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Social-ecological aspects of climate change impacts and adaptation in southern Africa

Ph.D. Thesis

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Author’s Declaration

I hereby declare that this Doctoral Thesis (Social-ecological aspects of climate change impacts and adaptation in southern Africa) is my own work and quoted only according to the references listed within. Neither any part of this thesis has been submitted as fulfilment to award a degree to any other institution. The thesis was written under the guidance of prof. RNDr. Tomáš Hlásny, PhD.

I agree to the publication of the thesis according to Act No. 111/1998 Coll. on universities as amended, regardless of the outcome of its defense.

Prague, 2023 Signature…………………….

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Abstract

Southern Africa is characterized by a wide range of ecosystems, including savannas, grasslands, forests, and wetlands, as well as a mixture of rural and urban communities. These social and ecological systems are, however, being significantly impacted by climate change.

This thesis uses systematic literature review, ecosystem modelling, GIS, vulnerability assessment approaches, and the social-ecological system framework to investigate the impact of climate change on social and ecological systems of southern Africa, covering eighteen countries (36% of the continent) and local populations' responses to these challenges. The thesis consists of four original scientific publications addressing various aspects of climate change impacts and adaptation in southern Africa.

Two studies, Kapuka et al., (2022) and Kapuka & Hlásny, (2021) focused on literature review to identify knowledge gaps in the current understanding of climate change impacts and adaptation in ten southern African countries. The results revealed significant advances in climate change research in southern Africa since 2005 in terms of the number of publications and African authors in first positions, however, regional inequalities are noticeable. The findings further identified barriers in climate change research in the region, such as insufficient use of modern technologies, models, climate change scenarios, and Earth Observation products. The review also revealed high diversity of observed and projected climate change impacts on terrestrial, marine, and freshwater ecosystems of southern Africa, including local extinction, increased mortality, and loss of habitats. Measures aiming to mitigate these impacts included active ecosystem management, policy development, and increased research and monitoring.

The study, Kapuka et al., (2022) modelled the vulnerability of eight major woody species to climate change in southern Africa, covering eighteen countries, as well as implications for the provisioning of ecosystem services such as timber, energy, and food. The results portrayed distinct regional differences in species range vulnerability, including hotspot and coldspot areas (i.e., areas where climatic suitability of multiple species are projected to retreat or persist). The baseline suitability range of Mopane (*Colophosperm mopane*) was least affected by climate change, rendering it a regional winner. While the baseline range of African rosewood (*Guibourtia coleosperma*) declined entirely rendering the species a regional loser. Timber provision was the most affected, while species providing food and energy were affected less.

Finally, Kapuka & Hlásny (2020) focused on identifying patterns of socio-ecological vulnerability in Namibia. The results show that populations with the poorest socio-economic performance were mostly distributed in the northern districts, which are also exposed to the highest frequency and severity of natural hazards, particularly to floods and wildfires. This coincidence of highly sensitive populations with high exposure to hazards renders these populations particularly vulnerable.

The results of the thesis can inform targeted adaptation and conservation actions and strategies, which are currently lacking in many African regions. The results can support the development of national and regional management strategies and investment priorities and contribute towards achieving the Sustainable Development Goals. The findings further have implications for climate change adaptation and ecosystem conservation, and the formulation of future research priorities for southern Africa.

Keywords: southern Africa, vulnerability, ecosystem management, climate change adaptation, social-ecological system.

1 Background

Climate change continues to threaten the sustainability of ecosystems and the wellbeing of many human populations globally (Fedele et al., 2019). It generates cascading risks propagating through the global social, ecological, and economic systems (Fortini & Schubert, 2017; Lindner et al., 2009; Littell et al., 2011; Williams et al., 2008).

Extreme temperatures, erratic rainfall, and increasing evapotranspiration demand are likely to result in major impacts on human populations and exceed the resilience limits of many ecosystems and trigger irreversible landscape transformations (IPCC, 2019). Millions of human communities and various ecosystems are projected to be exposed to the impacts of climate change in the coming decades (IPCC, 2018), resulting in limited access to key ecosystem services (Godde et al., 2020; Schewe et al., 2014; Schmidhuber & Tubiello, 2007; Thornton et al., 2014; Van Vliet et al., 2013). For example, climate change can drive complex changes in ecosystem structure and their interactions with the environment over a range of spatial and temporal scales and thus affect the ecosystem services rendered by these ecosystems. As a result, the wellbeing of human communities who heavily rely on these ecosystem services for their livelihoods are affected too (Díaz et al., 2006). Therefore, the human societies and ecosystems will require support to adapt to climate change-driven impacts (Fedele et al. 2019).

There is ample evidence attesting that variability in global climate continues to have adverse impacts on the world's social, ecological and economic systems (Fortini & Schubert, 2017; Lindner et al., 2009; Littell et al., 2011; Williams et al., 2008), as there has been an increase in the intensities and frequencies of extreme events, such as floods, heat waves and droughts (Hoegh-Guldberg et al., 2018; IPCC, 2019; Vishwambhar, 2015), including negative impacts on human health (Ebi et al. 2018; Foley et al., 2005; Thompson et al., 2010), and the acceleration of the process of land degradation (IPCC, 2019). Other observed impacts include early greening of natural vegetations in springs due to longer growing seasons (Lindner et al., 2009). The current vulnerability to climate change and inequality within systems is expected to intensify in some parts of the world (Otto et al., 2017). A system's vulnerability and adaptation to climate change impacts greatly depends on the frequency and intensity of climate change related hazards in a particular region, the sensitivity of the system and adaptation measures being implemented (Barry & Wandel, 2006; Brian et al., 2017; Littell et al., 2011).

Climate change, however, is not affecting human populations and ecosystems equally around the world, but it generates complex pattern of vulnerability depending on the level of climatic exposure, political and governance context, social-economic conditions of the populations, and their adaptive capacity (Smit & Wandel, 2006; Brian et al., 2017; Littell et al., 2011; Thomas et al., 2019). The current vulnerability to climate change and inequality within systems are expected to intensify in some parts of the world, such as Africa (Otto et al., 2017).

1.1 Climate change and why it matters in Africa

The African continent, with a considerable proportion of poor population, is one of the most vulnerable continents to climate change, with disproportionately threatened social and ecological systems (Hély et al., 2006; López-Carr et al., 2014; Palazzo et al., 2017). Moreover, the distribution of climate change vulnerability hotspots indicates that Africa is one of the regions where moderate and high multi-sector vulnerabilities predominantly occur (Byers et al., 2018; Hély et al., 2006; López-Carr et al., 2014; Palazzo et al., 2017). According to the IPCC (2019), impacts of the changing climate (i.e., extreme temperatures and high evapotranspiration) coupled with high dependence of human populations on ecosystems for their livelihoods, have transformed ecosystems in the region at an accelerating rate. Many African populations are directly and indirectly threatened by climate change due to their poor social-economic conditions and low capacity to implement effective adaptation measures (Baarsch et al., 2020; Thompson, et al., 2010).

1.1.1 Regional perspective

Southern Africa, (Fig. 1) represent a region with varying social-economic and natural conditions that are increasingly threatened by climate change-related events (e.g., unpredictable rainfall, floods, and recurrent droughts), land use, and other pressures (Guo et al., 2016; Rippke et al., 2016). It is one of the regions in Africa that is facing extreme temperatures, changes in rainfall pattern, increasing aridity, and rise in sea level (Girvetz et al., 2019). Moreover, various studies have suggested the presence of climate change hotspots of global importance in southern Africa (Bauer & Scholz, 2010; Hoegh-Guldberg et al., 2019). Climate projections have further predicted an increase in droughts, frequency and intensity of wildfires, and increased land degradation in the region (Keja-Kaereho & Tjizu, 2019; Midgley et al., 2005). Decrease in rainfall, leading to drier summers with extreme temperatures are also projected to affect large parts of the southern African region (Archer et al., 2017; Engelbrecht et al., 2011).

Major climate change-related impacts in the region include limited access to clean water, increase in water-borne diseases, and reduced agricultural productivity, leading to increased food insecurity (Archer et al., 2017). Changes in climate may also compromise the region's natural and cultural values and its rich biodiversity with severe implications for tourism that is an important source of income for many local communities in the region (Mushawemhuka et al., 2018). Increasing risk of wildfires and droughts affects adversely many ecological systems, mainly in arid and semi-arid areas (Pricope et al., 2015; Sintayehu, 2018).

The high climatic exposure of the southern African region coincides with societal issues such as extreme poverty, poor governance, low awareness of climate change-related risks and the population's high dependence on climatically vulnerable natural resources for their livelihoods (Dieckmann et al., 2013; Makate et al., 2017). Climate change-related risks are therefore particularly high for disadvantaged, rural and poor communities due to high vulnerability to climate change, and the lack of capacity to plan, finance, and effectively coordinate adaptation initiatives. Facing such risks requires swift and coordinated actions which are supported by profound understanding of the dynamics within social-ecological systems under climate change and transferring such understanding into informed decisions and policies (Cochrane et al., 2017; Posada et al., 2018).

Therefore, in the face of global challenges such as climate change, there is a need to understand the complex interactions between human communities and ecological systems. There is a need to assess possible societies' responses to climate change-related risks, to better inform effective strategies for maintaining ecosystems' resilience and sustainable development for the human communities. However, climate change related risks to regional ecosystems and human populations are understudied in southern Africa, leading to lack of understanding of climate change processes and their interactions with the social and ecological systems. Such a lack of knowledge undermines efforts on addressing climate change risks in the region, making climate change mitigation and adaptation efforts challenging.

2 Objectives

The thesis presents a framework that utilizes the interdisciplinary approaches and the social-ecological framework to enhance knowledge on the dynamics of the social-ecological systems under climate change in southern Africa. It focuses on selected aspects of climate change impacts on ecosystems and societies in southern Africa based on well-established vulnerability concepts, which may facilitate the development of effective adaptation strategies. The focus of the thesis is on southern Africa due to high complex ecological and social settings of the region, which is crucial to the transfer of the research findings to other region with similar socio-economic settings.

The main objectives of the thesis are to:

i. understand the current state of knowledge on various aspects of climate change in southern Africa. Specifically, we aimed to (1) understand the temporal development of climate change research, its geographical differences, coverage of different thematic areas, and level of research internationalization in ten southern African countries, and (2) understand observed and projected impacts of climate change on various species, populations, and ecosystems, with management and policy recommendations aiming to mitigate these impacts in nine southern African countries.

ii. assess projected climatic vulnerability of major woody species in southern Africa and risk for the provisions of main ecosystem services. Specifically, we aimed to investigate how climate change threatens the potential current and future distributions of eight major woody species and the ecosystem services they provide in southern Africa.

iii. evaluate the patterns of vulnerability of the human societies to natural hazards in Namibia as a case study. Specifically, we aimed to identify the main factors influencing social vulnerability in the districts of Namibia and evaluate how the socio-economic fitness of populations coincide with the distribution of high-hazard areas.

3 Literature review

3.1 The social-ecological system framework

The strong relationship between human communities and the environment has led to the emergence of the social-ecological system (SES) framework (Barreteau et al., 2016). It characterizes conditions where different components of human community (e.g., economic, cultural, and political) and environment (e.g., biological, geological, chemical, and physical) are strongly coupled and interact with each other (Herrero-Jáuregui et al., 2018). The interactions within the SES play a vital role in shaping ecosystems. For instance, the environment provides ecosystem services to human society and the society manipulate the ecological processes through various management interventions (Thonicke et al., 2020).

The concept of SES provides insights, as well as the need for multidisciplinary approaches to understand the dynamic relation between human society and the environment (Stojanovic et al., 2016). The study of SES has therefore, increasingly become a crucial framework for understanding the interactions between social and environmental systems (Leenhardt et al., 2015). The SES framework has also been widely used across the world and form an important part of many adaptation initiatives and policy formulations (e.g., Sustainable Development Goals) (Fischer et al., 2015).

Despite the progress in the applications of the SES framework, the concept still faces many challenges and uncertainty as an interdisciplinary framework (Fischer et al., 2015). This includes the challenge of assessing and quantifying the interactions within the SES, the need to determine key drivers of climatic vulnerability and measures to address climate extremes (Thonicke et al., 2020), and the lack of a common definition for SES (Colding & Barthel, 2019; Herrero-Jáuregui et al., 2018).

3.2 The concepts of vulnerability and resilience to climate change

Vulnerability and resilience concepts have gained increasing attention in literature (Noy & Yonson, 2018). The term vulnerability has been defined in numerous ways in literature. For example, Cutter et al., (2003) defined it as the probability of a system or its processes being negatively impacted by climate change related hazards, Kantamaneni, (2019) described it as the ability of a population to cope with and adapt to external stress such as environmental hazards, and Leichenko & O’Brien, (2002) defined vulnerability as a measure of the degree to which an entity may be impacted or influenced by an object or event. However, most authors agree on the three key components of vulnerability of a system as being composed of exposure, sensitivity, and adaptive capacity (Birkmann, 2006).

Although resilience has been an important concept in literature since its emergence, it is still not well understood on its application in various disciplines, as the concept has been evolving (Li et al., 2020; Mumby et al., 2014). Like vulnerability, resilience has various definitions. For example, the United Nations (UN) define resilience as: “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, to transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures, and functions through risk management” (United Nations, 2016). Some authors define resilience as the magnitude of a stressor that a social and ecological system is capable of enduring and its ability to recover to its original characteristics in the presence of shocks (Cutter et al., 2008), while others (e.g., Adger, 2000) attempt to differentiate resilience between social and ecological by defining social resilience as the ability of groups or communities to cope with external stresses and disturbances due to social, political, and environmental change, and ecological resilience as a characteristic of ecosystems to maintain themselves in the face of disturbance. Mumby et al., (2014) categorized resilience into ecological (ability of a system to be able to exhibit recovery trajectories through disturbance) and engineering resilience (measures the rate of recovery to an equilibrium state). However, there is no significant differences in the meanings of the above definitions of resilience, and all definitions demonstrate that the main characteristic of resilience is maintaining a balanced state of the social-ecological systems.

The two concepts have become increasingly vital in social and environmental policy formulation and in informing environmental and development discourse (Cannon & Muller-Mahn, 2010). Moreover, the concepts can be seen as being strongly interrelated, as vulnerability is viewed by some as a component of sensitivity and resilience capacity (Lei et al., 2014). For example, assessing the vulnerability of a system can also reveal the level of resilience of that system to withstand shocks, and the lack of resilience capacity can increase vulnerability of a system to the impacts of various stressors (Nunes, 2021).

Within the SES, vulnerability can be significantly minimized by collectively maintaining the resilience capacity of the ecological components. For example, reducing pressure on the ecosystem and conserving biodiversity through effective management practices and enhancing adaptive capacity of the social components of the system to cope with adverse changes within the environment (Mumby et al., 2014; Thonicke et al., 2020). Vulnerability and resilience assessments thus form an essential step in mapping and identifying patterns and level of sensitivity or exposure to external stressors (Dintwa et al., 2019), and provide knowledge which can support the formulation of area-specific solutions to enhance a system's adaptative capacity (Chakraborty et al., 2019).

3.2.1 Assessment of vulnerability and resilience of the social-ecological systems

Vulnerability and resilience assessments have become crucial components of decision-making across the world (Skondras et al., 2020), which can be carried out at micro or macro level (Leichenko & O'Brien, 2002). The key focus of vulnerability assessments was either on the social system (e.g., vulnerability of people) or on the biophysical assessment of natural hazards and their impacts to various sectors such as agriculture (Adger, 2006). However, increasing pressure from various stressors on human communities and environmental components have stimulated an increase in demand for transdisciplinary approaches to examine the complex interactions and vulnerability of human societies and the environment (Stojanovic et al., 2016).

Since SES is an interdisciplinary framework, it requires approaches which integrate different scientific disciplines to conduct effective transdisciplinary assessments (Folke et al., 2010; Holzer et al., 2019). As a result, various methodological approaches, concepts, theories, and models which may be applied to describe and analyze the characteristics of SES, including their vulnerability and resilience, have been developed and tested in academia (e.g., Epstein et al., 2014; Fischer et al., 2015; Metzger et al., 2005; Nguyen et al., 2016; Otto et al., 2017). This includes, for example, methods for identifying main indicators, integrated assessment approaches comprising both biophysical and social components of vulnerability, the development and application of vulnerability indices, and recommending appropriate adaptation strategies (Kapuka & Hlásny, 2020).

In vulnerability assessments, indicator-based approaches are some of the most common methods (e.g., Kapuka & Hlásny, 2020; Nguyen et al., 2016; Noy & Yonson, 2018). However, collective approaches such as climate change vulnerability assessments has been also applied in mapping and identifying environmental components with higher risk of decline due to climate impacts (see, Kapuka et al., 2022; Pacifici et al., 2015). Metric-based approaches have been used to assess the vulnerability of rural communities to flood risks (see, Adeloye et al., 2015).

Assessment of resilience, however, can be approached through the analysis of the ability of a system to withstand stressors, re-organize, respond, and maintain its basic functions in the presence of disturbances (Osbahr et al., 2010). For example, the use of resilience indices to measure the effect of disturbance absorption and determine a system's qualities to cope with current and future challenges (Briguglio et al., 2009). Some authors (e.g., Stanickova & Melecký, 2018) have noted that resilience can be determined through the analysis of available adaptation strategies. These underlying adaptation strategies can then be used to establish how well a system is likely to resist any current and future shocks.

Although there are no standard methods of assessing resilience currently available, some models and approaches have shown great success in their applications (e.g., Cross-scale resilience model, Network analysis, Agent modelling etc) (Li et al., 2020; Siders, 2019). Multivariate statistical approaches and software such as ANOVA, regression, spearman's rank correlation, logistic regression, cluster, and principal component analyses are also useful tools for exploring the relationships between interacting systems (Menzie et al., 2007). The concept of exposure-sensitivity-adaptive capacity has also been widely used to assess and understand the level of vulnerability of a system to climate variability and climate change in a spatially explicit manner (e.g., Fortini & Schubert, 2017; Lindner et al., 2009; Pandey et al., 2015).

Despite efforts in the development of conceptual and analytical knowledge of vulnerability and resilience assessments, several challenges persist and limits the realization of full potential that integrated approaches can offer to the assessment of vulnerability (Bruno Soares et al., 2012). For example, the complexity of theoretical and conceptual frameworks applied in the assessments of vulnerability makes it difficult to assess vulnerability and compare different assessments and results at different spatial scales (Malone & Engle, 2011).

3.3 Adaptation strategies to climate change impacts

It is apparent that the progress of human development and environmental processes are being hindered by the aggravating impacts of climate change around the world (IPCC, 2019). The intensity and severity of current climatic regimes has become a cause for concern (De Souza et al., 2015) and has prompt human societies to take collective actions to address the impacts of climate change. To enable sustainable development, multiple adaptation strategies are being implemented around the world, including where extreme climate conditions always prevail and exhibit high vulnerability, such as the arid part of sub-Saharan Africa (Bunting et al., 2013). Effective adaptation efforts, however, need to be area-specific and consistent with the underlying settings of the specific system (Abson et al., 2012), as adaptation approaches are influenced by various factors, including the structure of the system, temporal and spatial scale, key beneficiaries, type of response required, and sector involved (Holman et al., 2019).

Adaptation strategies to climate change can take different forms, including reducing the populations' dependence on natural resources. This can be done through the provision of various alternative sources of livelihoods, technology inputs, effective natural resources management, effective implementation of climate change policies and strategies (Thompson et al., 2010). For example, in some parts of southern Africa, collective adaptation strategies such as the adoption of Climate-Smart Agriculture (CSA), which involve a shift in agricultural practices and the participatory Community Based Natural Resource Management (CBNRM) programme, have shown major improvements in enhancing populations' resilience to climate change related stress (Osbahr et al., 2010).

A system's response to external stress was for example, categorized by Fedele et al., (2019) into three major types: coping responses, incremental adaptation, and transformative adaptation. Coping strategies are usually applied by the affected populations to resist or minimize the impacts from external challenges and maintain the original characteristics of the affected systems (Whitney et al., 2017). This type of adaptation approach is usual short term and might not be the ideal strategy to enhance a system's adaptive capacity in the long run.

Incremental adaptation strategies on the other hand involves minor, but effective changes to a system's settings, with the main purpose of enhancing its resilience to shocks (Kates et al., 2012). For instance, shifts in agricultural and land management practices (e.g., introduction of irrigation systems, reduction of livestock numbers) to adapt to the challenges affecting the agricultural sector (Nguyen et al., 2016).

Society can also respond to environmental shocks and reduce their vulnerability to environmental stress through transformative adaptation. For example, by completely rehabilitating degraded landscapes. Transformative adaptation strategies are long term and focuses on addressing or tackling the main sources of environmental challenges (Olsson et al., 2004). They create changes that leads to new interactions between social and ecological systems (Wahid et al., 2019) .

Despite various adaptation approaches being implemented across the world, there is still a growing demand for increased external financial investments into adaptation mechanisms, particularly in developing countries with limited resources and human capacity (Osbahr et al., 2010). For example, different cultural beliefs in most part of the southern African region makes it difficult to effectively implement some of the underlying adaptation strategies. Some parts of southern Africa, farmers and some ethnic groups with strong cultural and religious beliefs are often unwilling to take up adaptation measures, such as the reduction of the livestock herd size during droughts. Adaptation interventions in the southern African region are further being hindered by the predominant lack of quality information on regional precipitation patterns and specific future climate change impacts (Bauer & Scholz, 2010). Furthermore, efforts aimed at enhancing resilience will require some adjustments in the policies to effectively address the dynamics of social-ecological systems and achieve priorities needed for adaptation (Garmestani & Benson, 2013).

4 Material and Methods

4.1 Study area

The study focused on the southern African region (Fig.1), which is already facing the impacts of climate extremes, leading to severe economic and social implications in most parts of the region. As a result, at both national and regional levels, southern African countries are focused on understanding the impacts associated with climate change on social and ecological systems and formulating effective response strategies through research, particularly on climate change vulnerability in agriculture and other sectors.

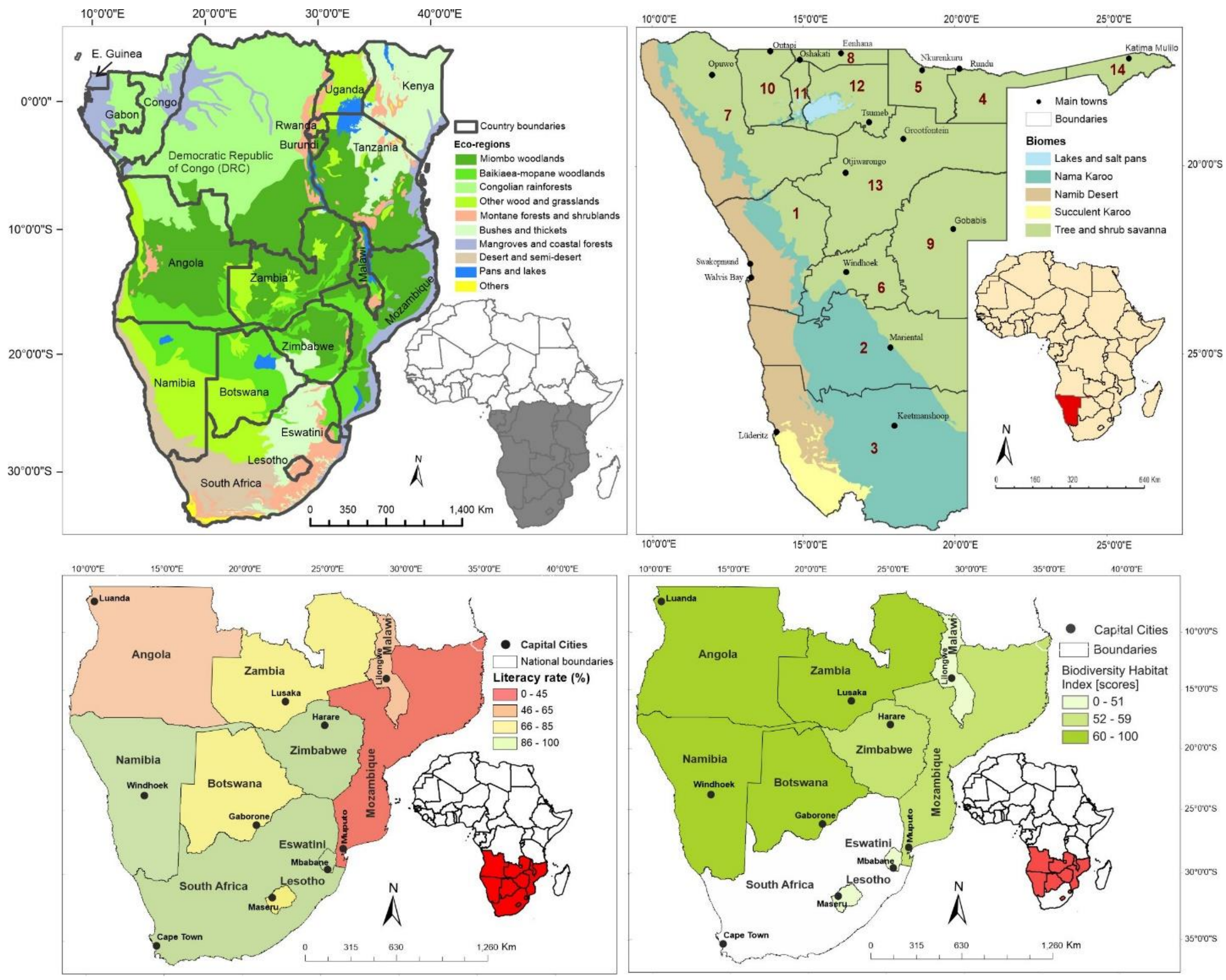

Figure 1. Areas in southern Africa investigated in this study and their locations in Africa.

