Assessing the climate change vulnerability of reptile and amphibian species found in Table Mountain National Park

Jack Harper

Supervisors: Dr Susan Cunningham, Prof Wendy Foden, Dr Nicola van Wilgen

DST/NRF Centre of Excellence at the

Percy FitzPatrick Institute of African Ornithology

University of Cape Town

Rondebosch 7701

South Africa

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Abstract

It is increasingly apparent that climate change and its associated impacts are a major threat to the rich biodiversity of the Cape floristic region. As the knowledge of the associations between biological traits and climate change impacts strengthens it has become clear that the assessment of climate change vulnerability is a key consideration in the management of biodiversity. This study is the first attempt to use a trait-based approach at the scale of a single national park, focusing on the climate change vulnerability of reptile and amphibian species found in Table Mountain National Park (including historically present species). The park and its immediate surrounding areas are home to a rich diversity of herpetofauna including the Critically Endangered Table Mountain ghost frog (*Heleophryne rosei*), Rose's mountain toadlet (*Capensibufo rosei*) and micro frog (*Microbatrachella capensis*), and the Endangered western leopard toad (*Sclerophrys pantherina).* Amphibian and reptile-specific assessment frameworks of biological and ecological traits were designed to identify the species most sensitive and least able to adapt to climate change pressures. Using a combination of a literature review and expert consultation, 18 species of amphibian and 41 species of reptile were assessed. The assessment highlighted that, in the worst-case scenario, 85% of the park's reptile species and 67% of the park's amphibian species are predicted to be highly vulnerable to climate change. The southern adder (*Bitis armata*), Cape long-tailed seps (*Tetradactylus tetradactylus*), Table Mountain ghost frog (*Heleophryne rosei*) and the Lightfoot's moss frog (*Arthroleptella lightfooti)* were identified as being the species most vulnerable to climate change within their respective taxa. All three of the Critically Endangered amphibian species were identified as having both high sensitivity and low adaptive capacity to climate change.

Among the focal reptile species, climate change vulnerability was independent of current IUCN Red List status, highlighting that species currently not identified to be under threat by other anthropogenic pressures could imminently become threatened by climate change. Spatially-explicit presentation of the assessment output will help prioritise the management of areas within Table Mountain National Park that contain a high diversity of climate-vulnerable species. By reducing the threats from other human-associated impacts to these species, and by identifying when direct intervention is appropriate, the park's management can give these species the best opportunity of persistence in an uncertain climate future.

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Plagiarism declaration

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Introduction

As the first documented cases of climate-induced extinctions are reported, it is increasingly apparent that climate change vulnerability is a key consideration in the management of biodiversity (Pounds et al. 2006; Whitfield et al. 2007; Foden & Young 2016; Wiens 2016; Woinarski & Burbidge 2016; Foden et al. 2018). Changes have been observed within multiple components of the global climate system, the impacts of which have been seen on a variety of scales from organismal to ecosystem level (Garcia et al. 2014b). These impacts include but are not limited to: behavioural, demographic and phenological changes; species range displacement; changes in species range size; and novel species assemblages (Pitelka & Group 1997; Jackson & Overpeck 2000; Visser & Holleman 2001; Parmesan & Yohe 2003; Root et al. 2003; Williams et al. 2007; Foden et al. 2007; Sinervo et al. 2010; Miller-Rushing et al. 2010; Garcia et al. 2014b). Between 1880 and 2012 global mean temperatures increased by approximately 0.85 °C, while the current global failure to reduce greenhouse gas emissions sees an increasing probability of a global temperature rise of $\geq$2 °C by 2100 (IPCC 2013; Foden et al. 2018). The impacts of climate change are expected to intensify over the coming decades, as will human responses to climate change (e.g. migration, increased dam and coastal infrastructure, changing agricultural localities). Such human responses are likely to further disrupt species' ability to survive and adapt to climate change (IPCC 2014; Maxwell et al. 2015; Segan et al. 2016). Accurately predicting the vulnerability of species to climate change is therefore vital in order to minimise these negative impacts and prevent further climate change-driven extinctions. However, predicting these impacts and prioritising responses remains a major challenge for the scientific community (Foden & Young 2016).

One way in which conservation biologists attempt to predict climate change impacts is by carrying out climate change vulnerability assessments at various scales including at species, subspecies, or subpopulation level (Foden & Young 2016). In a conservation context, climate change vulnerability can be defined as "the extent to which biodiversity will be adversely affected by climate change" (IPCC 2007). The vulnerability of a species can be estimated by examining three fundamental components, namely exposure, sensitivity and adaptive capacity (Williams et al. 2008).

Exposure refers to the type, size and rate of change in climate variables in a species' current range, as well as the secondary impacts of such climate changes (e.g. changes in drought regularity) (Foden & Young 2016; Foden et al. 2018). These climate change related pressures can be broken down into abiotic, biotic, and human response pressures. Abiotic pressures are caused by changes in atmospheric concentrations of greenhouse gases, and lead to climate changes (e.g. changes in seasonality, temperature, precipitation, and drought frequency) and physical environment changes (e.g. changes in fire regime, sea level rise, and ocean acidity) (Foden et al. 2018). Biotic pressures are caused by the responses of ecosystems to climate and physical environment change. These include pressures caused by changes in community composition and habitat availability, such as dietary shift by generalist consumers and declines in dietary specialists, or more direct impacts such as the increased levels of productivity in certain plant groups from increased levels of available carbon dioxide, and subsequent bush encroachment (Hoffmann et al. 2000; Lurgi et al. 2012; Ockendon et al. 2014; Foden et al. 2018). Finally, human attempts to mitigate (e.g. conversion of natural habitat to grow biofuels (Groom et al. 2008)) and adapt (e.g. the construction of dams (Winemiller et al. 2016) to climate change have the potential to have significant impacts on biodiversity and should not be ignored when considering species exposure to climate change pressures (Turner et al. 2010; Watson & Segan 2013; Maxwell et al. 2015; Foden & Young 2016). It is important to understand that the abiotic, biotic and human response pressures described interact strongly, and these interactions are the drivers of the emerging biological responses ecologists are grappling with (Foden et al. 2018).

The sensitivity of species or ecosystems to climate change is defined as the degree to which they are likely to be affected by or responsive to changes (Foden & Young 2016). Negative and positive effects must both be considered to gain a complete understanding (IPCC 2007, 2014; Foden & Young 2016; Foden et al. 2018). A species' sensitivity to climate change is mediated by intrinsic attributes that are likely to determine the sensitivity of the species to climate change-based pressures. These attributes are most commonly defined into several broad categories: a) Specialist habitat and/or microhabitat requirements; b) Environmental tolerances or thresholds (at any life stage) that are likely to be exceeded due to climate change; c) Dependence on environmental triggers that are likely to be disrupted by climate change; d) Dependence on interspecific interactions that are likely to be disrupted by climate change; e) Rarity; f) Sensitive life history and g) High exposure to other pressures, with the most recent definitions presented in Foden et al. (2018). Detailed knowledge of the ecology of each species is required to accurately assess its sensitivity attributes, something which is unfortunately lacking for many taxa (Böhm et al. 2016; Foden & Young 2016; Foden et al. 2018).

Adaptive capacity is the degree to which a species or system is able to escape or lessen the negative effects of climate change (Foden & Young 2016; Foden et al. 2018). Adaptive capacity can be facilitated by large dispersal ability, high phenotypic plasticity, and strong micro-evolutionary potential (Foden et al. 2013, 2018). Assessing the adaptive capacity of a species or system requires consideration of both intrinsic and extrinsic elements. For example, a species may have high intrinsic dispersal ability (able to move several kilometres per day) but may be surrounded by an impermeable urban environment which limits this dispersal ability (Williams et al. 2008; Nicotra et al. 2015; Foden & Young 2016; Beever et al. 2016; Foden et al. 2018).

Currently there are three commonly used approaches to carrying out climate change vulnerability assessments: correlative, mechanistic, and trait based. Some authors use a combination of these (e.g. Midgley et al. 2010; Thomas et al. 2011; Garcia et al. 2014a; Smith et al. 2016). Conservation practitioners must consider the scope, data availability, and time available for an assessment before committing to a particular approach (Pacifici et al. 2015; Foden et al. 2018).

When fine-scale point locality data are available for a species, it may be most appropriate to undertake a correlative or mechanistic approach. The correlative or ‘climate-matching’ approach uses data from the observed geographical distribution of a species to estimate the current climatic conditions in which the species occurs, i.e. the “climate envelope”. Climate envelopes are then used in combination with climate projections to model the suitable climate space available to a species in the future (Foden et al. 2018). In essence these models try to assess the realised climate niche of the species currently and in the future, and how this will influence their distribution spatially (Pacifici et al. 2015). The vulnerability of a species can be predicted by examining the differences in the current distribution and the projected future distribution in terms of the area’s location, size, fragmentation and the degree to which the two distributions overlap (Huntley & Green 2007; Garcia et al. 2014a; Foden et al. 2018). This correlative approach is the most commonly used because it is relatively cheap, rapid to undertake, and occurrence data are available for many species (Pacifici et al. 2015).

The correlative approach has been shown to perform relatively well at predicting recent population trends when compared to species' observed responses to recent climate changes (Gregory et al. 2009). However, it does have its drawbacks. The first problem is that the general circulation models used to predict future climate conditions do so at a coarser resolution than the biological and environmental data used to train the correlative models. This is particularly problematic for species which have few location data points (rare or under-sampled species) or have small geographic distributions because the general circulation models are at an inadequate resolution to produce meaningful results (Guisan & Thuiller 2005; Pacifici et al. 2015; Foden et al. 2018). Additional problems may arise when a lack of biological knowledge of a species leads to inappropriate assumptions being made around which factors drive the current realised niche of a species. Abiotic, geographic, historical, biotic and anthropogenic factors can all influence a species' niche, and it is often difficult to assess to what degree a species' climatic tolerances determine its current realised niche (Guisan & Thuiller 2005; Pacifici et al. 2015). Furthermore, the results of correlative models can vary greatly depending on method and model selection used, and thus it is recommended to use an ensemble of statistical methods to summarise trends (if any) across model predictions (Pacifici et al. 2015). However, it is important to take into account the assumptions of each model; if all the models have the same incorrect assumptions then this recommendation would not increase confidence in the model prediction.

Where detailed life history information as well as fine-scale species occurrence data are available then a mechanistic approach can be used. Mechanistic models use process-based simulations to predict climate change impacts on a species and its likely responses to these impacts by incorporating known biological tolerances, interactions and processes (Morin & Thuiller 2009; Foden & Young 2016). Mechanistic models can be categorised into niche or demographic models (Foden et al. 2018). Demographic models aim to assess the vulnerability of a species through probability of extinction. Niche models aim to predict the future distribution of species by using estimates of their fundamental niche, which can be defined through experiments or observations of the species' physiological tolerances (e.g. Monahan 2009; Sunday et al. 2012) and through energy balance equations (e.g. Kearney & Porter 2009). The benefit of mechanistic models compared to a correlative approach is that they can incorporate a diverse collection of climate change impact mechanisms, such as changes in availability of suitable habitat and resources (e.g. Hunter et al. 2010), interspecific interactions such as competition and predation (e.g. Fordham et al. 2013), genetic adaptation, phenotypic plasticity (e.g. Chevin et al. 2010), sub-population or demographic-class-specific mortality estimates, and morphological factors. They can also facilitate the inclusion of the interaction of climate change with other pressures such as land use change (Mantyka-Pringle et al. 2016; Foden et al. 2018). Although likely to be the most robust method, the extensive and detailed data requirements, high cost, current poor performance and high expertise required to parameterise and run these models hinder the application and practicality of this approach (Kearney & Porter 2009; Pacifici et al. 2015; Foden & Young 2016; Foden et al. 2018).

Where life history information and broad-scale distribution data are available, a trait-based vulnerability assessment (TVA) can be used (Foden & Young 2016). This approach uses the developing knowledge of associations between biological traits and climate change impacts, in conjunction with the best available biological and life history information, to rank and/or score climate vulnerability of species based on the presence of biological traits that may increase/reduce a species' sensitivity and/or adaptive capacity to climatic changes (e.g. Foden et al. 2013; Zhang et al. 2019). Biological traits in this context include behavioural, physiological and life history characteristics which determine the species ability to withstand changes in environmental cues and interspecific interactions and exposure to sub-optimal conditions, and their ability to recover from climate change impacts (Foden & Young 2016). The approach is often applied at the scale of specific taxa (e.g. Californian birds (Gardali et al. 2012) and reptiles globally (Böhm et al. 2016)), using taxon-specific frameworks containing biological traits known to increase sensitivity and/or lower adaptive capacity to climate change (e.g. low physiological tolerances to changes in temperature and limited intrinsic dispersal ability). Each species within the scope of the study is then examined for the presence of these traits (Foden & Young 2016; Foden et al. 2018). Depending on the scale of the assessment, the approach may also consider exposure of each species to climate change, which can be estimated using GIS based modelling, various statistical methods, or expert judgement. The approach is applicable to all species (including range restricted and rare species) and can be used to evaluate which species are most in need of conservation intervention (Foden & Young 2016).

The trait-based approach is limited by the lack of certainty in defining thresholds of sensitivity or low adaptive capacity within continuous traits which are used to define extinction risk (Pacifici et al. 2015). Thus, in many cases traits such as these are given arbitrary thresholds, e.g. low vulnerability is scored for the species with the highest 75% of precipitation variance and high vulnerability is given to species with the lowest 25% of precipitation variance (e.g. Foden et al. 2013; Böhm et al. 2016). Furthermore, in some assessment’s traits are weighted with equal importance in determining a species vulnerability when in reality this is unlikely to be the case (Pacifici et al. 2015). The specific nature of each assessment framework does not yet allow for cross-assessment comparisons, although recent developments in the methodology may change this (Thurman et al. in review). Furthermore, large data gaps in species-specific knowledge of these traits is often the Achilles’ heel of the approach, and there is a currently a lack of validation for the approach (Pacifici et al. 2015; Foden & Young 2016; Foden et al. 2018). However, trait-based assessments are less time-intensive, cheaper, and require less modelling expertise than the alternatives, and are therefore more attractive to conservation organisations (Foden & Young 2016; Foden et al. 2018). The trait-based approach also allows for the examination of many climate change pressures simultaneously, and the incorporation of biological traits allows for the consideration of species' individualistic responses to climate change (Foden & Young 2016).

