temperature (right of circles) related variables for available data up until 2009. Park names are as follows: 1, Richtersveld; 2, Namaqua; 3, West Coast; 4, Table Mountain; 5, Kalahari Gemsbok; 6, Augrabies Falls; 7, Tankwa Karoo; 8, Bontebok; 9, Agulhas; 10, Karoo; 11, Garden Route; 12, Mokala; 13, Camdeboo; 14, Mountain Zebra; 15, Addo Elephant; 16, Marakele; 17, Golden Gate Highlands; 18, Mapungubwe; 19, Kruger. Grey-shaded parks had less than 30 years of rainfall or 20 years of temperature data available. Parks with no associated symbols demonstrated no significant annual trends over the available time period. The four major rainfall regions identified using correspondence analyses are depicted by dotted lines. Source: van Wilgen et al. 2016.

Aim and objectives

The aim of this study was to develop a method for assessing the relative vulnerability of protected areas to climate change and to apply this to South Africa's 19 national parks, with the intention of informing South African National Parks (SANParks)'s climate change strategy, by:

1. Developing a model for assessing the vulnerability of protected areas to climate change;
2. Applying this model to South Africa's 19 national parks; and
3. Interpreting the results for use in adaptation planning.

This study expands on the existing vulnerability assessment literature by developing a quantitative index of the likely severity of climate change impacts on protected areas as well as the capacity of protected area management to mitigate these threats. Furthermore, the study adds to the literature on the potential impacts of climate change on protected areas by considering not only the impact of climate change on the biodiversity conserved but also the climate impact on the functioning of a protected area by considering the socioeconomic factors that affect the ability of protected areas to meet their conservation mandates.

Literature review

Vulnerability assessment literature over the past decade has been concerned with the evaluation of which individual, community, region, species or nation is more vulnerable to climate change. Although the IPCC has endorsed the current vulnerability framework, vulnerability studies are still a developing field of research. In fact, the conceptual framework is still fragmented and subject to different terminology (Vincent 2004). This study uses the following vulnerability definitions:

Vulnerability (V) is a function of:

- Exposure (E). Exposure is the degree to which a system is experiencing changes such as precipitation and temperature changes, the magnitude and frequency of extreme events, sea-level rise, increased risk of fires, etc.
- Sensitivity (S). Sensitivity is the degree to which a system will be affected by climate hazards. Not all systems exposed to climate change will be affected the same way and therefore each system will have its own sensitivity to climate change.
- Adaptive capacity (AC). Adaptive capacity is the potential or capability of a system to adjust to climate change so as to moderate potential damages, to take advantage of opportunities, or to cope with consequences (Smit and Pilifosova, 2001). Each system will have its own capacity to adapt based on a number of factors pertaining to the type and functioning of the system (O'Brien *et al.* 2004).

As an equation, it can be expressed as:

$$V = f(E, S, AC) \quad \text{or} \quad V = (E * S) / AC$$

Equation 1. The vulnerability equation.

An overall vulnerability index can be useful when trying to identify which particular system is most vulnerable to climate change so that resources can be allocated accordingly (Eakin and Luers 2006; Füssel and Klein 2006; Glick *et al.* 2011). In developing a vulnerability index, protected areas can be ranked according to their vulnerability scores thereby indicating which protected areas are most in need of resources to implement adaptation strategies. Furthermore, a vulnerability assessment can help identify the key vulnerabilities for a particular system. For example, it will help identify what is making a system sensitive to climate change or what is contributing to a system's capacity to adapt. This information can assist with identifying priority areas for adaptation (Füssel and Klein 2006). Apart from the benefits of prioritising resource allocation and identifying priority areas for action, vulnerability assessments can also assist in raising awareness about climate change.

Vulnerability assessments at a protected area level

Very few vulnerability assessments have been applied to protected areas (Table 1), despite the need for information by management agencies on what potential climate change impacts to expect, as well as how to increase their capacity to adapt.

Table 1. Summary of climate change vulnerability assessments on protected areas, globally.

Author	Year	Protected area type	Scale	Methods	Potential impacts assessed	Adaptive capacity included	Quantified	Index
Australian National University	2009	World Heritage Sites	Australia	Qualitative, expert-led	Species, ecosystems and cultural values such as rock art	Yes, but the score was based on the level of threat and not on the capacity of the system to adapt	No	No
Dunlop and Brown	2008	National parks, botanic gardens and marine protected areas	Australia	Qualitative, expert-led	Species, ecosystems, infrastructure, tourism and cultural and recreational values	No	No	No
Hansen <i>et al.</i>	2014	National parks	United States	Climate envelope models	Ecosystems (a shift in biome type)	No	Yes	No
IUCN	2012	World Heritage Sites	Global	Climate envelope models	Ecosystems (change in capacity for plant species richness)	No	Yes	Yes
Lemieux <i>et al.</i>	2010	All	Canada	Literature review and survey	Species, ecosystems and tourism	Yes, the survey was used to gauge the level of climate change understanding among management agencies	No	No
Belle <i>et al.</i>	2016	All	West Africa	Species distribution models and traits-based vulnerability assessments	Species	No	Yes	No
Perry	2011	World Heritage Sites	Global	Spatial analysis	Exposure only	No	No	Yes
Saunders <i>et al.</i>	2009	National parks	United States	Species distribution models	Species, ecosystems, tourism and cultural values	No	No	No
Scott and Suffling	2000	National parks	Canada	Literature review	Species, ecosystems and tourism	No	No	No

Most studies, apart from the two global World Heritage Site studies and the regional West Africa study, have assessed the vulnerability of a country's protected area network to climate change. These studies have been commissioned to identify the potential threats to a protected area and a protected area network, with the intention of developing strategies to increase the resilience of PAs to climate change so that park managers can plan for adaptation. The majority of studies have been literature reviews of impact assessments on species and ecosystems or expert-led studies that have focused on the identification of biophysical impacts at the protected area-level. A few studies have mentioned the impact of climate change on tourism demand, where the focus has been on the temperature impact on tourist's comfort levels. In all but three studies, no quantification of potential impacts has been computed and where they have, they have focused on the biophysical impacts only. Only the two global World Heritage Site studies have developed a relative index for the ranking of protected areas according to their level of vulnerability.

Apart from the two global studies mentioned above, these assessments, although useful in raising awareness about the vulnerability of protected areas as well as what the potential impacts may be, do not provide a relative measure of vulnerability for the protected area system that would allow protected area management to allocate resources more efficiently. Furthermore, there have been few attempts at quantifying the potential impacts on a protected area that would allow park management to assess the severity of climate change impacts and to prioritise interventions.

Potential impacts on the biophysical and socioeconomic aspects of protected areas

Expanding on the current methods for assessing protected area vulnerability, this study identified the following five categories of potential impacts for consideration: species, ecosystems, infrastructure, neighbouring communities and tourism. The way in which climate change is expected to impact these five biophysical and socioeconomic categories, as well as adaptive capacity, is described below. The current methods for quantifying these impacts are also discussed.

Species

Climate change is predicted to become a major threat to biodiversity in the 21st century, impacting individual species through to ecosystem functioning (Williams and Jackson 2007; Dawson *et al.* 2011; Foden *et al.* 2013; Moritz and Agudo 2013; Scheffers *et al.* 2016).

The most commonly used approach for predicting the impact of climate change on biodiversity is to use climate niche species distribution models to predict species range changes (Dawson *et al.* 2011). Species occurrence and climate data are used to model how species have responded to a changing climate in the past by shifting their distribution and range (Kearney and Porter 2009). The model then extrapolates the results to accommodate future climate scenarios (Hijmans and Graham 2006). This methodology is only useful in predicting range changes where the expected climate change is comparable to what has been experienced in the past. This becomes important when we consider that between 4 and 39% of the world's landmass will exhibit novel climates, where no past or present comparison can be made (Williams and Jackson 2007). A further limitation of the climate niche modeling approach is that it does not consider range-limiting factors other than climate, such as biological traits (Willis *et al.* 2015).

To address limitations of the climate niche modeling approach, the IUCN (International Union for Conservation of Nature) developed a traits-based vulnerability assessment for individual species that relies on species' biological traits (Pacifi *et al.* 2015). Where the species distribution models are concerned with exposure, the IUCN approach looks at the biological traits that increase sensitivity and decrease adaptive capacity. Species vulnerability is measured by weighting exposure, sensitivity, and adaptive capacity scores (Foden *et al.* 2013). The IUCN conducted a global assessment on birds, amphibians, and coral species where species were classified in terms of the magnitude of their vulnerability: (1) highly vulnerable (exposed, sensitive and low adaptive capacity); (2) potential adapters (exposed and sensitive but high capacity to adapt); (3) potential persisters (exposed and low adaptive capacity but not sensitive); and (4) high latent risk (sensitive and low adaptive capacity but not exposed).

Ecosystems

There are two widely-used methods for modelling the response of ecosystems to climate change. The first is the correlative climate envelope model which is similar to the climate niche species distribution model in that each biome has a characteristic 'climate envelope' or range and pattern of temperature and rainfall values within which it occurs and by projecting future temperature and rainfall, the climate suitable area can be mapped for each biome (Driver *et al.* 2012). This provides the biome refugia, the area that supports that specific biome given the change in future climatic variables.

The second is the dynamic global vegetation model which, unlike the correlative models which model vegetation based only on temperature and rainfall variables, are dynamic in that processes important for plant functioning are simulated, such as elevated CO₂ levels. DGVMs simulate the distribution and functioning of groups of species with similar ecological and physiological behaviour and the interactions among them. The rates at which processes fundamental to plant functioning occur are simulated, allowing rates of change to be evaluated (Moncrieff *et al.* 2015). This is a significant advance on correlative models as the dominant biome during periods of intermediate rainfall can more easily be modelled. This is important for South Africa where drivers of observed vegetation change point to elevated CO₂ levels as a central factor (Wigley *et al.* 2010). A limitation of dynamic global vegetation models is that while projections of change are available for biomes dominated by forest trees, savanna trees and grasses, the models are weak on some of South Africa's most vulnerable biomes, such as the Fynbos and thicket biomes, as well as the succulent Karoo (Moncrieff *et al.* 2015).

Infrastructure

Climate change is predicted to have a negative impact on infrastructure as a result of damage caused by more extreme weather events, sea-level rise and increased incidence of fires (Nicholls 2014; Markham *et al.* 2016; Davis-Reddy and Vincent 2017). Since 2000, parks in South Africa, especially the Kruger National Park, have been affected by flooding which have led to a loss of tourism revenue as well as the replacement and repair of damaged infrastructure (Biggs *et al.* 2014).

The infrastructure risk associated with flooding and sea-level rise is well documented (Davis-Reddy and Vincent 2017) but the risk associated with fire is less so. van Wilgen *et al.* (2017) argue that the impact of climate change on fire frequency is too complex to quantify and there is no evidence for a trend in

increased fire frequency owing to climate change. In fact globally, burned area has declined about 17% in the last 20 years, despite higher temperatures and more extreme weather (Andela *et al.* 2017).

Neighbouring communities

Local communities living in and around parks are heavily dependent on the surrounding ecosystems, and are becoming increasingly affected by climate change (Lemieux *et al.* 2010; Belle 2016). The ability of parks to meet their conservation mandate may be jeopardized by demands for access to resources in them by neighbouring communities (van Wilgen and McGeoch 2015).