Most parts of the southern African region are characterized of high proportion of poor population with limited access to essential services, escalating unemployment, and high levels of human inequalities. Agricultural practices, which greatly depends on rainfall is one of the main sources of livelihoods and economic development in southern African countries. However, agriculture, including forests and rangelands are also some of the most vulnerable economic sectors to climate change and variability (Kamali et al., 2019; Rapolaki et al., 2019).

The southern Africa region is categorized as a climate hot-spot due to erratic climatic regimes, diverse social and ecological conditions, and low human adaptive capacity (Bunting et al., 2013). Climatic conditions vary from arid to temperate and savanna in small parts of the region, with annual average rainfall ranging between 100 - 2000 mm (Spear et al., 2015). Vegetation types in the region are miombo, mopane, baikiea, acacia, and tropical moist and mangroves. In most parts of the southern Africa, seasonal patterns of precipitation and temperature are strongly related to inter-annual and inter-decadal variability, as well as influenced by El Nino Southern Oscillation (ENSO) (Archer et al., 2017; Bunting et al., 2013).

The southern African region is also subjected to frequent natural hazards such as droughts, wildfires, and floods which threaten food security. For example, the region has already experienced extreme poor rainfall in the 2014/2015, 2015/2016 and 2018/2019 rain seasons, resulting in some of the worse drought events (Archer et al., 2017). Climate change projections predict that the impacts of climate change are likely to intensify in the region (Zinyengere et al., 2013). The southern African region is likely to experience extreme temperatures, changes in rainfall patterns, and increasing aridity, as well as an increase in sea level and result in significant consequences for main development areas (Serdeczny et al., 2017). Other projected impacts include reduction in the availability of clean water, increased water-borne diseases, and reduction in agricultural productivity (Archer et al., 2017).

The southern African region also belong to some of world’s favorite tourist destinations, due to the region’s diverse cultural and biodiversity attractions. Erratic climatic regimes in the region, however, have significant impact on nature-based tourism, which greatly relies on climate conditions to maintain its diverse natural ecosystem (Hambira, 2017). In addition, extreme temperatures, incidence of wildfire, and decreasing rainfall are expected to have significant impacts on the structure and functions of the ecological system of arid and semi-arid areas of the southern Africa (Pricope et al., 2015). Vulnerability to climate change in southern Africa is mainly driven by the level of exposure to underlying environmental and climatic conditions, poor governance, and other socio-economic settings of the population (Kusangaya et al., 2014; Spear et al., 2015).

4.2 Methods

The methodology of the thesis entails integrative and interdisciplinary approaches to explore the concept of social-ecological system framework in order understand the dynamics of social-ecological systems under climate change and support the formulation of effective adaptation mechanisms in southern Africa. Transdisciplinary research approaches were used to examine the characteristics of selected southern African social and ecological systems facing climate change. The social-ecological framework was used to answer the main question addressed by the thesis: "*How different social-ecological systems are influenced by climate change in southern Africa and how the societies respond to these challenges?".* Detailed methodologies are explained in the individual original research articles that are included in this thesis. Here, we briefly describe main methodological approaches used in the presented research papers:

Identifying knowledge gaps in current understanding of climate change impact and adaptation options in Sub-Saharan Africa

We conducted a systematic literature review aiming to identify scientific papers dealing with various aspects of climate change in the southern African region. The publications were extracted from Scopus (SciVerse Scopus 2013) and Web of Science (WoS) databases following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) workflow. The search covered the period from January 2000 to April 2019. We then reviewed the retrieved publications and retained only those that met our selection criteria. The retained publications were further subjected to a detailed review to extract relevant information such as geographical location of the ecosystems, type of climate change-related impacts, thematic areas, and author's affiliations.

Identifying climate change impact on trees species distribution and ecosystem services provision in Sub-Saharan Africa

Species distribution modelling was conducted using MaxEnt algorithm to model the investigated species' current and future climatic suitability. We developed a MaxEnt model for each species using occurrence records from the Global Biodiversity Information Facility database (GBIF) and bioclimatic variables from AFRICLIM dataset. The models' predictive performances were evaluated by the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) and the True Skill Statistics (TSS). We further used two complementary metrics to evaluate the relative importance of climatic predictors to the models: percent contribution and permutation importance. We used a logistic output of MaxEnt to produce continuous distribution maps with suitability values ranging from 0 (unsuitable) to 1 (highly suitable). We deployed the trained models with future climate data to produce maps of species-specific climatic suitability for 2071–2100.

Identifying patterns of socio-economic vulnerability in Namibia

The vulnerability of the Namibian population was evaluated based on the interaction between socio-economic conditions approximated by the Social Vulnerability Index (SVI) and the level of exposure to natural hazards approximated by the introduced hazard index. Based on district positions in the space defined by the SVI and the aggregate hazard index, we categorized the districts into three vulnerability classes using the K-means clustering technique. In the final evaluation, we conducted the analysis based on composite indices with socio-economic or hazard profiles constructed for each district using the full set of underlying variables.

4.2.1 Data

Key data for southern Africa including forest vegetation, socioeconomic, and climate data were obtained from publicly available datasets. A comprehensive literature search of Web of Science (WoS) and SCOPUS was conducted, including the assessment of scientific studies published during the recent two decades (2000 –2019) on different aspects of climate change in southern Africa. Past and future climate data were obtained from various sources including Cordex Africa climate projections under different emission scenarios until 2100 and WorldClim data for the reference period 1950-2000. Data on the distribution of key woody species in southern Africa were retrieved from GBIF. Social, economic, and demographic data for the social vulnerability study for the Namibian population were obtained from the Namibia Inter-censal Demographic Survey of 2016 conducted by the Namibia Statistics Agency (NSA), while data representing natural hazard indicators, inducing fire, flood, and drought were obtained from various sources. The collected data were then processed and stored in Microsoft Access and ArcMap geodatabases that were used to support the entire research.

5 Results

The thesis' objectives were addressed through four original studies published in scientific journals with impact factors (IF). The studies were in line with the topic of the thesis, focusing on various aspects of climate change impacts and adaptation in southern Africa.

Identification of knowledge gaps in current understanding of climate change impact and adaptation options in Sub-Saharan Africa were addressed in two research papers.

The first study under this objective addressed the trends and pattern in climate change research in Sub-Saharan Africa:

5.1 Kapuka, A., Hlásny, T., Helmschrot, J., 2022. Climate change research in southern Africa in recent two decades: progress, needs, and policy implications. Reg Environ Change 22, 1–16. https://doi.org/10.1007/S10113-022-01886-3

The second paper addressed knowledge gaps in climate change impacts on ecosystems, species, and populations and adaptation options in nine countries in southern Africa.

5.2 Kapuka, A., Hlásny, T., 2021. Climate change impacts on ecosystems and adaptation options in nine countries in southern Africa: What do we know? Ecosphere 12, e03860. https://doi.org/10.1002/ECS2.3860

Climate change impact on trees species distribution and ecosystem services provision in Sub-Saharan Africa were addressed in the following study:

5.3 Kapuka, A., Dobor, L., Hlásny, T., 2022. Climate change threatens the distribution of major woody species and ecosystem services provision in southern Africa. Sci Total Environ 850, 158006. https://doi.org/10.1016/j.scitotenv.2022.158006

Patterns of socio-ecological vulnerability in Namibia were addressed in the following study:

5.4 Kapuka, A., Hlásny, T., 2020. Social Vulnerability to Natural Hazards in Namibia: A District-Based Analysis. Sustainability 12, 4910. https://doi.org/10.3390/su12124910

The above scientific publications are complemented by other two research papers, which I published during my study:

Nikodemus, A., Abdollahnejad, A., Kapuka A., Panagiotidis, D., Hájek, M., 2023. Socio-economic benefits of Colophospermum mopane in a changing climate in northern Namibia. Forests 14(2), 290; https://doi.org/10.3390/f14020290

Phiri, J., Malec, K., Kapuka, A, Maitah, M., Appiah-Kubi, SNK., Gebeltová, Z., Bowa, M., Maitah, K., 2021. Impact of Agriculture and Energy on CO2 Emissions in Zambia. Energies 14(24):8339. https://doi.org/10.3390/en14248339

5.1 Climate change research in southern Africa in recent two decades: progress, needs, and policy implications

Regional Environmental Change (2022) 22:18
https://doi.org/10.1007/s10113-022-01886-3

REVIEW

Climate change research in southern Africa in recent two decades: progress, needs, and policy implications

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Abstract
Southern Africa is a diverse region harbouring exceptional natural and cultural values, which are increasingly threatened by climate change. We investigated the progress of climate change research in ten countries in the region during 2000–2019. We reviewed 972 publications included in the Scopus database, which addressed different aspects of climate change and explicitly referred to the management, adaptation, or mitigation actions. We found that the number of such focused publications started to increase rapidly after 2004. The majority of publications addressed South Africa, while the coverage of the remaining countries was unequal. The largest proportion of the publications addressed agriculture, although social aspects of climate change started to prevail in recent five years. Local case studies dominated, while studies addressing the regional scale and employing model- and Earth Observation–based approaches were less abundant. The proportion of African authors occupying leading positions in the author teams was increasing during the investigated period. International collaboration was an important research driver, and it was particularly developed with European organizations. Publication frequency was mainly driven by the level of social and economic globalization expressed by the KOF Globalization Index. Although we identified numerous positive trends, issues such as geographical imbalance, the prevalence of local studies, and insufficient use of advanced methodologies are aspects deserving recognition in future research planning. Our findings suggest an increasing ability of African authors to contribute to the global discussions about climate change as well as improving options for the science-based formulation of continental and regional policies.

Keywords Africa · Literature review · Scopus · Adaptation · Research internationalization · Research investments

Introduction

Climate change is a prominent threat to the sustainability of many human populations (Fedele et al. 2019). Hundreds of millions of people will be exposed to the impacts of climate in the coming decades (IPCC 2018), facing reduced access to vital resources such as water and food (Schmidhuber and Tubiello 2007; van Vliet et al. 2013; Schewe et al. 2014; Thornton et al. 2014; Godde et al. 2020). Climate change is not affecting human populations equally worldwide, but it generates complex patterns of vulnerability depending on the level of climatic exposure, political and governance context, social-economic conditions of people, and their adaptive capacity (Littell et al. 2011; Thomas et al. 2019). The distribution of climate change vulnerability hotspots indicates that moderate and high multi-sector vulnerabilities occur predominantly in southern Asia, and spread to Sub-Saharan Africa (Byers et al. 2018). For example, many African populations are directly and indirectly threatened by

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climate change because of their poor socio-economic conditions, dependence on natural resources, and low capacity to take efficient adaptation actions (Thompson et al. 2010; Tucker et al. 2015; Baarsch et al. 2020).

Southern Africa is a climatically highly exposed region (Bauer and Scholz 2010), facing increasing extreme temperatures, changing rainfall patterns, increasing aridity, sea-level rise, and desertification (Zinyengere et al. 2013; Girvetz et al. 2019; IPCC 2019). Drier summers with more extreme temperatures and high risks of wildfires are projected to affect large parts of southern Africa (IPCC 2019), mainly Zimbabwe and Botswana (Engelbrecht et al. 2011). Decreasing rainfall is projected to occur in subtropical southern Africa, particularly in Angola and South Africa (Archer et al. 2017), potentially causing a decrease in agricultural yield (IPCC 2019).

High climatic exposure of the southern African region coincides with societal issues such as poor governance, low awareness of climate change-related risks, and dependence of many populations on climatically vulnerable natural resources (Kusangaya et al. 2014; Makate et al. 2017). Major impacts of climate change in the region include reduced availability of clean water, increase in water-borne diseases, and reduced agricultural productivity (Archer et al. 2017). Climate changes may also compromise the region's natural and cultural values, biodiversity, and safety, with severe implications for tourism that is an essential source of income for many communities (Mushawemhuka et al. 2018). The increasing risk of wildfires and droughts adversely affects many ecological systems, mainly in arid and semi-arid areas (Pricope et al. 2015; Sintayehu 2018).

Climate change generates cascading risks propagating through physical systems, ecosystems, economy, and society (Adger et al. 2018). Facing such risks requires a profound understanding of multisectoral vulnerabilities and transferring such understanding into informed decisions and policies (Cochrane et al. 2017; Posada et al. 2018). However, large regional differences in the engagement in scientific endeavours related to climate change compromise global adaptation efforts. For example, Blicharska et al. (2017) described a striking divide in the research relevant to climate change policies between northern (mostly OECD) and southern countries primarily located in parts of Asia, Africa, and Latin America. Such a divide may impact most on least developed countries, which are the most vulnerable to climate change, while their contribution to relevant research is disproportionally small. A similar imbalance can be observed at the continental scale—for example, 80% of African authorships in geosciences were found to stem from only five countries (North et al. 2020).

Although climate change–related research in southern Africa has significantly advanced (Ford et al. 2015; Vogel et al. 2019), it still faces challenges such as insufficient availability of data, research infrastructure, and human resources (Haselip and Hughes 2018). For example, the poor availability of reliable climate data is an essential obstacle to understanding current and future risks to human populations and their environment (Ziervogel et al. 2014; Posada et al. 2018). Other limitations include the lack of methodologies and tools for monitoring climate change and assessing the vulnerability of different social and ecological systems (Posada et al. 2018). African authors are significantly underrepresented in high-impact publications and rarely occupy leading positions in author teams (Tarkang and Bain 2019; North et al. 2020).

Research internationalization and social-economic globalization are essential drivers of scientific performance, alleviating inequalities between countries in the access to the most recent understanding (Kwiek 2015). In Africa, initiatives such as Climate Research for Development (CR4D), the Collaborative Adaptation Research Initiative in Africa and Asia (CARIAA), the Science Service Centre for Climate Change, and Adaptive Land Management in southern and western Africa (SASSCAL and WASCAL) have been implemented to support international collaboration in different areas, including climate change research. Historical relationships between Africa and the European Union (EU) led to the establishment of agreements such as the Joint Africa – EU Strategy (JAES) that addresses key areas of climate change mitigation and adaptation, with a strong focus on international collaboration, research, and social and technological innovations (Haselip and Hughes 2018).

Although there is a body of literature on different aspects of climate change in southern Africa (Crespo et al. 2011; Kusangaya et al. 2014; Hoffman et al. 2019; Lawal et al. 2019), studies mapping the temporal development of climate change research, its geographical differences, coverage of different thematic areas, and level of research internationalization are lacking (but see, for example, Thompson et al. 2010; Mpandeli et al. 2020). Such information, however, is vital to setting future research and funding priorities and an understanding of mechanisms driving research performance in the region.

Here, we strived to fill this knowledge gap by reviewing studies published during the recent two decades (2000–2019) dedicated to different aspects of climate change. We particularly focused on studies providing information relevant for adaptation, mitigation, and management of natural resources. We also strived to understand how international collaboration and the role of African authors in climate change research have been developing. Finally, we evaluated how publication performance was associated with different demographic, economic, and other characteristics of the investigated countries.

Materials and methods

Study area

We investigated ten countries in the southern African region, which are part of the Southern African Development Community (SADC). The study region includes Angola, Botswana, the Kingdom of Eswatini (further Eswatini), Lesotho, Malawi, Mozambique, Namibia, South Africa, Zambia, and Zimbabwe (Fig. 1a). These countries cover 19.8% of the African continent and shelter 170 million inhabitants. The countries exhibit significant differences in political, social-economic, and natural conditions. The average GDP per capita in the region is 3000 USD, ranging from 360 USD in Malawi to 7600 USD in Botswana (Table S1 in Online Resources) (The World Bank World Development Indicators. 2020). According to The Economist Intelligence Unit's Democracy Index (2020), Botswana exhibits the highest level of democracy (7.81 score), followed by South Africa (7.24) and Lesotho (6.54). On the other hand, Eswatini (3.14), Zimbabwe (3.16), and Angola (3.75) are the least democratic countries in the region (Fig. 1b).

Population growth, food insecurity, and diseases such as HIV/AIDS severely compromise the region's ability to achieve political stability and economic and social development (Shackleton and Shackleton 2012). Approximately half of the population in the region lives below the poverty line (Osabohien et al. 2020). Southern Africa has also experienced increased population migrations due to conflicts, social and economic inequalities, increased natural hazards, and environmental changes (Flahaux and de Haas 2016; Mpandeli et al. 2020). Still, the region has developed rapidly with the support of different development programmes and due to overall economic and political globalization (Leichenko and O'Brien 2002). Despite regional differences, a widespread acceptance and increasing uptake of new technologies, such as mobile communication, supports economic development (Aker and Mbiti 2010), while traditional industries such as agriculture and mining remain dominant.

The region represents one of the global climatic vulnerability hotspots due to its erratic climatic regimes and high current and projected climate risks (Hoegh-Guldberg et al. 2019). Climate extremes, particularly drought, regularly trigger wildlife mortality, cause habitat degradation, reduce the abundance of different species, and place conservation objectives at risk (Sintayehu 2018). Climate-mediated risks in the region include deforestation and desertification, forest fires, floods, and recurring droughts (Davis-Reddy and Vincent 2017). For example, the region has experienced extremely poor rainfalls in the seasons 2014/2015, 2015/2016, and 2018/2019 (Archer et al. 2017). The most damaging recent event was the tropical Cyclone Idai (March 2019) that affected more than 3 million people, particularly in Malawi, Mozambique, and Zimbabwe (Mercy Corps 2019; Mavhura 2020; Chari et al. 2021). In the same year, the cyclone Kenneth hit the northern part of Mozambique, affecting millions of people (Unicef 2019; Baltazar and Rossetto 2020).

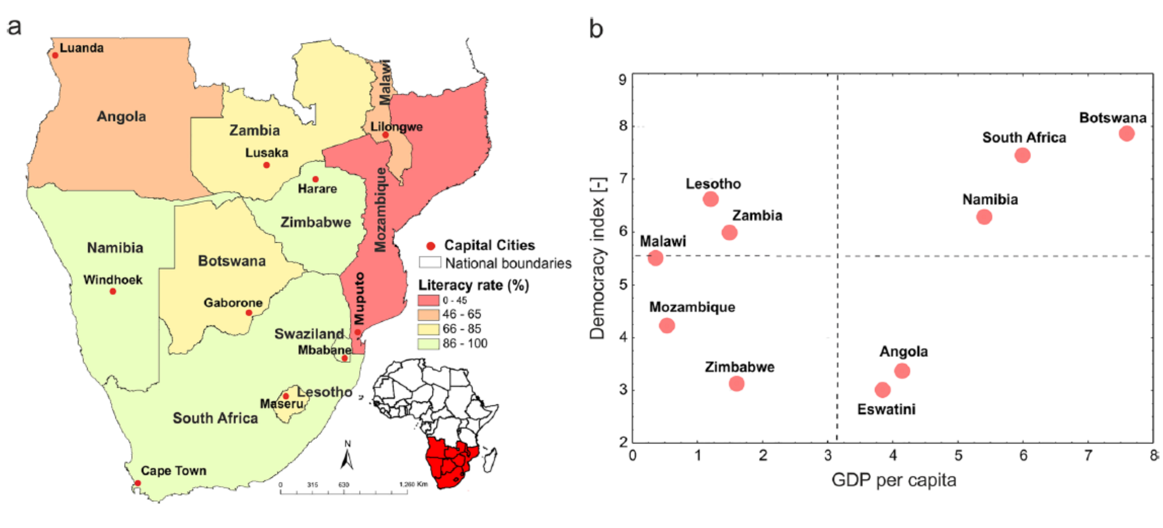

Fig. 1 Southern African countries investigated in this study and their location in Africa (**a**). Countries' position is defined by the Gross Domestic Product per capita and the Democracy Index (**b**). The dashed lines indicate the average value of either indicator. The data are for 2015–2019 (Source: The World Development Indicators, The World Bank 2019; The Economist Intelligence Unit 2020)

Methods

Literature review

We performed a literature search using the Scopus database (SciVerse Scopus 2013) that is frequently used in systematic reviews (Biesbroek et al. 2013; Jurgilevich et al. 2017). The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Fig. S1 in Online Resources) (Moher et al. 2009). We aimed to identify studies that address different aspects of climate change research in southern Africa and, at the same time, have management or policy implications. We addressed observed and projected changes in climate, empirical and modelling studies, effects of climatic extremes and long-term trends, and impacts on various sectors, ecosystems, and human communities. The search was conducted on April 27, 2020, and addressed title, keywords (both author and index keywords), and abstract. We set the cut-off year for the inclusion of the records to the year 2019. We used the following search criteria:

("climate change" OR "climatic change" OR "climate warming" OR "global warming" OR "global change") AND (adaptation OR mitigation OR management) AND Africa.

Then, this search output was refined to address ten target countries only:

"Angola" OR "Botswana" OR "Eswatini" OR "Swaziland" OR "Lesotho" OR "Malawi" OR "Mozambique" OR "Namibia" OR "South Africa" OR "Zambia" OR "Zimbabwe" OR "southern Africa".

Finally, we limited search results to the subject areas: "*environmental sciences*", "*social sciences*", "*earth* and *planetary sciences*", and "*agricultural and biological sciences*", and excluded publications from the "*review*" category. In total, we preserved 1902 records in this phase. We referred to these records as the primary search output (see Online Resources for a detailed description of the review procedure).

Second, we conducted a manual assessment of the retrieved records to identify studies that addressed climate change as an organic part of the research and/or have clear implications towards management and policy-making. Except for titles, abstracts, and keywords, we reviewed at this stage also the main texts. The most frequent reason for discarding studies identified in the primary search was their focus on African countries outside our target region and an insufficient focus on climate change (e.g. climate change was not a fundamental and integral part of the research design, and formulations related to climate change were vague). This refined set included 972 studies, i.e. 51% of the original dataset. We referred to these records as the secondary search output.

We collected several attributes for each publication, including addressed countries, thematic areas, and author's affiliations (Table 1). In thematic categories, we aimed to cover major sectors, such as agriculture, water management, forestry, and fishery. However, some categories were added ad hoc to fit better the investigated publications' scope (e.g. interdisciplinary, climate policy, and governance). To understand the level of research internationalization, we collected attributes on the author's affiliations. These attributes were also used to evaluate the proportions of African and non-African authors in the authors' teams and to identify publications in which the African authors occupied the first position. Multiple attributes were allowed for each publication (e.g. more countries or thematic categories). All records were stored and processed in the MS Access database (Microsoft, 2006–2016).