Although each of the approaches described have draw-backs, their predictive capacity may improve when they are used together (Willis et al. 2015; Foden et al. 2018). For example, information from a TVA can be incorporated into species distribution models (SDMs) used in a correlative approach. This information could include traits such as dispersal ability or habitat preferences (Warren et al. 2013; Willis et al. 2015). In a hypothetical scenario, an SDM may predict that a species will see an increase of 80% in its available climate space, however when information such as dispersal ability is included, the model may show that the species' available space will actually only increase by 20%, because much of the new climate space exceeds the dispersal ability of the current population (Willis et al. 2015). Information from SDMs can also be incorporated in TVAs. For instance, where high quality data on species distribution and climate variables are available, SDMs can be used to highlight the most important climate variables to be considered when assessing climate change exposure and sensitivity of each species. Furthermore, the outputs from SDMs can also be used to provide relevance to the degree of dispersal ability of each species, and evaluate whether this is adequate to track climate shifts (Willis et al. 2015). The most comprehensive assessment places species into categories of risk based on the outputs of correlative and mechanistic modelling approaches in combination with biological and life history information (e.g. Thomas et al. 2011). However, these assessments are extremely rare and impractical for most species because the level of detailed data required is lacking for the majority of the world's taxa.

Two taxa predicted to be particularly vulnerable to climate change are reptiles and amphibians. Many may instinctively think that reptiles may be one of the most resilient taxonomic groups to climate warming because of their generally good ability to avoid thermal stress, resist water loss, and withstand high body temperatures (Huey et al. 2010). However, there is evidence that reptiles are negatively affected by climate change in many ways, including, but not limited to, skewed population sex ratios, altered distributions, increased competition, reduced body size, and reduced pathogen resistance (Janzen 1994; Bickford et al. 2010; Dang et al. 2015). The ectothermic physiology of reptile species is a key consideration when examining the climate change vulnerability of the group (Huey et al. 2012). For example, many temperate-zone reptile species may experience energetic shortfalls during the spring when reproductive energy requirements are most acute. This is due to increased spring temperatures forcing individuals to spend increased periods of time in cool thermal refuges, leaving less available time for foraging and resulting in reduced reproductive success (e.g. as seen in *Sceloporus serrifer* (Sinervo et al. 2010)). Alarmingly, *S. serrifer* is a strong model for many lizard species. For example, it thermoregulates carefully, is active at high body temperatures and is diurnal (Huey et al. 2010). It is becoming clear that reptiles are extremely vulnerable and could potentially suffer devastating population declines within the next 60 years (Sinervo et al. 2010).

Amphibians share many of the vulnerabilities of reptiles, but face exposure to both terrestrial and aquatic changes in temperature and precipitation. Amphibians have shell-less eggs, permeable skin, and complex life histories which often require specific microhabitats, all of which make them particularly vulnerable to climate changes (Li et al. 2013). There is a growing body of literature highlighting the current and predicted future impacts of climate change on amphibians. As with many taxa there is already evidence of climate change induced changes in body size, breeding phenology, and shifts in species distributions (Beebee 1995; Raxworthy et al. 2008; Caruso et al. 2014). Climate change induced disease dynamics is having a particularly destructive impact on global amphibian biodiversity. The pathogenic chytrid fungus (*Batrachochytrium dendrobatidis*) is suspected to have contributed to many recent extinctions in the American tropics (Pounds et al. 2006). Pounds and colleagues proposed that climate-change-induced increase in temperatures in many highland localities in the region favours growth of *Batrachochytrium*, leading to more outbreaks. An additional threat which is particularly damaging to amphibians is increased ultraviolet-B radiation (UVB). Depletion of the stratospheric ozone layer has increased the levels of UVB radiation reaching the Earth's surface (Kerr & McElroy 1993; Madronich et al. 1998). However, exposure to increased UVB and its impact on amphibians has been the subject of debate, as effects of UVB radiation appear to be species-specific (Bancroft et al. 2008). UVB radiation is most damaging when it acts synergistically with other environmental stressors (e.g. agricultural contaminants) (Bancroft et al. 2008). For example, embryos of the Pacific treefrog (*Pseudacris regilla*) had a lower survival rate when exposed to both UVB radiation and nitrate, compared to exposure to either of these stressors individually (Hatch & Blaustein 2003).

Reptiles and amphibians may also be limited in their ability to adapt to the predicted climatic changes because many species have relatively long generation times, inhibiting rapid genetic responses (Huey et al. 2010). Although several species have shown evidence of adaptive behavioural responses it is unclear whether these will in fact buffer them against selection and therefore hinder genetic adaptation (Huey et al. 2003; Kearney et al. 2009). Furthermore, anthropogenic barriers caused by human development may limit the range shift of even the species with strongest dispersal ability (Foden et al. 2013, 2018).

Here I use a trait-based method to assess the climate change vulnerability of reptiles and amphibians in Table Mountain National Park (TMNP). TMNP is one of the most iconic natural wonders in the world. It is located in the hyper-diverse Cape Floristic region (CFR). This biome covers just 3.5% of southern Africa but contains 41% of its plant species (Cowling & Hilton-Taylor 1994). Much of the CFR is found within the Western Cape, home to a rich diversity of herpetofauna with 60 indigenous species of amphibians, of which 36 are endemic, and 146 indigenous species of reptile, of which 22 are endemic (Turner & de Villiers 2017a, 2017b). TMNP is approximately 24 500 hectares in size and is currently home to 41 species of reptile and 18 species of amphibian, four of which are endemic to the park or are restricted to the park and within 5kms of its boundary. Three of these species are listed as Critically Endangered on the IUCN Red List, namely micro frog (*Microbatrachella capensis),* Table Mountain ghost frog (*Heleophryne rosei*), and Rose’s mountain toadlet (*Capensibufo rosei*) (IUCN SSC Amphibian Specialist Group 2017a, 2017b, 2017c). Unfortunately, TMNP is not immune to the effects of climate change. It has seen an average minimum temperature rise of 1.05 °C since 1960 and average maximum temperature rise of 1.25 °C, and average annual temperature is predicted to rise by between 0.9 to 1.8 °C by 2050 (van Wilgen et al. 2016; van Wilgen & Herbst 2017). However, these climate change predictions are mild relative to many of the other national parks of South Africa, thus the park is a key area of climate change refuge (van Wilgen & Herbst 2017). The high diversity of herpetofauna and presence of several Critically Endangered endemic species within the park makes it a priority area for a climate change vulnerability assessment.

In order to assess the vulnerability of the reptiles and amphibians to climate change in TMNP, I set the following objectives**:**

1. Identify biological and ecological traits that elevate risk of climate change impacts for reptiles and amphibians.
2. Use this information to provide the basis of an amphibian- and reptile-specific climate change vulnerability framework.
3. Use these two frameworks to carry out a climate change vulnerability assessment of all reptile and amphibian species of Table Mountain National Park, using published data and expert opinion.
4. Compare the assessment outputs with changes in the scoring methodology (e.g. trait weightings).
5. Provide the outputs of the assessment in a format which can be incorporated into the spatial planning of South African National Parks.

Methods

Assessment area and species present

This study aimed to assess the climate change vulnerability of all terrestrial and freshwater reptile and amphibian species known to be indigenous to the Table Mountain National Park (TMNP; 33.9604° S; 18.4013° E); including species that historically occurred within the park but no longer have extant populations (Figure 1). TMNP offers the difficult challenge of conserving a vital biodiversity hotspot which is almost completely surrounded by South Africa’s third largest city, Cape Town. This has led to a plethora of pressures for the park management to deal with, including: increasing densification of urban settlements surrounding the park; heavy utilisation of the park’s biodiversity for recreation, traditional medicines, food, and water; invasion by alien species; and the synergistic effects of the aforementioned pressures with climate change (van Wilgen & Herbst 2017). The initial reptile and amphibian species lists for the park were provided by scientists from South African National Parks (SANParks), but they acknowledged that the reptile list in particular required several updates. To check the accuracy of the lists I consulted distribution estimates in field guides (Marais 2004; Alexander & Marais 2007; du Preez & Carruthers 2009), The Red Atlas and Data Book for both amphibians and reptiles (Minter et al. 2004; Bates et al. 2014), and IUCN Red List species distribution shape files (IUCN 2019). Using the software ArcGIS version 10.7.1. I clipped the distributions of all reptiles present in the IUCN dataset to the park boundaries of TMNP to create a preliminary species list. Once the literature and IUCN distributions had been cross-checked, an updated version of each groups' species list was created and sent to several herpetology experts (K. Tolley, J. Measey, A. de Villiers, A. Turner, B. Maritz, personal communication). Although the southern adder (*Bitis armata*) and micro frog were not classified as present in the park using the methodology described, they were added to this study because they were likely to have occurred in the park within the recent past, and thus could be candidates for reintroduction (K. Tolley, J. Measey, A. de Villiers, A. Turner, B. Maritz, personal communication). A total of 17 reptile and four amphibian species previously listed were removed, with 18 having insufficient evidence of ever occurring within the park and three being extralimital or alien species (Appendix A1a and b). Alien and extra-limital species were excluded from this initial assessment because they were deemed to be of lower conservation value, and therefore not considered for management prioritization. A total of 41 reptile species and 18 amphibian species remained for assessment (Appendix A2 and A3).

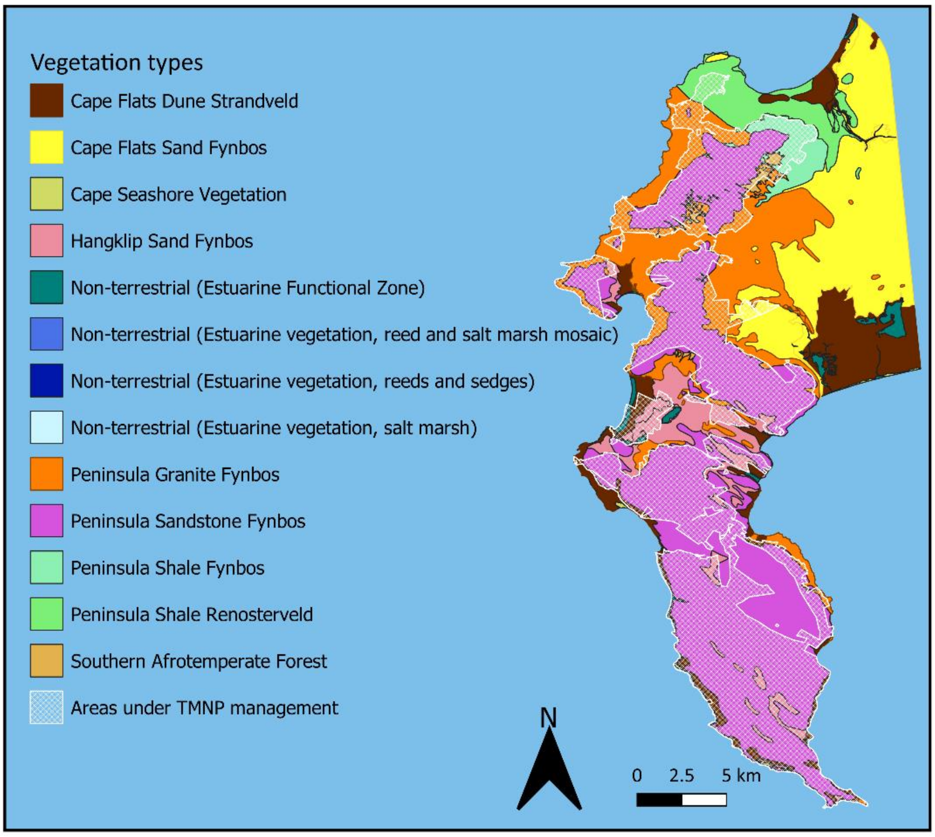

Figure 1. The Cape peninsula and its associated vegetation types (SANBI 2018). Areas under the management of Table Mountain National Park are highlighted by white crosshatching.

Species distributions

Each species' global distribution polygon was downloaded from IUCN Red list spatial data and mapping resources (IUCN 2019). To improve accuracy, I consulted experts to review and refine the IUCN distributions, particularly to refine distributions within the park (J. Measey, A. de Villiers, K. Tolley, personal communication). Appropriate edits were made to the distributions in ArcGIS. The Frog Atlas and Reptile Atlas resources were considered during the delineation of the IUCN range maps and were therefore not consulted again. Other distribution data sources such as iNaturalist could be used to further refine range information, but the extent of the cleaning requirements was deemed beyond the scope of this study. It must be highlighted that the resolution of the reptile distributions was coarser than that of the amphibian species. This is largely due to more extensive knowledge of amphibian distributions within the park and the fact that the specific microhabitats of some species make the amphibian distributions easier to refine.

Trait-based vulnerability assessment

While species distributions are commonly used to assess species' vulnerability to climate change, TMNP's small geographic extent, highly varied topography and small ranges of many focal species make use of such methods unreliable (Platts et al. 2014, Foden & Young 2016). Instead, we followed a trait-based approach, which can be applied at localised scales and for species with small geographic ranges. This is the first use of a trait-based assessment approach at protected area scale in South Africa. A key aspect of the trait-based approach is the development of the framework of traits deemed to be adequate proxies to assess each species sensitivity and adaptive capacity to climate change (Foden & Young 2016; Foden et al. 2018). Considering that the life histories and ecology of reptiles and amphibians can differ, it was important to design a tailored framework for each group. One of the most obvious differences between these taxa is that amphibian species face exposure to both terrestrial and aquatic changes in temperature and precipitation, while the reptiles face mainly terrestrial changes. To build each framework, I carried out an extensive literature review of the life histories and associated vulnerabilities to climate change of each species, and the traits used in previous attempts to assess these taxa. An initial draft of each trait framework was presented to a panel of expert herpetologists (Appendix C) during a workshop held on the 4th of November 2019 at the Cape Research Centre to discuss the approach and to critique my selection. Several traits were added and removed from each framework (Appendix B1 and B2). The final reptile framework comprised 13 traits affecting sensitivity and four affecting adaptive capacity. The amphibian framework also consisted of 13 sensitivity traits and four adaptive capacity traits. The frameworks followed a similar format to that of Foden et al. (2013), with thresholds set for each trait to enable categorisation into the vulnerability categories: ‘Low’, ‘High’ or ‘Unknown’. Data were collected per species for each of the traits using published and grey literature. After the initial literature review, traits that had missing information for any species were examined by several herpetology experts to identify additional literature sources and add expert knowledge on particular species or traits (Appendix D). For species trait combinations with no published literature or expert knowledge, ‘Unknown’ was scored. The experts were also asked to give each trait a low, medium or high score based on the estimated impact each particular trait could have on a species climate change vulnerability. In the following sections I outline the traits sets used within the assessment and the hypotheses for the inclusion of each trait. As outlined in Foden et al. (2018), the trait sets aim to ensure a complete assessment of sensitivity and adaptive capacity of each species to climate change. The abbreviations RS and RL represent reptile sensitivity trait and reptile low adaptive capacity trait, respectively, AS and AL represent amphibian sensitivity trait and amphibian low adaptive capacity trait, respectively.

Trait sets

The trait variables and thresholds used to score each of the taxon groups are summarised in Appendix E1 and E2. All spatial data analysis was carried out in ArcGIS version 10.7.1. Each species’ sensitivity and adaptive capacity was considered across its entire South African distribution.

High Sensitivity

A. Specialised habitat and microhabitat requirements

Traits used within this trait set were the same for both the reptile and amphibian frameworks. However, the variables used to score them were specific to the taxa (see Appendix E1 and E2).