Harvesting of wild foods, medicines, firewood and raw materials for subsistence use and sustaining livelihoods is practiced by millions of South Africans (Shackleton *et al.* 2001; Shackleton and Shackleton 2004; Lannas and Turpie 2009; Peterson *et al.* 2012), especially where economic opportunities are limited (Dovie *et al.* 2006). Poorer households and higher population density have been shown to contribute to an increased reliance on protected areas for sustaining livelihoods (Guerbois and Fritz 2017) and South Africa's national parks provide access to a rich and diverse number of harvestable species for neighbouring communities, either legally or illegally (van Wilgen and McGeoch 2015). Because the poor are typically disproportionately affected by the negative impacts of climate change as they are more dependent on climate-sensitive sectors and they have less capacity to adapt (Turpie and Visser 2013), during periods of adverse weather, reliance on protected area resources increase (Advani 2014). The illegal harvesting of park resources gives rise to conflict between park management and neighbouring communities (Andrade and Rhodes 2012; Ayivor *et al.* 2013; Baker *et al.* 2013).

Increased conflict as a result of climate change is however driven by two factors: the increased harvesting and poaching of natural resources from within park boundaries (including marine resources from no-take zones) as a result of adverse weather events as discussed above, as well as an increase in predation by park predators on community livestock. Predator's range distributions are likely to change as a result of climate change which has the potential to force predators outside of park boundaries and into community land where livestock may be preyed on.

There are many studies that link predation to climate, however, there is no consensus on the direction of change in predation levels with respect to rainfall. In some areas periods of low rainfall result in increased predation while in other areas periods of above-normal rainfall result in increased predation. Bailey and Conradie (2013) found a statistically significant negative relationship between lagged rainfall and predation levels lending support to the theory of *low* rainfall years leading to *greater* predation in subsequent years. This could be a result of higher predator build-up during low rainfall years when the pickings are easy as prey are forced to find food and water in localised areas. Similarly, Natrass *et al.* (2017) argue that that *low* rainfall leads to greater livestock loss from jackal predation but reasons that this is because livestock have to walk further each day to reach grazing after farmers were forced to kraal their livestock as a result of persistent predation. Sacks and Neale (2007) however suggest that a *high* rainfall year leads to more prey build-up which leads to greater predator density and therefore *greater* predation the following year. Patterson *et al.* (2004) found that lions in particular are more likely to attack livestock after rains as these allow for prey dispersal. It can be argued therefore that the link is area- and species-specific. Further studies should aim to obtain monthly historic predation

numbers for each park, making it possible to run a regression of rainfall and temperature climate variables on predation levels.

Tourism

Climate change is also predicted to impact the tourism industry in several ways:

- By affecting the distribution of disease carrying vectors such as the malaria transmitting mosquito (Markham *et al.* 2016). Malaria risk acts as a deterrent to tourism demand as it affects the destination decision of travellers (Naude and Saayman 2005; Rossello *et al.* 2017). The spatial limits of malaria and other diseases are sensitive to climate factors and are predicted to expand their ranges under a warming world (Rogers and Randolph 2000; De Souza *et al.* 2012; Caminade *et al.* 2014).
- By increasing temperatures which results in reduced tourist comfort levels (de Freitas 2003; Fisichelli *et al.* 2015; Markham *et al.* 2016).
- By shifting the ranges of charismatic species outside of park boundaries (Pearson and Dawson 2003; Hijmans and Graham 2006). These charismatic species are an important reason for tourists visiting parks (Di Minin *et al.* 2012).
- By elevating bush encroachment which would make it more difficult to see animals and therefore acts as a hindrance to game-viewing (Gray and Bond 2013; Arbieu *et al.* 2017). The drivers of bush encroachment are strongly debated, but recent literature recognises the importance of increases in atmospheric carbon dioxide concentrations (CO₂) (Wigley *et al.* 2010; Bond and Midgley 2012; Buitenwerf *et al.* 2012; Stevens *et al.* 2017).

The methods for assessing the impact of each of the components on tourism demand are described below.

Discomfort

A recent study by Mathivha *et al.* (2017) on the impact of drought on tourism demand in the Kruger National Park, found that there was no statistically significant correlation between drought years and the change in tourist arrivals. A study conducted in the US assessing the relationship between park visitation and climate used temperature instead of rainfall as an explanatory variable and in this case, statistically significant relationships were found for the majority of parks (Fisichelli *et al.* 2015). For the entire US park system, a cubic function explained 69% of the variation in historical visitation numbers. Furthermore, linear, quadratic and cubic models were found for individual parks, with 95% of parks having a statistically significant relationship between temperature and tourism demand. These models were then used to predict future tourist arrivals under different emissions and temperature scenarios but only using the models that explained more than 50% of the variation in historical visitation numbers (R squared > 0.5).

Bush encroachment

Visitor surveys conducted in SA's oldest park, Hluhluwe–iMfolozi, indicate that over 40% of potential future visitors to the park may be lost if animals become more difficult to see and an increase in woody plants, as a result of rising CO₂ levels, would likely result in this (Gray and Bond 2013). Furthermore,

Arbieu *et al.* (2017) found that visitors are positive towards vegetation up to a threshold of about 30%, after which tourist's attitudes became negative as it becomes more difficult to see animals.

Malaria

Using regression analysis, Rossello *et al.* (2017) found that countries with malaria risk receive 47% fewer tourists than countries where the disease is not endemic. Furthermore, eradicating the disease from tourist destination countries would result in an increase in tourist arrivals of 14.4% for these countries, at the aggregate.

Charismatic species

Charismatic species such as wild dog, lion, leopard, cheetah, black and white rhino, elephant, buffalo, hippopotamus, giraffe, spotted and brown hyena, and zebra are deemed to be responsible for attracting most tourists to protected areas (Lindsey *et al.* 2007; Di Minin *et al.* 2012). Using survey analysis to assess tourist preferences for big game species in South Africa, Di Minin *et al.* (2012) found that 45% of international tourists and 30% of national tourists indicated that the opportunity to see charismatic species is the main interest in visiting parks.

Adaptive capacity

A further component of a protected area vulnerability assessment is the capacity of a park to mitigate the threats of climate change through adaptation. The capacity of a park to adapt to climate change is measured by assessing the capacity of park management to respond to these threats, such as expanding the park to accommodate species range shifts or restoring degraded areas back to pristine ecosystem functioning, both of which would build resiliency. Parks will differ in their ability to respond to threats owing to differing levels of financial capacity (budget), technology, education, information, skills, access to resources, and management capabilities (O'Brien *et al.* 2004).

The internationally accepted Management Effectiveness Tracking Tool (METT) was developed by the World Commission for Protected Areas and World Wide Fund for Nature to provide an over-arching framework for assessing the management effectiveness of protected areas world-wide (Stolton *et al.* 2007). The METT comprises 70 indicators that track, amongst others, the financial capacity (budget), technology, education, information, skills, access to resources, and management capabilities of each park. The State of Biodiversity (SoB) survey, a SANParks-specific assessment, is aimed at assessing the effectiveness of park management to conserve its biodiversity.

Indicator approach to vulnerability assessments

An indicator approach is often used in vulnerability assessments to represent complexity and if the indicators are spatially explicit they can then be mapped (Babel *et al.* 2011). Schröter *et al.* (2005) have developed the following eight step guide for conducting an indicator assessment:

- 1) Define study area together with stakeholders and choose spatial and temporal scale.

- 2) Get to know place over time by reviewing literature, contacting and collaborating with researchers, spending time in the field with stakeholders and assessing nearby areas.
- 3) Hypothesise who is vulnerable to what: refine focus on stakeholder subgroups, and identify driving stresses and interactions of stresses.
- 4) Develop a causal model of vulnerability:
 - a. Examine exposure, sensitivity and adaptive capacity.
 - b. Formalise into model(s).
- 5) Find indicators for the elements of vulnerability:
 - a. Exposure indicators.
 - b. Sensitivity indicators.
 - c. Adaptive capacity indicators.
- 6) Operationalise model(s) of vulnerability:
 - a. Apply model(s) to weight and combine indicators.
 - b. Validate results by comparing them with the intuitions of stakeholders or case studies from similar systems in other places.
- 7) Project future vulnerability:
 - a. Choose scenarios with stakeholders.
 - b. Apply model(s) to produce a measure of vulnerability.
- 8) Communicate vulnerability creatively:
 - a. Use multiple interactive media.
 - b. Be clear about uncertainty.
 - c. Trust stakeholders.

There are weaknesses to the indicator approach (Eriksen and Kelly 2004; Barnett *et al.* 2008; Klein 2009), which include:

- The aggregation of indicators can be subjective and combining them into indices would produce different results if aggregated in a different manner
- The weighting of indicators can be subjective
- There is a danger that the chosen indicators do not represent the real condition as they may generalise or omit certain system characteristics that affect the vulnerability of the system
- Scale issues are a critical concern in selecting representative indicators

However, the use of the indicator approach for vulnerability assessments allows for the identification of attributes that make the system vulnerable as well as ranking and comparing vulnerability across regions. Following Glick *et al.* (2011), it also facilitates the subsequent selection of indicators measuring the effectiveness of conservation responses, which aim to increase adaptive capacity and/or reduce exposure and sensitivity.

Methods

An indicator-based vulnerability assessment, expressing vulnerability as a function of the potential impacts of climate change on a protected area, as well as the adaptive capacity of the protected area, was used to assess the vulnerability of South Africa's national parks. This approach used easily-measurable indicators representing stress on the park system and the adaptive capacity of the park's management. Potential climate impacts that hamper a park's ability to meet its conservation mandate were considered and confined to the following:

- The direct impact of climate change on biodiversity, as indicated by climate impacts on the spatial distribution of species and ecosystems; and
- The indirect impact on park mandate via the climate change impacts on infrastructure, neighbouring communities and tourism.

These five categories of impacts were considered: species, ecosystems, infrastructure, neighbouring communities and tourism. The scores from the potential impacts assessments, as well as the adaptive capacity scores, were used to develop a vulnerability index. A simple model for compiling the index was used based on the vulnerability equation (Equation 1 on page 6), where the climate impact on each park is equally weighted across the five categories and then divided by the adaptive capacity (AC) score (Equation 2). The AC score is converted from a score out of 100 to a score out of 20 so that each component of the vulnerability assessment has equal weighting.

$V = \text{ave. (species + ecosystems + tourism + infrastructure + neighbouring communities)} / (AC * 20\%)$

Equation 2. Protected area vulnerability equation.

The methods for developing the category indicators, as well as the adaptive capacity indicator, are provided below.

Study area

SANParks' 19 national parks constitute 52% of terrestrial protected area in the country and are located throughout South Africa (Figure 4). Each park has its own unique climate, topography and water resources, resulting in a diversity of vegetation and species conserved at the national level. Furthermore, these unique attributes lend themselves to specific tourist attractions for most parks.

Data analysis

All spatial analysis was conducted using the Q and Arc GIS programs. Much of the assessment required spatial analysis as the parks are located in different climatic regions across South Africa. All regression analyses were conducted using the Microsoft Excel statistical programs and R: a language and environment for statistical computing.

