Climate Change Impacts on Dwarf Succulents in Namibia as a Result of Changes in Fog and Relative Humidity

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***Abstract*-The Succulent Karoo is well known for being rich in species with approximately 5,000 vascular plant species, and has a high floral endemicity. In this study, we investigate the current status of the dwarf succulents of Namibia, as represented by two genera in the Aizoaceae: *Conophytum* (restricted distribution) and *Lithops* (wider distribution) and examine possible climate change impacts on these genera by studying the effects on non-rainfall moisture availability (number fog days and relative humidity). Both genera show a contraction and loss of habitat, despite their drought resistant nature and adaptation to the current arid environment. This study demonstrates that climate-change induced alterations to the number of fog days in Namibia results insignificant changes in the distribution of the dwarf succulents, and shows the Atlantic coast and Orange River areas as potential refuge areas for dwarf succulents such as *Conophytum* and *Lithops*.**

Keywords- Climate Change; Conophytum; Lithops; Dwarf Succulents; Fog; Relative Humidity; Succulent Karoo; Namibia

I. INTRODUCTION AND BACKGROUND

Anthropogenic climate change is recognised as one of the main threats to floral biodiversity today [1]. As it is impossible to halt the climate changes that are setting the course of impacts upon the environment, it is important to track the possible changes to inform future conservation strategies of species. The Succulent Karoo biome is considered to be a biodiversity hotspot by Conservation International and is rich in species with approximately 5,000 vascular plant species, including many rare and red listed species. The biome also displays a high floral endemicity [2]. The Succulent Karoo is a semi-desert region characterised by relatively low levels of winter-rain. The coastal areas of South-Western Namibia and South Africa experience a strong maritime influence, where the cold Benguela upwelling system produces frequent advective fogs, which may extend up to 100km inland. The hyper-arid Desert biome (bordering the Succulent Karoo) also benefits from these fogs which are thought to be the main source of moisture there [3-4].

Fig. 1 *C. ricardianum* (photo: A. J. Young)

Fig. 2 *L. ruschiorum 'nelii'* (photo: A. J. Young)

Succulent plants display several adaptations to the arid conditions they experience especially with respect to drought resistance. In order to retain moisture these plants have thick fleshy stems and/or leaves, often possess a prominent wax layer and hairy leaves. Succulents have the distinct ability to live on limited water sources and do not depend on rainfall only, being

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able to use mist, dew and fog. Together with the other adaptations listed above this allows these plants to survive in an extremely arid ecosystem and to survive droughts. In this study, we examine two succulent genera belonging to the Aizoaceae family, namely *Conophytum* and *Lithops* in Namibia. *Conophytum* is a good plant model for studying patterns of diversity and speciation in the Succulent Karoo biome, and the possible effects of climate change on the dwarf succulents in general [2]. As the distribution of *Conophytum* in Namibia is restricted, *Lithops* was used as a comparative genus as it has a much wider distribution, yet posseses similar adaptations to their environment. These two genera work as good comparisons as *Conophytum* are exclusive to certain geological and climatic conditions, while *Lithops* are much more widespread and suited to many different environmental conditions. *Conophytum*, in particular, can be considered to be a niche occupier, often seeking out small areas of rocky substrate, typically in areas that afford some shade.

Species of *Conophytum* are variable in growth form, but they usually occur as single bodies or in small clusters of bodies, in which the leaves are partially or entirely fused along their centers [5]. By contrast, *Lithops* consist of one or more pairs of bulbous almost fused leaves opposite to each other and very little stem, with the leaves mostly buried below the surface [3]. Fig. 1 and Fig. 2 provide illustrations of species in both genera that are endemic to Namibia. Fig. 1 shows an example of *C. ricardianum* growing southeast of Rosh Pinah, Namibia close to the Orange River; and Fig. 2. shows an example of *L. ruschiorum 'nelii'* growing in the fog belt of the Skeleton Coast near Cape Cross, Namibia [5].