Habitat specialisation (RS1 and AS1): This trait is based on the hypothesis that habitat specialists are more sensitive to climate change as they are tightly coupled to a specific habitat requirement and thus have fewer habitats available to them. It has been found that species which have become specialised to a single habitat type are disproportionately among the species identified to be declining and threatened by extinction (Lurgi et al. 2012; Foden et al.

2013). A changing climate is likely to lead to novel ecosystems, as coexisting species experience different degrees of sensitivity and responses (Lurgi et al. 2012). Species which have evolved to utilise specific conditions are less likely to be resilient to changes in their habitat.

Reptile species were scored using the number of substrate types occurring within their distribution. Substrate type data was sourced from The Soil and Terrain Database for Southern Africa (SOTERSAF version 1.0) at a scale of 1:2,000,000 (Batjes 2004). Substrate types were deemed to be a more biologically meaningful representation of habitat specialisation for reptiles than vegetation types (K. Tolley personal communication). Species were assumed to have high habitat specialisation if their whole distribution was made up of one substrate type. Amphibian species were scored using the number of vegetation types occurring within each species distribution. Vegetation data was sourced from the 2012 Vegetation Map of South Africa, Lesotho and Swaziland at a resolution of 1:250,000 (SANBI 2012). The 2012 version was selected over the more recent 2018 version because it also includes water bodies, making it more meaningful for many amphibian species (Z. Ebrahim personal communication). Species were assumed to have high habitat specialisation if their entire range was made up of one vegetation type.

Microhabitat specialisation (RS2 and AS2): Similar to habitat specialisation but at a finer scale, this trait is based on the hypothesis that species that occur only or predominantly in microhabitats likely to be negatively impacted by climate change are at greater risk of sensitivity. Furthermore, species that are dependent on specific microhabitats are likely to be more reliant on buffering from extreme temperatures, and thus loss of these microhabitats through climate change will no longer provide temperature buffers for these species (Scheffers et al. 2014). However, if the microhabitat space was unlikely to be affected by climate change (e.g. cave specialists) then these species were not considered to be climate change sensitive.

Reptile and amphibian species were assessed by examining the microhabitats utilised by each species. For the reptile species these were categorised into: Saxicolous (rock dwelling); Arboreal; Terrestrial; Under dead organic matter; Semi-aquatic and Termite mounds. Reptile species which rely exclusively on dead organic matter were assumed to be highly sensitive based on microhabitat specialisation. Amphibian microhabitats were categorised into: Torrents; Temporary water (Puddles, Vleis/Pans); Seeps; Lake/Estuarine systems; Permanent Water (excluding torrent); Terrestrial; and Garden Ponds. Species were assumed to be of high sensitivity if they are specialised to only one particular microhabitat (excluding garden ponds) or are associated with temporary water, and/or seeps, and/or terrestrial microhabitats.

High elevation specialist (RS3 and AS3): This trait is based on the hypothesis that high-elevation specialists face the two-pronged threat from loss of suitable climate space, and increased competition from generalist species shifting their ranges into areas previously climatically sub-optimal to them. This hypothesis is based on evidence of shifting climate conditions and the subsequent observed and modelled response of species through the shifting of their distributions to higher elevations, leading to the loss of high elevation specialists (Raxworthy et al. 2008; McCain & Colwell 2011). Both reptile and amphibian frameworks assessed species by maximum elevation records available in published or grey literature. Species were assumed to be highly sensitive if they occurred exclusively above 1000m.

B. Narrow environmental tolerances or thresholds that are likely to be exceeded due to climate change at any stage in the life cycle

Narrow temperature (RS4 and AS4) tolerances: The assessment of this trait is based on the hypothesis that species that experience low temperature variability across their known distribution are most sensitive to temperature change due to climate change. For both reptile and amphibians, the average absolute deviation (AAD) in temperature across the species range was measured. AAD examines the dispersion within a data set and is defined as:

$$\frac{1}{n}\sum_{i=1}^{n}|X_i - m(X)|$$

In this case each x represents a monthly mean temperature for a cell within a species' range (Foden et al. 2013). The data comprised average monthly temperatures (°C) between the years 1970 – 2000, sourced from WorldClim 2.0 version 1 at a resolution of 1km^2 (Fick & Hijmans 2017). Climate data was clipped to the distribution of each species within ArcGIS. AAD was calculated using R version 3.5.1 (R Core Team 2018), with the additional packages 'Raster' and 'DescTools' (Hijmans 2019; Signorell 2019).

Narrow precipitation (RS5 and AS5) tolerances: This trait is based on the hypothesis that species that have low variability in precipitation across their range are most sensitive to precipitation change. Species with narrow tolerance ranges for environmental variables such as temperature and precipitation are particularly vulnerable to climate change because their physiology and ecology is adapted to these specific conditions (Deutsch et al. 2008). For example, many arid-adapted/thermal specialist species operate at critical physiological levels of water and temperature requirements and are thus under particular threat from climate change (Huey et al. 2012; Trull et al. 2018).

Average absolute deviation (AAD) in precipitation across reptile and amphibian species' ranges was used to assess this trait. The data comprised of average monthly precipitation levels (mm) between the years of 1970 – 2000, sourced from WorldClim 2.0 version 1 at a resolution of 1km^2 (Fick & Hijmans 2017). AAD was calculated using the method described in the previous trait description.

<u>Intolerant of changes to fire regime (RS6 and AS6)</u>: This trait is based on the hypothesis that species that rely on a specific fire regime across their range are more likely to be sensitive to climate change. It is predicted that the frequency and intensity of wildfires will increase due to climate change within the Cape Floristic Region (Wilson et al. 2010, 2015). For both reptile and amphibian frameworks, species were examined for evidence of high fire-based mortality and/or fire listed as a threat within a species Red List assessment. Where evidence was found, species were assumed to be intolerant to changes to fire regimes.

<u>Seasonal activity period restricted by temperature and/or rainfall (RS7)</u>: This trait is based on the hypothesis that species whose activity is already limited by low rainfall or high temperature will see increasing periods of conditions unsuitable for activity under predicted climate change. Increased periods of temperature and/or precipitation exceeding the physiological limits of the species will leave less time for important activities such as food acquisition (e.g. Sinervo et al. 2010). Reptile species were examined for evidence of seasonal activity related to climatic conditions. Species were identified to have high sensitivity when evidence that they aestivated for part of the year because high temperatures and/or low precipitation levels were present.

<u>Reliant on cloud/fog cover (RS8 and AS7):</u> Based on the hypothesis that species that are reliant on cloud cover to stay within the limits of their temperature and precipitation tolerances are more vulnerable to changes in cloud cover frequency (e.g. Pounds et al. 1999). Both reptiles and amphibians were examined for the presence of evidence of reliance on cloud cover within the literature or from expert opinion where the former was non-existent. Where evidence was found, the species was assigned as having high sensitivity based on a reliance on cloud/fog cover.

<u>Tadpoles reliant on highly oxygenated water bodies (fast flowing streams) (AS8):</u> An amphibian-specific trait. Based on the hypothesis that species restricted to highly oxygenated

habitat are likely to be sensitive to declines in dissolved oxygen predicted at warmer temperatures. Fast flowing water bodies are generally associated with higher oxygen concentrations than still water. The habitat requirements of tadpoles of each species were examined, those which had tadpoles requiring fast flowing water bodies (e.g. torrents) were deemed to be highly sensitive to the effects of climate change.

Low environmental heterogeneity within range (RS9): A reptile-specific trait. Based on the hypothesis that more heterogeneous environments offer more opportunity for climate refugia to buffer changes in environmental conditions. To assess the environmental heterogeneity of each species distribution, I calculated the Vector Ruggedness Measure (Sappington et al. 2007) within ArcGIS. This measure of ruggedness was selected because it incorporates the heterogeneity of both aspect and slope, and thus provides a better representation of the heterogeneity of terrain than methods based only on slope or elevation alone (Sappington et al. 2007). This is because it measures vector dispersion in three dimensions and then combines variation in slope and aspect into a single value. This allows for differentiation between steep even terrain and steep uneven terrain, important for determining the diversity of microclimates in an area (Sappington et al. 2007). The AAD of values of ruggedness across the species' ranges were calculated using identical methodology described in trait RS5 and AS5. Species with the lowest 25% of AAD values of ruggedness were identified as being particularly sensitive to climatic changes because of fewer opportunities for climate refuge within their range when compared with the other reptile species within the assessment.

C. Dependence on a specific environmental trigger or cue that is likely to be disrupted by climate change (AS9): Based on the hypothesis that species may become asynchronous or uncoupled from the required resources or conditions, if specific life events (e.g. migration, breeding, egg laying, hibernation and emergence) are triggered by environmental conditions (Donnelly & Crump 1998; Carr et al. 2013). The relevant published and grey literature was examined for evidence of environmental triggers within any period of their life history. Species that rely on these triggers were assumed to be of high sensitivity. This trait was also considered for reptiles but a lack of data inhibited its use.

D. Dependence on interspecific interactions that are likely to be disrupted by climate change

Narrow diet breadth (RS10 and AS10):

It has been established that dietary niche breadth/ diet specialisation is likely to be a key determinant of climate change sensitivity across taxa. This is largely based on a theoretical understanding that predicts that species with narrower diet breadth are more vulnerable to dietary shifts and phenological mismatches than dietary generalists (McKinney 1997; Lurgi et al. 2012). More specifically, if the food resource of a specialised species is likely to decline in the area of assessment then said specialist is likely to see population declines if it is unable to adapt behaviourally or follow the range adjustments of its food resource. Low dietary versatility was defined as a species which is dependent on one species for the majority (>90%) of its diet due to physiological or morphological adaptation (Colles et al. 2009).

E. Rarity

Endemic/rare (RS11 and AS11): This trait is based on the hypothesis that inherent vulnerability of small populations to Allee effects and stochastic events and their lower ability to recover following perturbations makes these species more at risk (Allee & Bowen 1932; Foden et al. 2013). Within both reptile and amphibian frameworks species were deemed to be of high sensitivity if they were endemic to TMNP.

F. Sensitive life history

Semelparity (RS12): A reptile-specific trait. Based on the hypothesis that species with semelparous life histories (i.e. breed once and die) have no buffer if they fail to reproduce, which is predicted to occur more frequently under novel conditions (R. Huey personal communication). If evidence of semelparity was present for a species it was deemed to have high vulnerability.

Eggs laid in leaf litter, moss, ephemeral water sources (AS13): An amphibian-specific trait. Based on the hypothesis that species that lay in leaf litter, moss, or ephemeral water sources will be more vulnerable to desiccation and/or flooding before metamorphosis, when exposed to the likely increase in temperature and more erratic and heavy rainfall (Bickford et al. 2010; van Wilgen et al. 2016; van Wilgen & Herbst 2017).

Inability to reproduce more than once annually in the event of lost clutch/litter (RS13 and AS12)

A trait used in both reptile and amphibian frameworks. Based on the hypothesis that species limited to few reproductive attempts (≤1 per year) are more likely to be at risk from breeding failure from increasingly common extreme events. The maximum number of clutches per year and the ability to reproduce at any time of year were examined for each species. Species which had a mean number of ≤ 1 clutches per year and which could only reproduce once annually were deemed to be of high sensitivity.

Low adaptive capacity

G. Poor dispersibility

Dispersal limited by physical barriers (RL1 and AL1): This trait was examined within both taxa frameworks. This trait is based on the hypothesis that species which are limited to cooler latitudes already have no ability to shift latitudinally in order remain within their environmental tolerances. Within ArcGIS each species distribution was examined relative to its position latitudinally to the most southerly point of Africa. Following the methodology described in Foden et al. 2013, species whose distribution occurred completely within 10 degrees of latitude of the most southerly point were deemed to have limited dispersal ability. Examining species intrinsic dispersal ability was deemed unnecessary considering the park is at a similar latitude to Africa's most southerly point (Cape Agulhas). Furthermore, species-specific information was lacking.

H. Limited behavioural adaptation

No commensalism with humans (RL2 and AL2)

This trait falls into both G (Poor dispersibility) and H (Limited behavioural adaptation) trait set groups, and was considered in both frameworks. It is based on the hypothesis that species which are unable to utilise or move through human-dominated landscapes face the two-pronged threat of a lack of connectivity with populations outside the park and declining suitable habitat outside of protected areas. This is particularly applicable to TMNP as it has become almost completely surrounded by dense urban landscapes. Species that have no evidence of being able to utilise or move through urban environments were therefore deemed to have lower adaptive capacity.

Foraging mode limits behavioural adaptation (RL3): A reptile specific trait, based on the hypothesis that active visual foragers will be most affected by an increase in temperatures above optimal tolerances as it is unlikely that they could shift to nocturnal activity considering their diurnal visual adaptations (K. Tolley personal communication). Where data were available, species that rely strictly on diurnal active visual foraging were scored as highly vulnerable under this trait. Species with evidence of cathemeral or nocturnal ability were excluded as were those that use sit and wait or mixed foraging techniques.

I. Poor evolvability

Low microevolutionary potential (RL4 and AL3): This trait was considered for both taxa. It is based on the hypothesis that species with low microevolutionary potential will likely be unable to adapt to the rate of climate change predicted to occur in the future. To examine the microevolutionary potential of each species, its mean annual reproductive output, genetic diversity, and degree of population fragmentation was examined. Species were evaluated to have low microevolutionary potential if they were found to have ≤2 offspring per year (a), and/or evidence of low genetic diversity within populations, and/or highly fragmented populations (b).

Slow generation time (AL4): This trait is based on the hypothesis that species with greater longevity and/or generation length have lower microevolutionary rates. Includes species with delayed sexual maturity (relative to life span). The lack of available data on the lifespan of the amphibian species within the study made it difficult to set thresholds relative to life span. Thus, all species that spend ≥12 months as a tadpole were designated to have lower adaptive capacity.

Vulnerability scoring and analysis

A challenging and poorly explored aspect of trait-based assessment is the role of different methods for combining trait and trait dimension scores in influencing overall measures of climate change vulnerability. Currently the majority of assessments have used one of three methods to score each species (Foden & Young 2016). These methods include scoring each species' traits via numerical values (e.g. 1 to 3 (Gardali et al. 2012)), ordinal categories (e.g. High/Low (Foden et al. 2013)) or ranks (e.g. using a hierarchical decision tree (Smith et al. 2016)). Once each species has a score for each trait there is then the challenge of combining these scores into a meaningful overall vulnerability score. When traits do not interact, it is recommended to use a simple additive method (e.g. score 1 + score 2 + ….). This method is based on the assumption that any single trait can be substituted for another to represent the same level of sensitivity. Where traits are likely to mitigate or exacerbate the impact of others, a multiplicative approach is most appropriate (e.g. score 1 x score 2 x…) (Foden & Young 2016). A rule-based system can also be used when certain traits make others irrelevant, in essence 'trumping' the others (Foden & Young 2016). Considering the lack of literature on score-combining approaches, I decided to examine the impact of selecting different approaches on the overall scores of each of the species I considered. I scored each species' vulnerability using ordinal and additive approaches. The ordinal approach used the methodology of Foden et al. (2013) and Böhm et al. (2016), which sets thresholds to define high and low scores for each trait. The presence of one or more high scores within a vulnerability dimension (e.g. sensitivity, adaptive capacity and exposure) leads to a high score being given for that particular dimension. Species with both high sensitivity, low adaptive capacity and high exposure are deemed to be the most vulnerable to climate change. In the current assessment, it was appropriate to assess sensitivity and adaptive capacity, considering exposure would be uniform within the park. For each trait, the species was scored using the thresholds outlined in Appendices E1 and E2. As with previous assessments, if a species scored high for one or more traits it was scored high for the associated dimension. For example, if a species of amphibian displayed a low diet breadth it would be deemed to be highly sensitive to climate change, and if it displayed evidence of low genetic diversity then it would be scored as having low adaptive capacity. Species that scored high for both the sensitivity and adaptive capacity dimensions would be identified to be the most vulnerable using this method.