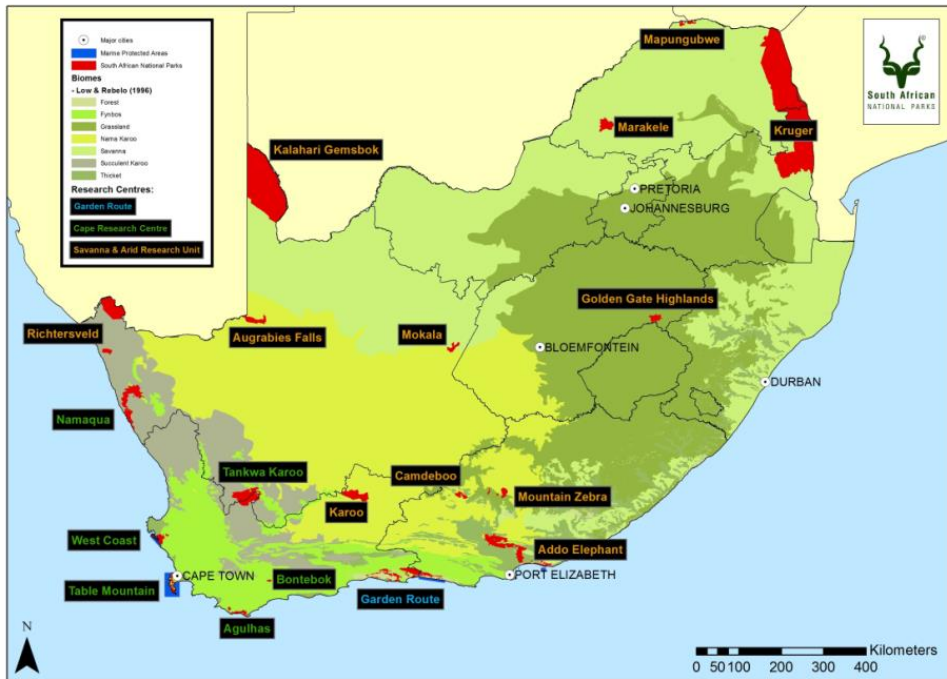


Figure 4. Map showing the national parks of South Africa and the biomes they conserve. Source: SANParks

Climate data and projections

The assessment of impacts of future climate change on the environmental and socioeconomic elements of the park system is subject to a range of uncertainties (New and Hulme 2000; Figure 5). However, uncertainty does not mean that there is no confidence in the projections of future climate. Rather, it implies there is a probability or level of confidence associated with a particular outcome.

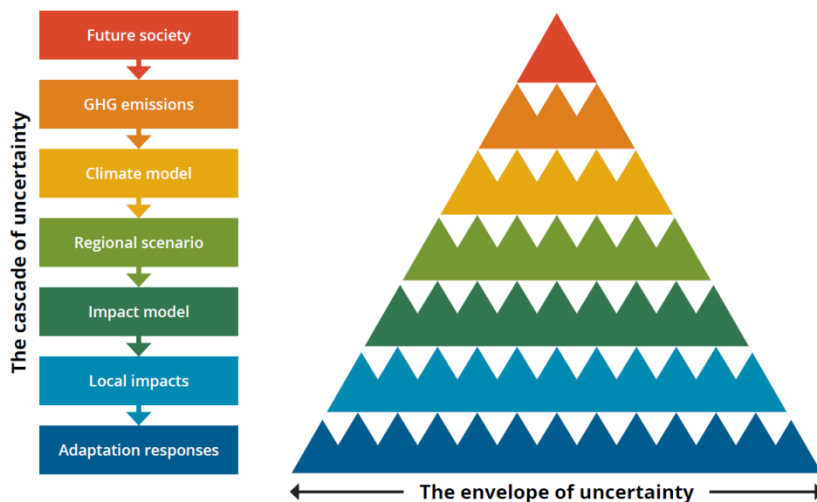


Figure 5. A diagram depicting the cascading uncertainty in climate projections. Source: Wilby and Dessai 2010.

Global climate models (GCMs) project changes in temperature more reliably than rainfall at a regional and local scale because the physical processes responsible for warming are well-captured by these models but for rainfall they are not. GCMs are applied at spatial scales of 200-300 km which cannot capture the local scale processes that influence rainfall. For this reason GCMs are often downscaled to finer spatial scales (Pielke and Wilby 2012). Although downscaled simulations are expected to provide a more accurate description of regional climate and its expected future change, the higher resolution offered by these simulations does not necessarily mean higher confidence in the projections. This is because the performances of downscaling techniques are highly dependent on the quality of the input data. This means that downscaled data may inherit assumptions and errors in the GCM simulations.

In this study, the conformal-cubic atmospheric model (CCAM) data were used. The CCAM data are configured from a set of six climate simulations that have been performed by the Climate Studies, Modelling and Environmental Health Research Group of the CSIR in South Africa (Davis-Reddy and Vincent 2017). In these experiments, a variable-resolution atmospheric global circulation model was applied as a regional climate model to simulate both present-day and future climate over southern Africa and its surrounding oceans. The GCM used to perform the downscalings is the CCAM of the Commonwealth Scientific and Industrial Research Council in Australia (McGregor 2005). The resolution is at 0.5 degrees or 50 km which is still quite coarse. The CSIR are currently running a finer resolution (8 km) model for South Africa and future work should use this output. All projections used in this study are based on the median (50th percentile) of the “ensemble” of the six dynamically downscaled GCMs used to compile the CCAM data. An ensemble is used for combining multiple predictions into a single prediction.

The decision on which emissions pathway and time frame to use for the study rested on the level of uncertainty I was willing to accept. Although a concerted effort is being made globally to curb greenhouse gas emissions, up to at least 2014 emissions have been tracking just above the representative concentration pathway (RCP) 8.5 scenario, considered the worst-case scenario by the IPCC (Sanford *et al.* 2014). Furthermore, because the climate change we experience over the next few decades will primarily be caused by past emissions (Glick *et al.* 2011), the RCP 8.5 scenario was used in this study. Furthermore, because near-term projections of climate change scenarios tend to have a higher degree of certainty, a relatively short time horizon of 2050 was used. Apart from the uncertainty inherent in longer time frames, the choice of 2050 limits the magnitude of divergence between the different RCPs (Figure 6). Furthermore, the surface temperature increase by 2050 under RCP 8.5 is much lower than the 2100 projection and is at a similar level to what is projected for 2100 under RCP 4.5.

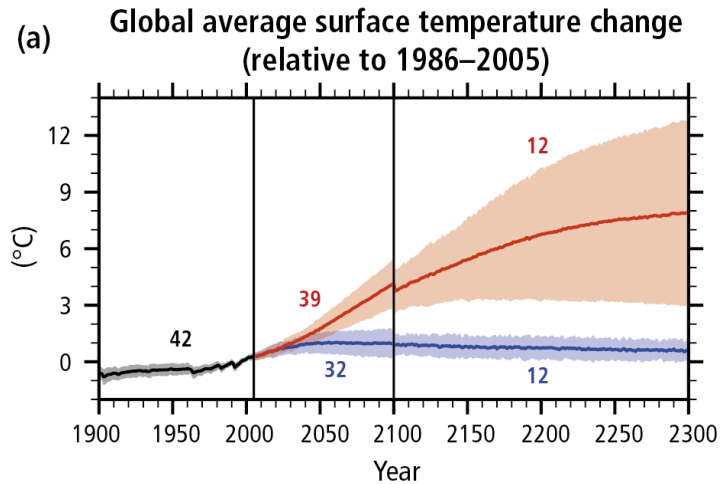


Figure 6. A graph depicting global average surface temperature projections under different emissions scenarios. The red solid line is RCP 8.5 and the blue solid line is RCP 2.5. The black solid line is the historical emissions pathway. Source: IPCC AR5 2014.

The CCAM data were used to project a series of climate variables for each park for the year 2050 under the RCP 8.5 emissions scenario. The projections were compared to current climate variables to determine the expected change (Figure 7 and 8; Table 2 and 3). These projections were used in the different assessments to determine the potential impacts in 2050. No data could be captured for Agulhas National Park owing to scale issues and alternate data was used for this park. For historic climate data for each park, Climate Research Unit (CRU) data was used. CRU data are a monthly time series of climate data for the period 1901–2015. The global data are at a 0.5 degree resolution (50 km) and is compiled from more than 4000 individual weather station records.

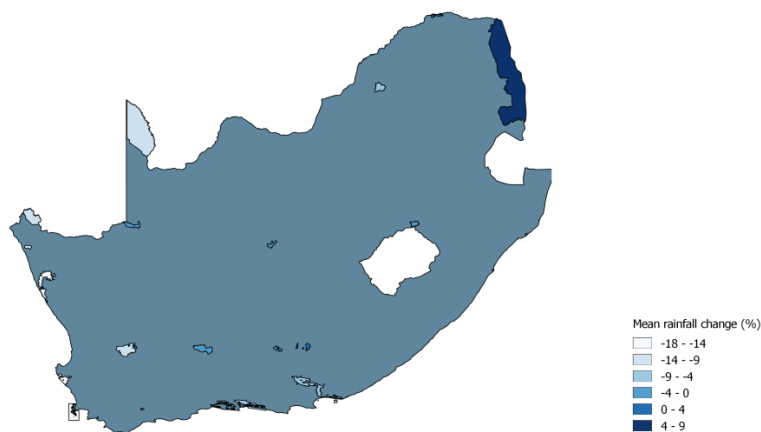


Figure 7. Mean annual rainfall percentage change across the park system.

Table 2. CCAM projections of the change (%) in rainfall variables for each park by 2050.

Park	Mean annual rainfall (% change)	Heavy rainfall days (>10 mm within 24 hr) (% Change)	Extreme rainfall days (>20 mm within 24 hr) (% change)
Addo	-6.8	-0.5	-6.1
Agulhas			
Augrabies	-2.0	0	-7.8
Bontebok	-7.5	-33.6	-5.3
Camdeboo	-1.4	33.4	0.4
Garden Route	-7.1	-5.2	-8.4
Golden Gate	-3.9	-8.6	-1.8
Karoo	-10.8	0.0	-8.7
Kalahari Gemsbok	-0.3	2.7	-15.2
Kruger	8.8	81.9	12.6
Mapungubwe	3.7	290.4	20.7
Marakele	-5.5	-25.4	-8.1
Mokala	0.2	43.9	-4.7
Mountain Zebra	2.4	72.1	0.7
Namaqua	-17.7	0.0	-14.2
Table Mountain	-9.5	0.0	-11.9
Tankwa Karoo	-14.1	0.4	-4.2
West Coast	-9.7	0.0	-13.4
Richtersveld	-16.2	-48.6	-1.2

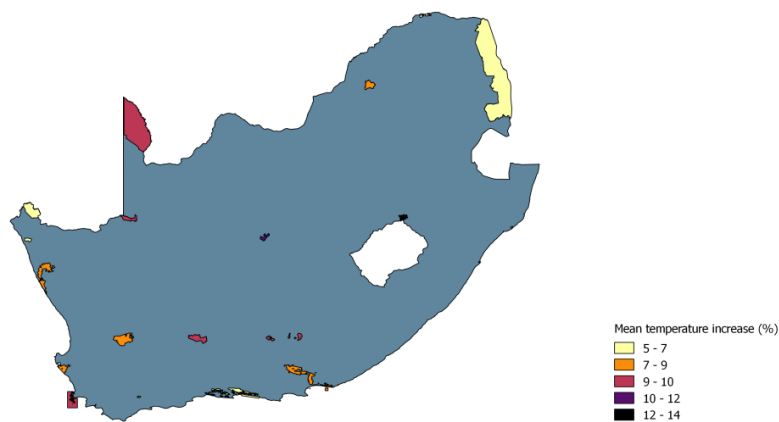


Figure 8. Mean annual temperature percentage change across the park system.