Drivers of publication frequency

We focused here on publications from 2015 to 2019, encompassing 54% of publications retained in the secondary search ($n = 972$). We explored the main associations between the publication frequency and various factors explaining the differences between the countries' performance. We used a number of predictors related to the countries' social,

Table 1 Permissible ranges of attributes collected for the investigated publications

Attributes	Variables
Country	Angola; Botswana; Eswatini; Lesotho; Malawi; Mozambique; Namibia; South Africa; Zambia; Zimbabwe
Thematic area	Social; Nature conservation; Agriculture; Water management; Fishery; Tourism; Education; Climate policy & governance; Forest & Forestry; Greenhouse gas management; Interdisciplinary
Authors affiliation	African; Non-African; Mixed
Non-African affiliation	All world's countries
First author's affiliation	African; Non-African
Addressed system	Ecological; Social; Social-ecological; Physical
Scale of analysis	Local, National, Regional, Continental to global (continental + international)
Methods of assessment	Empirical, Modelling, Combined (empirical and modelling), Theoretical/Conceptual

economic, demographic, and environmental characteristics. The underlying data were retrieved from the World Bank's world development indicators and other sources (Table S1 in Online Resources). We tested the predictor set for redundancy using Spearman's rank correlation coefficient with a threshold value of 0.7. We retained the variable that showed a greater relevance to our study from each pair of correlated variables.

Because country-specific data on the number of publications are not comparable due to the different population sizes of the countries, we standardized the data with respect to actual population size in the countries. Using the number of publications per million inhabitants as an indicator of publication performance was not feasible because of the high differences in population size between the countries. This caused, for example, severe downweighting of South Africa and upweighting of sparsely populated Namibia. We, therefore, exploited a linear relationship between the publication frequency and the number of inhabitants and retained the residual values from this relationship (Fig. S2 in Online Resources). The produced variable thus represents the publication performance of the countries that is free of the effect of population size. To ease the interpretation of the residuals, we expressed them as the percentage of the mean value of publications in all countries in the region (158); the final quantity thus represents over- or under-performance of the countries relative to the average performance of the entire region (relative residuals, R%) (Table 2). All presented analyses were conducted in Statistica 13.4 (TIBCO) (2018) and ArcGIS Desktop v. 10.8, (ESRI 2020).

Results

Temporal and geographical patterns of climate change research

The number of publications identified in the primary search ($n = 1902$) increased during the recent two decades, reaching 150–250 papers published annually after 2015 (Fig. 2). The increase started to be pronounced in 2004 and 2008; only a few publications were recorded before 2004. Papers published after 2015 represented 54% of all publications since 2000.

The publications retained after their manual assessment (i.e. the secondary search outputs, $n = 972$) represented 51% of the primary search, with temporal pattern closely matching the pattern of the primary search. Publications addressing South Africa were most abundant (520 publications, 53%). Proportions of publications addressing the remaining countries were relatively equal (Fig. 2).

Table 2 Number of inhabitants in countries in the study region and number of publications identified in the SCOPUS database using the search criteria described in the text. The data are for the period 2015–2019. Relative residuals indicate the under- or over-performance of individual countries with respect to the average performance of the entire region

Country	Number of inhabitants*	Total number of publications (total)**	Relative residual [%]
Angola	29.34	112	–59.04
Botswana	2.18	134	20.71
Eswatini	1.12	105	4.94
Lesotho	2.1	115	8.94
Malawi	17.44	156	–2.37
Mozambique	28.25	136	–41.22
Namibia	2.4	139	23.39
South Africa	56.59	392	52.00
Zambia	16.61	140	–10.47
Zimbabwe	14.13	152	3.13

*(millions, average, 2015–2018)

**As the same publications addressed multiple countries, the number of publications indicates how many times a country has been addressed rather than the absolute number of publications

Thematic areas and methodologies

Agriculture, hydrology and water management, social aspects of climate change, and nature conservation were thematic categories that received the greatest attention (Fig. 3). While publications on agriculture dominated in 2000–2014, social aspects of climate change, including climate justice, local climate perception, and vulnerability, started to prevail after 2015. The increasing proportion of social studies can also be seen in the inserted pie charts, indicating the prominence of social research after 2015. At the same time, the proportion of studies on ecological and physical (atmosphere, hydrology, etc.) systems slightly decreased. Publications on rural and urban aspects of climate change impacts, tourism, and fishery received only minor attention in both periods.

The largest proportion of publications (44%) addressed the local scale, mostly represented by different case studies. Then, 27% of publications addressed the national scale. The remaining publications presented different large-scale assessments (Fig. 4a). The published research was mainly was based on empirical approaches, relying on field research and past climate observations (34%). Modelling approaches aiming to forecast the impacts and formulate forward-looking management strategies were identified, too, accounting for 24% of the publications (Fig. 4b). Finally, 16% of publications employed combined empirical-modelling

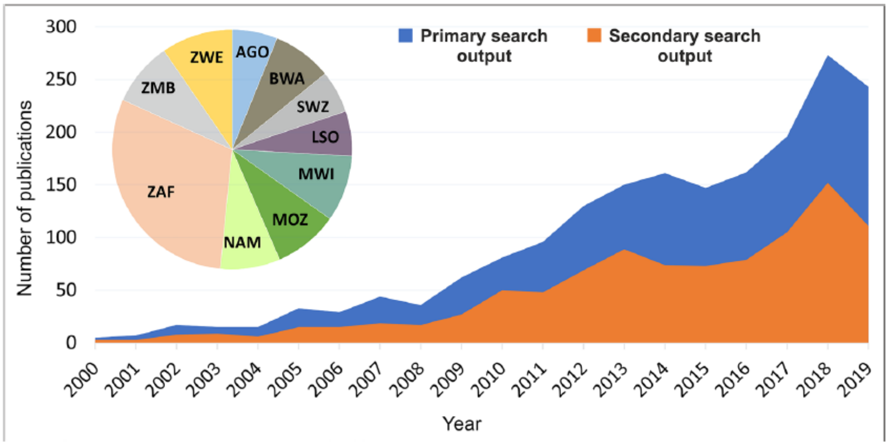

Fig. 2 Temporal evolution of publications on different aspects of climate change research in southern Africa identified in the Scopus database. Primary search output indicates the total number of publications extracted from Scopus ($n=1902$). Secondary search output ($n=972$) indicates studies, which were retained after the manual evaluation of the primary search. The insert shows the distribution of the retained publications by country. Country codes: AGO – Angola; BWA – Botswana; SWZ – Eswatini; LSO – Lesotho; MWI – Malawi; MOZ – Mozambique; NAM – Namibia; ZAF – South Africa; ZMB – Zambia and ZWE – Zimbabwe

approaches, and 27% of publications addressed various conceptual and theoretical questions.

Authorship

We found that 42% and 39% of all studies published during 2000–2014 and 2015–2019, respectively, were published by authors affiliated with African organizations only (Fig. 5). The mixed authorship (i.e. authors with African and non-African affiliations) accounted for 29% of all publications in 2000–2014 and increased to 32% in 2015–2019. The proportion of studies with mixed authorship steadily increased during the recent two decades, peaking in 2017 and 2018 (38 and 34% of the total publications, respectively) (Fig. S4 in Online Resources).

Non-African authors in the mixed authorship category were dominated by European affiliations accounting for 57% and 63% of all publications in the two studied periods (Fig. 5). There was no clear geographical pattern in the frequency of publications with mixed authorship. While Zimbabwe showed the highest proportion of mixed authorship studies in the former period (37%), it ranked last in the latter period (Fig. S3 in Online Resources). Still, differences between countries are not large. Finally, studies published by the non-African teams accounted for 29% of all publications in both two periods and were dominated by the European authors (54 and 56%, respectively).

In the mix-authorship category, 55% of publications ($n=296$) had the first author with an African affiliation. This proportion increased to ca 65% in the period 2015–2019. However, these publications represented only 17% of the total number of publications (i.e. African, non-African, and mixed authorship; $n=972$), reaching 19% of all publications during the recent 6 years (Fig. 6).

Research drivers

The standardized publication performance (R%; Table 2 and Table S1 in Online Resources) indicates significant underperformance of Mozambique (−41% relative to the regional average) and Angola (−59%) during the entire study period. On the contrary, South Africa exceeded the regional average by 52%. The remaining countries remained in the band of ±25% of the regional average.

We found a loose correlation of R% with the GDP per capita (Fig. 7). Mozambique and Angola showed significantly lower values of R% than was the expected (fitted) value. South Africa, on the other hand, was superior to the rest of the countries in the region. It significantly outperformed Namibia and Botswana, which have a similar GDP.

Government spending on education (% of GDP) showed a certain association with the publication frequency too. High relative investments into education in Mozambique (6% of GDP) did not materialize in publication performance, and the country substantially lagged behind the rest of the region. The smallest investments into education are in Angola (3.5% of GDP), showing the most inferior standardized publication performance. Publication performance of the remaining countries shows tight association with the spending on education, with South Africa being a positive outlier.

The level of political and social globalization represented here by the KOF Globalization Index (Gygli et al. 2019) was

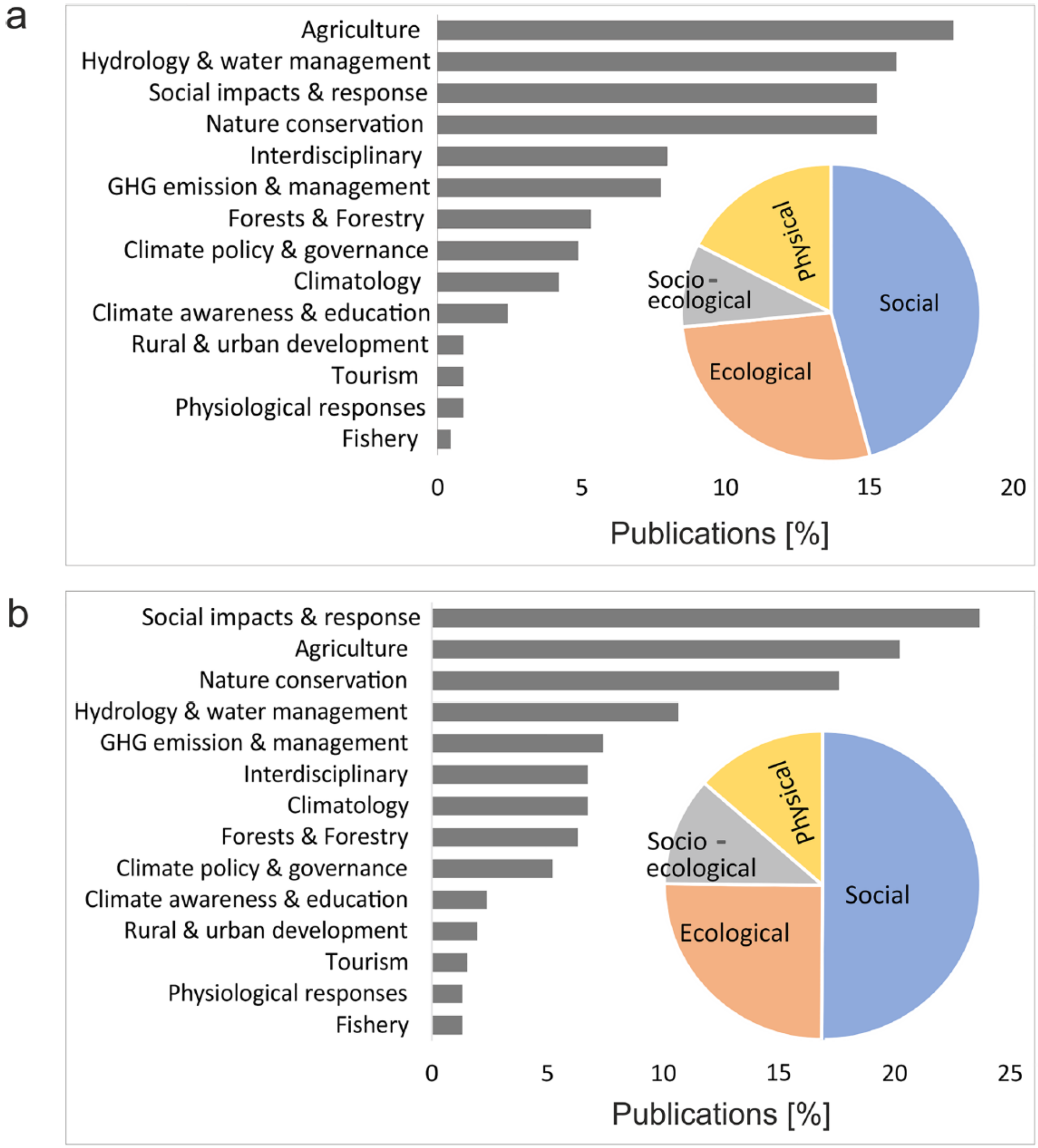

Fig. 3 Relative frequency of publications on different thematic areas (%). The inserted pie charts indicate the distribution of publications in broader categories. Results for periods 2000–2014 (**a**) and 2015–2019 (**b**) are shown. We note that if a publication addressed multiple thematic areas, it was counted multiple times

most closely associated with the region's publication performance. Similar to the previous indicators, Angola and Mozambique showed the smallest performance, and South Africa the highest.

Discussion and conclusion

Climate change research is increasing globally, yet geographical differences in our understanding of major

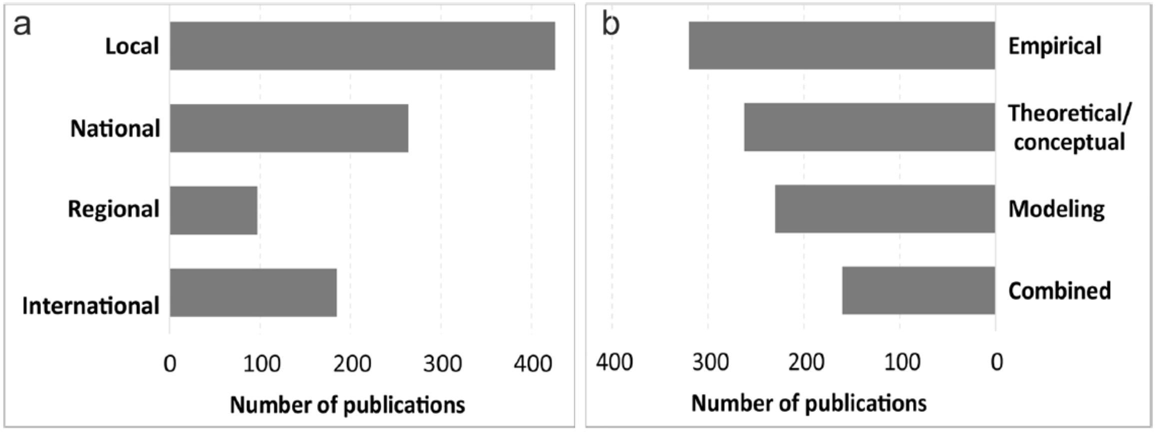

Fig. 4 Publications on different aspects of climate change categorized with respect to the scale of research (**a**) and used methodological approaches (**b**). The category Combined includes publications combining empirical and model-based approaches

impacts, drivers, and responses remain large (Blicharska et al. 2017; Arnell et al. 2019). Although southern Africa, except for South Africa, represents one of the world's most understudied regions with poor research infrastructure and human resources (Kusangaya et al. 2014), we found that the region has experienced remarkable progress in climate change research during the recent two decades. We further discuss a broader background of our findings and implications for future research planning and development in the region.

Publication patterns and drivers

We found that research addressing climate change impacts jointly with management responses received only marginal attention before 2004. However, during the recent 15 years, this field has accelerated, reaching up to 200 papers published annually after 2015. Interestingly, research on the adaptive capacity to climate change was found to accelerate after 2004 also globally (Siders 2019), corresponding with the recognition of climate change impacts and the need for adaptation actions (Mcdowell et al. 2016; IPCC 2018). The identified acceleration of climate change research agrees with Zinyengere et al. (2013) and Ford et al. (2015). The latter authors even found that research on adaptation to climate change in southern and eastern Africa outperformed the remaining African regions. This development complies with the continent's strategic framework, the Africa 2063 Agenda. It also corresponds with the increasing involvement of the African governments in global discussions, including those leading to the formulation of strategic documents such as the Paris Agreement adopted at "The 2015 United Nations Climate Change Conference in Paris" (United Nations 2015), and the "Sustainable Development Goals" adopted by the United Nations in 2015.

Despite the imbalanced natural and socio-economic conditions amongst the countries, we found that the investigated publications paid relatively balanced attention to all major sectors, such as agriculture, forestry, and water management. The geographical imbalance in the research performance was, however, large. The investigated dataset was greatly dominated by the South African publications (53%), while countries such as Angola, Lesotho, and Eswatini received only minor research attention (Sooryamoorthy 2018). However, the research environment in Angola is strongly influenced by a partnership with Portugal, Brazil, and Cuba. A certain proportion of publications was thus published in Portuguese, and therefore, it was not included in our review. This has likely underestimated this country's performance.

The prominence of South Africa reflects on the advanced research infrastructure, including climate observation and monitoring programmes (Ziervogel et al. 2014) and social-economic indicators that significantly exceed the remaining countries. South Africa is also engaged in strategic actions such as Climate Change Research guided by South Africa's National Climate Change Adaptation Strategy or different bilateral initiatives (e.g. Swiss-South African Joint Research Programme, UK-SA Newton Fund, South Africa/German Collaborative Programme), which support national research organizations. South Africa has also established the National Research Foundation, a national funding entity missing in the remaining countries in the region.

Our analysis of thematic areas addressed by the investigated publications indicated that climate change impacts on agriculture and adaptation actions have received the greatest attention. Such a finding was expected because agriculture is the most important sector supporting the majority of the

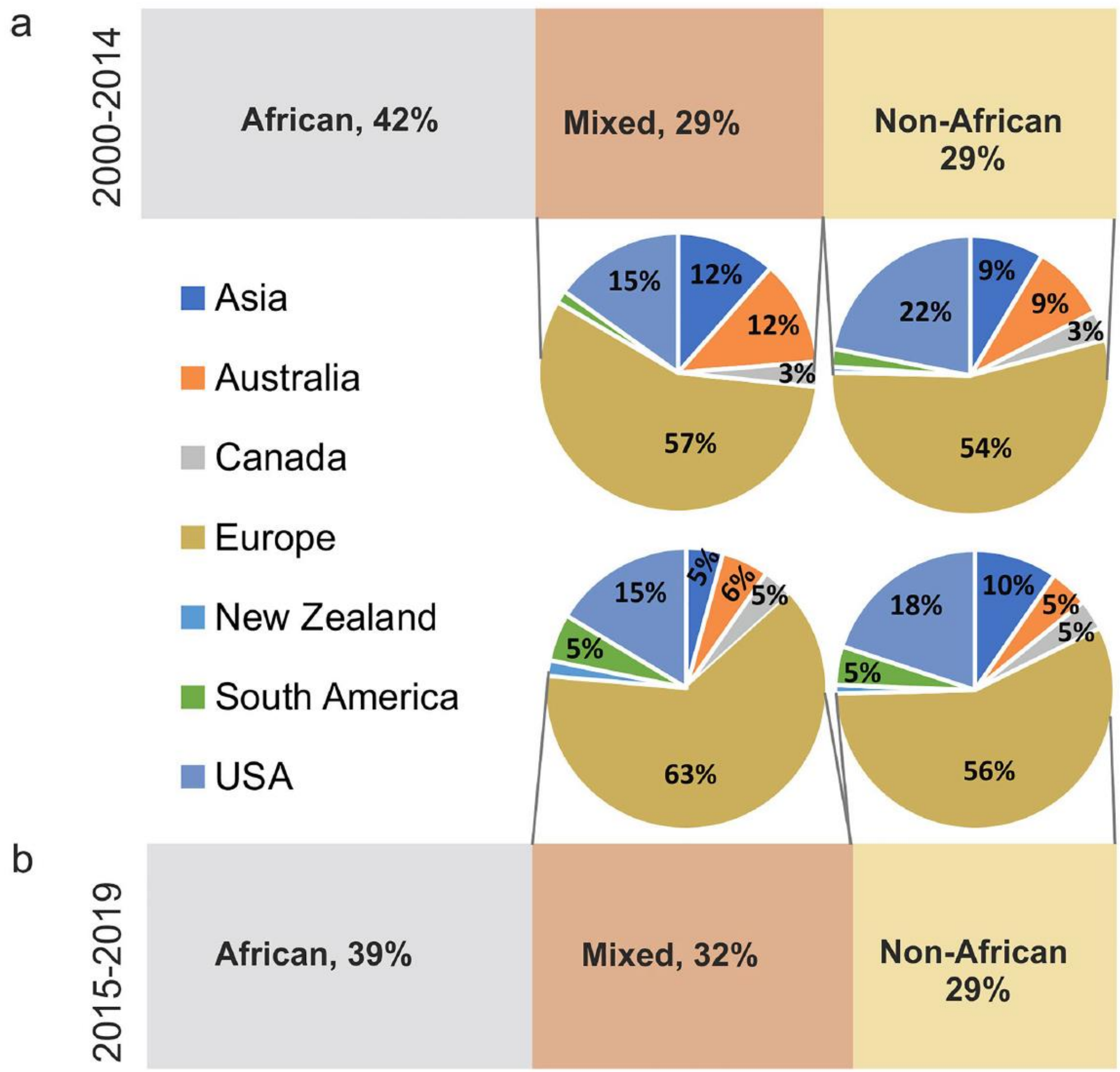

Fig. 5 International composition of the author teams in the investigated publications. Horizontal blocks on the top and bottom indicate the proportion of publications with different authorship (African: only Africa-affiliated authors; Non-African: only authors with affiliations from outside Africa; Mixed: authors with African and non-African affiliations). The embedded pie charts indicate the contribution of different countries to studies published by mixed teams. Results for two periods, 2000–2014 and 2015–2019, are shown

population in sub-Saharan Africa (Calzadilla et al. 2013). It agrees with Ford et al. (2015), who found out that about one-third of the reviewed studies on the status of climate change adaptation in 47 countries in Africa and Asia addressed the agriculture sector, particularly in semi-arid countries. Also, Bizikova et al. (2015) claimed that the main climate change adaptation priorities at the national and sectoral planning level in the semi-arid areas of Africa and Asia are focused on agriculture.

However, a closer look at the temporal frequency of main thematic areas reveals a certain shift in the research focus. While the publications on agriculture dominated up to 2014, studies on social aspects of climate change impacts and adaptation started to prevail after 2015, likely reflecting on the increasing demand to reinforce social sciences in climate change research (Billi et al. 2019). Such a shift corresponds with the Sustainable Development Goals introduction, which strongly focuses on the social aspect of climate

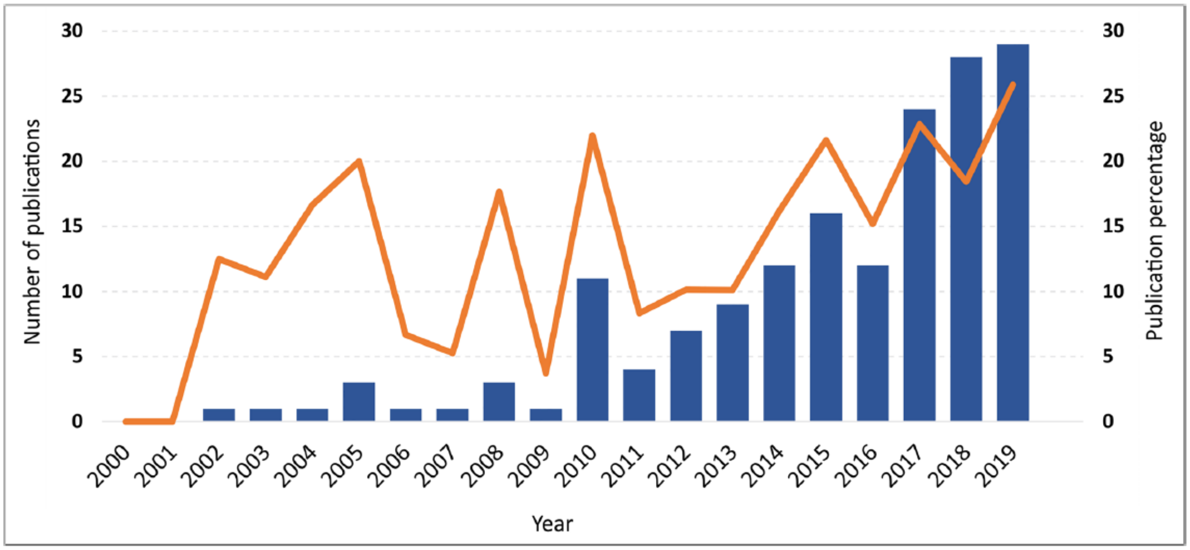

Fig. 6 Number of publications on different aspects of climate change in southern Africa with an African affiliation of the first author (columns, left axis). Percent of these publications out of the total number of publications in each year is indicated, too (line, right axis)

change (Herrero-Jáuregui et al. 2018). De Vos et al. (2019) suggested that research of coupled social-ecological systems has significantly advanced in southern Africa, compared to other parts of the continent. Such a development was also observed in water research in southern Africa, which increasingly adopts a holistic perception, addressing natural (water cycle) and human (social, economic, governance, and policy aspects) dimensions (de Clercq et al. 2018; Nhamo et al. 2018; Olagunju et al. 2019). Finally, we found that research on the fishery, tourism, climate change awareness, education, and rural and urban development received a smaller attention than the earlier mentioned major categories. However, the social-ecological dimension of rural and urban systems seems to be understudied globally (Herrero-Jáuregui et al. 2018).