I then repeated the scoring using an additive approach (e.g. score trait RS1 + RS2+…), with the species with highest scores being most vulnerable. It was assumed that a greater number of high sensitivity and low adaptive capacity traits present was an adequate representation of increased vulnerability. This method was also repeated but with weighted scores. Traits were weighted based on expert opinion, which attempted to differentiate between the relative impact their presence would have on a species. Traits were weighted with values of 1 (Low), 2 (Medium), and 3 (High). It is likely to be inaccurate to assume that all traits hold equal importance amongst the species within this assessment. By using expert-based weightings, we were able to attempt to account for this.

Exploring uncertainty

Where information was missing within the data sets, the previously described scoring methods were run twice, once with all the missing data assumed to score as low and once with all missing data assumed to score high. This allowed for the creation of best- and worst-case scenarios. Some traits within both the reptile and amphibian framework involved continuous variables which had no species-specific established vulnerability thresholds. For these variables the species whose trait values fell within the lowest 25% of all values were scored within the 'high' threshold. The reptile framework had a total of three traits which used the 25% thresholds, namely narrow temperature tolerance (RS4), narrow precipitation tolerance (RS5) and low environmental heterogeneity within range (RS9). By examining the effect of shifting thresholds by 10 % (+10% for more lenient and -10% for a stricter threshold) for the traits RS4, RS5, RS9, I attempted to minimise the influence of the arbitrary thresholds on the results.

Spatial representation of scores

To provide recommendations for park management it was important to present the scores spatially. This allows for identification of areas within the park that contain high richness of climate change vulnerable species. Using the refined species distributions described previously, the distributions of each species identified to be highly vulnerable to climate change were overlaid to create a heat map of vulnerable species diversity. Maps were created for each group under worst- and best-case scenarios in ArcGIS. All polygons were rasterised to a resolution ~40m^2.

Comparison between trait-based assessment and IUCN Red List status

To examine the relationship between this assessment and the current IUCN Red List categorisation of each species, a Spearman's rank correlation was run. The test examined the correlation between the scores of climate change vulnerability and the current statuses of the species under the IUCN Red List assessment criteria. Each of the assessments and their associated categories was assigned a rank in order to carry out the test (e.g. Least Concern = 1, Near Threatened = 2…., High = 1 and Low = 2). The R package 'pspearman' and function 'spearman.test' were used (Savicky 2014).

Body size and vulnerability

A biological characteristic that is believed to have an important impact on climate change vulnerability is body size. Among reptiles and amphibians, the relationship between body size and environmental variables is complex. There is evidence that some reptile groups follow Bergmann's rule (Bergmann, 1847), whilst others follow a converse relationship (Ashton & Feldman 2003). A recent study highlights that there is no evidence of Bergmann' rule among squamate reptiles (lizards, snakes and amphisbaenians), with the authors stressing that the evolutionary relationships between body size and climate should be examined on a case-by-case basis (Slavenko et al. 2019). Studies of thermoregulation among amphibians highlight skin resistance to water loss as well as body size both significantly affect body temperature and time to desiccation (Tracy et al. 2010). It seems that having smaller or larger body size may be advantageous depending on the nature and extent of temperature changes. In theory it is predicted that it will be advantageous to have smaller body size in the face of increasing mean annual temperatures because smaller size may offer more thermoregulatory opportunities (e.g. access to a greater number of microclimates such as rock crevices) (Huey et al. 2012). However, under short-term exposure to extreme high temperatures, larger body sizes may be advantageous because smaller individuals might be more vulnerable to overheating and dehydration (Gardner et al. 2011).

Given the uncertainty of the relationship between body size and temperature increases, I did not consider it as a trait within my frameworks. However, providing insight into the direction of this relationship in local species could be valuable and therefore I examined the relationship between the climate change vulnerability of each species and its body size. To do this a Wilcoxon two-sample rank sum test was run with body size as the outcome variable and climate change vulnerability score as the explanatory variable. The R package 'stats' and function 'wilcox.test' were used (R Core Team 2018).

Results

Data availability and quality

Trait data availability for each framework varied considerably. Within the reptile framework, data gaps were most prevalent for species' intolerance of changes to fire regimes (46% of species had missing data); presence of semelparity (24%), and ability to reproduce more than once a year (17%). Within the amphibian framework, data gaps were most prevalent for species sensitivity to declines in cloud and fog cover (33%), diet breadth (22%), tadpole generation time (17%), and intolerance of changes in fire regimes (17%). For all other traits within these respective frameworks data gaps were less than 15%. For the traits "sensitive to decline in cloud and fog cover" (RS8 and AS7) and "intolerant of changes to fire regimes" (AS6 and RS6) empirical evidence was lacking for many species and therefore scores were derived from expert opinion or left as unknown if robust estimates could not be made.

Summary of the sensitivity dimension

In the worst-case scenario 40 (98%) of reptile species had at least one sensitivity trait present, compared to 36 (88%) of species in the best-case scenario (where all traits with missing data are assumed absent for a species) (Table 1). The trait that appeared most amongst sensitive reptile species was an inability to reproduce more than once annually (RS14), affecting a total of 22 species from a possible 41 (Table 1). This was followed by low environmental heterogeneity within range (RS9) (score 10) and sensitive to decline in cloud and fog cover (8) (Table 1).

Both the worst and best-case scenarios indicated that 17 (94%) amphibian species with at least one sensitivity trait present (Table 2). The trait that appeared most amongst sensitive amphibian species was a dependence on environmental cues predicted to be disrupted by climate change (AS9), with a total of 16 species from a possible 18. Microhabitat specialisation (AS2) was present in 11 of the species, while an inability to reproduce more than once annually in the event of a lost clutch/litter (AS12) was present in 10 species (Table 2).

Table 1. The number of species which scored High, Low, or Unknown for each sensitivity trait within the Table Mountain National Park reptile framework (Total species = 41).

Trait Group	Trait	No of species 'High'	No of species 'Low'	No of species 'Unknown'
A. Specialised habitat and/or microhabitat requirements	RS1: Habitat specialisation	0	41	0
	RS2: Microhabitat specialisation	0	41	0
B. Narrow environmental tolerances or thresholds that are likely to be exceeded due to climate change at any stage in the life cycle	RS3: High elevation specialist	0	41	0
	RS4: Narrow temperature tolerance (adults)	10	31	0
	RS5: Narrow precipitation tolerance (adults)	10	31	0
	RS6: Intolerant of changes to fire regime	6	16	19
	RS7: Seasonal activity period restricted by temperature/rainfall	2	39	0
	RS8: Reliant on cloud/fog cover	8	32	1
	RS9: Low environmental heterogeneity within range	10	31	0
D. Dependence on interspecific interactions which are likely to be disrupted by climate change	RS10: Narrow diet breadth	5	36	0

E. Rarity	RS11: Endemic/rare	0	41	0
F. Sensitive life history	RS12: Semelparous?	0	31	10
	RS13: Inability to reproduce more than once annually in the event of lost clutch/litter	22	12	7

Table 2. The number of species which scored High, Low, or Unknown for each sensitivity trait within the Table Mountain National Park amphibian framework (Total species = 18).

Trait Group	Trait	No of species 'High'	No of species 'Low'	No of species 'Unknown'
A. Specialised habitat and/or microhabitat requirements	AS1: Habitat specialisation	0	18	0
	AS2: Microhabitat specialisation	11	7	0
B. Narrow environmental tolerances or thresholds that are likely to be exceeded due to climate change at any stage in the life cycle	AS3: High elevation specialist	0	18	0
	AS4: Narrow temperature tolerance (adults)	4	14	0
	AS5: Narrow precipitation tolerance (adults)	4	14	0
	AS6: Intolerant of changes to fire regime	2	13	3
	AS7: Reliant on cloud/fog cover	6	6	6
	AS8: Tadpoles reliant on highly oxygenated water bodies (fast flowing streams)	1	17	0
C. Dependence on specific environmental triggers that are likely to be disrupted by climate change	AS9: Dependent on environmental cues predicted to be disrupted by climate change	16	2	0
D. Dependence on interspecific interactions which are likely to be disrupted by climate change	AS10: Narrow diet breadth	0	14	4
E. Rarity	AS11: Endemic/rare	3	15	0
F. Sensitive life history	AS12: Inability to reproduce more than once annually in the event of lost clutch/litter	10	8	0

	AS13: Eggs laid in leaf litter, moss, ephemeral water sources	8	10	0

<u>Summary of the adaptive capacity dimension</u>

In both worst- and best-case scenarios 36 (88%) reptile species had at least one low adaptive capacity trait present. The trait that was most common among species with low adaptive capacity was a lack of commensalism with humans (AL2), with a total of 32 species from a possible 41. Nine species had a foraging mode which limited behavioural adaptation (RL3), while two species were found to have low micro-evolutionary potential because of a mean annual reproductive output of less than two (RL4a). No species were found to have dispersal limited by physical barriers (RL1) or have low microevolutionary potential because of low genetic diversity and/or severe population fragmentation (RL3b).

Within the amphibian framework, both best- and worst-case scenarios contained 12 out of a possible 18 (67%) species with at least one low adaptive capacity trait. The most frequently occurring traits were: Dispersal limited by physical barriers (AL1), No commensalism with humans (AL2), and Low microevolutionary potential because of low genetic diversity and/or population fragmentation (AL3b), all of which were present in 9 species. One species was identified as having a relatively long generation time as a tadpole, while no species were known to have low microevolutionary potential because of a mean annual reproductive output of less than or equal to two offspring.

Table 3. The number of species which scored High, Low, or Unknown for each adaptive capacity trait within the Table Mountain National Park reptile framework (Total species = 41).

Trait Group	Trait	No of species 'High'	No of species 'Low'	No of species 'Unknown'
G. Poor dispersibility	RL1: Dispersal limited by physical barriers	0	41	0
H. Limited behavioural adaptation	RL2: No commensalism with humans	32	9	0
G. Poor dispersibility & H. Limited behavioural adaptation	RL3: Foraging mode limits behaviour adaptation	9	30	2

I. Poor evolvability	RL4a: Low microevolutionary potential (Mean annual reproductive output)	2	39	0
	RL4b: Low microevolutionary potential (Genetic diversity and population fragmentation)	0	29	12

Table 4. The number of species that scored High, Low, or Unknown for each adaptive capacity trait within the Table Mountain National Park amphibian framework (Total species = 18).

Trait Group	Trait	No of species 'High'	No of species 'Low'	No of species 'Unknown'
G. Poor dispersibility	AL1: Dispersal limited by physical barriers	9	9	0
H. Limited behavioural adaptation	AL2: No commensalism with humans	9	9	0
I. Poor evolvability	AL3a: Low microevolutionary potential (Mean annual reproductive output)	0	17	1
	AL3b: Low microevolutionary potential (Genetic diversity and population fragmentation)	9	8	1
	AL4: Long generation time (Tadpoles)	1	12	5

Summary of the overall vulnerability scoring

A full summary of the scores for each species and best- and worst-case assumptions for missing trait data are presented in Table 5 and Table 6. Unless stated otherwise all results presented within the text are from the worst-case scenario assumptions for missing trait data.

Reptiles

Ordinal scoring

Overall, 35 reptile species (85%) were identified as being the most biologically vulnerable (both high sensitivity and low adaptive capacity) to climate change in the worst-case scenario. In the best-case scenario, where all unknown traits were assumed to be absent, 31 species (76%) of reptile were identified as being highly vulnerable to climate change (Table 5).

Additive scoring

Unweighted

When each reptile species was scored using the unweighted additive approach southern adder, Cape long-tailed seps (*Tetradactylus tetradactylus*), southern blind legless skink *(Typhlosaurus caecus)* and Cape mountain lizard (*Tropidosaura gularis*) were identified as the most vulnerable species, displaying seven vulnerability traits (Table 5). Six traits were found to be present in many-spotted snake, black girdled lizard (*Cordylus niger*), common padloper (*Homopus areolatus*), angulate tortoise (*Chersina angulata*), silvery dwarf burrowing skink (*Scelotes bipes)*, Cape crag lizard (*Pseudocordylus microlepidotus*) and short-legged seps (*Tetradactylus seps*) (Table 5).

Weighted

Upon scoring the reptile species using the additive method with expert-based trait weightings, southern adder was identified as the species most vulnerable to climate change, with a score of 21. Cape long-tailed seps and Cape mountain lizard were the next most vulnerable (19), followed by many-spotted snake, black girdled lizard and common padloper (18) (Table 5). Under the weighted method southern blind legless skink saw its relative vulnerability compared to other reptile species decline, with a score of 17 (Table 5).

Amphibians

Ordinal scoring

The amphibian assessment highlighted that in both worst- and best-case scenarios, 12 out of the 18 species (67%) assessed were identified as being vulnerable to climate change (Table 6).

Additive scoring

Unweighted

When the amphibian species were scored using the unweighted approach, Table Mountain ghost frog (12) (Critically Endangered) and Lightfoot's moss frog (*Arthroleptella lightfooti*) (11) were identified as having the greatest number of vulnerability traits present (Table 6). These were closely followed by flat caco (*Cacosternum platys*), Cape platanna (*Xenopus gilli*) and micro frog (Critically Endangered) which had a total of 10 traits present. The Critically Endangered Rose's mountain toadlet was found to have nine traits of high sensitivity and low adaptive capacity to climate change (Table 6).

Weighted

When the weighted method was applied to the amphibian species, Table Mountain ghost frog (34) (Critically Endangered) and Lightfoot's moss frog (33) were again identified as having the highest vulnerability to climate change (Table 6). These were followed by flat caco and Cape platanna (30). Unlike the unweighted scoring method micro frog, scored slightly lower than the flat caco and Cape platanna, with a score of 28 (Table 6).

Table 5. The scores for each reptile species within Table Mountain National Park according to each scoring method and worst- and best-case scenarios. Species are ordered by additive weighted scores under the worst case. The higher the score, the darker the shade of the cell. Total species = 41.