Table 3. CCAM projections of the change (%) in temperature variables for each park by 2050.

Park	Mean annual temperature	Mean annual minimum temp.	Mean annual maximum temp.	Very hot days (>35° C)	High fire danger days
	(% change)	(% Change)	(% change)	(% change)	(% Change)
Addo	6.7	9.5	5.4	41.4	26.5
Agulhas					
Augrabies	9.5	15.5	6.8	43.3	-84.5
Bontebok	6.0	8.2	4.9	44.5	62.2
Camdeboo	9.8	18.4	7.1	81.7	17.1
Garden Route	6.3	10.9	5.1	51.8	115.2
Golden Gate	13.5	43.9	8.8	369.6	357.5
Karoo	9.4	15.3	7.0	58.7	-80.9
Kalahari Gemsbok	10.0	17.2	7.0	54.7	-39.1
Kruger	5.6	8.5	3.8	26.1	-74.8
Mapungubwe	5.9	9.3	4.1	24.6	-87.5
Marakele	8.3	13.9	5.8	129.9	-26.0
Mokala	10.5	18.9	7.4	72.7	-47.2
Mountain Zebra	8.9	17.3	6.9	62.4	12.1
Namaqua	7.7	12.7	6.1	44.5	-36.8
Table Mountain	6.4	10.5	4.7	47.8	-81.0
Tankwa Karoo	9.4	17.1	6.7	59.1	44.5
West Coast	6.9	9.0	5.9	39.9	-58.7
Richtersveld	7.7	13.4	5.9	38.3	-12.7

Indicators developed

Indicators of potential impact were developed for each of the five categories considered: species, ecosystems, infrastructure, neighbouring communities, and tourism. An indicator of the adaptive capacity of parks was also developed. Existing models were used to assess the impact of climate change on species and ecosystems and the assessments required spatial analysis to assess the impact for specific parks. For the socioeconomic indicators (tourism, neighbouring communities and infrastructure), new indicators were developed that required not only the use of spatial tools but also regression analysis (Table 4). Indicators are not linked to the performance of other parks which makes the results more meaningful when undertaking update assessments, as well as making the tool useful for individual assessments.

Table 4. Indicators developed and methods used for each of the five potential impact categories, as well as adaptive capacity

Categories	Indicator	Methods used
Species impact	Species turnover Vulnerable species	Species distribution models Traits-based vulnerability assessments
Ecosystem impact	Biome shift/transformation	Climate envelope model Dynamic global vegetation model
Infrastructure impact	Value of infrastructure at risk	Flood hazard model Sea-level rise
Neighbouring communities impact	Households at risk of adverse weather	Household density
Tourism impact	Tourist temperature discomfort Bush encroachment and game viewing Malaria risk Charismatic species turnover	Tourism demand & temp. regressions Dynamic global vegetation model Species distribution model Species distribution models
Adaptive capacity	Management performance Capacity for park expansion	METT and SoB assessments Household density

Potential impacts

Species

For the climate change impact on species, both vulnerable species and species turnover for each park was assessed using already-developed data in the case of species vulnerability, and already-developed models in the case of species turnover. For the species listed as vulnerable to climate change for each park, the IUCN's global traits-based and spatially-mapped vulnerable species data was used. For the species turnover per park, the current and projected species distribution models developed by SPARC (Spatial Planning for Protected Areas in Response to Climate Change Conservation Biodiversity) were used.

Species impact score

The species vulnerability score was computed by allocating equal weight to the vulnerable species and species turnover assessments (Equation 3). The way in which each of these scores was computed is described below.

Species impact score = 50% (vulnerable species score) + 50% (species turnover score)

Equation 3. Species impact score.

Vulnerable species

Only birds and amphibians considered to be highly vulnerable (category 1) were considered for the vulnerable species assessment as these species are most at risk of climate change (exposed, sensitive and low adaptive capacity) and it can be argued that these species are in most need of conservation and adaptation efforts. The vulnerability score for this assessment was taken as the percentage of bird and amphibian species that fall into the IUCN's category 1.

Species turnover

For species turnover the modelled current distribution of range-restricted birds and charismatic mammals were compared to the actual species lists for each park and only species where the model predicted the park to contain a species which was in fact found in the park were used for the species turnover analysis. Those species where the model accurately predicted the current park distribution were then compared to future projections of distribution based on an "ensemble" of 5 GCMs, to account for model uncertainty. The number of species for which the climate in a park becomes unsuitable in the future was then calculated as a percentage of all species assessed for that park.

Ecosystems

For the climate change impact on ecosystems, a dissimilarity measure (the complement of the Jaccard similarity index) of biome and vegetation representation in each park was computed using the result of an existing correlative climate envelope model and an existing dynamic global vegetation model. The dissimilarity measure represents the extent to which the biome and vegetation representation for each park will change under climate change and is calculated using Equation 4.

Dissimilarity = 100% - |total negative change in in 2050|

Equation 4. Dissimilarity measure.

For the change in biomes, the results from SANBI's (South African National Biodiversity Institute) correlative climate envelope model were used and for the change in vegetation, outputs from Moncrieff *et al.*'s (2015) dynamic global vegetation model were used.

Ecosystem impact score

The dynamic global vegetation model better represents the dynamics between grassland, savanna and woodland biomes than between Fynbos, thicket and succulent Karoo biomes. More weight was therefore allocated to the outputs from the Moncrieff *et al.* model (75%) for the parks predominantly

been used in CSIR studies to indicate the upper limit of the damage zone for climate impacts based on a 1-in-50 year wave return period in the year 2100 (Rautenbach 2015).

Infrastructure at risk score

The replacement value of infrastructure at risk of damage from flooding and sea-level rise was computed for each park and then represented as a percentage of the total replacement value of infrastructure for each park (Equation 6). The way in which each component was calculated is described below.

$$\text{Infrastructure at risk score} = \frac{\text{replacement value of infrastructure at risk of flooding + sea-level rise}}{\text{total replacement value of infrastructure}}$$

Equation 6. Infrastructure at risk score.

Floods

Sampson *et al.* (2015) have designed a global flood hazard model which uses localised flood frequency analysis instead of hydrological models to produce return period flood maps globally. These maps are designed to indicate the probability of flooding spatially. They have developed a model for flood hazard assessment at 90 m spatial resolution where local detailed data and observations are not available. This study made use of the 1-in-100 year flood hazard output for South Africa from Sampson's model.

SANparks' assets have not been mapped spatially so Tracks4Africa's point-of-interest (POI) data was used to identify the park infrastructure that falls within the 1-in-100 year flood zone. The POI data is spatially mapped and is used by Tracks4Africa (a private tourism company) for tourism products and included assets such as bridges, picnic sites, waterholes, campsites, rest camps, etc. The flood model output was then overlaid with that of the POI data and a list of assets within the 1-in-100 year flood zone was compiled for each park.

Sea-level rise

To compute the value of infrastructure within a height of 5m above sea-level, the SRTM (Shuttle Radar Topography Mission) digital elevation model was used. Tracks4Africa's POI data was overlaid with the digital elevation model to determine the assets for each park that fall within the 5m contour line.

Fire

Due to the uncertainties in climate change impacts on fire at present, we chose not to include them in this study, but we recognise the potentially large contribution they could play in exacerbating climate change vulnerability of South Africa's national parks.

Cost of infrastructure

SANParks made asset registers available for each park but these did not include replacement values. Without a replacement value, an average cost of replacement per asset type was developed based on the most recently acquired assets (Table 5).

To determine the replacement value of total park infrastructure, an average age of 10 years for existing infrastructure was used. It was assumed that the cost of replacement of infrastructure has grown by 6% per year (in line with historical inflation rates) to yield the present value of replacing all infrastructure per park.

Table 5. The average cost of replacement per asset type.

Bridge	R 5,000,000	Picnic spot	R 90,000
Entrance gate	R 500,000	Ablutions	R 950,000
Hide	R 50,000	Lodge	R 5,000,000
Safari tent	R 100,000	Hut	R 500,000
Chalet	R 1,000,000	Fuel garage	R 5,000,000
Staff house	R 300,000	Restaurant	R 15,000,000
Reception	R 250,000	Shop	R 5,000,000

Neighbouring communities

For the climate change impact on neighbouring communities, the potential for increased conflict between communities and SANParks management has been used as an indicator of vulnerability.

Neighbouring communities impact score

The number of poor households located within the non-climate resilient area of the buffer zone was calculated as a percentage of the total number of households within the non-climate resilient zone (Equation 7). The non-climate resilient zone was taken from SANBI’s climate resilience spatial layer. The layer has been compiled from seven individual GIS layers: (1) coastal corridors; (2) riparian corridors and buffers; (3) areas with important temperature, rainfall and altitudinal gradients; (4) areas with high biotic diversity; (5) centres of floral endemism; (6) local refugia (south-facing slopes and kloofs); and (7) priority large unfragmented landscapes (Holness 2017).

Neighbouring communities impact score = number of households within non-climate resilient area of buffer zone / total number of households within the non-climate resilient zone

Equation 7. Neighbouring communities impact score.

Increased conflict between communities and park management

Poor households neighbouring a protected area will experience the same change in climate as is predicted for the protected area. We therefore assume that adverse weather will cause stress and greater vulnerability of communities neighbouring parks, thereby leading to greater reliance on park resources to sustain livelihoods. Some areas around protected areas are more climate resilient than others and will therefore impact neighbouring community livelihoods less. Therefore, the density of poor households within the low climate resilient area within a 10 km buffer zone around the park was used as a proxy for increased reliance on the park for sustaining livelihoods during adverse weather

events. For poor household density, low-income and no-income households from Census 2011 data were used. The density measure is the number of poor households within 1000 km², based on the area of the buffer zone and expressed as a percentage of the total number of households found within that area.

Predation

Due to the uncertainties in climate change impacts on predation at present, we chose not to include them in this study, but we recognise the potentially large contribution they could play in exacerbating conflict between neighbouring communities and park management.

Tourism

For the climate change impact on tourism, a composite index was developed that incorporates the impact of elevated temperatures on tourist comfort levels, the impact of a changing climate on vegetation and resultant bush encroachment which acts as a hindrance to game-viewing, the impact of climate change on the distribution of disease carrying vectors (malaria) and the resultant effect it has on tourist destination decisions, and the impact of climate change on the distribution of charismatic species and the resultant effect it has on tourism demand.

Tourism impact score

The tourism impact score for each park was computed by summing the scores from each assessment (Equation 8). The way in which each of these scores was computed is described below.

$$\text{Tourism impact score} = 25\% (\text{discomfort score}) + 25\% (\text{bush encroachment score}) + 25\% (\text{malaria risk score}) + 25\% (\text{charismatic species turnover score})$$

Equation 8. Tourism impact score.