We identified the dominance of studies based on empirical research and focusing on the local scale. These publications were more abundant than publications exploiting modelling approaches (including research driven by the outputs of climate models) and covering regional and global scales. Kusangaya et al. (2014) stated in this regard that even though the importance of model-based climate scenarios has been widely recognized, this information is not consistently included in decision-making and lags behind more developed regions. The reasons likely stem from the lack of skilled experts and resources and the lack of well-funded and coordinated initiatives on the observation and assessment of the environmental changes.

The observed publication patterns raise questions about the drivers responsible for the differences between countries. It is recognized, for example, that research expenditures per capita correspond with quality and quantity research outputs (Dragos and Dragos 2014; North et al. 2020). Although we identified this relationship in our dataset, we found that (standardized) publication performance was best explained by the level of social and political globalization. This is consistent with previous studies, which identified massive improvement in scientific research due to economic, political, and social globalization (Simon et al. 2012). Critical aspects of globalization such as global economy and competition for market were found to be among the main drivers of scientific collaborative research and development (Ahmad 2014). Therefore, increased investments into research, education, and infrastructure will certainly support countries in improving their standards but may not deliver the desired effects unless sound globalization tendencies accompany them. Still, the relationships identified herein should be interpreted with caution due to the small sample size and the use of the standardized number of publications, limiting the comparability with other studies.

Research leadership and international collaboration

Numerous indicators are used to assess and compare institutional or national scientific performance (de Rijcke et al. 2016; Docampo and Cram 2017). We focused here on two informative yet straightforward indicators that could have been directly extracted from the used database: affiliation of the first author and the proportion of publications conducted

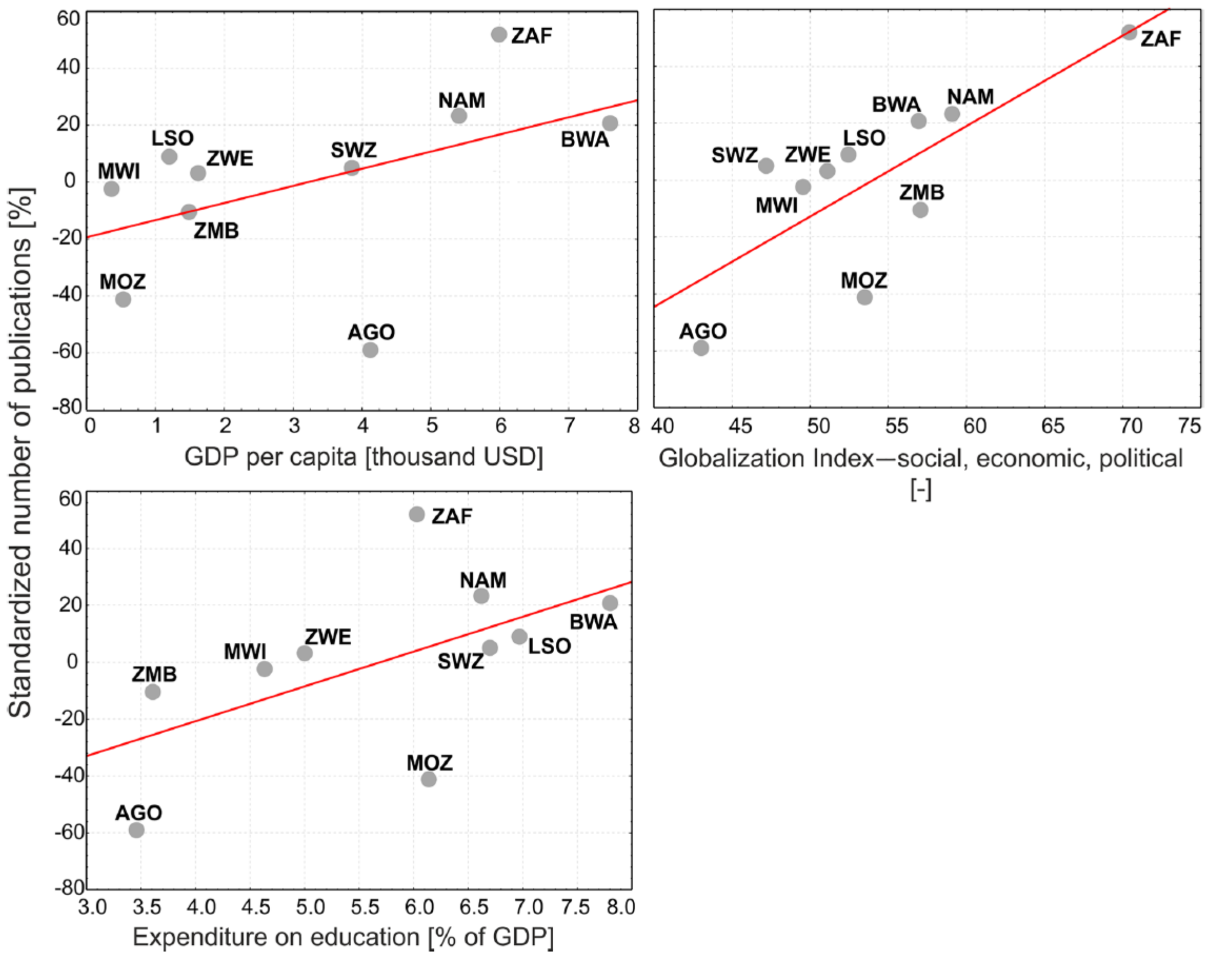

Fig. 7 Associations between the standardized number of publications on different aspects of climate change in southern Africa and GDP per capita, Globalization Index, and Expenditures on education. Country codes are explained in Fig. 1

by the international teams involving African authors (de Moya-Anegon et al. 2018; Fox et al. 2018).

We found that the proportion of publications with mixed authorship (i.e. with African and non-African affiliated authors) steadily increased after 2008, reaching between 33 and 38% after 2013, and 55% of these publications had the first author with an African affiliation. This is comparable with the study of (Siders 2019), who found that half of the studies on climate change adaptive capacity conducted in Africa had an African researcher as the first author. Despite the positive trend, African authors' secondary role and the low ability to publish in international journals remain issues deserving attention (Tarkang and Bain 2019). For example, North et al. (2020) found out that about 25 of the most highly cited geoscience articles in 21 surveyed journals were published by 2744 authors and, of these, only 13 were Africans. The non-African authors in the author teams were greatly dominated by authors affiliated with European organizations (56%), followed by the USA (18%). Such a proportion likely reflects on the solid historical relationships between Africa and the European Union (EU) that has led to the establishment of different strategic agreements such as Joint Africa – EU Strategy (JAES) (Haselip and Hughes 2018).

The first authorship provides only partial information about the role of African authors, and more complex approaches need to be used in future studies, for example based on questionnaires and interviews (Breet et al. 2018). The recent tendency of splitting the credit between the first author, last author, and the corresponding author makes assessing the role of African authors in the teams even more complicated (Vasilevsky et al. 2021). Evaluating specific authors' contributions (e.g. based on the Contributor Roles Taxonomy; (McNutt et al. 2018)), which are indicated by some journals, could provide a more comprehensive picture (Whetstone and Moulaison-Sandy 2020).

The second indicator used to characterize the regional research environment was the level of research internationalization. We found that the mixed authorship accounted for 30% of all publications, while the African teams published 40% of all studies. We, however, note that our investigation aimed at a specific field of climate change impacts and adaptation; the overall level of international collaboration can differ from these values. Still, the robustness of the herein reported values is supported, for example, by North et al. (2020), who found about 30% of the articles published in geoscience journals included African authors. The large proportion of publications authored by African teams may also account for the Scopus strategy to include also national journals. The use of a more selective database could provide a different picture. Moreover, publications in non-English languages (e.g. Portuguese), which are particularly important in countries such as Angola and Mozambique, were not considered. This could have underestimated the performance of these countries.

It is noteworthy that the proportion of the international authorship may correspond with the phase of the scientific development of the countries (de Moya-Anegon et al. 2018). Following this assumption, the investigated countries—except South Africa—are in a building-up phase, i.e. starting to participate in international networks, although their role often remains secondary. The proportion of papers with the international co-authorship is typically high in such countries, particularly in international journals.

Implications for research and education planning

Numerous studies have indicated an improving research environment in southern Africa, which, as we showed here, also applies to climate change impacts and adaptation. Another sign of positive development is an increasing contribution of the African authors to global discussions on climate change, including contributions to the IPCC Special and Assessment reports. Still, these advances need to be considered in the context of underdeveloped intra-African collaboration, a pronounced "Brain Drain" phenomenon, high teaching loads of researchers, limited research funding resulting in increased competition among institutions, language barriers, and an overall lack of incentives. Such an environment causes African research to remain underrepresented in international scientific media (Mouton et al. 2008; Boshoff 2010; North et al. 2020), and highlights a need for coordinated actions to improve the research environment in the region.

Implementing new curricula of climate change–related subjects in masters and doctoral studies could be a solid incentive to improving climate change research and awareness. Such initiative can be inspired by West Africa (ECOWAS countries) development, where ten doctoral and two master graduate study programmes related to climate change were recently established through the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL, www.wascal.org). Improved education could be an essential step towards increasing the proportion of interdisciplinary studies and broader use of advanced technologies and climate model outputs.

Improving research infrastructure and availability of climate data, including bias-corrected climate projections, would significantly enhance the current options for process-based understanding of climate change impacts in the region and formulation of adaptation strategies. The infrastructure facilitating climate change research has been recently significantly advanced in southern Africa (e.g. Kaspar et al. (2015); Helmschrot et al. (2018); Muche et al. (2018)), yet further investments are needed to reach a fully operational stage to boost the existing research. It is estimated that up to 550 million € are required over the next 30 years to develop a continent-wide observational infrastructure and human resources for greenhouse gas emissions monitoring reaching the European standards (López-Ballesteros et al. 2018).

Policy and institutional frameworks play a crucial role in improving research performance, which is another field that requires attention in southern Africa. The countries should, for example, establish national agencies such as the National Research Foundation in South Africa (NRF) or the National Commission on Research Science and Technology (NCRST) in Namibia, which were instrumental in overseeing and coordinating research activities. Initiatives such as the South African Applied Centre for Climate and Earth System Science (ACCESS) can be central to providing solutions for global change challenges aligned with national policies. National policies for research internationalization across the continent can be established, as it was recommended by the African Union's Agenda 2063 and its Science, Technology, and Innovation Strategy for Africa 2024 (STISA 2024). For example, the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL), which fosters climate change research based on the collaboration of African and German partners (Revermann et al. 2018), can be reinforced by additional initiatives. An improved policy and institutional environment would be conducive to joint activities of academia, the private sector, citizen science, and policy, as well as to the search for additional resources to support African publishers and scientists.

Conclusions

Our study showed that southern Africa has significantly advanced in the field of climate change research during the recent 15 years, although regional inequalities remained. This progress concerned the number of publications and the role of African researchers in author teams and international collaboration. At the same time, we identified weaknesses, such as insufficient use of modern technologies, models, climate change scenarios, and Earth Observation products, which deserve attention in further research planning and investments. Our investigation is helping to better understand patterns and drivers of the regional research, which are critical entries to informed decisions about research investments, infrastructure development, and education transformation.

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Declarations

Conflict of interest The authors declare no competing interests.

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5.2 Climate change impacts on ecosystems and adaptation options in nine countries in southern Africa: What do we know?

esa ECOSPHERE

SOCIO-ECOLOGICAL SYSTEMS

Climate change impacts on ecosystems and adaptation options in nine countries in southern Africa: What do we know?

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Abstract. Southern Africa harbors exceptional biodiversity that is increasingly threatened by climate change, land use, and other pressures. However, risks to the regional ecosystems and quality and consistency of adaptation strategies remain understudied, making conservation and restoration efforts challenging. Here, we reviewed scientific articles published during the period 2000–2020, which (1) addressed observed and projected impacts of climate change on different species, populations, and ecosystems in nine southern African countries, and (2) formulated management and policy responses aiming to mitigate these impacts. We identified and evaluated 28 papers meeting these search criteria. We found that the three components of our investigation, that is, ecosystem type, type of impact, and management and policy responses, were covered by research rather fragmentarily. However, the reviewed publications addressed a large variety of species and ecosystems and a variety of processes, from local extinction, range contraction, and increased mortality to modified inter-specific interactions. The identified human responses included active vegetation and animal management, improved conservation policies, and monitoring. Most of the publications highlighted severe data limitations, lacking coordination of conservation policies, and insufficient consideration of transient environmental conditions in management and policy planning. We conclude that the current level of understanding of climatic threats to species and ecosystems is limited in southern Africa, and new coordinated research and monitoring actions are needed. This review characterized the high diversity of climate change risks to ecosystems and related social responses, potentially helping to attract further research attention and inform regional adaptation strategies.

Key words: biodiversity; climate change adaptation; ecosystem management; extinction; monitoring; nature conservation.

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Introduction

Climate change is a major threat to global biodiversity at all levels, from genes to biomes (Bellard et al. 2012, Pecl et al. 2017, Runting et al. 2017). Despite the commitments to halt these losses, including the Convention on Biological Diversity and United Nations Sustainable Development Goals, the outcomes today have been poor (Waldron et al. 2017). Africa harbors exceptional biodiversity values, which are increasingly threatened by climate change and other pressures (López-Carr et al. 2014, Palazzo et al. 2017, Vogel et al. 2019). Increased human population, urbanization, and limited alternative sources of livelihoods exert more pressure on natural resources and hamper conservation efforts (Darkoh 2009, Wangai et al. 2016). In many parts of Africa, these pressures have resulted in the degradation of ecosystems, further increasing their vulnerability to climate change (Sintayehu 2018). This concerns a broad range of ecosystems, including savannas, tropical forests, coral reefs, aquatic habitats, wetlands, and montane ecosystems (Thiaw 2015, Sintayehu 2018). The range collapse and steep decline in African elephants and rhinoceros' populations are examples of the most distinct impacts on wildlife (Dinerstein et al. 2019). Vegetation productivity is projected to decline over most of southern Africa (Lawal et al. 2019), with severe impacts on the structure and functioning of the savanna ecosystems (Ryan et al. 2016, Osborne et al. 2018). Climate change-driven sea-level rise affects coastal areas of southern Africa, causing increased coastal erosion, loss of coral reefs, and the salination of groundwater and river systems (Bauer and Scholz 2010). The valuable mangroves in southern Africa are experiencing elevated mortality due to excessive river flooding and heavy cyclonal rains (Nikolau et al. 2017).

Extreme temperatures, erratic rainfall, and increasing evapotranspiration demand, coupled with high intensity of human activities, are likely to exceed the resilience limits of many ecosystems and trigger irreversible landscape transformation (IPCC 2019). These impacts are particularly pronounced in southern Africa, where recent changes in climate severely affected various ecosystems and disrupted their services to society (Kusangaya et al. 2014, Rosendo et al. 2018). The recurrent droughts experienced in most parts of the region have seriously affected many ecological systems (Guo et al. 2016), including those of high conservation value. For example, recent increases in fire intensity and frequency have led to the decline of woody biomass in the African savanna woodlands, including the Miombo woodland (Kuyah et al. 2014), which was defined by the World Wildlife Fund (WWF) to be one of the Priority Places harboring exceptional biodiversity values (Warren et al. 2018).

The progressive loss of biodiversity and ecosystem degradation have been increasingly scrutinized because of the high dependence of human populations in Africa on ecosystem services (Wangai et al. 2016). The human populations, particularly in rural areas, depend on essential ecosystem services, including food, water, medicine, recreational, aesthetic, cultural, and spiritual values (Chirwa et al. 2008, Thiaw 2015, Ryan et al. 2016). It is estimated that more than ten million people in southern Africa reside within hazard-prone areas, and their livelihoods vitally depend on hazard-exposed agricultural practices (Global Drought Observatory 2019). Mitigating these impacts will be increasingly difficult because sub-Saharan Africa is expected to be one of the regions with the highest increase in population density (Jones and O'Neill 2016).

Southern African countries have recently made progress in many areas of ecosystem management (Darkoh 2009), including research and monitoring, biodiversity conservation, education, and awareness-building (Wisely et al. 2018). Such progress has been facilitated by initiatives such as The Southern Africa Development Community (SADC) Forestry Strategy, promoting the sustainable utilization of forest resources; The Regional Biodiversity Strategy, providing a framework for cooperation on transboundary environmental issues (SADC 2008); and The Protocol on Shared Watercourses Systems, defining the principles for managing shared water ecosystems in the region (Muller 2018).

Halting the progressive biodiversity loss, restoring disturbed ecosystems, and adapting them to climate change requires a profound understanding of ecosystem dynamics affected by climate change (Walther 2010, Hruska et al. 2017, Inman et al. 2020, Malhi et al. 2020). Such understanding facilitates, for example, the formulation of policies accommodating transient ecosystem dynamics into conservation planning (Heller and Zavaleta 2009, Watson et al. 2012, Wisely et al. 2018). However, southern Africa—except for South Africa, is relatively understudied concerning vulnerabilities related to climate change, social perception of these risks, and effects of local management practices, which can both enhance and erode the adaptive capacity of ecosystems (Kusangaya et al. 2014). This situation is related to the poorly developed research and monitoring infrastructure, insufficient human capacities, and institutional settings (Kusangaya et al. 2014, Haselip and Hughes

2018, Wisely et al. 2018). The lack of human resources was identified as a significant factor hampering the ability of local governments to address critical risks for coastal ecosystems, such as erosion, uncontrolled development, unsustainable utilization of resources, and habitat degradation in parts of South Africa and Mozambique (Rosendo et al. 2018).

We focused here on nine southern African countries, which have poorly developed research infrastructure and human resources, and where our understanding of climate change risks and adaptation measures significantly lags behind more developed countries and regions. Aiming to narrow the existing knowledge gaps, we reviewed the scientific literature published during the last 20 yr that was dedicated to climate change impacts on different ecosystems and, at the same time, formulated measures aiming to mitigate these impacts. Because the science production in the studied region is relatively low, our research is intended to highlight the diversity of impacts and social responses rather than provide consistent framework supporting management and policy decisions. Still, the countries addressed share many ecosystems and management practices, and this review can thus inform conservation and adaptation efforts in different locations.

Material and Methods

Study area

We investigated nine countries in the southern African region: Angola, Botswana, Swaziland/Eswatini, Lesotho, Malawi, Mozambique, Namibia, Zambia, and Zimbabwe (Fig. 1). We deliberately omitted South Africa in this research, as the country`s high science production would dominate the review, potentially distracting from our idea to evaluate the situation in countries where the gap between climate change risk and adaptation options is most severe. At the same time, the addressed countries cover diverse social–economic contexts and a range of natural conditions, suggesting a high diversity of impacts and adaptation strategies. Still, we consider numerous transnational ecosystems shared by the target countries and South Africa, and we discuss the options for transnational knowledge transfer when it comes to adaptation strategies.

Southern Africa is arid to semi-arid region containing diverse ecosystems such as savannas, wetlands, woodlands, deserts, marine, and freshwater ecosystems. The region contains biodiversity-rich ecosystems with transboundary conservation significance, such as the Kavango-Zambezi and Lubombo (Fox et al. 2017). The region comprises four ecoregions: tropical and subtropical moist broadleaf forests; tropical and subtropical grassland savannah and dry forests; montane grasslands and shrubland; and dryland desert and Mediterranean woodland (Abson et al. 2012). The Miombo and mopane woodlands are some of the dominant ecosystems (Dewees et al. 2010, Ryan et al. 2016). The region also contains important transboundary freshwater ecosystems such as the Okavango delta, Orange River Basin, Cuvelai Basin, Zambezi Basin, and the marine ecosystem of the Benguela Current along the coast of Angola, Namibia, and South Africa.

The study region represents one of the global climate change hot spots due to its erratic climatic regimes and high observed and projected climatic risks (Hoegh-Guldberg et al. 2019). Climate extremes, particularly droughts, regularly trigger wildlife mortality, cause habitat degradation, reduce the abundance of different species, and place conservation objectives at risk (Kupika et al. 2017, Sintayehu 2018). Climate-mediated risks in the region include deforestation and desertification, forest fires, floods, and recurring droughts. For example, the region has experienced extremely poor rainfalls in 2014/2015, 2015/2016, and 2018/2019 (Archer et al. 2017) and devastating cyclones in 2019 (Idai and Kenneth), which mainly affected Malawi, Mozambique, and Zimbabwe (Baltazar and Rossetto 2020, Mavhura 2020, Chari et al. 2021).

Methods

Literature review.—We conducted a systematic literature review aiming to identify scientific papers dealing with climate change impacts on different ecosystems of nine countries in the southern African region and, at the same time, formulating measures aiming to mitigate these impacts. The publications were extracted from the Scopus database (SciVerse Scopus 2013) following the PRISMA workflow (Appendix S1: Fig. S1) (Moher et al. 2009). The search covered

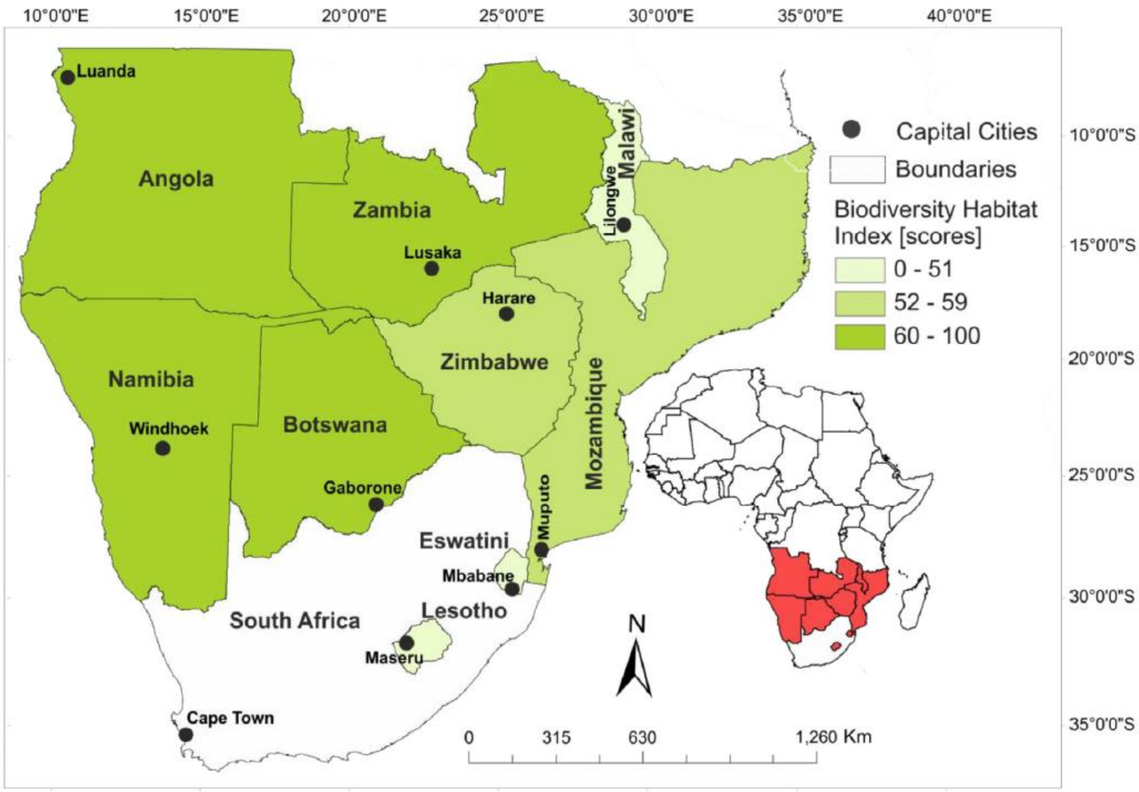

Fig. 1. Southern African countries investigated in this study and their location in Africa. The Biodiversity Habitat Index (Wendling et al. 2020) is shown.

the period from January 2000 to April 2020. We used the following search criteria:

("climate change" OR "climatic change" OR "climate warming" OR "global warming" OR "global change") AND (adaptation OR mitigation OR management) AND ("Africa")

The search was then limited to the following countries:

"Angola" OR "Botswana" OR "Eswatini" OR "Swaziland" OR "Lesotho" OR "Malawi" OR "Mozambique" OR "Namibia" OR "Zambia" OR "Zimbabwe"

We further limited the search results to publications in English and to subject areas: *"environmental sciences", "social sciences", "earth and planetary sciences" and "agricultural and biological sciences"*. Publications pertaining to *"review"* category were excluded.