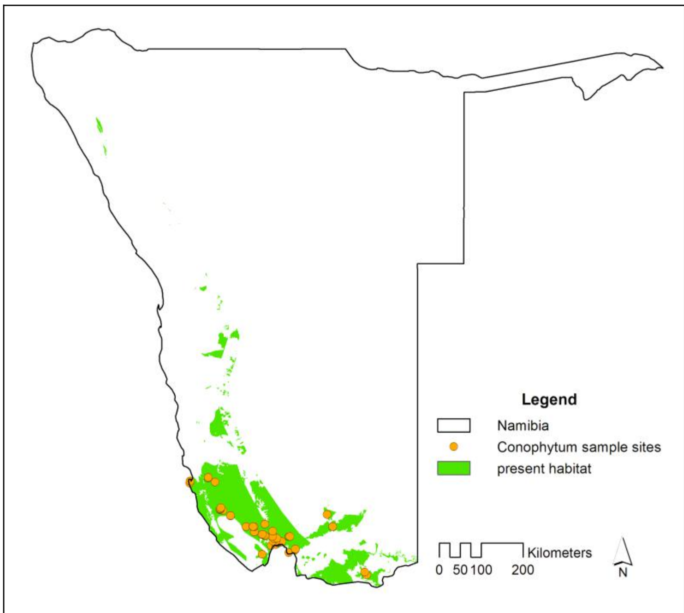

Fig. 3 Current *Conophytum* Habitat and Sample Sites in Namibia

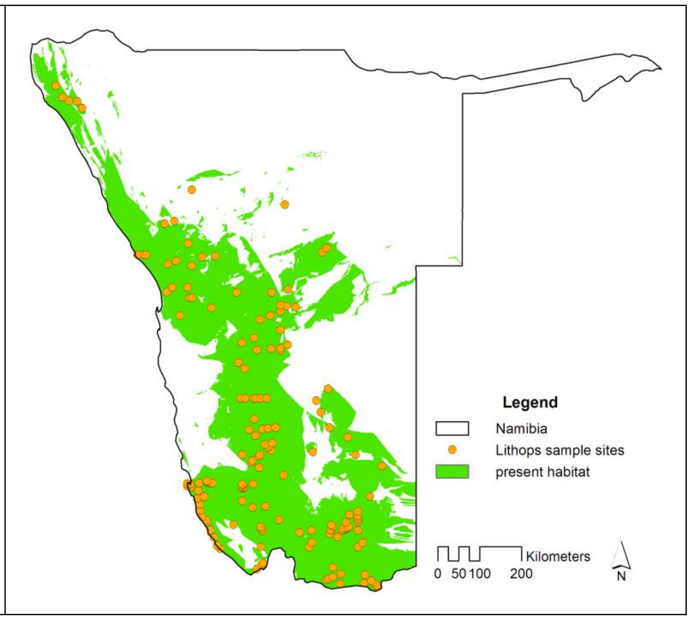

Fig. 4 Current *Lithops* Habitat and Sample Sites in Namibia

It is important to consider the environmental issues associated with climate change in Namibia. Namibia is an arid land with an open bare landscape that is affected by regular droughts. Some of the conservation issues affecting flora in Namibia include: the lack of water (both low levels and the irregular nature of rainfall), water pollution, harvesting of trees, bush fires in dry seasons, urbanisation, land transformation and the introduction of alien invasive species. These issues combined with climate change could adversely affect the succulent species, despite the fact that succulents are well adapted to the lack of water and droughts.

In Figs. 3 and 4, the current distribution and suitable bioclimatic envelope for *Conophytum* and *Lithops* in Namibia are shown. The *Conophytum* genus is narrowly distributed, while the *Lithops* are much more widely spread and experience a wider range of environmental conditions. However, both succulent genera are more concentrated along the Orange River (the border with South Africa) and along the Atlantic coast in primarily the Succulent Karoo but also in the Desert biome. Neither genera are found in the Savanna Biome in the far north and inland regions of Namibia.

II. CLIMATE DATA AND METHODOLOGY

In this study, the importance of fog and relative humidity as climate variables upon the dwarf succulent genera, *Conophytum* and *Lithops*, was studied. Previous studies have shown that the current distribution of *Conophytum* and *Lithops* is less dependent on rainfall and temperature, but instead relies more on non-rainfall moisture such as fog, dew, and water vapour [2, 6]. Due to the general lack of other forms of non-rainfall data, in this study we used fog data, with the additional variable of relative humidity as climate variables. Fig. 5 shows that the current average number of fog days per year in Namibia increases significantly by closer distance with the coast [7].