Discomfort

The potential impact of intolerable temperatures on tourism demand was estimated using regression models based on the Fisichelli *et al.* (2015) study. Monthly average temperature and holiday months were used as explanatory variables and occupancy rates were used for the dependent variables. The occupancy rates are for both units and campsites together. The holiday months differ from park to park for specific reasons but generally include the peak tourism (major school and university holidays) months of December, March, April, June and September. Both linear and quadratic regression functions were used to capture the impact of historic temperature on occupancy levels. Future temperature projections for each park were then used to predict occupancy levels in 2050 to yield the discomfort impact for each park.

Bush encroachment

The potential impact of bush encroachment on tourism demand was based on estimates of the extent of transformation from non-woody biomes into woodland and forest biomes by 2100. The transformation was measured using the same dynamic global vegetation model as was used for the ecosystem

assessment. A threshold of 30% change was used to identify parks where bush encroachment is significant enough to impact on tourism demand (Arbieu *et al.* 2017). It is assumed that bush encroachment would impact at most 40% of tourism demand, in line with the results obtained by Gray and Bond (2013). Furthermore, it is assumed that the severity of bush encroachment would influence the decline in tourism demand. Therefore, the change in bush encroachment for each park was multiplied by the maximum 40% change in tourism demand to yield the bush encroachment impact for each park.

Malaria risk

The potential impact of malaria on tourism demand was based on estimates of the change in range of malaria carrying vectors under climate change. The model developed by Caminade *et al.* (2014) was used to determine which parks are projected to be climatically suitable for malaria in 2050. A length of transmission season of greater than three months is assumed to indicate climate suitability for malaria which, when run on South Africa's current climate, best represents the current malaria distribution in South Africa's parks. It was assumed that malaria risk would impact at most 20% of tourism demand, a more conservative assumption than the nearly 50% figure indicated by Rossello *et al.* (2017). Furthermore, it is assumed that the magnitude of malaria risk would influence the decline in tourism demand. Therefore, the change in park area climatically suitable for malaria transmission is multiplied by the maximum 20% change in tourism demand to yield the malaria impact for each park.

Charismatic species turnover

The potential impact of a loss of charismatic species on tourism demand was based on charismatic species turnover for each park. Charismatic species turnover was computed using the same species distribution models as were used in the species assessment. Charismatic species turnover was calculated as the number of charismatic species no longer climatically suited for a park as a percentage of the number of charismatic species found in each park. Furthermore, it is assumed that the severity of charismatic species turnover would influence the decline in tourism demand. It is assumed that the loss of charismatic species would impact at most 20% of tourist demand, a more conservative assumption than the nearly 40% figure indicated by Di Minin *et al.* (2012). Therefore, the species turnover for each park is multiplied by a more conservative 20% change in tourism demand to yield the charismatic species impact for each park.

Adaptive capacity

The adaptive capacity for each park was based on their most recent scores in the METT and SoB assessments (management performance), as well as the capacity for park expansion.

Adaptive capacity score

A composite adaptive capacity score was computed by allocating equal weight to the METT score, the SoB survey score and the capacity for park expansion score (Equation 9). The way in which each of these scores was computed is described below.

AC score = 33.3% (METT score) + 33.3% (SoB score) + 33.3% (capacity for park expansion score)

Management performance

There is some overlap between the SoB indicators and those of the METT however, the METT considers the aspects and management tools that equip park management to meet its mandate while the SoB includes indicators that directly assesses how well park management has met its mandate by assessing the state of biodiversity over time. The latest METT in SA is version 3 which was published in 2016 and is updated biennially. The METT indicators are weighted and aggregated to a score out of 100 where the higher the score the more effectively a park is managed. The latest SoB is for 2012 and it is updated every 5 years. Again the indicators are weighted and aggregated to a score out of 100 where the higher the score the healthier a park's biodiversity is.

Capacity for park expansion

The capacity for park expansion score is estimated by computing the percentage of area within the 10 km buffer zone that is found in the climate-resilient area of the buffer. The climate-resilient area again utilizes the SANBI climate-resilient GIS layer that was used for the neighbouring community impact assessment. This is the area within the buffer zone that would support corridor expansion for species and ecosystems. Household density within this area of potential expansion was computed using the Census 2011 data to ascertain the ease (or dis-ease) with which park management could expand the park into that area. This is based on the assumption that the more densely populated an area is, the more difficult it would be for park management to negotiate relocation of affected households.

The score is calculated by dividing the number of households located within the climate-resilient area of the buffer zone by the percentage of the buffer area that is considered climate-resilient. This provides a score out of 100 where the higher the score the more likely park management would be to negotiate expansion into the corridor area.

Results

Potential impacts

Species

The scores ranged from 1.6 for Marakele National Park to 25.5 for Bontebok National Park (Table 6). All parks include vulnerable bird species but only a few, mostly coastal, parks include vulnerable amphibian species. Very few parks house any of the range-restricted birds and of the few that do, only Bontebok National Park is projected to be unsuitable for a species' habitat by 2050, namely the Cape Sugar Bird.

Table 6. Species impact assessment including vulnerable birds and amphibians, as well as bird and charismatic species scores for each park. The asterisk signifies the parks with the highest species impact scores.

Park	Vulnerable birds	Vulnerable amphibians	Turnover birds	Turnover charismatics	Total species impact
	(%)	(%)	(%)	(%)	
Addo Elephant	12.4	0.0	0.0	0.0	3.1
Agulhas	16.9	45.3	0.0	0.0	15.5
Augrabies Falls*	12.3	0.0	0.0	66.7	19.8
Bontebok*	13.5	38.6	50.0	0.0	25.5
Camdeboo*	12.4	0.0	0.0	50.0	15.6
Garden Route	13.2	28.2	0.0	0.0	10.4
Golden Gate	10.9	0.0	0.0	0.0	2.7
Kalahari Gemsbok	11.2	0.0	0.0	33.3	11.1
Karoo	14.7	0.0	0.0	0.0	3.7
Kruger	4.7	3.0	0.0	9.1	4.2
Mapungubwe*	5.9	0.0	0.0	66.7	18.2
Marakele	6.6	0.0	0.0	0.0	1.6
Mokala	11.9	0.0	0.0	0.0	3.0
Mountain Zebra	12.2	0.0	0.0	20.0	8.1
Namaqua	19.2	0.0	0.0	0.0	4.8
Richtersveld	14.2	14.3	0.0	33.3	15.4
Table Mountain*	14.5	48.9	0.0	0.0	15.9
Tankwa Karoo	15.0	0.0	0.0	33.3	12.1
West Coast	15.6	42.9	0.0	0.0	14.6

Ecosystems

The projected area change in biomes ranged from 0.9% for Karoo to a high of 93.5% for Camdeboo and 93.8% for West Coast (Table 7). The resolution of the dynamic global vegetation model did not allow for the analysis of Agulhas National Park so the climate envelope model received a 100% weighting.

Table 7. The climate envelope and dynamic global vegetation model scores for each park. The percentage in parentheses is the weighting apportioned to that model type in the total ecosystem impact calculation. The asterisk signifies the parks with the highest species impact scores.

Park	Climate envelope model	Dynamic global vegetation model	Total ecosystem impact
	(%)	(%)	(%)
Addo Elephant*	79.2 (75%)	64.7 (25%)	75.6
Agulhas	31.5 (100%)	-----	31.5
Augrabies Falls	100.0 (25%)	60.0 (75%)	70.0
Bontebok*	100.0 (75%)	0.0 (25%)	75.0
Camdeboo*	91.4 (75%)	100.0 (25%)	93.5
Garden Route	48.0 (75%)	33.3 (25%)	44.3
Golden Gate Highlands	4.1 (25%)	66.7 (75%)	51.0
Kalahari Gemsbok	85.8 (25%)	0.0 (75%)	21.5
Karoo	3.5 (25%)	0.0 (75%)	0.9
Kruger	0.0 (25%)	9.5 (75%)	7.1
Mapungubwe*	0.0 (25%)	100.0 (75%)	75.0
Marakele*	15.4 (25%)	100.0 (75%)	78.8
Mokala	20.5 (25%)	0.0 (75%)	5.1
Mountain Zebra	72.1 (25%)	0.0 (75%)	18.0
Namaqua	1.5 (75%)	50.0 (25%)	13.7
Richtersveld	31.5 (75%)	14.3 (25%)	27.2
Table Mountain	0.0 (75%)	50.0 (25%)	12.5
Tankwa Karoo	5.1 (75%)	7.7 (25%)	5.7
West Coast*	100.0 (75%)	75.0 (25%)	93.8

Under the climate envelope model assessment, three of the 19 parks were projected to experience a complete change from their current biome representation and a further four parks were projected to experience at least a 70% change from their current biome representation. The changes of particular interest were a 65% reduction in the Fynbos biome, a 50% reduction for both grassland and Albany thicket, as well as an increase of 90% for the succulent Karoo biome for the entire SANParks system.

Under the dynamic global vegetation model assessment, three of the 19 parks were projected to experience a full change from their current biome representation, however these are not the same

three parks as were identified under the climate envelope model. The changes of particular interest were a 350% increase in woodland biome and a 150% increase in forest biome representation in the entire SANParks system. These gains were at the expense of the savanna and grassland biomes, as bush encroachment theory predicts.

West Coast National Park was projected to experience the largest ecosystem transformation, with a 100% change projected under the climate envelope model and a 75% change under the global dynamic vegetation model. Under the climate envelope model, the transformation was from a 100% Fynbos representation to a 100% succulent Karoo representation in 2050 (Figure 9). Under the dynamic global vegetation model, the transformation was from a 75% forest and 25% woodland representation to a 100% woodland representation in 2050 (Figure 10).

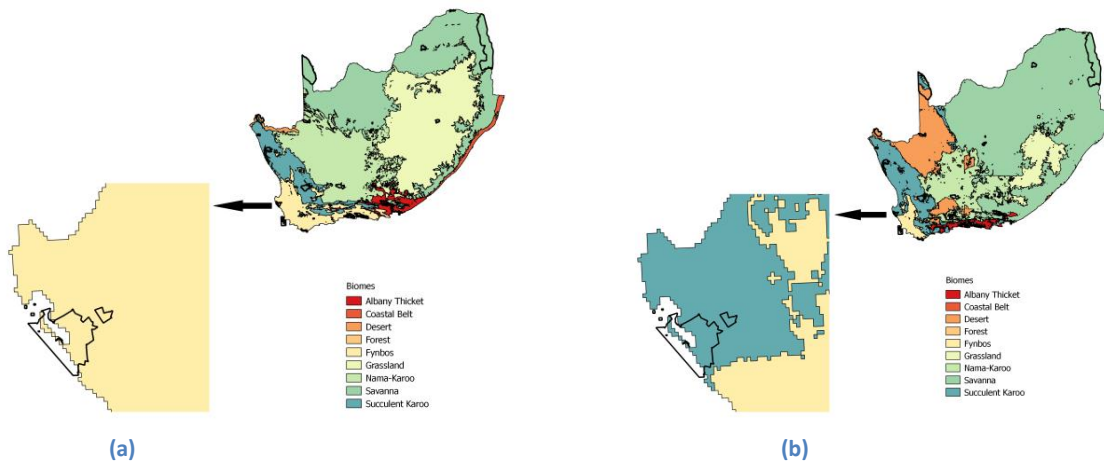


Figure 9. 9a represents the current biome representation and 9b represents the 2050 projected biome representation under the climate envelope model. The magnified view is of the West Coast National Park.