Further, we used the Google Scholar database to identify papers not captured by the previous SCOPUS-based search. In this way, we added seven more papers. This search yielded 438 publications. Next, we reviewed these publications and retained only those addressing explicitly different species, populations, and ecosystems in the target region. We retained 118 publications in this phase. Finally, we identified a subset of publications, which explicitly provided information about (1) climate change-related impacts on ecosystems, species, or populations, (2) provided evident characteristics of these ecological units, and (3) informed about management actions supporting adaptation to climate change. We retained 28 publications in this phase, that is, 6% of the original dataset ($n = 438$).

The retained studies were subjected to a detailed review in order to extract information such as the geographical location of the ecosystems, type of climate change-related impacts, and proposed management strategies and actions.

Results

The 28 studies that met our search criteria were published between 2006 and 2020, with most of them (18) appearing after 2014. The largest number of publications addressed Namibia (8) and Zimbabwe (6). Spatially, 43% of studies addressed geographically restricted systems, while the remaining studies addressed the entire study region or were part of continental or larger scale assessments (Fig. 2).

Addressed ecosystems, populations, and species

The identified publications addressed both terrestrial (86%, 24 papers) and aquatic (14%, four papers) ecosystems (Table 1). In the case of terrestrial ecosystems, 14 publications (58%) addressed vegetation, six publications (25%) addressed mammals, three publications (13%) birds, and one publication addressed insects.

In the case of aquatic ecosystems, we identified three papers addressing coral reefs (Mcclanahan et al. 2011), African penguins (*Spheniscus demersus*) (Sherley et al. 2017), and Cape fur seals (*Arctocephalus pusillus pusillus*) (Kirkman et al. 2011).

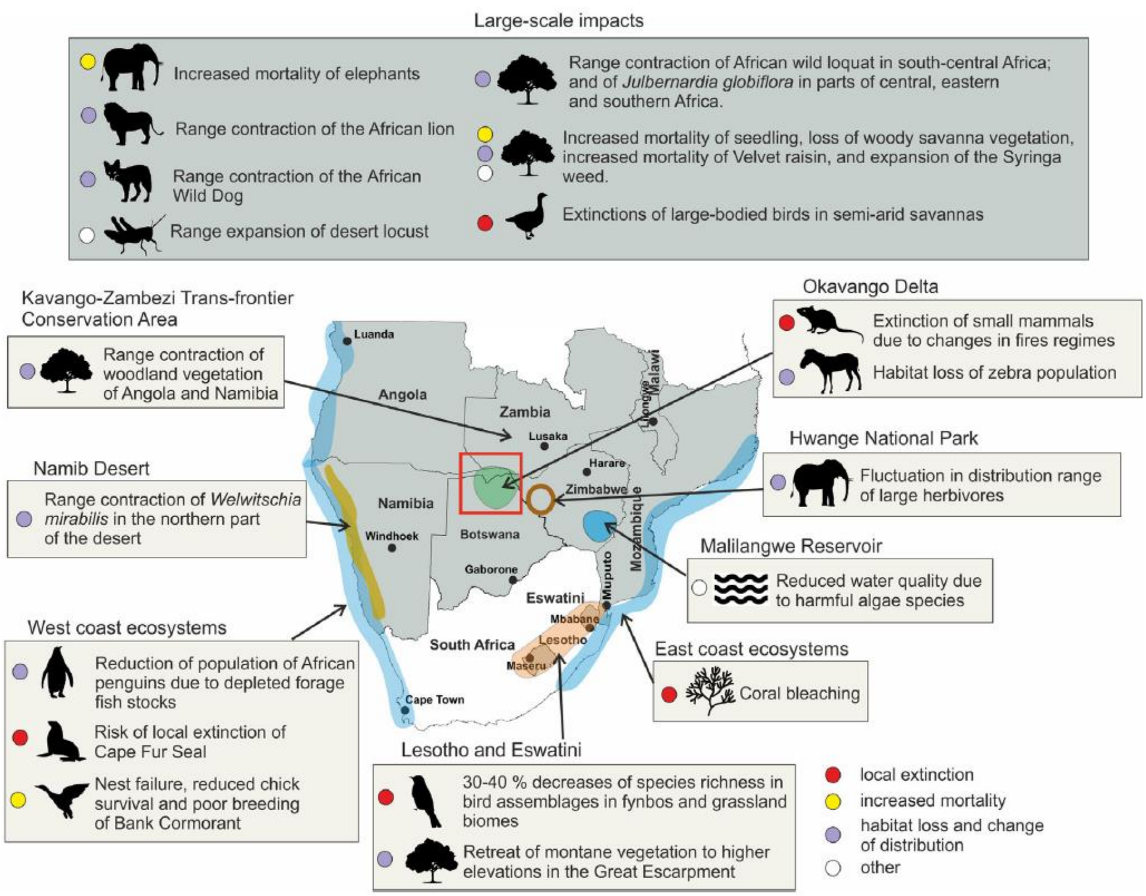

Fig. 2. Impacts of climate change on ecosystems, species, and populations in nine southern African countries identified in the reviewed publications. The silhouettes were obtained from https://silhouette-ac.com.

Table 1. Ecosystems, species, and populations addressed by the reviewed publications.

Ecosystem type	Group	Ecosystem, population, or species	Geographical location
Terrestrial	Mammals	Elephants (*Loxodonta africana*)	Ten national parks across southern African savannas: Namibia (Etosha and Khaudum National Parks); Botswana (Chobe National Park, Moremi Wildlife Reserve, and Ngamiland); South Africa (Kruger National Park); Zambia (Lower Zambezi, the northern, and southern parts of Kafue and South Luangwa National Parks)
		Burchell's zebra (*Equus quagga burchellii*)	Botswana, Moremi Game Reserve, Okavango Delta
		African lions (*Panthera leo*)	27 sites across Africa, including Botswana (Chobe, Moremi, Makgadikgadi, Central Kalahari and Gemsbok); Namibia (Kunene and Etosha); South Africa (Kalahari-Gemsbok, Kruger, and Hluhluwe-Imfolozi); Zambia (South Luangwa and Kafue); Zimbabwe (Mana Pools)
		African Wild Dog *(Lycaon pictus)*	Southern Africa
		Small mammals, including Bushveld gerbils (*Gerbilliscus leucogaster*), Desert pygmy mouse (*Mus indutus*), Brant's climbing mouse (*Dendromus mesomelas*), Fat mouse (*Steatomys pratensis*), and multimammate mice (*Mastomys natalensis and Mastomys coucha)*	North-western Botswana, Okavango Delta
		Population of herbivores	Hwange National Park, Zimbabwe
	Birds	Large-bodied savanna birds	Southern Kalahari savannas
		Different bird assemblages	Fynbos and grassland biomes of South Africa, Lesotho and, Eswatini
		Bank Cormorant (*Phalacrocorax neglectus)*	Robben Island (South Africa) and Mercury Island (Namibia)
	Insects	Desert locust (*Schistocerca gregaria gregaria)* and (*Schistocerca gregaria flaviventris)*	Southern Africa
	Vegetation	Vegetation *sensu lato*	Main biomes of Southern Africa
		Woody species (*Acacia erioloba; Acacia karroo; Baikiaea plurijuga; Boscia albitrunca; Burkea africana; Colophospermum mopane; Combretum imberbe; Faidherbia albida; Guibourtia coleosperma; Pterocarpus angolensis*)	Namibian savanna
		Woodland vegetation	Northern Botswana, Chobe district
		Mountain vegetation	Great Escarpment of South Africa and Lesotho
		African savanna woody species (*Acacia polyacantha, Acacia sieberana, Bauhinia thonningii, Dichrostachys Cinerea*, and *Ziziphus abyssinica*)	Savanna of Central Zambia
		Woody vegetation	Mozambique, Miombo woodland
		Shrubs *Acacia erioloba* and *Grewia flava*	Southern Africa, southern Kalahari savannas
		Perennial grass	Namibia, central Kalahari savanna
		Wild teak *Pterocarpus angolensis*	Southern Africa Kalahari
		Baikiaea-*Pterocarpus* woodland	Kavango—Zambezi Trans-frontier Conservation Area (KAZA TFCA)
		Welwitschia mirabilis Hook	Namibia, Namib Desert
		African wild loquat *Uapaca kirkiana*	South-central Africa, including Angola, Malawi, Zambia, and Zimbabwe
		Julbernardia globiflora and *Julbernardia paniculata*	Miombo woodlands of central, eastern and southern Africa including Angola, Malawi, Mozambique, Zambia and Zimbabwe
		Asiatic witchweed *Striga asiatica*	Zimbabwe, 10 provinces
Marine	Mammals	Cape Fur Seal (*Arctocephalus pusillus pusillus*)	South Africa, Namibia and, Angola; The Benguela Current Large Marine Ecosystem (BCLME)
	Birds	African penguins (*Spheniscus demersus*)	South Africa and Namibia; The Benguela Current Large Marine Ecosystem (BCLME)
	Coral	Coral reefs	Eastern coast of Mozambique and South Africa
Freshwater	Wildlife	Freshwater, Malilangwe Reservoir	South-eastern lowveld of Zimbabwe

The only study on freshwater systems addressed the effects of climate change on water quality in the Malilangwe Reservoir in Zimbabwe and the cascading effects on humans and wildlife (Dalu and Wasserman 2018).

Climate change impacts

We categorized the identified impacts as local extinction, increased mortality, habitat loss and/or change in distribution, and other specific impacts (Appendix S1: Table S3). From the time perspective, 13 publications reported observed impacts with the dominance of habitat loss and range contraction, and 15 publications addressed future impacts relying on various analytical projections (Appendix S1: Tables S1, S2). Most of the projections addressed the period between 2040 and 2070 (Fig. 3). However, two studies (Mcclanahan et al. 2011, Scherer et al. 2016) informed about the future risks to coral reefs and birds without specifying the target period. Most of the future impacts also addressed habitat loss and range contraction, while only two publications reported the projected mortality (Tews et al. 2006, de Cauwer et al. 2014). We note that we included only those impacts, which were explicitly associated with climate change by the authors.

Local extinction.—Potential local extinction of the Cape Fur Seals was identified in the Benguela Current Large Marine Ecosystem in the Western coast of South Africa, Namibia, and Angola (Kirkman et al. 2011). The extinction was mainly associated with the wide-scale changes in the marine environment, including a reduced abundance of seals' prey due to projected changes in climate.

Local extinction was predicted for large-bodied bird species in the semi-arid African savannas using a trait-based functional type model (Scherer et al. 2016). The main driver of the extinction was habitat loss due to increased shrub encroachment and degradation of herbaceous plant cover, driven by climate change and poor land management.

Climate change and industrial fishing were found to cause the depletion of forage fish stocks,

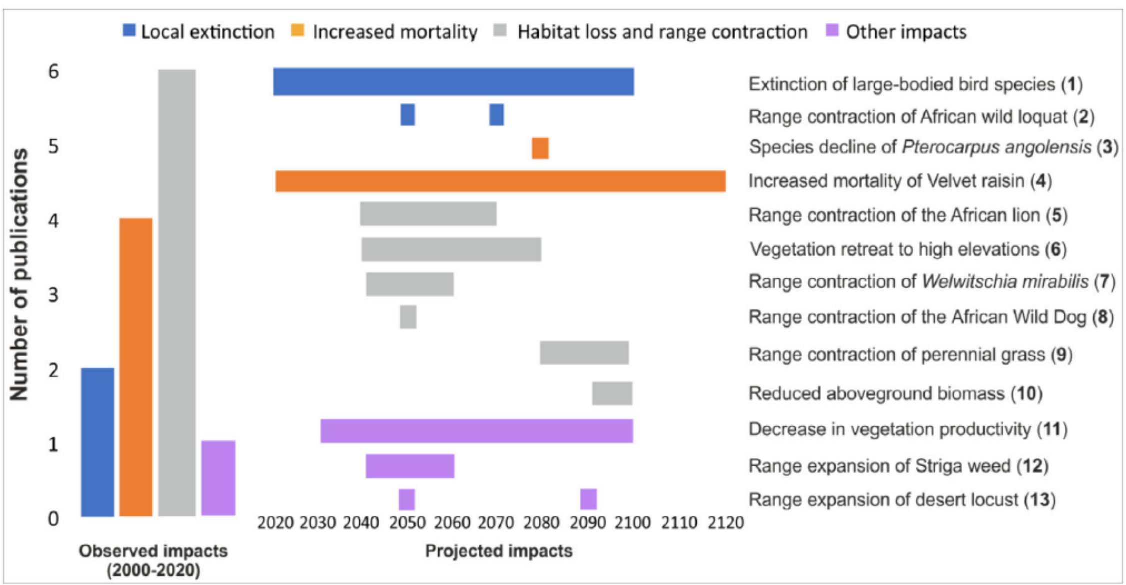

Fig. 3. Observed and projected impacts identified in the reviewed publications. The type of projected impacts and the addressed time horizons are indicated. We note that two papers, which addressed the projected impacts but did not specify the time frame, are not indicated in the figure. Publication codes: 1—Scherer et al. (2016); 2—Jinga et al. (2020); 3—De Cauwer et al. (2014); 4—Tews et al. (2006); 5—Peterson et al. (2014); 6—Bentley et al. (2019); 7—Bombi (2018); 8—Jones et al. (2016); 9—Lohman et al. (2012); 10—Saito et al. (2014); 11—Lawal et al. (2019); 12—Mudereri et al. (2020); 13—Meynard et al. (2017).

reducing the population of African penguins on the western coast of Namibia and South Africa (Sherley et al. 2017). The observed impact was pronounced in the juvenile individuals.

A decrease in species richness of bird assemblage of fynbos and grassland biomes by 30–40% was identified in South Africa, Lesotho, and Eswatini by 2085 (Huntley and Barnard 2012). This included the prominent pollinators such as the Cape Sugarbird (*Promerops cafer*), Malachite Sunbird (*Nectarinia famosa*), and Orange-breasted Sunbird (*Anthobaphes violacea*). The authors predicted the risk of complete extinction for two species, the Rudd's lark (*Heteromirafra ruddi*) and Botha's lark (*Spizocorys fringillaris*) by 2055.

The risk of local extinction resulting in the reduced natural range of distribution was identified for commercially and ecologically important tree species, the African wild loquat (*Uapaca kirkiana* Müll.) in south-central Africa. This risk was identified under different climate scenarios for the time horizons 2050 and 2070 by means of the maximum entropy method (Jinga et al. 2020).

Finally, the potential loss of coral reefs was predicted to occur in some parts of the eastern coast of Mozambique and South Africa (Mcclanahan et al. 2011). The authors used a multivariate stress model to identify the risks of coral bleaching due to projected high temperature, light, and sea current variability.

Increased mortality.—Elevated mortality was reported in ten national parks in southern Africa for African elephants (*Loxodonta africana*), particularly for young individuals. The mortality was pronounced in enclosed reserves limiting the elephant's migration and was likely associated with the reduced rainfall (Shrader et al. 2010).

Increased mortality risk was identified for the Bank Cormorant (*Phalacrocorax neglectus*) occurring on the southern African coastline of Robben Island (South Africa) and Mercury Island (Namibia) (Sherley et al. 2012). The authors used the Mayfield method and parametric survival approaches to attribute the mortality to heatwaves, level of sea waves, and strength of storms, which cause the nest failure, reduce chick survival, and compromise breeding productivity.

Increased mortality, particularly in the seedling stage, and decline in the distribution of shrub Velvet raisin (*Grewia flava*) were projected to occur in the southern African Kalahari savannas due to decreased annual precipitation and droughts (Tews et al. 2006).

A warmer climate was found to cause the decline in seedling emergence and mortality of seedlings of savanna woody species, such as *Acacia polyacantha*, *Bauhinia thonningii*, *Dichrostachys cinerea*, and *Ziziphus abyssinica* (Chidumayo 2008).

Climate change is expected to reduce the range of Wild teak (*Pterocarpus angolensis*) in the western part of southern Africa, with a risk of species decline by up to 50% across Namibia and Botswana (de Cauwer et al. 2014).

The increased seasonal climate variability is expected to increase the mortality of woody vegetation in north-eastern Botswana (Chobe district), leading to a decline in woodland cover in the savanna and an increase in shrublands. These processes were mediated by the intensified climate–fire feedback (Fox et al. 2017).

Habitat loss and range contraction.—Range contraction of the population of African lion (*Panthera leo*) was projected to occur across southern and western Africa by means of ecological niche models. The drivers of the contraction were particularly the increasing temperature and decreasing rainfall (Peterson et al. 2014).

Habitat loss and related population decline were identified for the population of Burchell's zebra (*Equus* quagga *burchellii*) in the Moremi Game Reserve of the Okavango delta. This mainly concerned the loss of floodplains maintained by the climatically sensitive seasonal flooding regime (Bartlam-Brooks et al. 2013).

Small mammals of the Okavango Delta (north-western Botswana), such as Bushveld gerbils (*Gerbilliscus leucogaster*), Desert pygmy mouse (*Mus indutus*), Brant's climbing mouse (*Dendromus mesomelas*), Fat mouse (*Steatomys pratensis*), and multimammate mice *Mastomys natalensis* and *M. coucha*, were found to experience the loss of their microhabitats, which are the key determinant of the population recovery after fire. The habitat loss was mainly associated with the expansion of wildfires driven by climate change (Plavsic 2014).

Range suitability for the African Wild Dog (*Lycaon pictus)* was projected to decline by 2050, particularly in Namibia, Botswana, Zimbabwe, and Mozambique. The decline is mainly related to the changes in climatic conditions and land use and high interspecific competition with the African lion (*Panthera leo*) (Jones et al. 2016).

Climate-driven fluctuations of surface water affected the distribution of large herbivores in the Hwange National Park (Zimbabwe) (Chamaillé-Jammes et al. 2007). The variability in annual rainfall mainly drove the water level variation.

Climate warming caused the retreat of montane woody vegetation toward higher elevations in the Great Escarpment of South Africa and Lesotho (Bentley et al. 2019). This is expected to result in the overall contraction of the distribution of the constituent species.

De Cauwer et al. (2016) identified potential range decline of species such as the Wild syringa (*Burkea Africana*), Wild Plum (*Ochna pulchra*), and Kalahari podberry (*Dialium englerianum*) in the woodlands of the Kavango-Zambezi Transfrontier Conservation Area (KAZA TFCA) in Namibia and Angola. The range contraction was likely driven by climate change, particularly increasing temperatures and droughts.

Several woody species of the Namibian savanna, such as the African teak (*Baikiaea plurijuga*), Wild syringa (*Burkea Africana*), African rosewood (*Guibourtia coleosperma*), and Wild teak (*Pterocarpus angolensis*) were found to experience decline in their physiological performances, resulting in the decrease of their distribution. The range decline was driven by reduced rainfall and increased temperature, and the associated water deficit (Burke 2006).

The severe decline in perennial grasses, leading to the reduction in the carrying capacity of the grassland ecosystem, was projected to occur in the central Kalahari savanna, Namibia. The main drivers of the decline were decreased precipitation, higher temperature, and increased interannual climatic variation (Lohmann et al. 2012).

The climatically driven increase in fire frequency and intensity was projected to reduce aboveground woody biomass and the mean tree size in the Miombo woodland in Mozambique (Saito et al. 2014). The authors also predicted the future warming and CO_2 increase to significantly affect woody plants in the Miombo woodland, compensating for some adverse effects of future fire regimes.

The decrease in the distribution range of the evergreen tree *Julbernardia paniculata* was observed in the Miombo woodlands in central, eastern, and southern Africa. The range contraction was mainly driven by high mean annual maximum temperatures and increased evapotranspiration. The increasing temperatures were found to favor the cooccurring *J. globiflora* at the expense of the *J. paniculata* (Chidumayo 2017). Finally, climate warming was projected to cause a range contraction of the *Welwitschia mirabilis* in the northern part of the Namib Desert (Bombi 2018).

Other impacts.—Climate change is expected to increase the range of Desert locust (*Schistocerca gregaria flaviventris*) in southern Africa (Meynard et al. 2017). Such an expansion can have serious implications for agricultural production and food security.

Projected range expansion of Striga weed (*Striga asiata*) was predicted to occur in some agro-ecological regions of Zimbabwe. Although the expansion was not large, it is expected to compromise the productivity of arable land, in addition to severe degradation of the environment. The weed's expansion is likely driven by the increasing temperature and increasing precipitation variability (Mudereri et al. 2020).

A rather complex impact was identified by Dalu and Wasserman (2018), who reported an increase in the harmful algal species due to climate change, deteriorating the quality of freshwater in the Malilangwe reservoir (south-eastern lowveld of Zimbabwe). The reduced water quality represents a potentially high risk from toxigenic cyanobacteria to animals and humans in the region.

A temperature increase by 1.5–2°C was projected to drive the productivity decline of southern African woody vegetation, particularly in Mozambique, Namibia, Botswana, Zimbabwe, and Zambia (Lawal et al. 2019).

Responses

We identified a broad range of human responses to the earlier described impacts, which we organized in three major categories (Appendix S1: Table S4): (1) active vegetation and wildlife management; (2) improved management strategies and policies; and (3) improved research, education, and monitoring. Each response type addressed each of the earlier described impact categories (Fig. 4).

Active management interventions.—

1. Wildlife.—Measures aiming to protect elephant populations included establishing new artificial water sources and removing the fences to increase the range of elephant movement, which will likely reduce elephant mortality due to water shortage (Shrader et al. 2010).

Testing the different allocation of artificial water points in the Hwange National Park was proposed to control the herbivores' distribution to reduce the pressure on vegetation (Chamaillé-Jammes et al. 2007). This measure needs to be integrated into the management plans of the National Park.

Measures for increasing habitat connectivity of the African Wild Dog were proposed to halt the progressive loss of genetic diversity experienced by the species due to the increasing isolation of local populations (Jones et al. 2016). Supportive measures included the African Wild Dog's reintroduction, the establishment of conservation areas on private lands, and the implementation of ecotourism programs.

A comprehensive system of measures to maintain the flood levels in the Okavango Delta was proposed to prevent the loss of seasonal floodplains, representing an essential habitat for the Burchell's zebra and other wildlife (Bartlam-Brooks et al. 2013).