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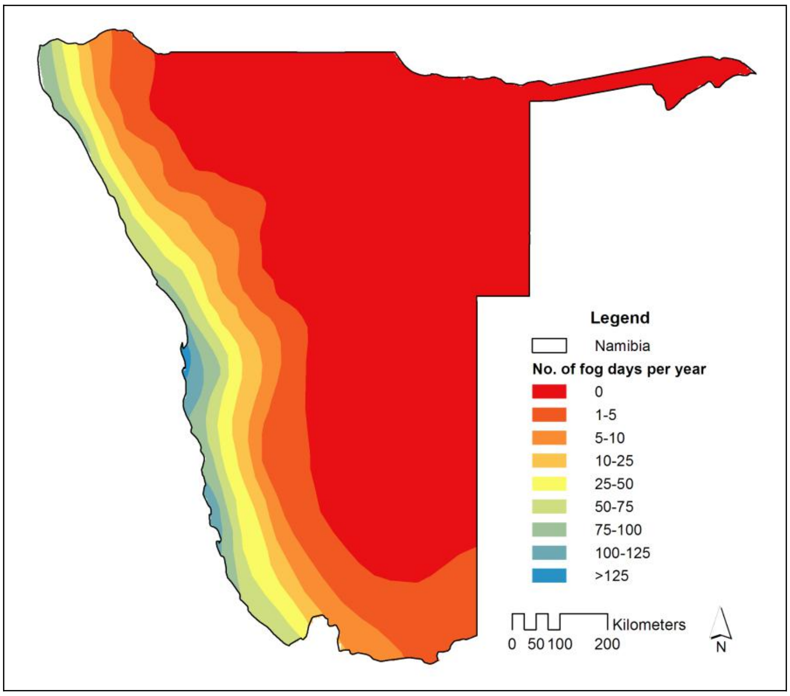

Fig. 5 Current Average Number of Fog Days Per Year in Namibia [7]

In addition to modelling future fog patterns, relative humidity has been used as additional climate variable, though it is not considered having as much a climatic impact on *Conophytum* and *Lithops* as the fog variable. In Figs. 6 and 7, one can observe the relative humidity or wetness in the driest months, and the relative humidity in the wettest months. Both show an increase in humidity towards the coast, and more dryness towards the inland regions.

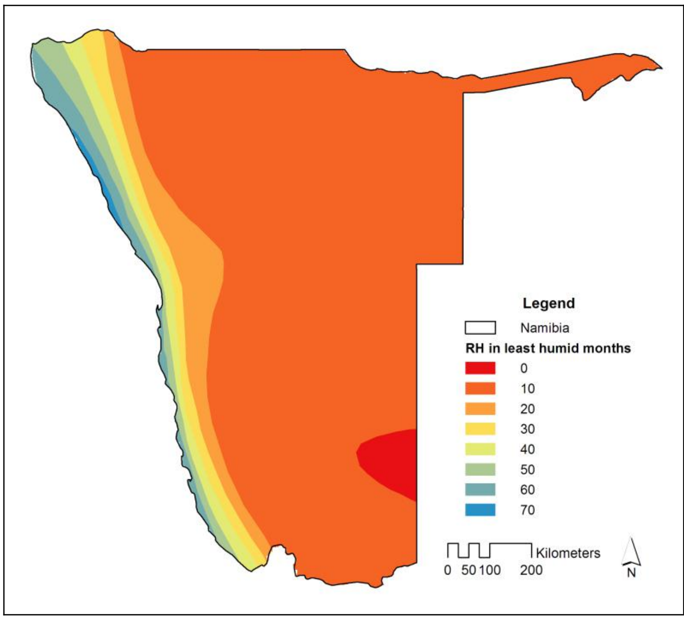

Fig. 6 Current Percentage Relative Humidity in Least Humid Months in Namibia [7]