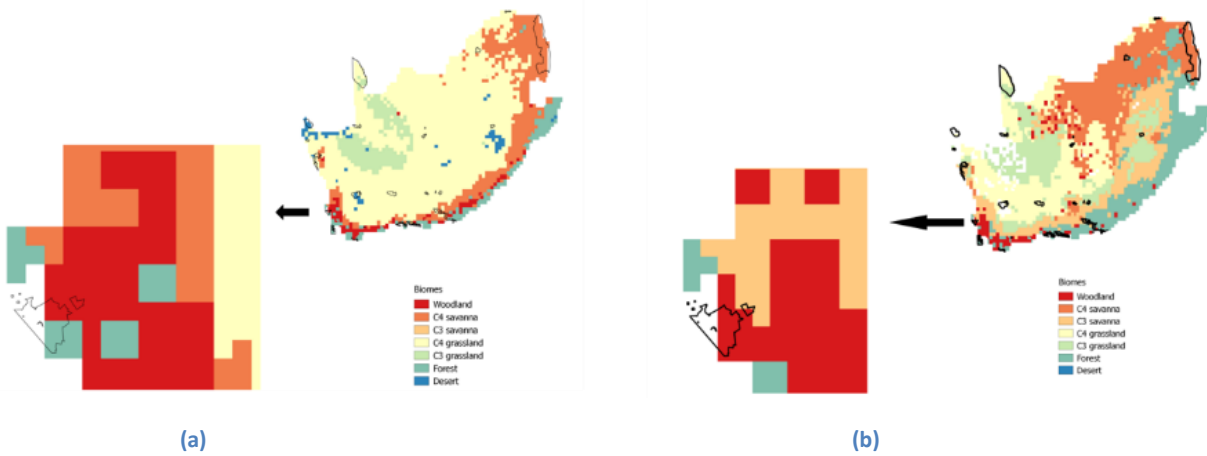


Figure 10. 10a represents the current biome representation and 10b the 2050 projected biome representation under the dynamic global vegetation model. The magnified view is of the West Coast National Park.

Infrastructure

For the infrastructure impact assessment, the value of infrastructure at risk ranged from R0 for Agulhas, Augrabies Falls, Golden Gate Highlands, Karoo, Marakele, and Mokala national parks to a high of R313 million for Kruger National Park (Table 8). Although Kruger had the highest value of infrastructure at risk - mostly bridges over rivers - it was the West Coast that had the highest proportion of infrastructure at risk. At 86.3% of infrastructure at risk of flooding and sea-level rise, almost the entire West Coast's infrastructure is at risk. Many of South Africa's parks are located adjacent to rivers which provide water and nourishment for species, creating optimal game-viewing experiences. This has resulted in infrastructure being constructed close to rivers and often within the 1-in-100 year flood zone. The majority of infrastructure at risk in the coastal parks was owed to sea-level rise and its associated storm surge and includes accommodation and restaurants providing sea views.

Table 8. The infrastructure at risk of flooding and sea-level rise, total infrastructure and proportion for each park. The asterisk signifies the parks with the highest proportion of infrastructure at risk.

Park	Infrastructure at risk of flooding and sea-level rise	Total infrastructure	Proportion of total infrastructure at risk
	R million	R million	(%)
Addo Elephant	16	227	7.1
Agulhas	0	69	0.0
Augrabies Falls	0	62	0.0
Bontebok	1	33	3.2
Camdeboo	0.5	8	6.1
Garden Route*	72	158	45.7
Golden Gate	0	160	0.0
Kalahari Gemsbok*	48	179	26.7
Karoo	0	101	0.0
Kruger*	313	1153	27.1
Mapungubwe	0.5	182	0.4
Marakele	0	98	0.0
Mokala	0	54	0.0
Mountain Zebra	5	50	10.0
Namaqua	0.5	43	1.3
Richtersveld*	33	70	47.5
Table Mountain	16	68	24.0
Tankwa Karoo	6	44	12.6
West Coast*	27	31	86.3
	539	2789	19.3

Neighbouring communities

The neighbouring community impact assessment scores ranged from a low of 2.6% for Tankwa Karoo National Park to a high of 29% for Table Mountain National Park (Table 9). Both the number of poor households in the non-climate resilient area, as well as the results as a percentage of the total number of households in the non-climate resilient area, is shown.

Table 9. Poor households in the non-climate resilient area of the buffer zone, as well as a percentage of total households in the non-climate resilient area of the buffer zone. The asterisk signifies those parks with the highest proportions.

Park	Poor HH in non-climate resilient area	Poor HH as % of total HH in non-climate resilient area
		(%)
Addo Elephant	16	4.8
Agulhas*	12	19.2
Augrabies Falls	1	4.0
Bontebok*	65	20.3
Camdeboo	24	14.6
Garden Route	32	4.5
Golden Gate*	740	25.2
Kalahari Gemsbok	1	13.0
Karoo	12	7.0
Kruger	34	4.2
Mapungubwe	5	11.8
Marakele	17	10.7
Mokala	4	12.3
Mountain Zebra	5	9.9
Namaqua	0.3	6.8
Richtersveld	2	9.3
Table Mountain*	7375	29.0
Tankwa Karoo	0.02	2.6
West Coast*	100	16.3

Tourism

The tourism impact assessment scores ranged from a projected 0% change in tourism demand in 2050 for Agulhas, Bontebok, Golden Gate Highlands, Namaqua and West Coast national parks, to a high of 30% for Mapungubwe National Park.

For the temperature discomfort impact assessment, a statistically-significant relationship between unit occupancy and monthly mean temperature was found for 18 out of the 19 parks and for one of the parks the model explained less than 50% of the variation in occupancy. The regression results were still

used to project future occupancy for these two parks. There was roughly a 50:50 split in quadratic to linear relationships. For the quadratic models, the R^2 value ranged from 62% to 90%, while for the linear models the R^2 value ranged from 54% to 94%. For the parks exhibiting a linear relationship, it can be inferred that as the temperature increases, the occupancy rates will increase too. For the parks exhibiting a quadratic relationship, it can be inferred that occupancy will increase with temperature until a temperature threshold is met and then occupancy levels decline. For example, a quadratic relationship was found for Kalahari Gemsbok National Park where occupancy levels rose with mean monthly temperature but then declined when the temperature increased above 18°C (Figure 11). The regression analysis included holiday months which enhanced the fit of the linear and quadratic models (Table 11 and 12).

The explanatory variables were then used to predict future occupancy based on the mean monthly temperatures expected in 2050 (Table 10).

For many parks, including some of the hotter summer month parks such as the Au-grabies Falls and Richtersveld national parks, the average annual occupancy rates were not negatively impacted by temperature rise. The reason for this is that the temperature increase during the colder winter months is more than the temperature increase in the hot summer months (Table 3 on page 18). This means that for many months of the year, occupancy levels are rising with the increased temperature during the colder months (historically the cold deterred visitation) which is outweighing the marginal decline in occupancy levels from extreme hot temperatures in the summer months.

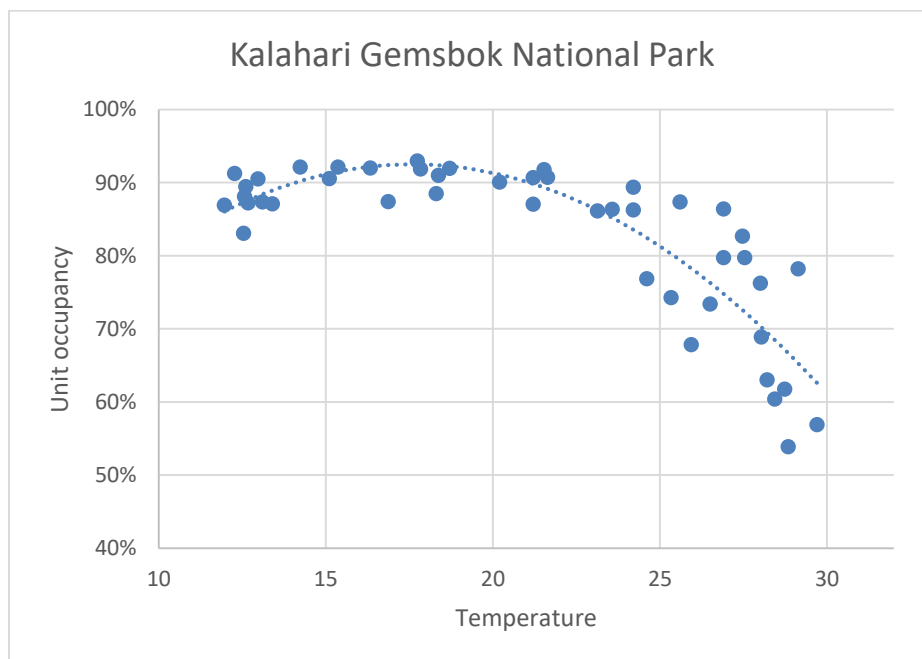


Figure 11. Scatter plot of the unit occupancy and temperature for Kgalagadi National Park.

For the malaria risk assessment, three parks were projected to experience an increase in the risk of malaria owing to the projected change in mosquito distribution: Addo Elephant (where 10.25% of the

park area was expected to be stable for malaria transmission), Garden Route (24.67%) and Marakele (65.78%) national parks (Figure 12 and 13). Kruger National Park was expected to experience no change (remaining at 100% of the area being stable for malaria transmission) while Mapungubwe was expected to become nearly devoid of malaria by 2050 (from 100% of its area historically to only 0.65% in 2050).

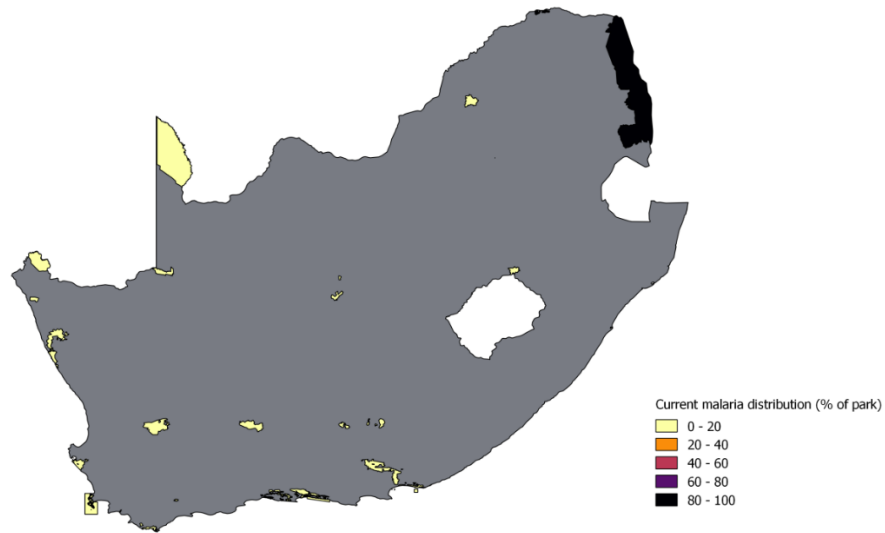


Figure 12. The current malaria distribution across parks. Only Mapungubwe and Kruger are malaria-risk parks.