Measures aiming to reduce the impact of climate change on the Bank Cormorant (*Phalacrocorax neglectus*) on the southern African coastline included establishing artificial structures providing new nesting conditions. This is expected to

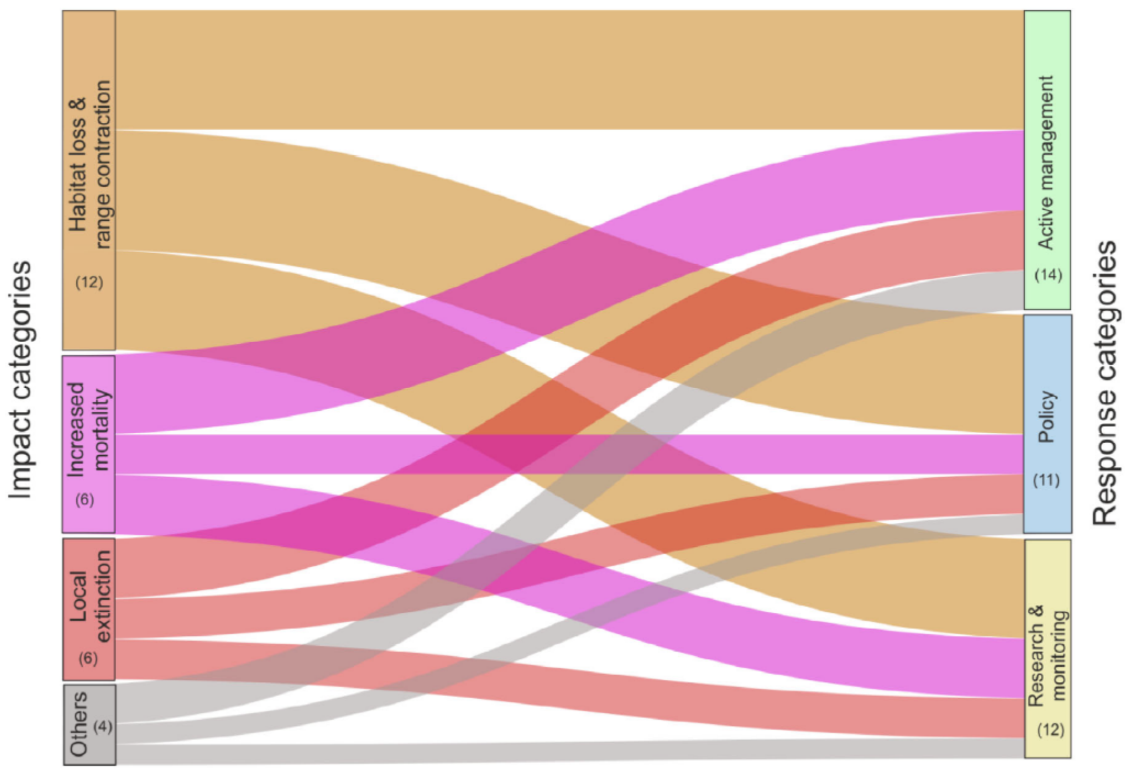

Fig. 4. Connections between the identified impacts of climate change (left) and response actions (right). The values on the left represent the number of reviewed publications under each category. The values on the right represent the number of identified responses under each category. The belts represent the connections between impacts and responses. The belt width is proportional to the number of identified responses. We note that while the number of impacts corresponds with the number of reviewed publications ($n = 28$), the number of responses is higher because some publications suggested more response actions.

support the bird's breeding and even expand the breeding range to new locations (Sherley et al. 2012).

The fishing suspension was proposed to be implemented in the western coast of South Africa and Namibia to allow for the recovery of depleted forage fish stocks to preserve the population of African penguins (*Spheniscus demersus*) (Sherley et al. 2017).

2. *Vegetation*.—The overall improvement of rangeland quality in the savanna of Namibia requires the introduction of desirable grass species (Lohmann et al. 2012). Suitable areas for regeneration trials should be identified to preserve and increase the distribution of a commercially important tree, the Wild teak (*Pterocarpus angolensis)* (de Cauwer et al. 2014). Preventing the anticipated contraction of the natural range of African wild loquat (*Uapaca kirkiana)* may require this species to be domesticated and introduced in protected areas, such as national parks (Jinga et al. 2020).

Changing the current fire management practices was proposed to protect woody vegetation from the intensified wildfires in the Miombo woodland of Mozambique (Saito et al. 2014). The authors proposed abandoning frequent burning and promoting more rigorous fire control, such as low-intensity prescribed fires and seasonal mosaic burning. Improved fire management strategies were also proposed to be applied in the fire-prone areas of the Chobe District's woodlands, particularly the fuel load control, fire reduction, and thinning (Fox et al. 2017). Finally, fire refuge areas were proposed to be established in the KAZA TFCA to reduce the impacts of fire on vegetation (de Cauwer et al. 2016).

Adaptation strategies aiming to stabilize the population of *J. globiflora* and *J. paniculata* in the Miombo woodlands include preserving the old-growth woodland and reducing human disturbances in designated areas, such as forest reserves and national parks (Chidumayo 2017).

3. *Aquatic systems*.—Measures aiming to protect the coral reef require complex strategies, including improved watershed and waste management and reduced air pollution in the most vulnerable coastal areas of Mozambique and South Africa (Mcclanahan et al. 2011).

The quality and availability of water need to be maintained in order to mitigate the harmful effects on ecosystems connected with the Malilangwe Reservoir. The proposed measure included the ex situ potable water purification and distribution (Dalu and Wasserman 2018).

Policy and strategic planning.—Adaptive conservation strategies were proposed to halt the anticipated decline in range suitability for the African Wild Dog, particularly in Namibia, Botswana, Zimbabwe, and Mozambique (Jones et al. 2016). These strategies include adaptive conservation measures focused on the African Wild Dog's distribution and measures aiming to control the high competition with the African lion. The need for regional management plans to protect the threatened lion's populations in southern and western Africa was also highlighted by Peterson et al. (2014).

New management policies are required to mitigate the impacts of wildfire on the ecosystems in the Okavango delta. This should include, for example, functional fire response strategies for small mammals based on their life history, resource use, and behaviors (Plavsic 2014). A revision of conservation policies and designing new conservation measures is required to accommodate the projected range shift of bird assemblages of fynbos and grassland biomes in South Africa, Lesotho, and Eswatini (Huntley and Barnard 2012).

Mitigating the adverse effects of climate change on mountain vegetation of the great Escarpment requires the unification of South Africa and Lesotho's management policies to protect and monitor the regional ecosystems and services they provide (Bentley et al. 2019).

New management policies are needed to facilitate the removal of invasive vegetation and the reduction of livestock stocking. This is a precondition for enlarging the existing grassland patches in the semi-arid African savannas, which provide a living environment for numerous species, including threatened large-bodied birds (Scherer et al. 2016).

Rangeland degradation in central Kalahari, which includes the transition of woody vegetation toward the perennial grasslands, requires new policies that consider the projected decline in shrub distribution and increased mortality of plants, such as Velvet raisin (*Grewia flava*). The Kalahari savannas also require new policies facilitating the shift from commercial to sustainable management practices, which is necessary to enhance the resilience of these ecosystems to climate change (Tews et al. 2006).

Finally, targeted conservation plans are needed to face the climate change-mediated range contraction of *Welwitschia mirabilis*, particularly in the northern part of the Namib Desert (Bombi 2018); and of Wild syringa (*Burkea Africana*), Wild Plum (*Ochna pulchra*), and Kalahari podberry (*Dialium englerianum*) in the woodlands of Kavango-Zambezi Transfrontier Conservation Area (de Cauwer et al. 2016).

Research and monitoring.—Better coordination and improvement of the existing monitoring initiatives was recommended for seal populations, mainly aiming to understand mechanisms driving this species' mortality (Kirkman et al. 2011); for cormorants, to better understand their feeding patterns (Sherley et al. 2012); and for small mammals in the Okavango Delta to better understand their life-history attributes and fire responses (Plavsic 2014). With regard to the devastating ecological and commercial effects of the desert locust, monitoring of the insect's population aimed at expanding and contracting edge of the insect's distribution was proposed (Meynard et al. 2017).

Improved monitoring of vegetation dynamics affected by climate change was considered to be a high priority too. This particularly concerned the vulnerable woody vegetation in the Namibian savannas (Burke 2006) and the Okavango Delta (Bartlam-Brooks et al. 2013); and land-use changes in the woodland landscapes of Botswana and the associated impacts on biodiversity (Fox et al. 2017).

Climatically sensitive areas at the transition of woodlands and shrub vegetation in the KAZA TFCA in Namibia and Angola should be increasingly monitored to identify early signs of climate change impacts (de Cauwer et al. 2016). Particular species required to be monitored systematically were *Welwitschia mirabilis* in the Namib Desert (Bombi 2018) and the *Pterocarpus angolensis* in Namibia and Botswana (de Cauwer et al. 2014). The monitoring should aim to identify early signals of decline and extend the knowledge of the adaptive potential of these species.

The ongoing expansion of the Striga weed in Zimbabwe requires increased monitoring and the development of an early warning system combining ground and remote sensing data. These actions are required for the effective containment of the species (Mudereri et al. 2020).

In the marine ecosystem, progressive coral bleaching requires determining the priority areas for conservation, particularly in the southern part of Mozambique (Mcclanahan et al. 2011).

Discussion

Climate change increasingly threatens global biodiversity (Malhi et al. 2020); however, information about the direction and magnitude of impacts remains incomplete for many regions and ecological systems. This particularly applies to southern Africa, where underdeveloped research infrastructure and human resources limit our understanding and hamper the implementation of knowledge-based adaptation strategies. Our findings highlighted the high diversity of climate change impacts on different species and ecosystems, as well as the high diversity of possible adaptation responses. We found that the current level of understanding is incomplete in many aspects, and further systematic research and monitoring is needed. We further discuss the implications of our findings for climate change adaptation and conservation, and the formulation of future research priorities.

Literature review

We combined the search outputs from the two bibliographic databases, which suggest that a large proportion of relevant papers could have been identified (Bramer et al. 2017). Still, the number of studies that met all the defined criteria was surprisingly low, given the broadly recognized vulnerability of African ecosystems and large-scale impacts reported by different global assessments (Dai 2011, Brian et al. 2017, Sintayehu 2018). This undoubtedly accounts for the strict criteria for the inclusion of papers, that is, the clear identification of the addressed species or ecosystem, attribution of the impact to climate change, and the provision of management and policy recommendations. Moreover, we considered only papers published in English, which could have discriminated countries where English is not commonly used (e.g., Mozambique and Angola). In our review, we also did not consider publications related to South Africa, where science production outperforms the remaining region (Sooryamoorthy 2018). However, South Africa shares numerous species, ecosystems, and management practices with the neighboring countries, highlighting the importance of knowledge transfer and transnational collaboration in narrowing the existing knowledge gaps (Boshoff 2010). We discuss such options in the remaining discussion. Finally, we found a relatively high geographical imbalance in the number of identified publications, dominated by Namibia (28%) and Zimbabwe (21%). Such a pattern should not be interpreted in terms of the higher vulnerability of these countries but rather in terms of their size and research environment that outperforms the remaining countries. These limitations need to be considered in the following interpretations.

Impacts

We found that publications addressing vegetation prevailed (50%) and were mainly focused on increased mortality and range shift. This agrees with Midgely and Thuiller (2011), who suggested that research on plant species in southern Africa is currently further developed than that on animals. On the contrary, we identified only a minor portion of publications addressing aquatic (marine and freshwater) systems. In fact, a number of the papers identified in the initial phase of the literature search ($n = 438$) focused on different hydrological aspects of climate change impacts, such as changes in river flow, discharge. and water availability (Andersson et al. 2006, 2011, Beck and Bernauer 2011, Zhu and Ringler 2012). Only a few papers, however, addressed the impacts on biodiversity and wildlife. This agrees with Pereira et al. (2010), who noted that quantitative scenarios focusing on the impacts of global change on freshwater and marine organisms are lacking. A similar lack of research was identified for insects; Midgely and Thuiller (2011) noted a dearth of studies addressing the impacts on insect species in southern Africa.

We identified high diversity of impacts, ranging from extinction to range contraction and expansion to changing interspecific competition. Habitat loss and range contraction were the most frequently reported processes, potentially leading to the loss of keystone species such as predators (e.g., African Wild Dog) and pollinators (e.g., *Promerops cafer*, *Nectarinia famosa*, and *Anthobaphes violacea*). These impacts were often accompanied by the increase in the abundance of undesired invasive and competitor species. This agrees with Sintayehu (2018), who found that the impacts of climate change have resulted in significant shifts in species' geographical ranges in many parts of Africa. In fact, the shift in geographical locations is the most common response of many species to climate change (Pecl et al. 2017).

The increased temperature is one of the most proximate factors leading to species extinctions globally due to species' physiological intolerance to high temperatures (Cahill et al. 2013). This impact was also distinctly shown in the reviewed papers: local extinctions associated with high temperatures were reported, for example, for coral reefs (Mcclanahan et al. 2011) and Bank Cormorants (Sherley et al. 2012). The combination of heat and drought is particularly threatening (Allen et al. 2015), and it was manifested by increased mortality of African elephants (Shrader et al. 2010), range contraction of the population of the African lion (Peterson et al. 2014), and decline in the distribution range of several woody species (Burke 2006, Chidumayo 2017).

Several publications reported a climatically driven increase in the abundance of harmful species, which cause ecosystem degradation in some parts of the region. For example, the climatically driven bush encroachment in southern African savannas was found to be an essential driver of habitat loss, leading to the potential extinction of large-bodied bird species (Scherer et al. 2016). The prominence of this effect was also highlighted by Muntifering et al. (2005), who indicated that bush encroachment threatens the population of carnivores such as cheetahs (*Acinonyx jubatus*) in the Namibian savanna, and Sirami et al. (2009), who found that bush encroachment reduces the richness of bird species. The other indications of habitat deterioration concerned the expansion of *J. globiflora* in the Miombo woodlands, which is an important competitor of the valuable *J. paniculate*, and the expansion of invasive weed *Striga asiata*, which deteriorates the productivity of agroecosystems (Chidumayo 2017, Mudereri et al. 2020).

The impacts identified in the reviewed papers represent only some of the climate change effects documented in the literature. This is likely related to the limited science production in the target region and our requirement to identify studies that inform about both impacts and management and policy responses. For example, southern Africa is thought to be one of the important pathways of climatically driven biological invasions (Wang et al. 2017, Sintayehu et al. 2020). Our search, however, did not include any publications on this. The same applies, for example, to large-scale projections of species distribution or effects of CO_2 fertilization on future vegetation productivity. Although such studies exist in the study region (Bond and Midgley 2000, 2012, Ndlela et al. 2018, Conradi et al. 2020), they did not explicitly address the connection between impacts and management responses and therefore were not included. Therefore, we recommend future studies considering different selection criteria (e.g., without requiring the connection to management responses) to investigate the impacts on ecosystems more comprehensively.

Research and management implications

Active human-aided adaption actions are essential in southern Africa to halt the progressive biodiversity loss (Biggs et al. 2008, Bauer and Scholz 2010) and maintain the provision of ecosystem services that support the majority of human populations in the region (Wisely et al. 2018). Adaptation actions need to be closely connected with and guided by research and monitoring (Swart et al. 2014, Janetos 2020). However, such connection is insufficient globally (Swart et al. 2014), and its lack can be critical in regions such as southern Africa.

Most of the publications identified in the initial phase of the literature search ($n = 438$) were rather vague regarding management and policies and mainly aimed to address different ecological processes. The criterion on providing specific policy and management recommendations was thus the most restrictive one, resulting in the severe reduction of the initial dataset. This situation corresponds with the chronically loose connection of research with management and policies, which is recognized across different sectors and disciplines (Arvai et al. 2006, England et al. 2018).

Even though the number of the investigated papers was limited ($n = 28$), they provided a rather complex perspective on the regional perception of how to face climate change risks. Most importantly, the papers collectively highlighted the importance of connecting active adaptation actions, underlying policy frameworks, and research and monitoring. The review of active management measures demonstrated the high diversity of approaches which need to be considered, including building artificial nesting spots and water points, revising fire management approaches, reintroducing threatened species, or regulating industrial fishing. Although these cases were somewhat fragmented and challenging to synthesize, they may inspire the development of adaptive management plans elsewhere in the region. The limitation of these approaches is that they are mostly recommended based on scientific understanding rather than on their previous implementation experience and testing. Therefore, logistic and policy issues, and inconsistency with traditional practices may limit their applicability.

The reviewed publications repeatedly indicated a limited understanding of climate change impacts and vulnerability of different species and ecosystems as a factor hampering adaptation actions. Therefore, the authors extensively called for more intensive and coordinated monitoring of vegetation and animal populations, which seems to be particularly needed for marine and freshwater ecosystems (Kirkman et al. 2011, Sherley et al. 2012, de Cauwer et al. 2014). In fact, earth monitoring and climate change research infrastructure in the region has significantly advanced in the last decade (Kaspar et al. 2015, Helmschrot et al. 2018, Muche et al. 2018). Still, further development is needed, particularly in moving the focus from the monitoring toward more integrative approaches, which account for the feedback between environmental drivers, biodiversity, ecosystem services, and socioeconomic conditions and developments (Pereira et al. 2010, England et al. 2018).

The implementation of active management measures needs to be embedded within an efficient policy framework, which is often missing in southern Africa (SADC 2008). Therefore, some of the reviewed publications suggested targeted policy improvements to facilitate the operational mitigation of climate change impacts (Huntley and Barnard 2012, Lohmann et al. 2012, Bentley et al. 2019). The recommendations highlighted the need to incorporate transient ecosystem dynamics into nature conservation and management planning, coordinate transboundary conservation policies, and strengthen and coordinate different monitoring systems. These recommendations are well consistent with the emergent concepts on biodiversity conservation under climate change (Heller and Zavaleta 2009, Watson et al. 2012). These new ideas and their implementation can benefit from the existing policy frameworks, such as the Regional Biodiversity Strategy for SADC (SADC 2008) and the SADC treaty of 1992 (SADC 1992), which collectively highlight the importance of ecosystem management and conservation through regional integration and cooperation.

We found an increasing tendency in the number of publications addressing the interface of climate change and management and policy. Such an increase corresponds with the global recognition of climate change-related threats and the urgency of coordinated actions (Ford et al. 2015, Siders 2019, Nalau and Verrall 2021). We also found that many of the reviewed studies (57%) addressed the projected impacts of climate change, while the remaining papers addressed actual observed impacts. This suggests an increasing recognition of model-based approaches and the use of climate projections in research in the region, which was previously found marginal (Kusangaya et al. 2014). These facts, along with the development of advanced research and monitoring infrastructure, and the increasing ability of local researchers to acquire external research funding, hold the promise of improved and knowledge-based adaptation strategies and policies in the region.

These positive tendencies do not negate that the level of understanding of climate change impacts and responses remains low. To narrow the major knowledge gaps, we suggest that knowledge transfer from South Africa should be increasingly considered in regional adaptation planning (Boshoff 2010). The South African experience can, for example, help address the knowledge gaps identified herein concerning the control of biological invasions (Bezeng et al. 2020, Mapaura et al. 2020), and infrastructure and capacity building (Ziervogel et al. 2014). Moreover, the cooler climate in South Africa represents potentially important climatic refugium, which should be considered in regional adaptation and conservation strategies, including assisted migration and translocation (Butt et al. 2021). For example, Foden et al. (2007) found the range of *Aloe dichotoma* to contract in Namibia and expand in South Africa, highlighting the importance of transboundary conservation efforts.

Finally, we advise maintaining the database of so-focused publications and update it regularly to support future, more comprehensive synthetic studies. A review of gray literature conducted by the local scientists would also be a valuable input increasing our understanding of climate change impacts and adaptation options in the region (Ford et al. 2015).

Conclusions

The nine southern African countries investigated here are characterized by an exceptionally diverse natural and cultural environment that is being increasingly threatened by climate change and other pressures. Facing these challenges requires swift and coordinated actions, which must be supported by a sound understanding of anticipated impacts and effects of different management actions. This understanding is currently limited, highlighting the importance of synthetic studies aiming to collate the available and often fragmented knowledge. We collected here publications, which investigated and purposely recommended management and policy responses. This research has demonstrated the high fragmentation of the available knowledge and an urgent need for coordinated research and monitoring actions.

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Data Availability

Data are available from Zenodo: https://doi.org/10.5281/zenodo.5558905

Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.3860/full

5.3 Climate change threatens the distribution of major woody species and ecosystem services provision in southern Africa

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Climate change threatens the distribution of major woody species and ecosystem services provision in southern Africa

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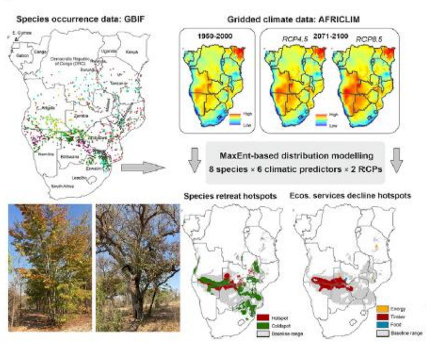
HIGHLIGHTS

- Future changes in the distribution of eight woody species in Sub-Saharan Africa were evaluated.
- A distinct pattern of loser and winner species was identified.
- Timber production-related species were affected the most.
- Hotspots of ecosystem services vulnerability were located in the Miombo and Mopane woodlands.

GRAPHICAL ABSTRACT



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ABSTRACT

In southern Africa, woody vegetation provides essential ecological, regulation, and cultural ecosystem services (ES), yet many species and ecosystems are increasingly threatened by climate change and land-use transformations. We investigated the effect of climate change on the distribution of eight species in 18 countries in southern Africa, covering 36% of the continent. We proposed a loser/winner ranking of the species based on the changes in land climatic suitability within their historical distribution and future gains and losses of suitable areas. We interpreted these findings in terms of changes in key ES (timber, food, and energy) provision and identified hotspots of ES provision decline. We used species presence data from the Global Biodiversity Information Facility, climatic data from the AfriClim dataset, and the MaxEnt algorithm to project the changes in species-specific land climatic suitability.
Among the eight investigated species, the baseline suitability range of Mopane (*Colophosperm mopane*) was least affected by climate change. At the same time, the area of its future distribution was projected to double, rendering it a regional winner. Another two species, manketti (*Schinziophyton rautanenii*) and leadwood (*Combretum imberbe*) showed high future gains too; however, the impact on their baseline suitability range differed between the climatic scenarios. The baseline range of African rosewood (*Guibourtia coleosperma*) declined entirely, and the future gains were negligible, rendering the species a regional loser. The effect of climate change was particularly severe on timber-producing species (four out of eight species), while species providing food (four species) and energy (four species) were affected less. Our projections portrayed distinct hotspot and coldspot areas, where climatic suitability for multiple species was concurrently projected to decline or persist. This assessment can inform spatially targeted adaptation and conservation actions and strategies, which are currently lacking in many African regions.

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1. Introduction

Climate change profoundly affects the distribution of species and biological diversity globally (IPCC, 2019; Warszawski et al., 2013). Changing climate often drives complex ecosystem reorganizations due to shifting climatic envelopes of species, modified biotic interactions, and changing disturbance regimes (Williams and Jackson, 2007). The underlying processes include drought-induced mortality and range contraction (Anderegg et al., 2019), species expansion due to the relaxed thermal limitations (Hampe and Petit, 2005), but also the invasion of new species, often posing biosecurity issues (Hulme, 2017; Robinson et al., 2020). These dynamics generate a complex pattern of losers and winners, in terms of species losing and gaining their competitive advantage, mainly driven by resource availability changes (Dyderski et al., 2018). Large-scale species replacements imply a functional reorganization of assemblages, impacting the provision of ecosystem services (ES) and disservices (Filgueiras et al., 2021). Humans, particularly the underdeveloped communities relying on local natural resources, will thus increasingly need to cope with the reassembled portfolios of ES provided by the winner species (Díaz et al., 2006).