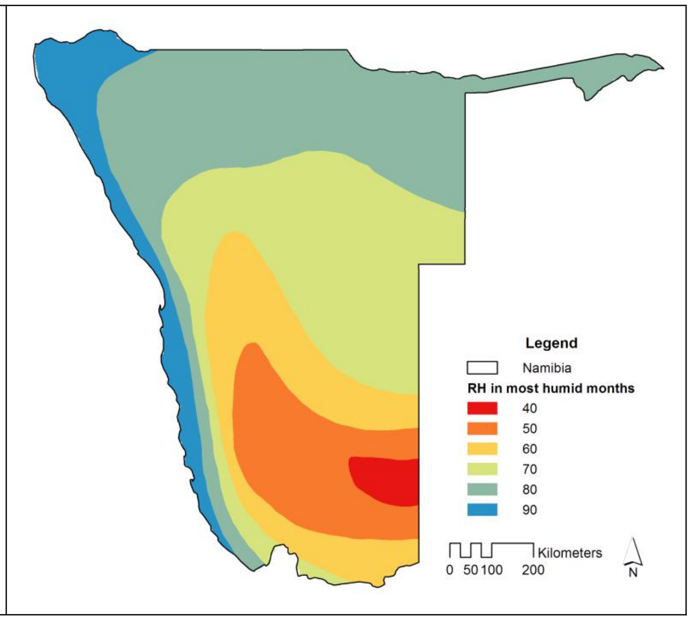

Fig. 7 Current Percentage Relative Humidity in Most Humid Months in Namibia [7]

In this study, in order to produce future fog and relative humidity data, future climate data are used, as there is no available projected fog or relative humidity data for the future. We used the MPI-ESM-MR model from the Max Planck Institute for Meteorology, as it proved to be a good global climate model by comparison to other current models [8]. The MPI-ESM is a comprehensive earth-system model, and it consists of component models for the ocean, the atmosphere and the land surface [9]. It is a conservative model, and was has been proven to be well suited for projections of the Southern African climate with its

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semi-arid regions [1-2, 8]. Representative Concentration Pathways (RCPs) are greenhouse gas concentration trajectories, which was adopted by the Intergovernmental Panel on Climate Change for its fifth Assessment Report in 2014. RCP8.5 was used as the future scenario in this case, for the projected future period 2061-2080 [10]. The RCP represents a possible range of radiative forcing values in the year 2100 relative to pre-industrial values, in this case +8.5 W/m2. RCP8.5 assumes the global annual emissions (measured in CO_2-equivalents) will continue to rise throughout the 21st century [11], and is considered as a highly realistic future scenario based on the present human activity. MaxEnt (Maximum Entropy modelling) was used as the species distribution model to estimate the relationship between species records at sites, as well as the spatial and hydrological characteristics of the sites [12-13].

The conventional Bayesian risk criterion is based on the use of a conjugate family, and the quadratic loss function [14], and MaxEnt is fundamentally a Bayesian inference, and it is established by using different risk criterions. Therefore, MaxEnt uses a Bayesian approach by which the species probability distribution subject to environmental constraints, are statistically estimated by searching the family of probability distributions under the maximum entropy criterions [15].

The Gibbs sampling is a statistical algorithm used by the Bayesian inference used in MaxEnt. The Gibbs family {$q_\lambda(x)$, λäL}, where

$$q_\lambda(x) = \frac{1}{Z_\lambda(x)} \exp\left(\sum_{i=1}^{m} \lambda_i f_i(x)\right) \quad (1)$$

with λ_i = (λ_1, λ_2,..., λ_m) as the weight vector, λ_i being the weight parameters, $f_i(x)$ representing species i's probability distribution, L being the m-dimensional space, each element x is a pixel of the investigated area, and $Z_\lambda(x)$ being the normalized constant, and the probabilities $f_i(x)$ represent the relative suitability of the environmental variable in each pixel [13, 15-17].

III. PROJECTED FUTURE CHANGES AND DISCUSSION

The future climate variables of fog and relative humidity have been used in the spatial modelling process [15, 18] to project the suitable bioclimatic envelope for both *Conophytum* and *Lithops* in the present and in the future. In addition, geology, altitude, morphology and soil type were used as environmental constraints. Previous studies have highlighted the importance of geology and soil type to the distribution of dwarf succulents [2]. Table 1 shows the contributions of the main climatic and environmental variables to the model. Fog is the single most important variable of those tested that defines the distribution of *Conophytum* in Namibia. Both morphology (plains, hills, mountains, dunes, lowlands…) and geology are also highly significant variables. Fog is also very important in defining the distribution of *Lithops*, but in addition, geology, morphology and soil type are equally important. In this model, neither variable relative humidity nor altitude demonstrated any influence over the distribution of these genera. This was unexpected since in other non-succulent plants, these variables would have generally expected to be more influential [1, 19].