	Scoring method					
Species	Ordinal – Worst Case	Ordinal - Best Case Variation	Additive Unweighted – Worst Case (Max = 17)	Additive Unweighted- Best Case (Max = 17)	Additive Weighted – Worst Case (Max = 45)	Additive Weighted – Best Case (Max = 45)
Bitis armata	High	-	7	7	21	21
Tetradactylus tetradactylus	High	-	7	5	19	15
Tropidosaura gularis	High	-	7	5	19	15

Amplorhinus multimaculatus	High	-	6	4	18	12
Cordylus niger	High	-	6	5	18	15
Homopus areolatus	High	-	6	6	18	18
Typhlosaurus caecus	High	-	7	5	17	13
Chersina angulata	High	-	6	5	17	14
Scelotes bipes	High	-	6	4	16	12
Pseudocordylus microlepidotus	High	-	6	5	16	15
Tetradactylus seps	High	-	6	4	16	12
Pachydactylus geitje	High	-	5	4	15	12
Psammophis notostictus	High	-	5	4	15	12
Duberria lutrix	High	-	5	4	13	10
Bitis atropos	High	-	4	4	12	12
Bradypodion pumilum	High	-	4	4	12	12
Dispholidus typus	High	-	4	3	12	9
Lycodonomorphus inornatus	High	-	4	3	12	9
Meroles knoxii	High	-	4	3	12	9
Psammophylax rhombeatus	High	-	4	3	12	9
Afrogecko porphyreus	High	-	4	2	10	6
Chamaesaura anguina	High	-	4	3	10	9
Leptotyphlops nigricans	High	-	4	3	10	7
Trachylepis homalocephala	High	-	4	2	10	6
Cordylus cordylus	High	-	3	3	9	9
Gerrhosaurus flavigularis	High	-	3	2	9	6
Homoroselaps lacteus	High	-	3	3	9	9
Lamprophis aurora	High	-	3	2	9	6
Psammophis crucifer	High	Low*	3	2	9	6
Rhinotyphlops lalandei	High	-	3	3	7	7
Crotaphopeltis hotamboeia	Low*	-	3	2	7	4
Acontias meleagris	Low*	-	3	1	7	3
Bitis arietans	High	-	2	2	6	6
Dasypeltis scabra	High	Low*	2	1	6	3

Lamprophis fuscus	High	Low*	2	1	6	3
Lycodonomorphus rufulus	High	-	2	2	6	6
Pseudaspis cana	High	Low*	2	1	6	3
Naja nivea	Low*	-	2	1	6	3
Trachylepis capensis	Low*	-	2	1	6	3
Pelomedusa galeata	Low*	-	2	2	5	5
Agama atra	Low*	-	1	1	3	3

*Species not classified as highly vulnerable to climate change under either or both the best- and worst-case scenarios, because of the lack of both high sensitivity and low adaptive capacity traits.

Table 6. The scores for each amphibian species within Table Mountain National Park according to each scoring method and worst- and best-case scenarios. In the case of the amphibians no variation was seen between the ordinal scores when place under worst- and best-case scenarios and therefore only one column is displayed. Species are ordered by additive weighted scores under the worst case. The higher the score, the darker the shade of the cell. Total species = 18.

		Scoring method			
Species	Ordinal	Additive Unweighted – Worst Case (Max = 17)	Additive Unweighted- Best Case (Max = 17)	Additive Weighted – Worst Case (Max = 49)	Additive Weighted – Best Case (Max = 49)
Heleophryne rosei	High	12	10	34	30
Arthroleptella lightfooti	High	11	11	33	30
Cacosternum platys	High	10	7	30	21
Xenopus gilli	High	10	8	30	24
Microbatrachella capensis	High	10	6	28	18
Breviceps rosei	High	9	8	27	24
Capensibufo rosei	High	9	9	27	27
Strongylopus bonaespei	High	8	6	22	18
Breviceps montanus	High	7	6	21	18
Hyperolius horstockii	High	6	5	18	15
Breviceps gibbosus	High	5	4	15	12
Vandijkophrynus angusticeps	Low*	5	4	15	12
Sclerophrys pantherina	High	4	3	12	9
Tomopterna delalandii	Low*	3	3	9	9
Semnodactylus wealii	Low*	3	2	7	6
Amietia fuscigula	Low*	1	1	3	3
Xenopus laevis	Low*	1	1	3	3
Strongylopus grayii	Low*	0	0	0	0

*Species not classified as highly vulnerable to climate change under either or both the best- and worst-case scenarios, because of the lack of both high sensitivity and low adaptive capacity traits.

Assessing the influence of trait thresholds on overall vulnerability

Some traits within both the reptile and amphibian framework involved continuous variables which had no species-specific established vulnerability thresholds. For these variables the species whose trait values fell within the lowest 25% of all values were scored within the 'high' threshold. The reptile framework had a total of three traits which used the 25% threshold, namely Narrow temperature tolerance (RS4), Narrow precipitation tolerance (RS5) and Low environmental heterogeneity within range (RS9). Shifting the thresholds by 10 % (+10% for more lenient and -10% for a stricter threshold) for the traits RS4, RS5, RS9 resulted in a change in the number of species scoring high in each trait by +10% and -10%. Within the amphibian framework 25% thresholds were used for the traits Narrow temperature tolerance (AS4), Narrow precipitation tolerance (AS5). Shifting the thresholds by 10% (+10% for more lenient and -10% for a stricter threshold) for the traits AS4 and AS5 resulted in a change in the number of species scoring high in both traits of +5% and -11%.

Traits present in the most vulnerable species

The reptile assessment highlighted that southern adder is the most likely to be highly vulnerable to climate change of the focal species (worst-case scenario). Narrow temperature tolerance (RS4), intolerance of changes to fire regimes (RS6), low environmental heterogeneity within its range (RS9) and an inability to reproduce more than once annually in the event of lost clutch/litter (RS13) were all identified to increase the sensitivity of southern adder to climate change. The southern adder was also identified to have poor adaptive capacity, with an inability to utilise human-dominated landscapes (RL2) and low microevolutionary potential (RL4a and RL4b).

Narrow precipitation tolerance (adults) (RS5), intolerance of changes to fire regimes (RS6), sensitivity to declines in cloud/fog cover (RS8), semelparity (RS12) (unknown but assumed under worst-case scenario) and an inability to reproduce more than once annually in the event of a lost clutch/litter (RS13) were all identified to increase the sensitivity of Cape long-tailed seps. In terms of low adaptive capacity, it was identified as having no commensalism with humans (RL2) and a foraging mode which limits behaviour adaptation (RL3).

Narrow temperature tolerances (RS4), intolerance of changes to fire regimes (RS6), sensitivity to changes in levels of cloud/fog cover (RS8), an inability to reproduce more than once annually in the event of a lost clutch/litter (RS13) were all found to increase the sensitivity of black girdled lizard (Figure 2c). In terms of low adaptive capacity, it was identified to lack an ability to be commensal with humans (RL2) and it has low microevolutionary potential because of an annual reproductive output thought to be ≤2 (RL4a).

Figure 2. The traits found to be present in a selection of the top 10 most vulnerable species southern adder (*Bitis armata*) (a), Cape long-tailed seps (*Tetradactylus tetradactylus*) (b), black girdled lizard (*Cordylus niger*) (c) and southern blind legless skink (*Typhlosaurus caecus*) (d). The number of widgets highlights the weighting of the trait (e.g. 3 widgets indicate a high weighted trait). Red widgets indicate the presence of a high sensitivity trait, while blue widgets indicate the presence of a low adaptive capacity trait. Widgets with lighter shades indicate traits which were unknown but assumed present in the worst-case scenario. Photo credits: Tyrone Ping (a and d), Alex Rebelo (b) and Jack Harper (c)

Narrow temperature tolerances (RS4), narrow precipitation tolerances (RS5), sensitivity to decline in cloud/fog cover (RS8), low environmental heterogeneity within its range (RS9), semelparity (unknown but assumed under worst-case scenario) (RS12) and an inability to reproduce more than once annually in the event of a lost clutch/litter (RS13) (unknown but assumed under worst-case scenario) were all identified to increase the sensitivity of southern blind legless skink to climate change. Southern blind legless skink was also identified as having low adaptive capacity because of a lack of ability to utilise human dominated landscapes (RL2).

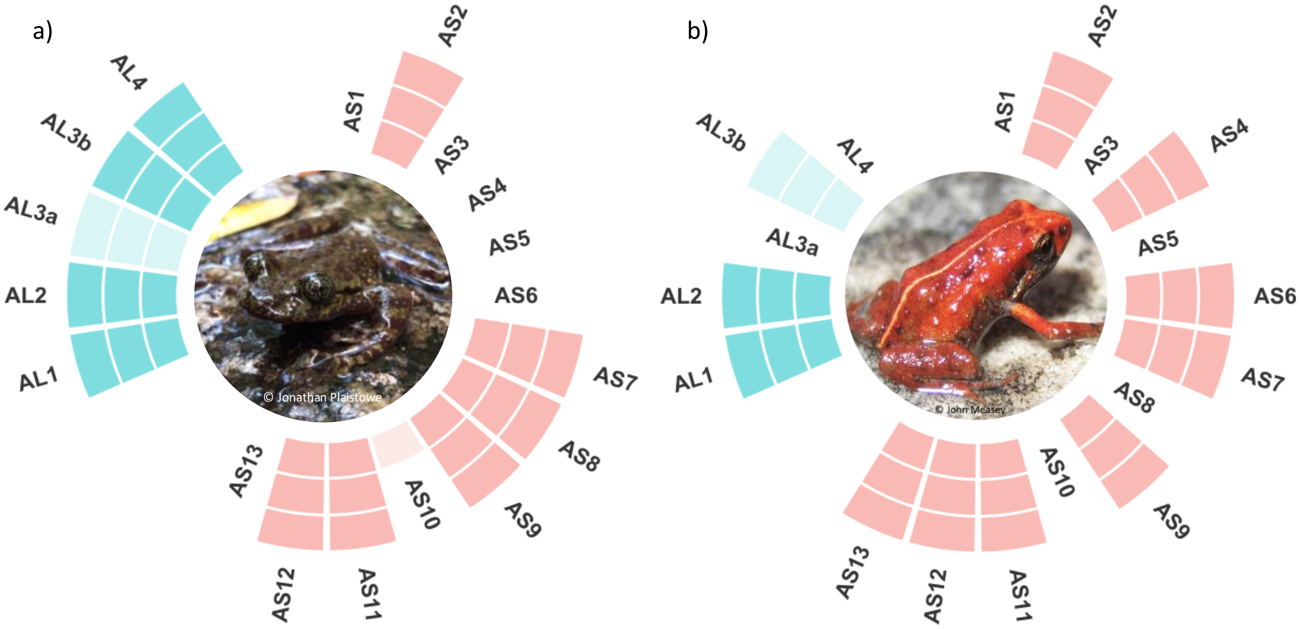

Figure 3. The traits found to be present in Table Mountain ghost frog (*Heleophryne rosei*) *(*a) and Lightfoot's moss frog (*Arthroleptella lightfooti*) (b). The number of widgets highlights the weighting of the trait (e.g. 3 widgets indicate a high weighted trait). Red widgets indicate the presence of a high sensitivity trait, while blue widgets indicate the presence of a low adaptive capacity trait. Widgets with lighter shades indicate traits which were unknown but assumed present in the worst-case scenario Photo credits: Jonathan Plaistowe (a) and John Measey (b).

Table Mountain ghost frog and Lightfoot's moss frog are predicted to be the most highly vulnerable to climate change of the focal amphibian species (worst-case scenario). Microhabitat specialisation (AS2), narrow temperature tolerances (adults) (AS4), intolerances of changes to fire regime (AS6), sensitivity to declines in cloud/fog cover (AS7), dependence on environmental cues predicted to be disrupted by climate change (AS9), endemic/rare (AS11), inability to reproduce more than once annually in the event of lost clutch/litter (AS12), eggs laid in leaf litter, moss or ephemeral water sources (AS13) were all identified to increase the sensitivity of Lightfoot's moss frog to climate change. Dispersal limited by physical barriers (AL1), no commensalism with humans (AL2) and low genetic diversity or severe population fragmentation (AL3b) (unknown but assumed under worst-case scenario) were all identified to decrease the adaptive capacity of Lightfoot's moss frog.

Microhabitat specialisation (AS2), sensitivity to declines in cloud/fog cover (AS7), tadpoles reliant on highly oxygenated water bodies (fast flowing streams) (AS8), dependence on environmental cues predicted to be disrupted by climate change (AS9), narrow diet breadth (AS10) (unknown but assumed under worst-case scenario), endemic/rare (AS11), inability to reproduce more than once annually in the event of lost clutch/litter (AS12) and an inability to reproduce more than once annually in the event of a lost clutch/litter (AS12) were all identified to increase the sensitivity of Table Mountain ghost frog to climate change. Dispersal limited by physical barriers (AL1), no commensalism with humans (AL2), low microevolutionary potential because of a low annual productive output (AL3a) (unknown but assumed under worst-case scenario) and low genetic diversity and/or severely fragmented populations (AL3b) were all identified to decrease the adaptive capacity of Table Mountain ghost frog.

Spatial analysis

The areas within and around the valley between Noordhoek and Fish Hoek have the greatest numbers of climate change vulnerable reptile species with 31 (worst-case) or 27 (best-case) present (Figure 4a and 4b). Under both scenarios the lower slopes of the southern suburbs are also highlighted as areas with among the greatest diversity of climate change vulnerable species. It must be highlighted that the resolution of the reptile distributions was coarser than that of the amphibian species. A summary of the species identified as climate vulnerable in these hotspot areas can been found in Appendix F1.

Within the amphibian assessment, the best- and worst-case scenarios produced the same outputs. The Cape Point section of the park is a clear area of high diversity for climate change vulnerable species. The north-west areas of Cape Point and in particular the Klaasjagersberg river area have the highest number of climate change vulnerable species with nine present (Figure 5). A summary of the climate vulnerable species found in this area can be found in Appendix F2.