Southern Africa is a region where risks related to the declining provision of ES are particularly high and where several assessments suggested the presence of climate change hotspots of global importance (Bauer and Scholz, 2010; Hoegh-Guldberg et al., 2019). Moreover, the region contains "crisis" and "very high risk" ecoregions facing severe habitat conversion and low coverage of protected areas (Watson et al., 2016). The anticipated impacts of climate change include, for example, the decline in vegetation productivity (Lawal et al., 2019), with particularly adverse effects on savanna ecosystems (Osborne et al., 2018; Ryan et al., 2016); range contraction and mortality of different tree and shrub species, such as wild loquat (*Uapaca kirkiana*), velvet raisin (*Grewia flava*), and wild teak (*Pterocarpus angolensis*) (Chidumayo, 2008; de Cauwer et al., 2014; Jinga et al., 2020; Tews et al., 2006); or the upward shift of mountain vegetation, for example, in the Great Escarpment of South Africa and Lesotho (Bentley et al., 2019). The direct climatic effects act synergistically with land conversion and exploiting management practices (including the reduction of large herbivores and carnivores; Shrader et al., 2010), amplifying habitat degradation, and the loss of biodiversity and ES (Kapuka and Hlásny, 2021; Sintayehu, 2018). These pressures have profound effects on the livelihoods of the local households (Ribeiro Palacios et al., 2013), compromising the provision of food, medicine, construction material, and energy (Kusangaya et al., 2014; Rosendo et al., 2018).

Although many of these impacts are manifested globally and receive increased research attention, their understanding is remarkably incomplete in southern Africa (except for South Africa; e.g., North et al., 2020; Sooryamoorthy, 2018). This is mainly due to the underdeveloped research and monitoring infrastructure, lacking human resources, political instability, and insufficient involvement of African researchers in international research networks (Haselip and Hughes, 2018; North et al., 2020; Tarkang and Bain, 2019). Such an environment predominantly produces local and descriptive studies, while synthetic, large-scale, and model-based assessments are lacking (Kapuka et al., 2022). Still, recent years have seen an increase in studies relying on Earth-observation systems and employing advanced modelling and forecasting tools (Andries et al., 2022; Balsamo et al., 2018; Dubovik et al., 2021). The increasing availability of high-resolution projections of future climates (Platts et al., 2015; Spinoni et al., 2018) and remote sensing-based products (e.g., Hansen et al., 2013) has accelerated the research of vegetation dynamics, including the effects of climate change (Catarino et al., 2021; Pelletier et al., 2019), and helped address some important knowledge gaps.

Species Distribution Models (SDMs), also known as Ecological Niche or Habitat Suitability Models, are one of the main tools providing spatially explicit information about the future environmental suitability for species, particularly when it comes to large-scale assessments (Dyderski et al., 2018; Mammola et al., 2021; Santini et al., 2021). SDMs relate species presence to different climatic and landscape features to assess the characteristic responses and interpret them, identify the most influential predictors, and project species distribution under different climatic scenarios (Elith and Leathwick, 2009; Booth et al., 2014). The applications are diverse and include identifying risks for biodiversity, setting future-oriented conservation and restoration priorities, identifying climatic refugia, and identifying target locations for the translocation of endangered species (Barbet-Massin et al., 2012; Jarvie and Svenning, 2018; Lentini and Wintle, 2015). SDMs can use different climatic and non-climatic variables, though studies employing climate data only prevail (Porfirio et al., 2014). For example, Bucklin et al. (2015) suggested that including non-climatic predictors had only a minor effect on model accuracy and a little to moderate effect on spatial prediction; yet, this finding can be context-specific.

SDMs rely on diverse statistical techniques such as the General Rule Set Production, Fuzzy Habitat Suitability Models, Generalized Additive Models, Random Forests, Generalized Linear Models, and the Maximum Entropy algorithm (MaxEnt) (Guisan et al., 2017). MaxEnt has received the greatest attention (e.g., Heneidy et al., 2019; Khanum et al., 2013; Ray et al., 2018; Tang et al., 2021) due to its high predictive accuracy, simplicity of use, and ability to handle presence-only data (Elith et al., 2006; Merow et al., 2013; Shcheglovitova and Anderson, 2013). Several studies showed that species distribution projections based on different algorithms are highly variable, implying the importance of robust multi-model assessments, which are, however, rare (Ryan et al., 2016). A review by Santini et al. (2021) suggested that 65% of the reviewed studies relied on single models, not considering the fact that future projections can markedly differ depending on the used SDM (Huang et al., 2018). The variability of future projections further depends on the used predictors and strategy for their selection, including treatment of variables' co-linearity, climatic scenarios, and other factors (Santini et al., 2021).

We focused on eight co-occurring woody species in southern Africa with high commercial, ecological, and cultural values. These species play critical ecological roles in local ecosystems, such as determining nutrient cycling and light availability, regulating climate, and creating habitats for other species (Ryan et al., 2016). Therefore, their dominance and distribution changes can trigger a cascade of ecological processes transforming traditional landscapes and threatening biodiversity. Moreover, their spatial reorganization may create new assemblies of ES with hard-to-predict impacts on native human communities.

Our objective was to investigate how climate change threatens these species' potential current and future distributions and identify regional winner and loser species, i.e., species gaining and losing areas with climatically suitable conditions. Next, we aimed to assess the implications for providing crucial ES by identifying areas where conditions for one or several species providing timber, energy, and food, are projected to persist, decline, or expand. We hypothesize that the projected changes will exhibit a distinct spatial pattern, forming hotspots and coldspots of multiple species retreat and persistence. Further, we hypothesize that this pattern will, at least partly, translate into the hotspots and coldspots of ES provision, which are the areas where multiple species providing a specific ES retreat or persist. Such research can inform where local human communities can face severe loss of ES due to the concurrent decline in several key species and where the provision of ES is likely to be sustained.

2. Materials and methods

2.1. Study area

We assessed a large part of sub-Saharan Africa, comprising Angola, Botswana, Congo, Democratic Republic of Congo, Equatorial Guinea, Eswatini, Gabon, Kenya, Lesotho, Malawi, Mozambique, Namibia, Rwanda, South Africa, Tanzania, Uganda, Zambia, and Zimbabwe (Fig. 1). The entire study area covers 36% of the continent. The region includes several biomes, including tropical and subtropical moist broadleaf forests; tropical and subtropical grassland savanna and dry forests; montane grasslands and shrubland; dryland desert; and the Mediterranean woodland (Abson et al., 2012; Olson et al., 2001). The region includes the Miombo and Mopane woodlands harboring exceptional biodiversity

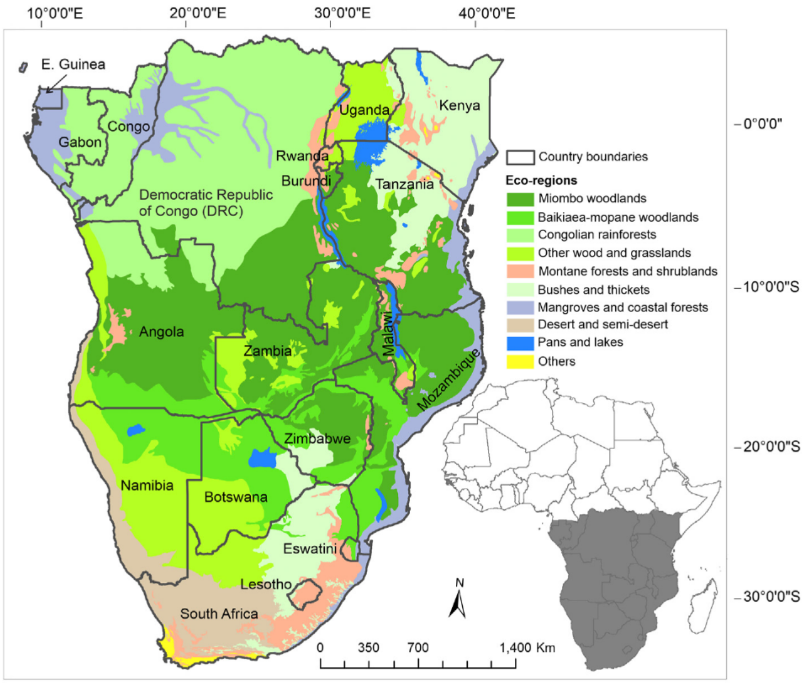

Fig. 1. Study area, state borders, and eco-regions by Olson et al. (2001). The study area's location in the African continent is shown too.

and conservation values, and semi-arid shrublands (Dewees et al., 2010; Munalula et al., 2020; Ryan et al., 2016). The regional woodlands provide around 26% of cash subsistence and income for people in rural areas (Ryan et al., 2016). Therefore, conflicts between nature conservation and human activities, such as agriculture, are frequent and threaten conservation objectives (Wangai et al., 2016).

2.2. Methods

2.2.1. Species selection and occurrence data

We focused on eight indigenous woody species (Chirwa et al., 2014): *Baikiaea plurijuga*, *Guibourtia coleosperma*, *Schinziophyton rautanenii*, *Combretum imberbe*, *Brachystegia spiciformis*, *Colophospermum mopane*, and *Strychnos cocculoides* (Table 1). They have high ecological and socio-economic values and provide construction material, fuel, food, and medicine to local communities and international markets (Chirwa et al., 2008, 2014; Ryan et al., 2016). The criteria for selecting the species were: (i) they provide a range of ES and goods, (ii) they occur over large climatic gradients, and (iii) there is a sufficient number of occurrence records available, allowing us to model their current and future distributions (Table 1).

The species' occurrence data were obtained from The Global Biodiversity Information Facility (GBIF.org, 2021a, b, c, d, e, f, g, 2022) (Fig. A.1). The GBIF data were collated from various sources, such as museum specimens, direct observations, and different published materials. We extracted records from all available sources. We removed duplicate records and records tagged as having suspicious coordinates. Further, we spatially rarefied the selected records, i.e., we replaced the clusters of points within the distance of 10 km (as suggested by Brown, 2014) with a single record. This operation was intended to reduce the spatial bias in the occurrence data known to have an adverse effect on SDM calibration (Boria et al., 2014; Brown et al., 2017).

2.2.2. Climatic variables

The gridded climate data were obtained from the AFRICLIM 3.0 dataset, which provides climate projections with the resolution of 30′ for entire Africa and several baseline datasets based on past observations (Platts et al., 2015). The dataset includes monthly temperature and precipitation grids and 21 bioclimatic variables (Table B.1). The baseline datasets are for different periods and include CRU CL 2.0 (1961–1990), TAMSAT TARCAT v2.0 (1983–2012), (1983–2012), and WorldClim v. 1.4 (1950–2000). Here we used AFRICLIM ENSEMBLES 3.0 based on WorldClim.

The climate projections are based on 18 combinations of five Regional Climate Models (RCMs) and ten General Circulation Models (GCMs). The projections are driven by two Representative Concentration Pathways of the IPCC-AR5: RCP4.5 and RCP8.5 (Moss et al., 2010). The high-resolution climate maps for the future were produced by the delta-change method (Platts et al., 2015) combining information from RCM results with the baseline observation-based data (Worldclim v. 1.4 in this study). First, the difference between the simulated future and past climatologies were calculated based on the RCM data, referred to as anomalies. Then, spline-interpolation of anomalies was used to produce high-resolution gridded anomaly maps (see also Hutchinson et al., 1996). Finally, the baseline observation-based maps were modified by the interpolated anomaly maps (Platts et al., 2015). This procedure was applied to monthly temperature and precipitation grids. Then, the projected temperature and precipitation grids were used to calculate future projections of all bioclimatic indices (Appendix B).

In this study, we used data for 2071–2100 calculated as the average of 18 projections (GCM-RCM pairs) separately for RCP4.5 and RCP8.5. We selected a subset of available bioclimatic variables by inspecting their correlation matrix and preserving those with Pearson's correlation below 0.8 (Raes and Aguirre Gutierrez, 2018) (Fig. B.1). We retained six variables, which represented temperature and water-related constraints, and characterized the initial set of 21 variables (Table 2). This approach is supported by Brun et al. (2020), who suggested keeping the number of predictors in SDMs reasonably small and their collinearity low.

2.2.3. Species distribution modelling

We used a MaxEnt algorithm (Phillips et al., 2006; Phillips and Dudík, 2008) to model the investigated species' current and future climatic

Table 1
Species addressed by this study, their habitats, number of occurrence records after rarefying, and social-ecological importance. Climatic limits (P, T) refer to the climatic conditions from 1950 to 2000 in species' current distribution.
Source (GBIF.org; IUCN, 2021; Orwa et al., 2009).

No.	Species	Habitat and ecology	Uses	No. of records
1	Rhodesian-teak (*Baikiaea plurijuga*)	Semi-deciduous tree. Dominant in tropical dry deciduous forest. P: 600–1100 mm; T: 27–30°C; E: 900–1200 m a.s.l.	A source of timber and charcoal. Bark is used for medicine and tanning traditional leather.	95
2	African rosewood (*Guibourtia coleosperma*)	Semi-evergreen tree. Occurs in open woodlands and deep Kalahari sands. P: 450–1100 mm; T: 20–28°C; E: 750–1400 m a.s.l.	Important timber species. Roots are used for medicine. Seed oil is used for cooking.	114
3	Manketti (*Schinziophyton rautanenii*)	Deciduous tree. Occurs mainly on Kalahari sandy woodlands, and grasslands. P: 150–1000 mm; T: 18–30°C; E: 200–1500 m a.s.l.	Fruits are an important food source, and are used to produce a traditional alcohol. Roots are used in the traditional medicine. Wood is used for woodcrafts.	49
4	Leadwood (*Combretum imberbe*)	Semi-deciduous shrub or tree. Common in open woodlands, wooded savanna, and along streams and rivers. P: 450–700 mm; T: 18–24°C; E: <1000 m a.s.l.	Source of construction material, firewood, and charcoal. Roots, leaves, and bark are used in traditional medicine, and foliage for animal fodder.	297
5	Zebrawood (*Brachystegia spiciformis*)	Deciduous shrub or tree. Occurs mainly in Kalahari woodlands on ridges and escarpments. P: 600–1200 mm; T: 14–28°C; E: 50–2000 m a.s.l.	An important source of fiber, fuelwood, timber, fodder, and medicine.	355
6	Mopane (*Colophospermum mopane*)	Deciduous medium-to-large tree. Occurs mainly in savanna woodlands, and river valleys of central and southern Africa. P: 250–700 mm; T: 26–36°C; E: 300–1000 m a.s.l.	Mopane worms is an important source of food and income for local people. Wood is used for timber, fuelwood, construction, and charcoal. Leaves are used in medicin.	340
7	Corky monkey — orange (*Strychnos cocculoides*)	Tropical evergreen shrub or small tree. Mainly occur in tropical deciduous woodlands and lowlands of Africa. P: 600–1200 mm.; T: 16–28°C; E: 400–2000 m a.s.l.	The fruits have economic importance and serve as a food source. Roots are used in medicine.	114
8	Wild teak (*Pterocarpus angolensis*)	Medium-to-large deciduous tree. Occurs in wooded grasslands and savannas. P: 700–1500 mm; T: 12–32°C; E: <1800 m a.s.l.	Key timbers species. Bark is used for medicine, leaves are used as animal fodder.	349

Pr — mean annual rainfall; Te — mean annual temperature; El —elevation above sea level.

suitability. MaxEnt applies the principle of maximum entropy distribution to predict the relative suitability values for a species based on species presence records and environmental predictors (Merow et al., 2013; Phillips et al., 2006). MaxEnt is a machine learning method used for making predictions or inferences from information that is often incomplete, such as species occurrence and biodiversity data (Chetan et al., 2014; Phillips et al., 2006). It uses an approach based on the presence-background data (Guillera-Arroita et al., 2014), with presence data representing observations and background data sampled at background locations either regularly or addressing known biases in the sampling process. MaxEnt's raw outputs represent relative suitability for a species, yet, modifications allowing for interpretation in terms of likelihood occurrence were proposed too (Royle et al., 2012).

We developed a MaxEnt model for each species using occurrence records from the GBIF (Table 1) and bioclimatic variables from AFRICLIM (Table 2). Based on the iterative testing of different combinations of feature classes and regularization multipliers, we used linear, quadratic, product, and hinge feature classes, and a regularization multiplier 1. These settings were found to maintain an appropriate balance between model simplicity and complexity (i.e., avoiding under- and overfitting) (Chłond and Junkiert, 2015; Kramer-Schadt et al., 2013; Levinsky et al., 2013). We applied a 10-fold cross-validation for each model building, partitioning the data into a training and a testing data set (Chetan et al., 2014; Chłond and Junkiert, 2015; Raes and Aguirre Gutierrez, 2018).

The models' predictive performance was evaluated by the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) (Kramer-Schadt et al., 2013; Porfirio et al., 2014; Raes and Aguirre Gutierrez, 2018), and the True Skill Statistics (TSS) (Allouche et al., 2006). The AUC measures the probability that a randomly drawn presence record has a higher predicted probability of occurrence than a randomly drawn absence (Raes and Aguirre Gutierrez, 2018). The metric ranges from 0 to 1, with values below 0.5 indicating that the model performs no better than the random model. Values between 0.7 and 0.9 are interpreted as a good performance and above 0.9 as perfect discrimination (Phillips et al., 2006; Phillips and Dudík, 2008). However, the AUC's use as a performance indicator of models relying on pseudoabsence data can be misleading due to the inflation of false absences (Elith et al., 2006), and other reasons discussed by Lobo et al. (2008). Therefore, we also used the TSS defined as:

$$\text{TTS} = \text{sensitivity} + \text{specificity} - 1 \quad (1)$$

where sensitivity is the fraction of correctly predicted presences and specificity is the fraction of correctly predicted absences.

We used two complementary metrics to evaluate the relative importance of climatic predictors to the models: percent contribution and permutation importance (Phillips et al., 2006; Raes and Aguirre Gutierrez, 2018). The percent contribution is calculated during the model building that incrementally increases the model's gain by modifying the coefficients of a single variable, assigning the gains to the variable, and recalculating the gains to percentages at the end of the training. The permutation importance uses a randomization procedure, where the values of the investigated variable are randomly permutated, and model performances with the original and permutated variable are compared.

We used a logistic output of MaxEnt, which provides continuous distribution maps with suitability values ranging from 0 (unsuitable) to 1 (highly suitable) (Kong et al., 2021; Yuan et al., 2015). We deployed the trained models with future climate data to produce the maps of species-specific climatic suitability for 2071–2100. We used MaxEnt v.3.4.4 (Phillips et al., 2004, 2006; Phillips and Dudík, 2008).

Table 2
Bioclimatic variables used for the species distribution modeling. The variables were selected out of the 21 candidate variables included in the AFRICLIM 3.0 dataset.

Code	Variable description	Unit
BIO1	Mean annual temperature (Mean of monthly means)	°C
BIO3	Isothermality (100 × Mean annual rainfall / Annual temperature range)	°C
BIO5	Maximum temperature of the warmest month	°C
BIO10	Mean temperature of the warmest quarter (Any consecutive three-month period)	°C
PET	Potential evapotranspiration (Hargreaves, 1985)	mm
MI	Annual moisture index (Mean annual rainfall / PET × 100)	$\text{mm mm}^{-1} \times 100$

2.2.4. Postprocessing of modelling outputs

To discriminate between areas considered suitable and unsuitable for a species, we applied a 10th percentile threshold calculated from the training data, excluding 10% of the occurrence records with the lowest probability of occurrence from the predicted occurrence range (Phillips et al., 2006; Raes and Aguirre Gutierrez, 2018; Ray et al., 2018). Previous studies recommended such a value as outperforming thresholds based, for example, on

Table 3
The investigated species and main categories of ecosystem services they provide.

Species	Ecosystem service		
	Timber	Food	Energy (fuelwood, charcoal)
Rhodesian-teak (*Baikiaea plurijuga*)	X		X
African rosewood (*Guibourtia coleosperma*)	X	X	
Manketti (*Schinziophyton rautanenii*)		X	
Leadwood (*Combretum imberbe*)			X
Zebrawood (*Brachystegia spiciformis*)			X
Mopane (*Colophospermum mopane*)	X	X	X
Corky monkey — orange (*Strychnos cocculoides*)		X	
Wild Teak (*Pterocarpus angolensis*)	X		

minimum training presence, equal training sensitivity and specificity, and 0.5 logistic probability (Escalante et al., 2013; Raes and Aguirre Gutierrez, 2018).

The binary suitability maps (depicting suitable and unsuitable areas discriminated by the threshold above) for the period 2071–2100 were compared with the baseline suitability maps to identify areas of range contraction, range expansion, and areas of no change; this has been done separately for the two RCP scenarios.

To identify winner and loser species, we ranked the species based on two indicators: (i) '(baseline range area − contraction area) / baseline range area', which describes the level of vulnerability of the baseline range; and (ii) '(expansion area − contraction area) / baseline range area', which indicates how the species can benefit from climate change in terms of its future gains of the suitable areas.

Next, we combined the projected ranges of all species to identify areas where climatic suitability for multiple species was projected to decline (hotspots), and areas where climatic suitability for multiple species was projected to persist (coldspots). We set the arbitrary threshold of four species retreating from or persisting within their baseline range to produce a binary classification of hotspots and coldspots. We focused this assessment on the central part of the study area, where at least four out of eight target species co-occurred under the baseline climate (3.4 million km^2, Fig. D.1b).

Finally, we extended this assessment by considering the major ES provided by the species, i.e., timber, food, and energy. We assigned an attribute to each species representing the category of ES or goods it provides (Table 3). Then, we identified areas where the potential for the provision of a given ES was projected to decline due to the decline in land's climatic suitability for one or multiple species and where the provisioning potential is expected to persist at the baseline level.

All analyses were conducted in ArcGIS Desktop v. 10.8 (ESRI, 2020), SDMToolbox v.2.4 (Brown et al., 2017; http://sdmtoolbox.org/), and Statistica 13.4 (TIBCO Software Inc., 2018).

3. Results

3.1. Models performance and predictor importance

The mean AUC calculated based on ten replicated runs ranged between species from 0.8 to 0.96 and TSS from 0.42 to 0.85 (Table C.1). The highest values were reached for *Baikiaea plurijuga* (AUC 0.96, TSS 0.85) and *Guibourtia coleosperma* (AUC 0.96, TSS 0.82). A model for *Pterocarpus angolensis* had the lowest performance with AUC 0.82 and TSS 0.42.

The relative contribution of underlying climate variables evaluated based on the permutation importance differed among species (Table C.2). Isothermality was the most influential for *S. rautanenii* (52.5%), *C. imberbe* (24.6%), *S. cocculoides* (38.5%), and *P. angolensis* (39.6%). Annual moisture index was the most influential for *B. plurijuga* (49.6%), *B. spiciformis* (39.7%), and *C. mopane* (50.6%). The potential evapotranspiration had the greatest effect on the distribution of *G. coleosperma* (60%). The importance values for the remaining variables are in Appendix C.

The assessments based on the jackknife analysis and the relative percent contribution are indicated in Table C.3 and Fig. C.1. The overall pattern does not differ from the results based on the permutation importance.

3.2. Species distribution ranges

The baseline ranges of suitability markedly differed among species, with *S. cocculoides* occupying the largest area of 5 million km^2 and *B. plurijuga* occupying the smallest area of 0.6 million km^2 (Table 4, Fig. A1). Climate change substantially modified the modelled baseline suitability. Yet, the impact differed among species and between RCPs (Fig. 2). The baseline suitability range of *G. coleosperma* was projected to disappear entirely under both climatic scenarios in 2071–2100. The new suitable conditions appeared in Angola and on large areas east of the baseline range under RCP4.5 but not RCP8.5. The baseline range of *B. plurijuga* was halved under RCP4.5 and nearly disappeared under RCP8.5. At the same time, conditions suitable for the species significantly expanded in the future under both RCPs (Table 4), mainly into Angola, Zambia, Zimbabwe, and South Africa. The baseline range of *P. angolensis*, was projected to decline under both RCPs, mainly in northern Namibia; western, southern, and eastern Angola; and central and southern parts of Zambia. Future suitable areas showed only minor gains (12% and 13% under the two RCPs, Table 4). The baseline range of *B. spiciformis* declined under both RCPs, while future gains in suitable areas were minor (9 and 6%), mainly between Angola and Zambia, and southeast of South Africa. Future suitable areas were rather fragmented compared to the remaining species. Finally, the baseline ranges of *S. rautanenii* and *C. mopane* were the least affected by climate change, while their area of future suitability nearly doubled.