TABLE 1 PERCENTAGE CONTRIBUTION OF THE ENVIRONMENTAL VARIABLES TO SPECIES DISTRIBUTIONS

Variables	***Conophytum***	***Lithops***
altitude	2.5899	5.772
average Number of Fog Days Per Year	42.5662	20.0418
geology	17.0265	18.0609
morphology	27.5763	23.7903
% Relative Humidity in Least Humid Months	0.0815	3.5608
% Relative Humidity in Most Humid Months	3.0758	7.3164
soils	7.0837	21.4578

The projected future (2070) fog and relative humidity values were generated in order to examine the future climate change impact on the dwarf succulents. In Fig. 8, a map of the projected future average number of fog days per year in Namibia is shown, (with different, lighter colours to differentiate it from the current fog map, Fig. 5). It is clear from the future projections that Namibia will experience an overall reduction in the number of fog days, becoming drier, with the highest incidence of fog days closest to the coast (as now) and very little occurrences of fog further inland. The category that previously defined the very highest incidences of fog days (i.e., classed as >125 fog days annually, Fig. 5) has disappeared, but the occurrence of the lowest category of fog days (i.e., 1-10 fog days annually) experienced in future has increased. The number of days lacking fog across the country remains the same.

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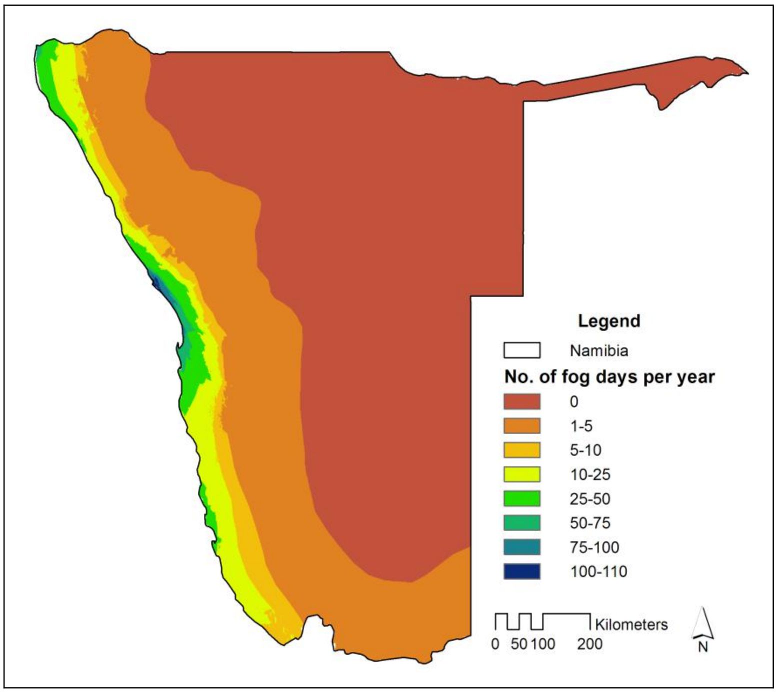

Fig. 8 Projected Future (2070s) Average Number of Fog Days Per Year in Namibia

In Fig. 9 the projected future (2070) estimates of relative humidity in the least humid months in Namibia are shown. By comparison with current data (Fig. 6) it is clear that there is an increase of the 10% category, while the higher values have been significantly reduced, with higher humidity levels only seen in some coastal regions. In Fig. 10 the projected future (2070) relative humidity levels in the most humid months in Namibia are shown. In this model, nearly all of Namibia would be predicted to experience 2-40% relative humidity, which is very different to the current data (Fig. 7) and shows a significant decrease in relative humidity levels during the most humid months.