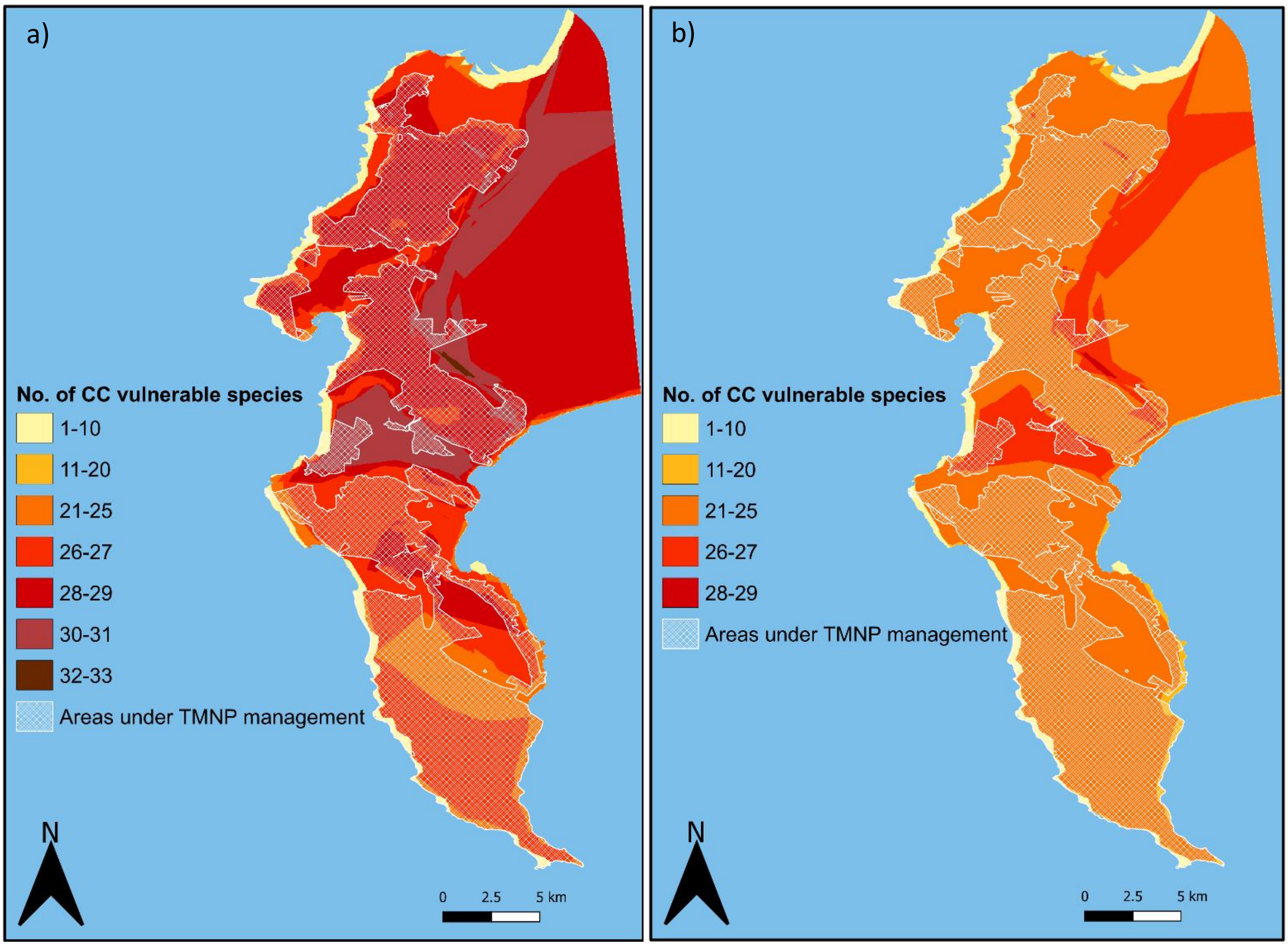

Figure 4. The number of highly climate change vulnerable reptile species within Table Mountain National Park and its immediate surrounding areas under the worst-case scenario (a) and best-case scenario (b).

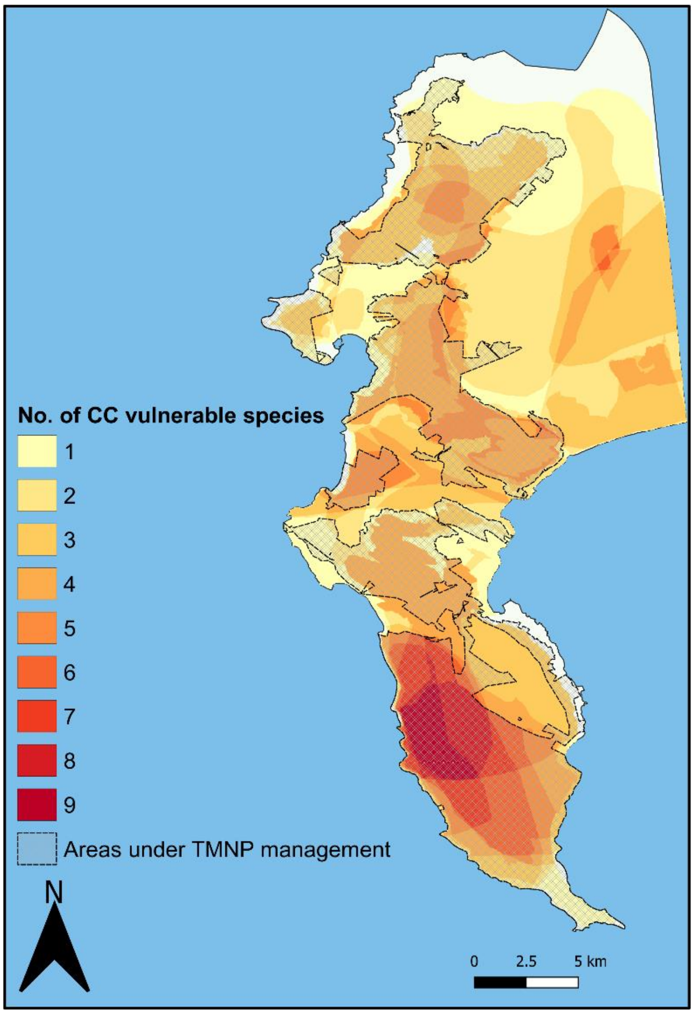

Figure 5. The number of highly climate change vulnerable amphibian species within Table Mountain National Park and its immediate surroundings.

Comparison between trait-based assessment and IUCN Red List status

There was no significant correlation between the IUCN Red List scores and this trait-based assessment for reptiles (Spearman's rank correlation, r_s= 0.094, p= 0.559). However, southern adder and Cape dwarf chameleon (*Bradypodion pumilum*) are categorised by the IUCN Red List as Vulnerable and Near Threatened, respectively (Maritz & Turner 2018; Tolley 2018), and also score as having high vulnerability to climate change within this assessment.

The climate change vulnerability scores for the amphibian species were significantly positively correlated with the IUCN categorisation (Spearman's rank correlation, r_s= 0.545, p= 0.021). Lightfoot's moss frog and Cape rain frog (*Breviceps gibbosus*) are categorised as Near threatened by the IUCN Redlist (IUCN SSC Amphibian Specialist Group 2016a, 2017d). Western leopard toad (*Sclerophrys pantherine*) and Cape platanna are classified as Endangered, while Rose's mountain toadlet, Table Mountain ghost frog and micro frog are classified as Critically Endangered (IUCN SSC Amphibian Specialist Group 2016b, 2017e, 2017c, 2017b, 2017a). These species were also amongst the highest scoring species in this trait-based assessment.

Body size and vulnerability

There was no significant relationship between the body size of the focal reptile species and their scores of high climate change vulnerability (Wilcoxon Rank-Sum Test, W = 94, *p*= 0.6984).

Discussion

This assessment presents the first documented attempt to implement the trait-based climate change vulnerability approach at the scale of a single national park, building on the approaches used at global, regional and national scales (e.g. Gardali et al. 2012; Foden et al. 2013; Böhm et al. 2016; Zhang et al. 2019). The assessment provides further support for the use of a trait-based approach as an important tool for assisting conservation biologists in the fight to maintain biodiversity in an uncertain climate future. By identifying potential climate change impact mechanisms and systematically assessing their prevalence amongst focal species, they assist managers in identifying appropriate management responses. This analysis highlights that alarming numbers of TMNP reptile and amphibian species are likely to be highly vulnerable to climate change. The number of reptile species identified as being highly vulnerable to climate change were 35 (85%) and 31 (76%) in worst- and best-case scenarios, respectively. While 12 (67%) (both scenarios) amphibian species were identified as being highly climate vulnerable, including all three Critically Endangered species.

Management implications

An examination of trends in the prevalence of traits and the hypothesised impact mechanisms associated with them, can identify whether and how climate change impacts may be mitigated. The reptile framework highlighted, for example, that a lack of commensalism with humans (RL2) was the most prevalent trait reducing adaptive capacity. The second most prevalent trait was an inability to reproduce more than once annually (RS13), followed by sensitivity to declines in cloud/fog cover (RS8) (Table 1 and Table 3). The amphibian framework highlighted that a dependence on environmental cues predicted to be disrupted by climate change (AS9), microhabitat specialisation (AS2) and an inability to reproduce more than once per year (AS12) were the most commonly present traits amongst climate vulnerable amphibians within the park. At the scale of park management, it is impossible to control the exposure to changes in direct climate variables (e.g. precipitation change). However, the management of the park does have the ability to control some of the associated factors of climate change (e.g. preventing increased fire frequency with careful prescribed burns). Furthermore, by ensuring that the areas within the park home to these climate vulnerable species remain as pristine as possible and by removing or reducing the threats from other anthropogenic pressures, it can give these species the best chance of persistence in an uncertain climate future. Studies have shown the effects of climate change exposure alone may not cause reduced survival within populations, but the synergistic impacts of both exposure to novel conditions and other anthropogenic pressures such as pollution can then cause significant declines in survival rate (e.g. Bancroft et al. 2008). Additionally, even though this assessment focused on species within TMNP, the identification of the most vulnerable species is useful in prioritising new areas for protection (e.g. by park expansion or land stewardship), ensuring that the most sensitive areas (e.g. breeding sites) are under protection.

By using both ordinal and additive methods it was possible to highlight the species at greatest risk from climate change, and the most vulnerable amongst them. Among the focal reptile species, southern adder was consistently identified as the most vulnerable across all scoring methods. It was closely followed by Cape long-tailed seps, Cape mountain lizard, many-spotted snake, black girdled lizard, common padloper and southern blind legless skink. Among the amphibian species, Lightfoot's moss frog and Table Mountain ghost frog scored highest consistently over the scoring methods. They were closely followed by flat caco, Cape platanna, micro frog, Rose's rain frog (Breviceps rosei) and Rose's mountain toadlet. By highlighting these species, it is possible to examine the traits that are driving these inherent vulnerabilities and to evaluate if any management actions or interventions are appropriate to limit exposure, reduce sensitivity and/or enhance adaptive capacity to climate change.

Southern adder was included in this assessment although it is thought to have been extirpated from TMNP (A. Turner personal communication). This species possesses several traits which could be mitigated by appropriate direct management interventions. These include an intolerance of changes in fire regime (RS4) and low microevolutionary potential because of severe population fragmentation (RL4b). According to the most recent IUCN Red List assessment of the species, a disproportionate amount of its coastal fynbos habitat has been lost when compared to natural land cover decline at a national scale (Maritz & Turner 2018). A reintroduction to the park may offer the species a vital extension of its currently severely fragmented distribution, as well as providing better control over the risk of associated threats from climate change (e.g. increased fire frequency). A study into the viability of reintroduction attempts should be considered strongly by SANParks and Cape Nature.

Of the most vulnerable species identified black girdled lizard is of particular interest because of its melanistic adaption to areas with high incidence of fog and cloud cover (Clusella-Trullas et al. 2009; Janse van Rensburg et al. 2009) (Table 5 and Figure 2c). Considering the potential of future decline in cloud and fog cover, this species seems like the ideal candidate for mechanistic modelling, giving us an idea of the potential future trends in population numbers.

Another interesting finding was the presence of a fossorial species (southern blind legless skink*)* among some of the most vulnerable species (Table 5 and Figure 1d). Under the worst-case scenario semelparity (RS12) and an inability to reproduce more than once annually in the event of a lost clutch/litter (RS13) were assumed to be present. However, the presence or absence of these traits is not known. It should therefore be a priority to gather more information on of the reproductive behaviour of this species and ensure that this assessment has not exaggerated its vulnerability. Furthermore, as a fossorial species it is important to consider the degree to which an underground lifestyle will buffer southern blind legless skink from the direct pressures of climate change (e.g. temperature and precipitation change). The effects of precipitation as well as temperature are thought to have an important impact on the thermal physiology of fossorial reptiles, and thus it is likely to be inappropriate to assume that their underground nature will buffer them from exposure to climate change (Clusella-Trullas et al. 2011).

As a Critically Endangered species the Table Mountain ghost frog is already a management priority within the park. Several of this species' traits (AS2, AS11, AL2) also make it highly vulnerable to other anthropogenic threats such as pollution and habitat loss. Though its entire range is within a protected area, the open-access nature of TMNP means that it can still be exposed to human disturbance and pollution. The results of this assessment reiterate the extreme importance that the streams associated with the frog are protected from human disturbance. Climate change is likely to add additional pressures to the species so it is vital that other more avoidable anthropogenic pressures are prevented. Important work on the ecology of the species will begin shortly (J. Weeber, personal communication) and any new information which is brought to light should be incorporated into this assessment. Among the traits identified in Lightfoot's moss frog intolerance to changes to fire regimes is a key area amenable to mitigation by direct management actions.

Spatial presentation of the assessment results informs selection of priority areas for conservation management effort within the park. In terms of amphibian conservation, the north-west areas of the Cape Point section, including the Klaasjagersberg river area are home to the greatest numbers of climate vulnerable species. Areas of high numbers of climate change vulnerable reptile species included the areas within and around the valley between Noordhoek and Fish Hoek and the lower slopes of the park close to the southern suburbs. The reptile maps indicate high diversity of vulnerable species close to or outside the park boundary along the urban fringe (Figure 4). These areas have relatively high topographic heterogeneity and it is thus likely that the apparent high species richness is a result of a number of species ranges beginning and ending in these areas. Considering that there is still work needed to improve the resolution of the reptile distributions in the park, it is important that fieldwork is carried out to ensure that the hotspots are accurate and are not products of artificial cut-offs. The next step would then be to identify any immediate threats to the habitat of these species, and evaluate which, if any, direct interventions are warranted.

Comparison of trait-based scores and IUCN Red Listing

There was no significant correlation between scores of climate change vulnerability and the IUCN Red List status among the reptile species. Of the reptile species included within our assessment, only 5% had Red List statuses of Threatened or Near Threatened but 85% were highly vulnerable to climate change (worst case scenario). On the other hand, there was a significantly positive relationship between climate vulnerability score and IUCN status for amphibian species. 44% of the amphibian species assessed were deemed to be Threatened or Near threatened by the Red List, while 67% were found to be highly vulnerable to climate change. Amongst the reptile species in particular, greater scrutiny and consideration of the future threat from climate change pressures should be included in future assessments of their Red List status. This follows similar findings reported in global and European climate change vulnerability assessments of reptiles (e.g. Carr 2011; Böhm et al. 2016).

Strengths and weaknesses of the method

This assessment highlights a prime example of where a trait-based approach allows for the assessment of multiple species at a scale that would not be possible using other methods. The trait-based approach allowed for the assessment of climate change vulnerability of all the reptile and amphibian species present within TMNP within a few months. Using correlative methods to predict suitable future climate space would not be useful because the study site is already a protected area close to the most southerly (poleward) point in the landscape. Furthermore, several of the species are endemic or near endemic to the park and therefore inherently do not have acceptable numbers of spatially distinct occurrence records to be used in correlative modelling (Platts et al. 2014). Mechanistic models have the potential to produce more powerful species level outputs because they are able to accommodate for interacting effects of climate change, as well as including morphological and demographic factors (Mantyka-Pringle et al. 2016; Foden et al. 2018). However, the amount of data required to correctly parameterise a mechanistic model for just one species alone would likely take several years of work. Furthermore, the general uncertainty around climate projection models may in fact limit the accuracy of this approach and it may be better to focus research and conservation efforts on the 'here and now' of climate change impacts for the species identified to be most vulnerable (Pacifici et al. 2017; Foden et al. 2018). Although a trait-based approach is arguably the best method for the scope of the study, it is important to highlight that it is not without its caveats.