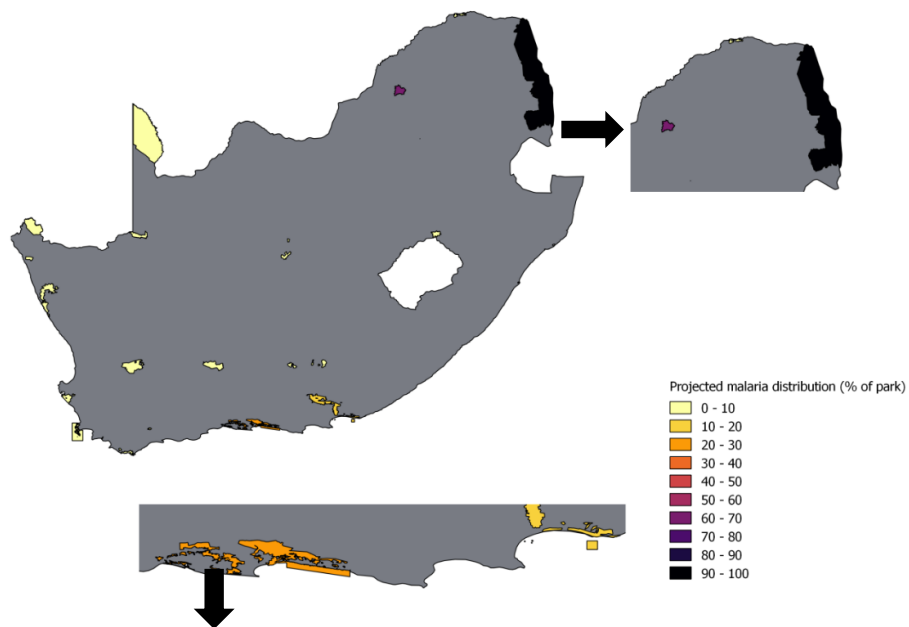


Figure 13. The projected malaria distribution across parks. The magnified view at the bottom shows the Garden Route and Addo Elephant national parks and the magnified view in the top right shows Kruger, Mapungubwe and Marakele.

For the bush encroachment impact assessment, bush cover by 2050 was projected to be 100% in the Garden Route, 65% in Addo, 40% in Marakele and 10% in Kruger (Figure 10 on page 29). However, in the baseline year, the Garden Route already had 65% bush cover, Addo had 10% and neither Kruger nor Marakele had any bush cover. Therefore, the increase above the 30% threshold yielded an increase of 35% for the Garden Route and Addo Elephant national parks, 10% for Marakele and 0% for Kruger. These values were then multiplied by the assumed 40% impact on tourism demand to yield the bush encroachment impact (Table 10).

For the charismatic species turnover assessment, eight out of the 19 parks were projected to experience charismatic species turnover with Mapungubwe and Au-grabies projected to experience the greatest turnover, both at 66.67% (Table 10).

Table 10. Projected loss in tourism by 2050 as a percentage of historic tourism demand for each tourism category. The asterisk signifies parks with the highest projected loss in tourism demand.

Park	Discomfort	Malaria	Bush encroachment	Charismatic species	Total tourism impact
	(%)	(%)	(%)	(%)	(%)
Addo Elephant	1.4	2.1	13.9	0.0	17.3
Agulhas	0.0	0.0	0.0	0.0	0.0
Au-grabies Falls	0.0	0.0	0.0	13.3	13.3
Bontebok	0.0	0.0	0.0	0.0	0.0
Camdeboo	1.7	0.0	0.0	10.0	11.7
Garden Route*	0.0	4.9	13.3	0.0	18.3
Golden Gate	0.0	0.0	0.0	0.0	0.0
Kalahari Gemsbok	4.6	0.0	0.0	6.7	11.3
Karoo	0.5	0.0	0.0	0.0	0.5
Kruger*	15.5	0.0	0.0	1.8	17.3
Mapungubwe*	16.7	0.0	0.0	13.3	30.0
Marakele*	12.7	13.2	4.0	0.0	29.9
Mokala	7.1	0.0	0.0	0.0	7.1
Mountain Zebra	3.0	0.0	0.0	4.0	7.0
Namaqua	0.0	0.0	0.0	0.0	0.0
Richtersveld	0.0	0.0	0.0	6.7	6.7
Table Mountain	2.1	0.0	0.0	0.0	2.1
Tankwa Karoo*	13.0	0.0	0.0	6.7	19.7
West Coast	0.0	0.0	0.0	0.0	0.0

Table 11 and 12. Table 11 (above) provides the coefficients and significance levels for the quadratic regression functions and table 12 (below) provides the coefficients and significance levels for the linear regression function.

	Addo	Camdeboo	Karoo	Kalahari Gemsbok	Kruger	Mapungubwe	Marakele	Mokala	Mountain Zebra	Tankwa
	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>
Intercept	-0,641 *	-0,358	-0,211	0,312 *	-2,276 **	-1,860 *	-0,574	0,018	-0,726 *	-0,177
Temp	0,148 ***	0,079 **	0,093 *	0,069 ***	0,311 ***	0,252 ***	0,133 **	0,061 *	0,157 ***	0,065 *
Temp ²	-0,004 ***	-0,002 *	-0,002 *	-0,002 ***	-0,008 ***	-0,006 ***	-0,004 **	-0,002 *	-0,004 ***	-0,002 *
January			-0,042	-0,080 *	0,017	-0,047	-0,051		0,006	
March		0,225 ***						0,055		
April		0,210 ***	0,061	0,012	-0,077 *	-0,047	0,021	-0,010	0,013	0,128 *
May	-0,129 ***									
June	-0,158 ***									
July			0,043	0,021	0,069	0,136 *	0,104 *	0,021	0,045	
Aug	-0,050 *									0,190 ***
September		0,124 **	0,158 **					0,112 *		0,319 ***
December		0,315 ***	0,183 **	0,079 **	0,219 ***	0,229 ***	0,164 ***	0,158 *	0,112 *	0,223 ***

	Agulhas	Bontebok	Garden Route	Golden Gate	Namaqua	Richtersveld	Table Mountain	West Coast
	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>	<i>Coefficients</i>
Intercept	-0,105	-0,119 *	-0,233 ***	0,262 ***	-0,072	0,436 ***	-0,200 *	-0,223 *
Temp	0,026 ***	0,019 ***	0,030 ***	0,005 *	0,010 ***	-0,013 ***	0,032 ***	0,046 ***
January	0,012	-0,019	0,149 ***		0,062 *		-0,072	
March	0,031			0,065				
April	0,077	0,086 *	0,087 ***	0,089 *	0,124 ***	0,156 ***		
July		-0,024	0,019		0,039			
Aug					0,244 ***	0,142 ***		0,397 ***
September				0,048	0,268 ***	0,225 ***		0,412 ***
November	-0,022						0,009	
December	0,149 **	0,183 ***	0,378 ***	0,189 ***	0,411 ***	0,102 ***	0,174 **	

Adaptive capacity

The adaptive capacity scores were fairly low as a result of the limited capacity for park expansion into climate-resilient corridors. This is predominantly a result of very low percentages of land within the buffer area being classified as climate-resilient. The area within the buffer considered climate-resilient ranged from 0% in the case of the Kalahari Gemsbok, Mapungubwe and Mokala national parks to a high of 36.9% for Camdeboo National Park. The Kruger and Table Mountain national parks exhibited the highest number of households residing in the climate resilient area of the buffer, which further decreased the capacity for park expansion scores (Table 12). Historic management performance, measured by the METT and SoB scores, provided an indication of the capacity of park management to react and adapt to climate change while the capacity for park expansion scores can be interpreted as the limitations to adaptation. Mokala National Park had the lowest adaptive capacity score despite scoring fairly highly in the management performance category, owing to 0% of land within the buffer zone being considered climate-resilient. This makes it difficult for park management to expand the park to accommodate species range change and ecosystem transformation.

Table 12. Management performance, park expansion capacity and overall adaptive capacity scores. The higher the adaptive capacity score, the lower the vulnerability to climate change. The asterisk signifies the parks with the lowest overall scores.

Park	Management performance			Capacity for park expansion	Overall score
	METT	SoB	Average		
	(%)	(%)	(%)	(%)	(%)
Addo Elephant*	62	58	60	2.6	40.9
Agulhas*	73	49	61	0.6	40.9
Augrabies Falls	74	52	63	4.3	43.4
Bontebok	78	74	76	12.9	55.0
Camdeboo	68	55	62	7.0	43.3
Garden Route	76	56	66	1.5	44.5
Golden Gate	78	66	72	2.2	48.7
Kalahari Gemsbok	74	78	76	0.0	50.7
Karoo	69	52	61	21.3	47.4
Kruger	71	72	72	0.1	47.7
Mapungubwe*	75	50	63	3.4	42.8
Marakele	77	56	67	13.4	48.8
Mokala*	63	55	59	0.0	39.3
Mountain Zebra	69	70	70	17.7	52.2
Namaqua	64	54	59	39.9	52.6
Richtersveld	62	68	65	6.6	45.5
Table Mountain*	68	59	64	0.1	42.4
Tankwa Karoo	66	54	60	33.8	51.3
West Coast*	73	55	64	0.3	42.8

Vulnerability index

Using Equation 2 on page 13, the composite vulnerability scores were computed. The worst score attainable is 100. The assessment indicated that the West Coast National Park was the most vulnerable owing to extremely high scores in the ecosystems and infrastructure potential impact categories, as well as scoring very low in the adaptive capacity assessment. The Karoo National Park was the least vulnerable owing to very low scores for all the potential impact categories, as well as scoring fairly highly in the adaptive capacity assessment (Table 13).

Table 13. The vulnerability scores for each park, ranked from highest to lowest vulnerability

Park	Vulnerability score
West Coast	4.93
Camdeboo	3.27
Mapungubwe	3.16
Garden Route	2.77
Addo Elephant	2.64
Marakele	2.48
Augrabies Falls	2.47
Richtersveld	2.33
Bontebok	2.26
Table Mountain	1.97
Kalahari Gemsbok	1.65
Agulhas	1.62
Golden Gate Highlands	1.62
Kruger	1.26
Tankwa Karoo	1.03
Mountain Zebra	1.01
Mokala	0.70
Namaqua	0.50
Karoo	0.25

For each park, the component scores are represented in a circumplex chart (Figure 14 and 15a - s).

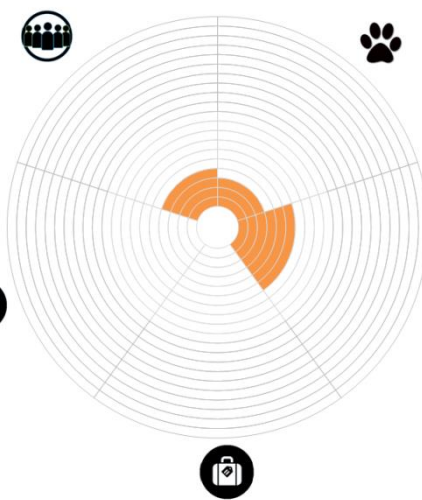


Figure 14. Legend for the circumplex charts.