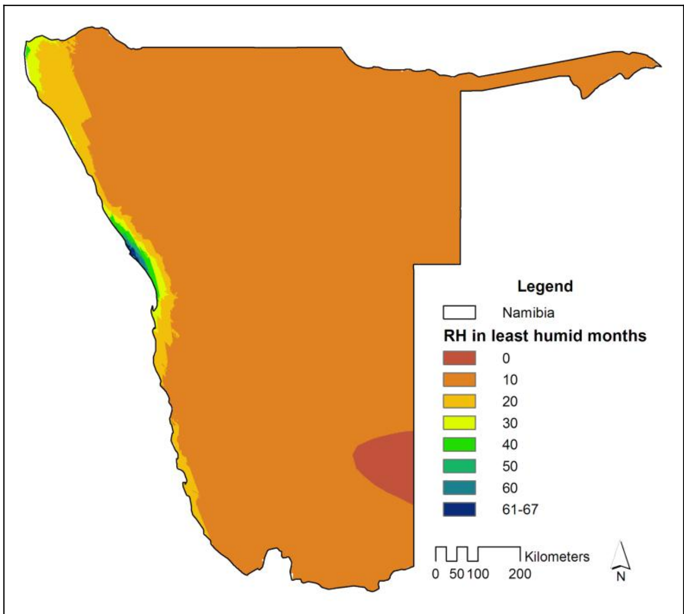

Fig. 9 Projected Future (2070s) Percentage Relative Humidity in Least Humid Months in Namibia

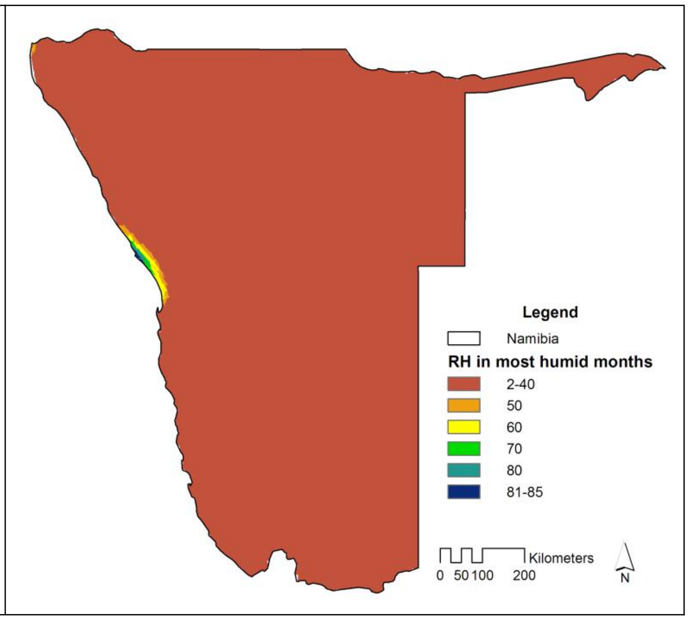

Fig. 10 Projected Future (2070s) Percentage Relative Humidity in Most Humid Months in Namibia

This model shows that these environmental variables for non-rainfall moisture will greatly influence the future suitable habitats for dwarf succulents such as *Conophytum* and *Lithops*. Of those variables tested, the most significant effect is likely to be due the predicted decrease in the number of fog days throughout the year. The predicted decrease in the number of fog days

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(coupled with a significant decrease in relative humidity), is predicted to affect the future distribution of genera such as *Conophytum* and *Lithops* significantly, as they are both heavily dependent on fog as a climate variable, and to a lesser extent, relative humidity as sources of moisture.