As mentioned previously, the traits narrow temperature tolerance (RS4 and AS4), narrow precipitation tolerance (RS5 and AS4) and low environmental heterogeneity within a range (RS9) were designated arbitrary thresholds for assigning vulnerability. These thresholds were used because of the absence of available empirical data upon which to decide evidence-based biologically-meaningful thresholds. However, it was deemed that these factors could not be left out of the framework without losing the representation of key climate change sensitivity characteristics. It is therefore important to remember that the species scoring highly within these traits only represent those relatively most sensitive to climate change, and additional species may be deemed vulnerable if less stringent thresholds were chosen. Following the methods outlined in Foden et al. (2013), changes in arbitrary thresholds by -10% and +10% saw similar proportional changes in the number of species categorised as high risk for these traits. This assessment also highlighted key data gaps currently present within the study species. Several traits had to be excluded because of a complete lack of available data and therefore should be given research priority. These traits included generation time and tolerances to flooding or waterlogging (Appendix B1 and B2). Additionally, within the taxa frameworks several traits had data missing for several species (Table 1, 2, 3 and 4). Research should be prioritised in the understanding of the tolerances of these species to changes in fire regimes and cloud cover, reproductive strategies, genetic diversity amongst populations and the benefits and/or negatives of fossorial specialisation, particularly amongst focal reptile species.

It almost certainly false to assume that all traits hold equal importance amongst the species within this assessment. I attempted to account for this by using weightings informed by expert opinion. A comparison of the relative vulnerability of species between unweighted and weighted additive scoring methods highlighted the need to improve the understanding of the importance of certain traits at a species level. For example, within the reptile assessment, the position of southern blind legless skink relative to other species changed considerably once weighting had been implemented (Table 5). Ensuring that weighting is done as accurately as possible is important considering the limited funds conservation organisations have and the inevitable prioritisations that need to be made.

Holding an expert workshop ensured that the best available knowledge of the focal species was shared and included. It also allowed for co-generation of assessments, ensuring their greater uptake and use by the herpetological community and promoting research on priority gaps as well as the sharing of new information by the community when discovered. A key benefit of this assessment methodology is the ability to update species scores (by removing data gaps for a species) and to reduce uncertainty in the results (by removing arbitrary thresholds) as new information becomes available. As highlighted by the number of data gaps currently present, it is critical that the herpetological community continues to engage with this assessment to ensure its accuracy improves over time and to attempt to validate the findings. The importance of filling the majority of these data gaps can be seen when worst- and best-case results are compared (Table 5 and Table 6). For example, no data currently exist with respect to four traits for micro frog. Therefore, its relative vulnerability compared to other species changes considerably when comparing its scores under worst- and best-case scenarios using additive methods.

Using a trait-based approach at this scale has highlighted some important considerations to be taken forward in the planned use of the approach for additional national parks. The use of an ordinal method alone is certainly not advisable at this scale. The finding that 76% to 85% of reptile species in TMNP are climate vulnerable is extremely high. This method does not highlight much variance in vulnerability among the species. However, having fine resolution distribution data available means that distribution hotspots for vulnerable species can be identified and prioritized. At the scale of national park level, where more specific traits to the region can be selected the ordinal method appears to be too sensitive. Using the additive methods in combination with the ordinal method does allow for some further insight into the relative vulnerabilities of species. However, in light of the results it is suggested that a hierarchical method should be tested using this framework (e.g. Smith et al. 2016). Hierarchical methods, although considerably more time intensive, would allow for important dependencies between components of vulnerability to be taken into account. Hierarchical methods also allow for other anthropogenic pressures to be taken into account, especially if they are known to interact with climate change to increase the vulnerability of specific species (e.g. invasive species). Furthermore, running species distribution models (for the species with suitable occurrence records) would allow for the identification of the most relevant climate variables to be included for each species (Willis et al. 2015), thus allowing for more species-specific consideration of climate sensitivity. Unfortunately, the limited time available for this thesis restricted the inclusion of this novel method.

Conclusions

This assessment highlights that trait-based approach can offer conservation organisations a relatively rapid and cost-effective method of assessing species-level climate change vulnerability at the fine scale of individual protected areas. It is clear that the diversity of reptile and amphibian species occurring within TMNP is under severe threat from climate change. It is vital that the park's management build upon the findings of this assessment and arrange appropriate actions and funds to support conservation of the climate change vulnerable areas and species identified in this study. Collaboration with local herpetologists provides the opportunity to fill data gaps and update the assessment framework as new information comes to light, whilst careful monitoring of the most vulnerable species is needed to identify whether the effects of climate change are already being felt. Furthermore, the findings of this assessment highlight that a greater consideration of the threat from climate change should be considered during updates of the IUCN Red List statuses, particularly in reptiles.

The framework created for each of the two taxa was designed to be used for assessments across all of South Africa's National Parks. This thesis has provided SANParks with the foundations to continue using trait-based methodology for other taxa and in the other 18 national parks of South Africa. By using 'climate smart' conservation strategies, SANParks management can limit the inevitable impacts of climate change on the important biodiversity that it must protect.

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Appendices

Appendix A1a. A summary of the species of reptile present on SANParks lists, which on review were deemed unlikely to have ever occurred within the park or were alien or extralimital species.

Species	**Common Name**	**Reason for removal**
Agama hispida	spiny ground agama	Lack of evidence of occurring within the park.
Aspidelaps lubricus	coral shield Cobra	Lack of evidence of occurring within the park.
Boaedon capensis	brown house snake	Lack of evidence of occurring within the park.
Causus rhombeatus	rhombic night adder	Lack of evidence of occurring within the park.
Goggia incognita	N/A	Lack of evidence of occurring within the park.
Goggia lineata	striped pygmy gecko	Lack of evidence of occurring within the park.
Hemachatus haemachatus	rinkhals	Consultation of various experts yielded that the species had not occurred within the park.
Karusasaurus polyzonus	Karoo girdled lizard	Lack of evidence of occurring within the park.
Lamprophis guttatus	spotted rock snake	Lack of evidence of occurring within the park.
Nucras lalandii	Delalande's sandveld lizard	Lack of evidence of occurring within the park.
Pedioplanis lineoocellata pulchella	common sand lizard	Lack of evidence of occurring within the park.
Psammophis leightoni	Cape sand snake	Lack of evidence of occurring within the park.
Pseudocordylus langi	Lang's crag lizard	Lack of evidence of occurring within the park.
Ramphotyphlops braminus	flowerpot snake	Alien species.
Stigmochelys pardalis	leopard tortoise	Extra limital species.
Trachylepis variegata	variegated skink	Lack of evidence of occurring within the park.
Tropidosaura montana	common mountain lizard	Lack of evidence of occurring within the park.

Appendix A1b. A summary of the species of amphibian present on SANParks lists, which on review were deemed unlikely to have ever occurred within the park or were alien or extralimital species

Species	**Common Name**	**Reason for removal**
Amietia delalandii	Delalande's river frog	Lack of evidence of occurring within the park.
Amietia poyntoni	Poynton's river frog	Lack of evidence of occurring within the park.
Cacosternum boettgeri	Boettger’s dainty frog	Lack of evidence of occurring within the park.
Hyperolius marmoratus	marbled reed frog	Extra limital species.

Appendix A2. A summary of the species of reptile assessed for this study. The table shows the scientific names of each species, their IUCN Red List Status, and their degree of endemism (Mlt = Multinational, SA = endemic to South Africa, CFR = endemic to the Cape Floristic Region, TMNP = endemic to Table Mountain National Park).

Species	**Common Name**	**IUNC Red List Status**	**Endemism**
Acontias meleagris	Cape legless skink	Least Concern	SA
Afrogecko porphyreus	marbled leaf-toed gecko	Least Concern	SA
Agama atra	southern rock agama	Least Concern	Mlt
Amplorhinus multimaculatus	many-spotted snake	Least Concern	Mlt
Bitis arietans	puff adder	Least Concern	Mlt
Bitis armata	southern adder	Vulnerable	CFR
Bitis atropos	berg adder	Least Concern	Mlt
Bradypodion pumilum	Cape dwarf chameleon	Near Threatened	CFR
Chamaesaura anguina	Cape snake lizard	Least Concern	Mlt
Chersina angulata	angulate tortoise	Least Concern	Mlt
Cordylus cordylus	Cape girdled lizard	Least Concern	SA
Cordylus niger	black girdled lizard	Least Concern	CFR

Crotaphopeltis hotamboeia	red-lipped snake	Least Concern	Mlt
Dasypeltis scabra	rhombic egg eater	Least Concern	Mlt
Dispholidus typus	boomslang	Least Concern	Mlt
Duberria lutrix	common slug eater	Least Concern	SA
Gerrhosaurus flavigularis	yellow-throated plated lizard	Least Concern	Mlt
Homopus areolatus	parrot-beaked dwarf tortoise	Least Concern	SA
Homoroselaps lacteus	spotted harlequin snake	Least Concern	SA
Lamprophis aurora	aurora snake	Least Concern	SA
Lamprophis fuscus	yellow-bellied snake	Least Concern	SA
Leptotyphlops nigricans	black thread snake	Least Concern	SA
Lycodonomorphus inornatus	olive ground snake	Least Concern	SA
Lycodonomorphus rufulus	brown water snake	Least Concern	Mlt
Meroles knoxii	Knox's desert lizard	Least Concern	Mlt
Naja nivea	Cape cobra	Least Concern	Mlt
Pachydactylus geitje	ocellated gecko	Least Concern	SA
Pelomedusa galeata	South African helmeted terrapin	Least Concern	Mlt
Psammophis crucifer	montane grass snake	Least Concern	Mlt
Psammophis notostictus	Karoo sand snake	Least Concern	Mlt
Psammophylax rhombeatus	spotted skaapsteker	Least Concern	Mlt
Pseudaspis cana	mole snake	Least Concern	Mlt
Pseudocordylus microlepidotus	Cape crag lizard	Least Concern	SA
Rhinotyphlops lalandei	Delalande's beaked blind snake	Least Concern	Mlt

Scelotes bipes	silvery dwarf burrowing skink	Least Concern	CFR
Tetradactylus seps	short-legged seps	Least Concern	SA
Tetradactylus tetradactylus	Cape long-tailed seps	Least Concern	SA
Trachylepis capensis	Cape Skink	Least Concern	Mlt
Trachylepis homalocephala	red-sided skink	Least Concern	SA
Tropidosaura gularis	Cape mountain lizard	Least Concern	SA
Typhlosaurus caecus	southern blind legless skink	Least Concern	CFR

Appendix A3. A summary of the species of amphibians assessed for this study. The table shows the scientific names of each species, their IUCN Red List Status, and their degree of endemism (Mlt = Multinational, SA = endemic to South Africa, CFR = endemic to the Cape Floristic Region, TMNP = endemic to Table Mountain National Park).

Species	**Common Name**	**IUNC Red List Status**	**Endemism**
Amietia fuscigula	Cape river frog	Least Concern	SA
Arthroleptella lightfooti	Lightfoot's moss frog	Near Threatened	TMNP
Breviceps gibbosus	Cape rain frog	Near Threatened	CFR
Breviceps montanus	mountain rain frog	Least Concern	CFR
Breviceps rosei	Rose's rain frog	Least Concern	CFR
Cacosternum platys	Flat caco	Least Concern	CFR
Capensibufo rosei	Rose's mountain toadlet	Critically Endangered	TMNP
Heleophryne rosei	Table Mountain ghost frog	Critically Endangered	TMNP
Microbatrachella capensis	micro frog	Critically Endangered	CFR
Hyperolius horstockii	Horstock's reed frog	Least Concern	SA
Sclerophrys pantherina	Western leopard toad	Endangered	CFR

Semnodactylus wealii	Weale’s running frog	Least Concern	Mlt
Strongylopus bonaespei	Banded stream frog	Least Concern	SA
Strongylopus grayii	Gray’s stream frog	Least Concern	Mlt
Tomopterna delalandii	Delalande’s sand frog	Least Concern	SA
Vandijkophrynus angusticeps	sand toad	Least Concern	SA
Xenopus gilli	Cape platanna	Endangered	CFR
Xenopus laevis	African clawed frog	Least Concern	Mlt

Appendix B1. Traits initially considered for the reptile framework which were removed upon expert consultation.

Trait	Hypothesis	Reason for exclusion
Low intrinsic dispersal ability	Species which have a physical dispersal ability that does not permit movement which will keep pace with climatic changes will be more sensitive to climatic changes.	Within the TMNP context there is limited opportunity to disperse as the park is on a similar latitude to that of the most southerly point of Africa. The trait therefore carries little relevance. Furthermore, species-specific information was lacking.
Thermal environment of embryos	The ‘cul-de-sac’ hypothesis predicts that reptile species which exhibit viviparity are more vulnerable to extinction from climate change than species exhibiting oviparous reproduction (Pincheira-Donoso et al. 2013; Jara et al. 2019). The evolution of viviparity is believed to be a unidirectional adaptation to cooler climates and thus will leave these species confined to a shrinking suitable climate conditions ((Lee & Shine 1998; Shine 2005; Jara et al. 2019). Alternatively - viviparous species are better able to control temperature of eggs and are thus less vulnerable (Shine 1985; Huey et al. 2012).	Although the hypotheses are valid there is too much uncertainty as to which will have a greater effect.
Temperature Dependent Sex Determination	Species that exhibit temperature-dependent sex determination are likely to be more vulnerable to changes in population sex ratios and subsequent population impacts (Böhm et al. 2016).	Relevant for tortoises, but is a trait that has evolved over a very long time and does not lead to complete loss of either sex. Also, there is sufficient temperature variation in where the clutches are laid that it is unlikely to be a problem.
Long generation time	Species with relatively long-life spans usually reproduce less frequently, thus genetic adaptations through natural selection take longer to develop.	<25% of species had data available.

Tolerance to flooding or waterlogging	Burrowing species are likely to be negatively impacted by increased flooding and waterlogging.	Appropriate potential area of sensitivity but lack of quality data prohibits its inclusion
Small body size	Based on a two-part hypothesis: 1. Species with larger body size will have greater dispersal distance capability; 2. Species with larger bodies will be better able to withstand temperature fluctuations	Uncertainty around the relationship between body size and thermal regulation among the study species was not clear.

Appendix B2. Traits initially considered for the amphibian framework which were removed upon expert consultation.