(a) Addo National Park



(b) Agulhas National Park



(c) Augrabies Falls National Park



(d) Bontebok National Park



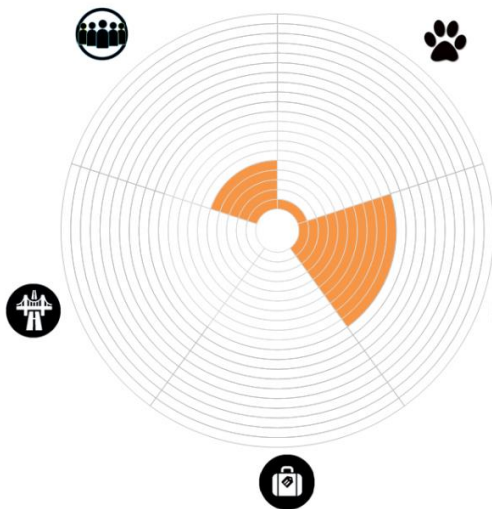
(e) Camdeboo National Park



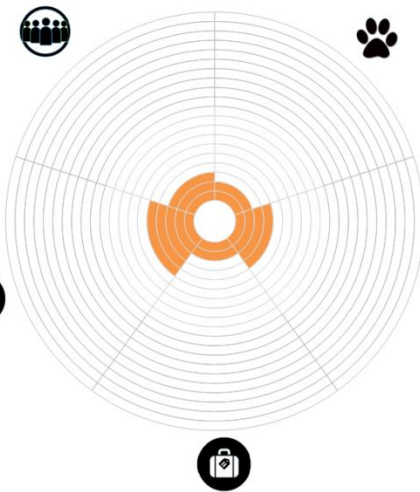
(f) Garden Route National Park



(g) Golden gate National Park



(h) Kalahari Gemsbok National Park



(i) Karoo National Park



(j) Kruger National Park



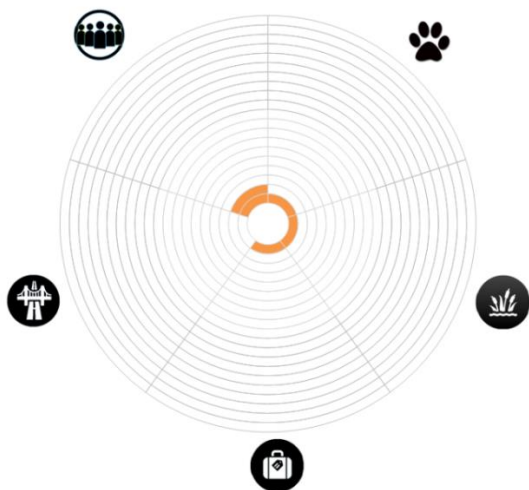
(k) Mapungubwe National Park



(l) Marakele National Park



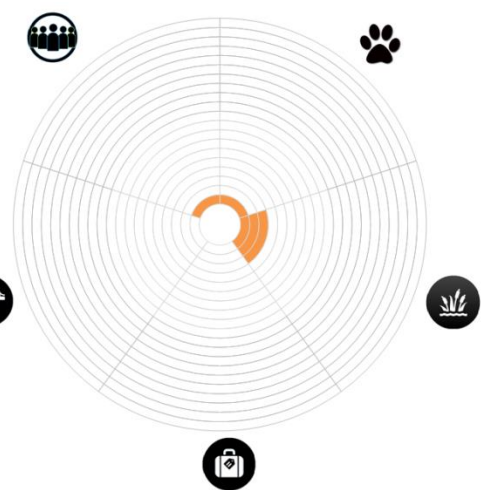
(m) Mokala National Park



(n) Mountain Zebra National Park



(o) Namaqua National Park



(p) Richtersveld National Park



(q) Table Mountain National Park



(r) Tankwa National Park



(s) West Coast National Park



Figure 15. Circumplex charts for each park indicating the scores for each potential impact category. Scores are out of 100% for each category.

Discussion

This assessment is intended to inform SANParks management of where the climate change vulnerabilities lie across the park system as well as within individual parks, which can be used to help shape the adaptation process. From this initial step, adaptation options can be identified and selected. Although this assessment provides information about the levels and sources of vulnerability of different protected area components to help in setting priorities, the assessment alone cannot prescribe what the priorities should be. Park managers will increasingly be faced with the dilemma of deciding how to allocate scarce resources to address various conservation needs. As Glick et al. (2011) explain in the IUCN climate change guidance for protected area managers, “The choice of whether to focus conservation efforts on the most vulnerable, the most viable, or a combination of the two, will of necessity be based not only on scientific factors, but also social, economic and legal values”.

Weaknesses in developing indicators

Concerns with developing vulnerability indicators is firstly that the different indicators have different levels of uncertainty, and secondly that the aggregation of indicators can be subjective and combining them into indices would produce different results if aggregated in a different manner or the aggregation of a number of indicators into a composite index can potentially dilute the results of the individual scores (Eriksen and Kelly 2004). For these reasons, it is important for park managers to analyse the results of the individual assessments for their parks so as not to overlook or misinterpret the aggregated scores. For example, although the species impact assessment scores were low for all parks, the results should not be interpreted as meaning that climate change will have a potentially low impact on species. The aggregated impact scores have diluted important underlying indicator scores. For instance, Agulhas, Bontebok, Table Mountain and West Coast national parks each have more than a third of their amphibian species being considered vulnerable to climate change, a substantial proportion that should influence conservation planning. Furthermore, Augrabies Falls, Camdeboo and Mapungubwe national parks each have 50% or more of their charismatic species projected to be unsuited for their new climates in 2050. These potential impacts, when considered on their own, should stimulate the discussion and direction of the adaptation process rather than relying on the aggregated indices to drive decisions.

The ecosystem impact assessment also highlighted a weakness with developing vulnerability indicators in that the largely subjective and arbitrary choice of weightings of indicators can influence the aggregated scores (Barnett *et al.* 2008; Klein 2009); two models were used to project the response of ecosystems to climate change, with very different results and the choice in weighting of the two models would have yielded very different aggregated scores. In the case of Bontebok and Mapungubwe national parks, the difference in model projections were at the extreme end of the spectrum, as high as 100%. For this assessment, it was important to identify which model was best suited to predict the response of specific biomes to climate change and then apply more weight to the model that was best suited. In doing so, weightings were applied based on the level of confidence in the model to represent the system. Figure 9 and 10 on page 29 highlight the importance of choosing appropriate weightings, using the West Coast National Park as an example.

A further issue identified by the study which is not related to developing indicators but rather with climate change vulnerability assessments themselves, is that it is not always possible or feasible to apply a standardised methodology for quantifying potential impacts for each potential impact category (Klein 2009). For example, although the incidence of extreme weather events, such as flooding and storm surges, are likely to increase with climate change (Fischer and Knutti 2015), the change in magnitude and frequency at a localised scale is nearly impossible to predict. This makes assessing the potential impacts associated with extreme weather events challenging to estimate. Instead, this study has estimated the vulnerability to current and historic experiences of frequency and magnitude of extreme events. The infrastructure impact assessment considered the current 1-in-100 year flood risk which suggests that the results are underestimating the value of infrastructure at risk. SANParks management should take heed of this assessment as nearly 20% of all SANPark's infrastructure is at risk of flooding and sea-level rise in today's terms.

Similarly, the neighbouring communities' impact assessment is likely to be underestimating the potential for future conflict as the study has not considered growth in the number of households by 2050. The number of households neighbouring national parks could increase significantly as climate change influences where people choose to live. The assessment scores identified the coastal parks as being most susceptible to conflict with neighbouring communities, despite not having considered the impact of climate change on inshore marine resources which, if found to be negatively impacted by climate change, could force local fishermen to increase harvesting from no-take zones in national parks, further exacerbating the problem. On the other hand, Table Mountain National Park was identified as scoring the worst in this category which could be an overestimate considering that the communities neighbouring this park fall within the City of Cape Town's boundaries, where residents receive support in terms of access to basic services. In many parks located in more rural areas, service delivery is likely not to be as efficient as with the City of Cape Town, resulting in a greater potential for conflict.

The tourism impact assessment scores highlight a further consideration with regards to indicator development, namely scale. The scores of the tourism assessment were low for all parks, however, the impact on park management of realising a decrease in tourism demand is not commensurate. For example, the potential 17% decrease in tourism demand identified for Kruger National Park would substantially impede the functioning not only of Kruger itself but the entire park system as revenue generated by tourism in Kruger helps subsidise the management and running costs of the entire park system.

The value of vulnerability assessments for park management

It is clear from the vulnerability assessment that not all parks will be impacted by climate change in the same way or with the same severity. It is important for park managers to analyse the results of each potential impact category in order to identify where their park's vulnerabilities lie, and to bear in mind that each potential impact category has its own level of uncertainty.

However, Tingley et al. (2013) argue that it is important not to assign too much weight to climate change in conservation priorities because of the uncertainties in projecting climate change, as well as not being able to fully comprehend how systems may respond. Furthermore, climate change is only one threat to

conservation in a changing world and conservation priorities need to be considered in light of all potential threats. van Wilgen and Herbst (2016) consider climate change as one of six global change drivers which include habitat change and land-use change, disease, alien species, freshwater change and resource use. As this study has indicated, climate change has the potential to exacerbate these other drivers and vulnerability might be increased when ecosystems are under stress from these other drivers.

Owing to the uncertainties mentioned already, identifying adaptation pathways that could be taken under alternative scenarios is important. Vulnerability should be assessed under different climate change scenarios to inform alternative adaptation pathways, should the climate change faster or slower than anticipated. This can also help to identify which adaptation plans are plausible under all the scenarios which will help to demonstrate that there are actions that can be taken now that will assist in building resilience to climate change regardless of how the change in climate unfolds.

Glick et al. (2017) have identified four general strategies for adapting to climate change, which are managing for persistence, resisting change, accommodating change, and directed change. The decision in which approach to take is based on how severe the impacts are likely to be. More on these adaptation options can be found in the IUCN's climate change guidance report.

Apart from a potentially devastating impact on species and ecosystems at a park level, the effects on tourism demand, community relations and infrastructure are of concern. Management strategies need to take heed of the magnitude of potential impacts identified in this study and work towards developing adaptation pathways. Furthermore, this vulnerability framework has the potential to be used in other protected area systems.

Recommendations

A protected area is a complex and dynamic system and not all the potential impacts and linkages between climate change and its resulting impact on the protected area have been quantified here. For instance, climate change has the potential to influence the fire regime (already discussed on page 8), the abundance and range of alien and invasive species, the functioning of wetland habitats and their biodiversity, freshwater flows, and the functioning of marine habitats and their biodiversity. Also not considered in this study are potential knock-on effects such as the potential constraint on tourism supply as a result of damaged infrastructure or the way climate change may influence land use practices and its concomitant impact on biodiversity. These all have the potential to hamper a protected area's ability to meet its conservation mandate and therefore are considered factors influencing the vulnerability of a protected area to climate change. Future studies should attempt to quantify these additional threats, as well as include a sensitivity analysis for the different components. The next step in the adaptation strategy process would be to identify the adaptation options available to the different park managers based on the results from this study.

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