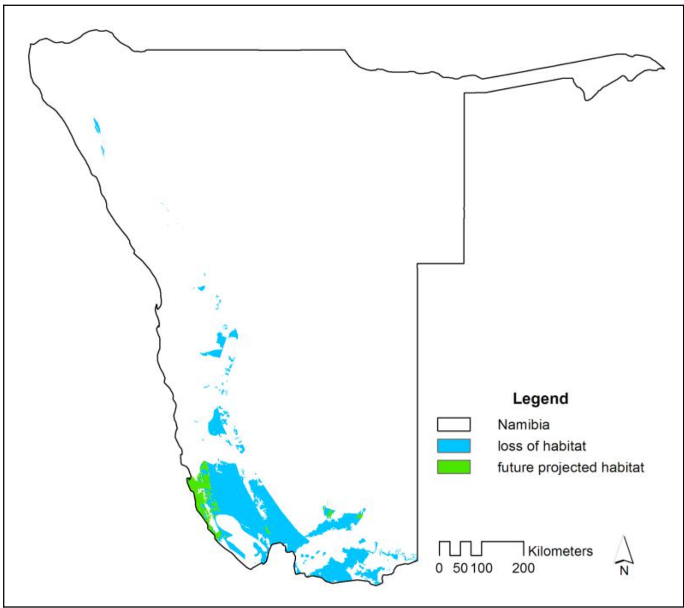

Fig. 11 Projected Future (2070s) Habitat for *Conophytum* in Namibia

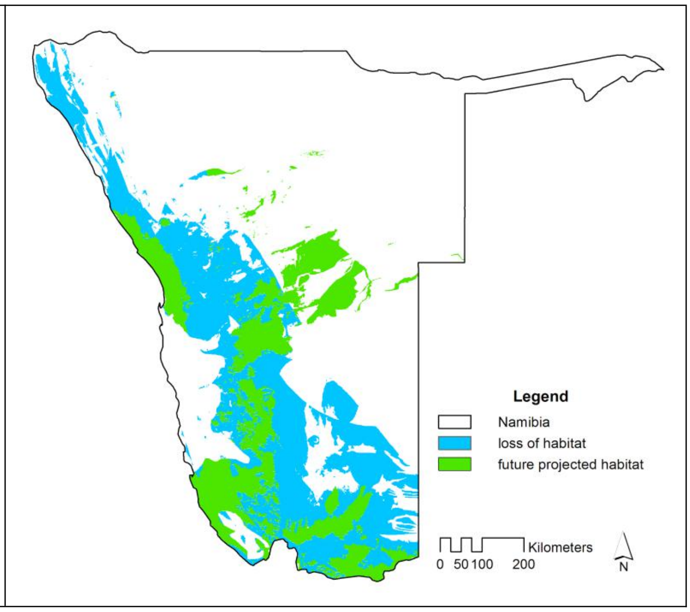

Fig. 12 Projected Future (2070s) Habitat for *Lithops* in Namibia

The projected future (2070s) suitable habitat distribution maps for both *Conophytum* and *Lithops* are shown in Figs. 11 and 12, respectively. In the case of *Conophytum*, a marked reduction in area of suitable habitat is predicted with a potential loss of current habitat for *Lithops* of 61% and for *Conophytum* of 89%. In particular, those habitats along the Orange River (which is home to several *Conophytum* endemics) in the Desert biome would be lost, and the remaining *Conophytum* taxa find refuge along the coast and on some inselbergs in the Sperrgebeit (Fig. 10), where the incidence of fog is predicted to remain high. For *Lithops*, a widespread loss of habitat and a fragmentation of current habitat is perdicted (Fig. 11). Overall, both genera of dwarf succulent show a significant loss in habitat and are negatively affected by the future climate changes especially as they rely heavily on non-rainfall moisture events such as fog, dew and water vapour [6]. The ability of these genera to migrate across the landscape and occupy newly suitable areas identified in this study is thought to be extremely limited, especially considering the timescale involved. In other climate change studies on *Conophytum* a zero migration model has been adopted.

IV. CONCLUSIONS

In this study, we assessed the current status of some dwarf succulents in Namibia, as represented by two genera: the narrowly distributed *Conophytum* and the more widely distributed *Lithops*. The projected future climate change impacts upon these succulents were explored, focusing especially on projections of non-rainfall moisture events (fog and relative humidity levels). Whilst both genera respond differently to climate change, they both show significant range contraction and loss of habitat, despite their drought resistant nature and specific adaptations to a xerophytic environment. The study has provided evidence that changes in the number of fog days in Namibia is a key factor in governing the distribution of dwarf succulents. The Atlantic coast is predicted to be an important refuge area for both genera and the Orange River area for *Lithops*. Although comparable fog data are not available for South Africa to enable detailed modelling to be performed, there are clear implications for parts of Namaqualand coastal region arising from this study. In conclusion, the results of this study are important with respect to both the current and future monitoring and conservation strategies of succulent flora in the Succulent Karoo and Desert biomes as a result of climate change.

Some of the other concerns rising from this study are issues related to the future monitoring and protection of genera such as *Conophytum* and *Lithops*. These are often situated in niche environments seeking out local sources of moisture and shade. Approximately a quarter of all *Conophytum* species can be considered to be point-endemics and are especially vulnerable to habitat loss and subsequent extinction. Modelling of such discrete populations is also challenging [20]. *In silico* climate change studies such as this are limited by the relatively large scale they operate at, often much larger than the distribution of some species. There is therefore a need for further, localised, environmental monitoring studies in order to better understand the local environments for many of these point-endemics. The vast majority of species in both *Conophytum* and *Lithops* are found in South Africa but the lack of fog data for the country prevented an analysis at a national level. Indeed, there are data limitations across Southern Africa.

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