Trait	Hypothesis	Reason for exclusion
Low intrinsic dispersal ability	As described in appendix B1.	As described in appendix B1.
Tadpoles restricted to poorly oxygenated swamps?	Species restricted to poorly oxygenated habitat are more likely to occur near to physiological thresholds of low oxygen tolerance.	Expert opinion concluded this trait lacked relevance to the TMNP study area.
Known to be sensitive to the chytrid fungus?	Impacts of disease are likely to increase due to climate change.	Several additional diseases affect amphibians all of which are predicted to be exacerbated by climate change. Lack of understanding around impact on a species level led to too much uncertainty to be included.
Seasonal activity period restricted by temperature and/or rainfall	Species whose activity is already limited by low rainfall or high temperature will see increasing periods of conditions unsuitable for activity under predicted climate change	The trait was present for all amphibian species and therefore prevented identification of any meaningful variation within the taxa.

Appendix C. Workshop attendees.

Name	Organisation
Mr Atherton de Villiers	Cape Nature
Dr Andrew Turner	Cape Nature
Prof Susanna Clusella-Trullas	DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch University
Prof John Measey	DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch University

Dr Raquel Garcia	Stellenbosch University
Prof Krystal Tolley	South African National Biodiversity Institute
Dr Jessica da Silva	South African National Biodiversity Institute
Mr Josh Weeber	South African National Biodiversity Institute
Mr Zishan Ebrahim	South African National Parks
Dr Bryan Maritz	University of the Western Cape
Mr Ferdi de Lange	North-West University
Dr Callan Cohen	DST/NRF Centre of Excellence at the FitzPatrick Institute of African Ornithology, University of Cape Town
Mr Chad Cheney	South African National Parks
Prof Wendy Foden	South African National Parks and IUCN Species Survival Commission - Climate Change Specialist Group
Dr Nicola van Wilgen	South African National Parks
Dr Susan Cunningham	DST/NRF Centre of Excellence at the FitzPatrick Institute of African Ornithology, University of Cape Town

Appendix D. Experts consulted and families examined.

Family/Group	Expert(s)
All amphibian families	Prof John Measey, Dr Andrew Turner, Mr. Atherton de Villiers
Agamidae and Cordylidae	Prof Susana Clusella-Trullas
Snake families	Dr Bryan Maritz
All reptile families	Prof Krystal Tolley and Dr Andrew Turner

Appendix E1. The reptile species traits for which data was collated, variables used to score each trait, and the vulnerability thresholds assigned to each trait. Expert weighting refers to the degree of relative importance a trait has on the sensitivity or adaptive capacity of a species when considered independently from the other traits. Trait sets letters refer: A. Specialised habitat and/or microhabitat requirements; B. Narrow environmental tolerances or thresholds that are likely to be exceeded due to climate change at any stage in the life cycle; C. Dependence on a specific environmental trigger or cue that is likely to be disrupted by climate change; D. Dependence on interspecific interactions which are likely to be disrupted by climate change; E. Rarity; F. Sensitive life history; G. Poor dispersibility; H. Limited behavioural adaption; I. Poor evolvability. Framework design adapted from Foden et al. (2013) and Böhm et al. (2016).

Trait set	Traits/Characteristics	Expert Weighting	Variable to score	Vulnerability threshold
<u>Sensitivity</u>				
A	RS1: Habitat specialisation	Medium	Number of substrate types present in species range (Batjes 2004)	High = Species occurs on only one substate type Low = Species on >1 substrate type
A	RS2: Microhabitat specialisation	High	Number of microhabitat types used by the species (Fossorial, Saxicolous, Arboreal, Terrestrial, Under dead organic matter, Semi-aquatic, Termite mounds)	High = Species is reliant on dead organic matter as a microhabitat Low = Species relies on microhabitats unlikely to be affected by climate change
A	RS3: High elevation specialist	Low	Minimum elevation at which the species occurs	High = Species occurs exclusively above 1000m elevation Low = Species occurs at a range of elevations including below 1000m
B	RS4: Narrow temperature tolerance	High	Average absolute deviation in temperature across the species' historical range (Fick & Hijmans 2017)	High = Lowest 25% (value) Low = Highest 75% (value)
B	RS5: Narrow precipitation tolerance	High	Average absolute deviation in precipitation across the species' historical range	High = Lowest 25% (value) Low = Highest 75% (value)

B	RS6: Intolerant of changes to fire regime	High	Evidence of fire-based mortality and/or fire listed as a threat by the IUCN Red List	High = Evidence of fire-based mortality and/or listed as a threat on the IUCN Red List Low = No evidence
B	RS7: Seasonal activity period restricted by temperature/rainfall	Medium	Evidence of seasonal inactivity because of high temperatures or low precipitation	High = Evidence found of seasonal inactivity related to climatic conditions Low = Species is active year-round
B	RS8: Sensitive to decline in cloud/fog cover	High	Evidence of the species reliance of cloud cover/fog to remain within its environmental tolerances	High = Evidence found Low = Species activity not limited by presence of cloud cover or fog
B	RS9: Low environmental heterogeneity within range	Medium	Mean score of vector ruggedness measure (Sappington et al. 2007)	High = Highest 25% (value) Low = Highest 75% (value)
D	RS10: Narrow diet breadth	Low	Evidence of species having high dietary specialisation (morphologically and/or physiologically determined)	High = Species relies on one species for the majority (>90%) of its food resources Low = Species consumes a wide variety of food types
E	RS11: Endemic/rare	High	Endemic to TMNP, CFR, SA, Multinational	High= Species in endemic to TMNP Low = Endemic to CFR, SA, or Multinational
F	RS12: Semelparous?	Low	Evidence that the species entire lifecycle is within one year	High = Evidence present Low = Species lifecycle is >1 year
F	RS13: Inability to reproduce more than once annually in the event of lost clutch/litter	High	1. Maximum number of clutches per year 2. Ability to reproduce at any time of year?	High = Reproduce ≤1 per year and timing limited to specific periods. Low= Can breed >1 per year at anytime

Low Adaptive Capacity				
G	RL1: Dispersal limited by physical barriers	High	Location of species distribution relative to Cape Agulhas	High = The whole of the species distribution is within 10 degrees latitudinally to the most southerly point of Africa Low = Species distribution covers >10 degrees of latitude
H	RL2: No commensalism with humans	High	Evidence of ability to utilise human dominate landscapes	High = Evidence that the species is able to move through and utilise human dominated landscapes Low = Species is sensitive to anthropogenic changes its environment
G & H	RL3: Foraging mode limits behaviour adaptation	High	Foraging behaviour of the species	High = Diurnal active visual forager Low = Alternative foraging behaviour
I	RL4: Low microevolutionary potential	High	a. Mean annual reproductive output b. Genetic diversity and degree of population fragmentation	High = ≤2 offspring per year (a). Evidence of low genetic diversity within populations, and/or highly fragmented populations (b). Low = Evidence contradictory to that of high threshold

Appendix E2. The amphibian species traits for which data was collated, variables used to score each trait, and the vulnerability thresholds assigned to each trait. Expert weighting refers to the degree of relative importance a trait has on the sensitivity or adaptive capacity of a species when considered independently from the other traits. Trait sets letters refer: A. Specialised habitat and/or microhabitat requirements; B. Narrow environmental tolerances or thresholds that are likely to be exceeded due to climate change at any stage in the life cycle; C. Dependence on a specific environmental trigger or cue that is likely to be disrupted by climate change; D. Dependence on interspecific interactions which are likely to be disrupted by climate change; E. Rarity; F. Sensitive life history; G. Poor dispersibility; H. Limited behavioural adaption; I. Poor evolvability. Framework design adapted from Foden et al. (2013) and Carr et al. (2013).

Trait set	Traits/Characteristics	Expert Weighting	Variable to score	Vulnerability threshold
Sensitivity				
A	AS1: Habitat specialisation	Medium	Number of vegetation types present in species range (South African Biodiversity Institute 2012)	High = Species range occurs within only one vegetation type Low = Species range occurs within >1 vegetation type
A	AS2: Microhabitat specialisation	High	Number of microhabitat types used by the species (Torrents; Temporary water (Puddles, Vleis/Pans); Seeps; Lake/Estuarine systems; Permanent Water (excluding torrent); Terrestrial; and Garden Ponds)	High = Species relies exclusively on one microhabitat (excluding garden ponds) or is associated with temporary water, seeps, or terrestrial microhabitats Low = Species occurs in multiple microhabitats including torrents, lake/estuarine systems, permanent water (excluding torrent), or garden ponds
A	AS3: High elevation specialist	Low	Minimum elevation at which the species occurs	High = Species occurs exclusively above 1000m elevation Low = Species occurs at a range of elevations including below 1000m

B	AS4: Narrow temperature tolerance (adults)	High	Average absolute deviation in temperature across the species' historical range	High = Lowest 25% (value) Low = Highest 75% (value)
B	AS5: Narrow precipitation tolerance (adults)	High	Average absolute deviation in precipitation across the species' historical range	High = Lowest 25% (value) Low = Highest 75% (value)
B	AS6: Intolerant of changes to fire regime	High	Evidence of fire-based mortality and/or fire listed as a threat by the IUCN Red List	High = Evidence of fire-based mortality and/or listed as a threat on the IUCN Red List Low = No evidence
B	AS7: Sensitive to decline in cloud/fog cover	High	Evidence of the species reliance of cloud cover/fog to remain within its environmental tolerances	High = Evidence found Low = Species activity not limited by presence of cloud cover or fog
B	AS8: Tadpoles reliant on highly oxygenated water bodies (fast flowing streams)	High	Evidence that tadpoles are restricted to highly oxygenated waters	High = Tadpoles reliant on fast flowing streams Low = Tadpoles not reliant on fast flowing streams
C	AS9: Dependent on environmental cues predicted to be disrupted by climate change	High	Evidence of dependence on rainfall or temperature cues to initiate breeding and/or migrating	High = Evidence found Low = Species uses environmental cues unaffected by climate change (e.g. photoperiod)
D	AS10: Narrow diet breadth	Low	Evidence of species having high dietary specialisation (morphologically and/or physiologically determined)	High = Species relies on one species for the majority (>90%) of its food resources Low = Species consumes a wide variety of food types
E	AS11: Endemic/rare	High	Endemic to TMNP, CFR, SA, Multinational	High= Species in endemic to TMNP Low = Endemic to CFR, SA, or Multinational
F	AS12: Inability to reproduce more than once annually in the event of lost clutch/litter	High	1. Maximum number of clutches per year 2. Ability to reproduce at any time of year?	High = Reproduce ≤1 per year and timing limited to specific periods.

				Low= Can breed >1 per year at anytime
F	AS13: Eggs laid in leaf litter, moss, ephemeral water sources	High	Evidence the species is restricted to laying in leaf litter, moss, or ephemeral water sources	High = Species restricted to laying in leaf litter, moss, or ephemeral water sources Low = Species is not restricted to the laying environments described in the high threshold.

Low Adaptive Capacity

G	AL1: Dispersal limited by physical barriers	High	Location of species distribution relative to Cape Agulhas	High = The whole of the species distribution is within 10 degrees latitudinally to the most southerly point of Africa (Foden et al. 2013). Low = Species distribution covers >10 degrees of latitude
H	AL2: No commensalism with humans	High	Evidence of ability to utilise human dominate landscapes	High = Evidence that the species is able to move through and utilise human dominated landscapes Low = Species is sensitive to anthropogenic changes its environment
I	AL3: Low microevolutionary potential	High	a. Mean annual reproductive output b. Genetic diversity and the degree of population fragmentation	High = ≤2 offspring per year (a). Evidence of low genetic diversity within populations, and/or highly fragmented populations (b). Low = Evidence contradictory to that of high threshold
I	AL4: Long generation time	High	Time to complete metamorphosis to adult form.	High = ≥12 months Low = <12 months

Appendix F1. Summary of the most climate change vulnerable reptile species found in the two hotspot areas of Noordhoek/Fish hoek valley and the lower slopes of the southern suburbs.

Scientific Name	Common Name	Hots spot	IUNC Red List Status
Afrogecko porphyreus	marbled leaf-toed gecko	Both	Least Concern
Amplorhinus multimaculatus	many-spotted snake	Both	Least Concern
Bradypodion pumilum	Cape dwarf chameleon	Both	Near threatened
Bitis arietans	puff adder	Both	Least Concern
Chamaesaura anguina	Cape snake lizard	Noordhoek/Fish hoek valley	Least Concern
Chersina angulata	angulate tortoise	Both	Least Concern
Cordylus cordylus	Cape girdled lizard	Both	Least Concern
Cordylus niger	black girdled lizard	Both	Least Concern
*Dasypeltis scabra**	rhombic egg eater	Both	Least Concern
Dispholidus typus	boomslang	Both	Least Concern
Duberria lutrix	common slug eater	Both	Least Concern
Gerrhosaurus flavigularis	yellow-throated plated lizard	Both	Least Concern
Homopus areolatus	parrot-beaked dwarf tortoise	Both	Least Concern
Homoroselaps lacteus	spotted harlequin snake	Both	Least Concern
Lamprophis aurora	aurora snake	Both	Least Concern
*Lamprophis fuscus**	yellow-bellied snake	Both	Least Concern
Leptotyphlops nigricans	black thread snake	Both	Least Concern
Lycodonomorphus inornatus	olive ground snake	Both	Least Concern
Lycodonomorphus rufulus	brown water snake	Both	Least Concern
Meroles knoxii	Knox's desert lizard	Both	Least Concern

*Psammophis crucifer**	montane grass snake	Both	Least Concern
Psammophis notostictus	Karoo sand snake	Both	Least Concern
Psammophylax rhombeatus	spotted skaapsteker	Both	Least Concern
*Pseudaspis cana**	mole snake	Both	Least Concern
Pseudocordylus microlepidotus	Cape crag lizard	Noordhoek/Fish hoek valley	Least Concern
Rhinotyphlops lalandei	Delalande's beaked blind snake	Both	Least Concern
Scelotes bipes	silvery dwarf burrowing skink	Both	Least Concern
Tetradactylus seps	short-legged seps	Both	Least Concern
Tetradactylus tetradactylus	Cape long-tailed seps	Both	Least Concern
Trachylepis homalocephala	red-sided skink	Both	Least Concern
Typhlosaurus caecus	southern blind legless skink	Lower slopes of southern suburbs	Least Concern

*Indicates the species was not categorised as highly vulnerable under the best-case scenario.

Appendix F2. Summary of the most climate change vulnerable amphibian species found in the north-west areas of Cape Point.

Scientific Name	Common Name	IUNC Red List Status
Arthroleptella lightfooti	Lightfoot’s moss frog	Near Threatened
Breviceps montanus	mountain rain frog	Least Concern
Breviceps rosei	Rose’s rain frog	Least Concern
Cacosternum platys	Flat caco	Least Concern
Capensibufo rosei	Rose’s mountain toadlet	Critically Endangered
Hyperolius horstockii	Horstock’s reed frog	Least Concern
Sclerophrys pantherina	Western leopard toad	Endangered
Strongylopus bonaespei	Banded stream frog	Least Concern
Xenopus gilli	Cape platanna	Endangered