From the perspective of winner and loser species (see the two indicators described in Methods), the baseline suitability range of *C. mopane* was least affected by climate change. At the same time, the area of its future distribution was projected to double. This pattern was consistent under both RCPs, rendering this species a regional winner (Fig. 3). *C. imberbe* and *S. rautaniemi* showed high future gains, too; however, the impact on their baseline suitability range differed between RCPs. The distribution of *G. coleosperma* was most affected: its baseline range has declined entirely, and the future gain was negligible, rendering the species a regional loser. The remaining species were projected to experience baseline range reduction by 30 and 80% and an expansion of 40 to 120% relative to the baseline range, with significant differences between RCPs. It is noteworthy that the two evaluated aspects, i.e., the vulnerability of the baseline range and the ability to benefit

Table 4
Predicted changes (%) in climatically suitable areas of the studied species relative to the baseline suitability range under two climatic scenarios.

Species	Baseline range (million km^2)	Expansion (%)		Contraction (%)		No change (%)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Rhodesian-teak (*Baikiaea_plurijuga*)	0.6	39.0	31.7	47.7	93.5	52.3	6.5
African rosewood (*Guibourtia_coleosperma*)	0.7	66.1	1.6	100.0	100.0	0.0	0.0
Manketti (*Schinziophyton_rautanenii*)	2.1	79.8	50.5	4.6	35.3	95.4	64.7
Leadwood (*Combretum_imberbe*)	2.9	27.5	52.8	33.2	25.4	66.8	74.6
Zebrawood (*Brachystegia_spiciformis*)	3.8	8.7	6.1	55.5	62.7	44	37.3
Mopane (*Colophospermum_mopane*)	1.6	65.2	102.8	6.7	19.7	93.3	80.3
Corky monkey — orange (*Strychnos_cocculoides*)	5.0	6.9	3.7	32.0	67.9	68.0	32.1
Wild teak (*Pterocarpus_angolensis*)	4.3	12.0	13.0	38.9	40.4	61.1	59.6

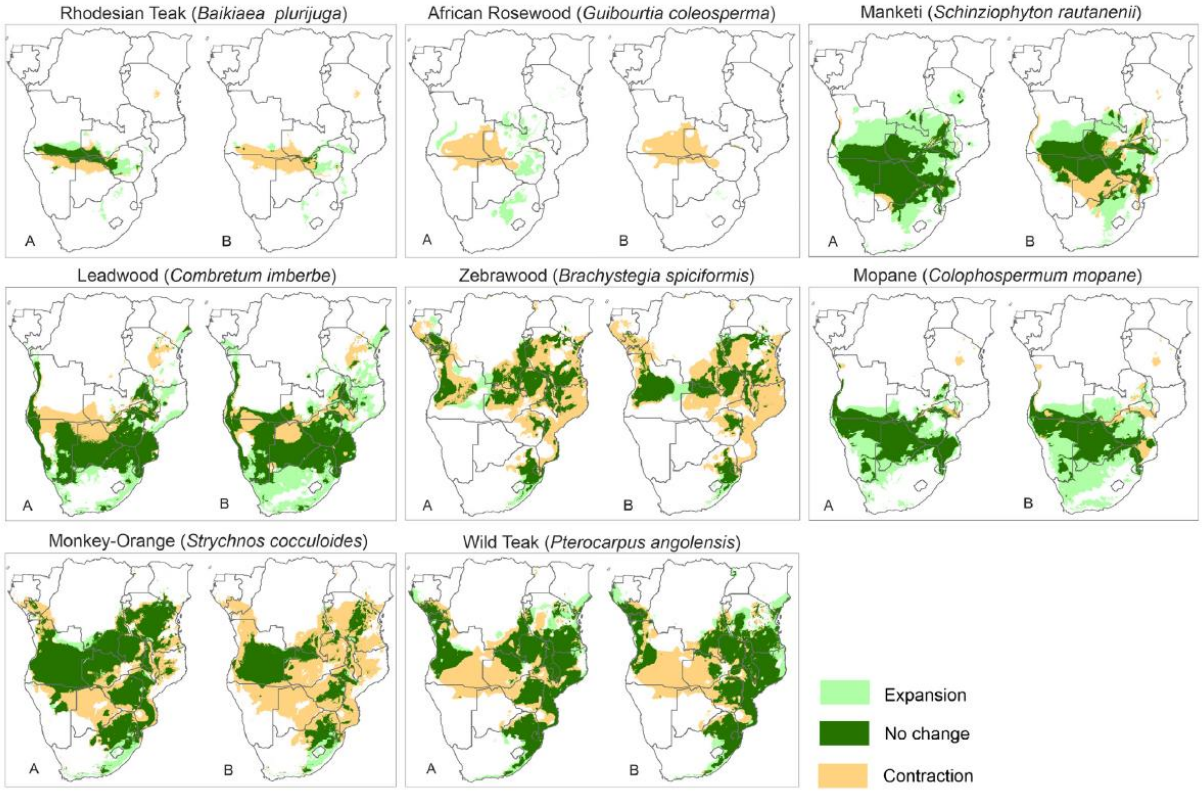

Fig. 2. Changes in the distribution of climatically suitable areas for eight woody species in southern Africa under two climatic scenarios: (A) RCP4.5, and (B) RCP8.5. State boundaries are displayed too.

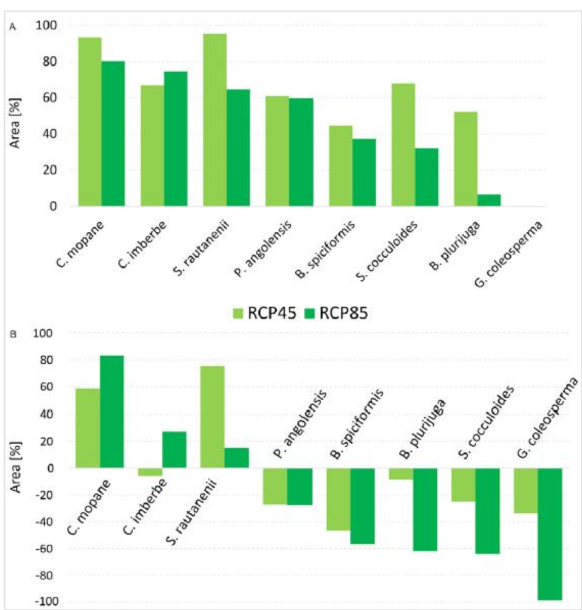

Fig. 3. Ranking of the investigated species by the values of (A) "(baseline range area − contraction area) / baseline range area" indicating the vulnerability of the baseline range; and (B) "(expansion area − contraction area) / baseline range area" indicating how the species can benefit from climate change in terms of future range relative to the baseline range. The species are ranked by the RCP8.5 projection.

from climate change in terms of future gains of suitable areas, produced the same species ranking.

3.3. A multi-species perspective

The major hotspot zone, i.e., the area where land climatic suitability was projected to decline in 2071–2100 for more than four out of the eight addressed species (see Methods section) formed an east-west oriented belt along the borders of Angola, Namibia, Botswana, Zambia, and Zimbabwe (Fig. 4). This pattern was present in both RCPs. The hotspot covered parts of the Baikiaea-mopane woodlands and the Miombo woodland in central southern Africa. It also partly stretched into the montane forests on the east, which belong to the Eastern Afromontane Biodiversity Hotspot (Mittermeier et al., 2011).

The coldspot area, where conditions suitable for at least four out of eight species were projected to persist, differed distinctly between the two RCPs (Fig. 4). It formed three distinct zones under the RCP4.5 distributed (i) along the west-central of Angola; (ii) in the border area of Angola, Zambia, Botswana, and Namibia in the Baikiaea-Mopane woodland; and (iii) in the area passing from the north of South Africa to Zambia. The latter zone consisted of many fragmented areas covering a range of ecosystems from the South African montane forests, Baikiaea-Mopane and Miombo woodlands, to the coastal forests (see Fig. 1). Under the RCP8.5, the coldspot areas distinctly shrunk and created a fragmented pattern scattered across the study region.

3.4. Ecosystem services perspective

Timber provision, which is mainly related to *B. plurijuga*, *G. coleosperma*, *C. mopane*, and *P. angolensis* (Table 3), was the most affected ES due to the

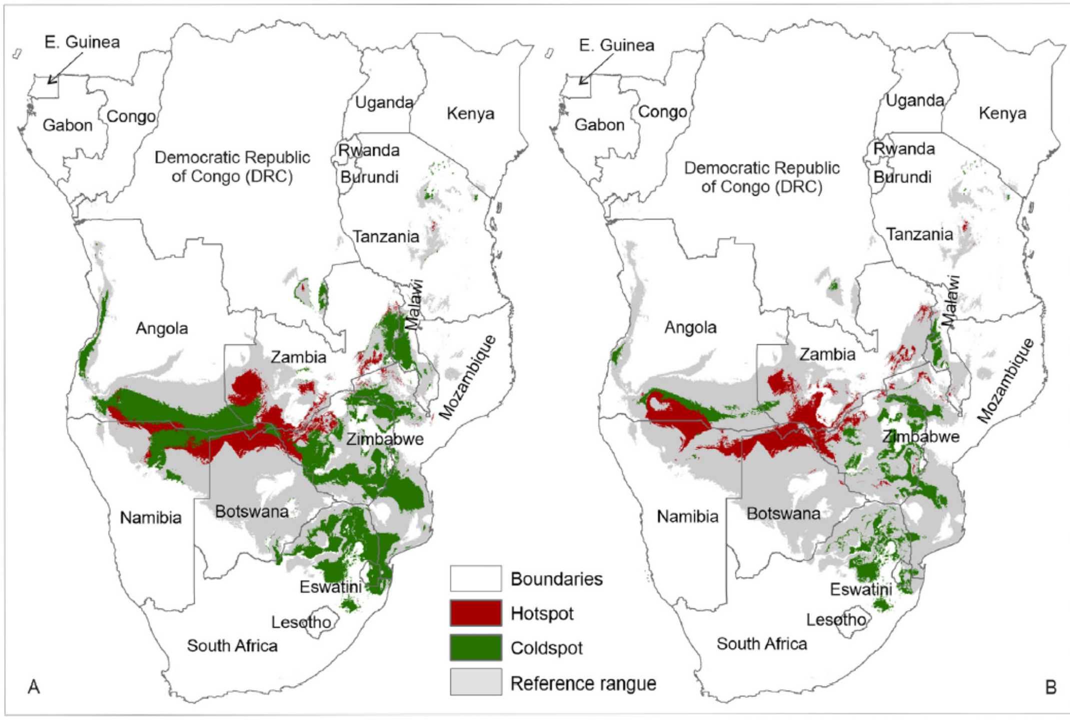

Fig. 4. Hotspot areas, where climate suitable for multiple species was projected to retreat in 2071–2100, and coldspot areas, where climate suitable for multiple species was projected to persist. The results are based on aggregating species-specific projections for 2071–2100 relative to the period 1950–2000. Two climatic scenarios were considered: (A) RCP4.5 and (B) RCP8.5.

extensive decline in land climatic suitability for the former three species (Fig. 5A–B). The most affected areas formed an east-west belt in southern Angola, northern Namibia and Botswana, and southern and western parts of Zambia. While this zone was relatively small under the RCP4.5 and was mostly located in the north of Namibia, it enlarged several-fold under the RCP8.5, covering an area of 1 million km^2. The coldspot (least affected) areas of timber provision were absent under RCP4.5 (Fig. 5C–D), and were fragmentarily distributed in the eastern montane forests, bushes, and the Miombo and Mopane woodlands under RCP8.5. We identified several coldspot areas of food provision, related to the presence of *G. coleosperma*, *S. rautanenii*, *S. cocculoides*, and *C. mopane*. However, no significant hotspot area was identified. We did not identify any distinct hotspot or coldspot pattern related to the species used for energy provision.

4. Discussion

In this study, we explored the anticipated changes in land climatic suitability for eight woody species known to provide a broad range of regulatory, provision, and cultural services. We proposed a novel methodology for identifying the most and least vulnerable areas from ecological and ES perspectives. We highlighted that vulnerabilities and risks exhibit distinct spatial patterns, which may need to be considered by managers, policy-makers, funding organizations, and individual donors seeking science-based guidance (Jantz et al., 2015; Leisher et al., 2022). We further discuss the implications and methodological limitations of our findings.

4.1. Methodological limitation

Using correlative models (i.e., models predicting species distribution as a function of environmental conditions) such as MaxEnt assumes that species occurrence data characterize species fundamental niche adequately, i.e., the entire range of conditions where species can survive was sampled (Booth et al., 2014). This is not true for many species because the sampling often does not cover their current distribution entirely, and their current distribution often does not correspond with their fundamental niche (Botella et al., 2020; Costa et al., 2010). The latter effect can be particularly severe in African species used for timber and charcoal with human-altered distributions such as *C. mopane*, *P. angolensis*, and *G. coleosperma* (Pelletier et al., 2019). Lacking knowledge of species phenotypic plasticity and local adaptation is another potentially important factor when it comes to species persistence and expansion under changing climatic conditions (des Roches et al., 2017). However, such processes are rarely considered in SDM-based projections (e.g., Benito Garzón et al., 2019; Valladares et al., 2014), mainly because intraspecific trait data are too scarce to allow parametrizing such models. Provenance experiments, where species are intentionally translocated to conditions different from their original sites, can elucidate these effects' importance; such experiments are, however, rare in southern Africa (Akinnifesi et al., 2004). Generally, models considering species phenotypic plasticity and local adaptation are likely to deliver less alarming messages than models neglecting this information (Benito Garzón et al., 2019); a fact that warrants attention in interpreting the outcomes of SDM projections.

The quality of climate data and choice of a dataset are other aspects affecting the presented predictions (Abdulwahab et al., 2022; Datta et al., 2020). For example, the used AFRICLIM contains an RCM-based climate change signal (Platts et al., 2015), making it superior to Worldclim, which uses GCM-based anomaly values (see Methods). On the other hand, the used version of AFRICLIM uses Worldclim 1.4 as a baseline, though Worldclim 2.1 based on a denser station network has already been released (Fick and Hijmans, 2017). The effect of differences between Worldclim versions on SDM outputs has been assessed for Europe (Cerasoli et al., 2022), yet the transferability of these findings to sub-Saharan Africa with different station density (Kaspar et al., 2022) can be limited. Finally, the 30′ resolution of the used climate data limits smaller scale assessment,

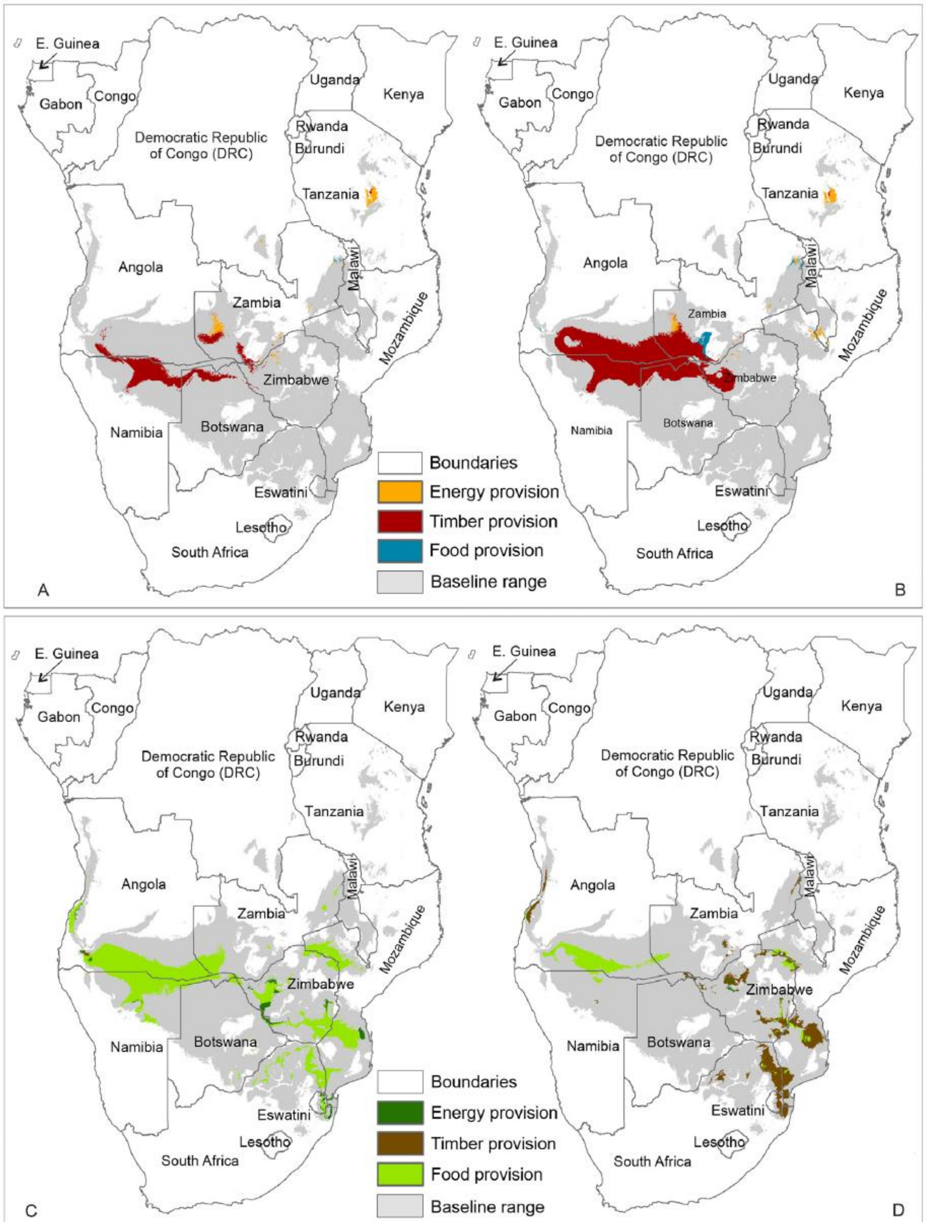

Fig. 5. Areas where climatic suitability for multiple species providing specific ecosystem service was projected to retreat (A–B) and persist (C–D). The results are based on aggregating species-specific projections for 2071–2100 relative to the period 1950–2000. Two climatic scenarios were considered: RCP4.5 (A, C) and RCP8.5 (B, D).

such as the identification of microclimatic refugia (Barrows et al., 2020), yet this limitation should not be severe in the presented large-scale assessment. Using higher-resolution data that better captures the effects of terrain-induced climate transitions, water bodies, and other features would increase these projections' applicability at smaller scales. Still, the so-called effective resolution that depends on the density of underlying station data (Daly, 2006) is particularly limiting in sub-Saharan Africa, where monitoring infrastructure is largely underdeveloped (Haselip and Hughes, 2018; Posada et al., 2018).

We considered two RCP scenarios to capture the variability of future developments. Yet, we used the average ensemble of climate projections produced by different combinations of GCMs and RCMs driven by each RCP. This averaging likely underestimated future projections' variability, particularly concerning precipitation-related variables, which typically vary between the RCM-GCM pairs more than between the RCPs (Saini et al., 2015). Future studies could consider all or a subset of the underlying climate projections, which, even if combined with different SDMs, can capture the future uncertainty of vegetation responses more comprehensively (Jiang et al., 2012).

Although we considered climate predictors only, model performance was high, supporting the validity of our findings. Previous studies have supported the prominence of climate in determining species distribution on a large scale, for example, those focused on the distribution of palm species in Africa (Blach-Overgaard et al., 2010) and vertebrate species in Florida (Bucklin et al., 2015). Still, land-use, soil conditions, and non-environmental constraints should be considered, particularly at smaller scales and for species with azonal and man-altered distributions (Pelletier et al., 2019; Sieben, 2019; Hageer et al., 2017).

We proposed a methodology for mapping species distribution vulnerability hotspots and coldspots by identifying areas where climatic conditions for multiple species were projected to persist or decline. Although this approach is straightforward, the interpretations should be cautious. This approach, for example, assumes that the baseline species pool is equal across the study region and that the social or ecological impact of different species retreats is similar. However, compensatory dynamics emerging from species diversity and functional asynchrony, which may involve species not included in this analysis, can potentially mitigate some impacts and stabilize the provision of ES (Gonzalez and Loreau, 2008; Winfree and Kremen, 2008). This is particularly relevant for highly diverse and species-rich ecosystems such as the Miombo and Mopane woodlands, where such dynamics can be anticipated (Gonçalves et al., 2017). Therefore, the identified hotspot and coldspot areas need to be interpreted with respect to the baseline distribution of the eight addressed species, which is obviously limiting. We strived to mitigate this limitation by carefully selecting ecologically and socially relevant species, which could thus approximate the overall pattern of future risks.

4.2. Ecological and social implications

Our projection highlighted remarkable differences in climatic sensitivity of species distribution, rendering a specific pattern of winners and losers and the distinct geographical pattern of multi-species vulnerability. Generally, the distribution of species with a small baseline range, such as *B. plurijuga*, and *G. coleosperma*, were found to be the most threatened by climate change, i.e., the climatic suitability within their baseline range declined, and future gains were insignificant. At the same time, species with large baseline distributions, such as *S. rautanenii*, *C. imberbe*, and *C. mopane*, benefited from climate change in terms of (i) the persistence of suitable conditions within their baseline range and (ii) large future gains. This finding supports the hypothesis of the positive relationship between the niche breadth and range size, which, although generally positive, was found to largely vary between the species (Slatyer et al., 2013; Staude et al., 2020). Among the studied species, for example, *S. cocculoides* and *P. angolensis* occupied relatively large ranges under the baseline climate; they, however, did not benefit from climate change in terms of future gains. Our assessment indicated that *C. mopane* is a regional winner, which is particularly important regarding the broad range of ES the species provides, including timber, food, medicine, and energy (Makhado et al., 2014; Sekonya et al., 2020). A similar result was presented by Ngarega et al. (2021), who considered a broader range of climatic and non-climatic predictors in their assessment, and found species distribution relatively resistant to climate change. Yet, their estimate of species expansion was more conservative than ours.

Although we considered the expansion of climatically suitable areas for the species, this information should be treated cautiously because of numerous constraints on the physical species expansion (Gonçalves et al., 2021; Weiskopf et al., 2020). These include, for example, landscape fragmentation, new biotic interactions, and a fast pace of climate change, which many species are unable to track (Littlefield et al., 2019). Still, the presented expansion patterns may inform assisted migration and species translocation efforts by identifying suitable target locations (Hällfors et al., 2016); this application is less constrained by the factors thereof.

In the recent decade, the identification of "hotspot" regions that are particularly vulnerable to climate change and where human security can be at risk has received significant attention as a tool for communicating climatic exposure, multivariate risks, and multi-sectoral vulnerabilities (de Sherbinin, 2014; Hlásny et al., 2021; Piontek et al., 2014). The hotspot maps were also found to be a transparent, science-based, and defensible tool for priority setting for donor organizations and individuals (Barnett et al., 2008). Here we identified several distinct hotspots of species range vulnerability, where climatic suitability for multiple species was projected to decline, and coldspots of potential species persistence. Interestingly, while coldspot were unstable under the two RCPs, and their area shrunk significantly under RCP8.5, the hotspot areas exhibited high stability. The central hotspot area was located at the borders of Angola, Zambia, Namibia, and Botswana in the Miombo and Mopane woodlands. This finding is alarming because of the potential loss of vital ecological functions over the large areas of the woodlands, which support the livelihood of ca 10 million rural people and 50 million urban dwellers (Ryan et al., 2016). In fact, the high vulnerability of these woodlands has been reported in previous studies, including risks such as phenological disruption and species turnover driven by a shorter and shifted growing season, reduced water availability, and fire regime shift (Prichard et al., 2017). However, Ryan et al. (2016) suggested that these projections can be uncertain given many unknown responses and feedbacks, including the positive CO_2 fertilization effect (Scheiter et al., 2020), and ambiguous results of studies on remote sensing-based assessment of vegetation conditions (e.g., Zhu et al., 2016). Therefore, further research on the emergent biotic interactions and implications for ES is needed in southern Africa to reduce some of the most pronounced known uncertainties in assessing future impacts of climate change (Carpenter et al., 2012).

The uncertainties in ecological responses make the assessment of the impact on ES even more problematic (Ryan et al., 2016). Still, we identified the hotspots and coldspots of ES provision by considering the decline and persistence of land climatic suitability for species providing specific ES. Species important for timber production (*B. plurijuga*, *P. angolensis*, and *G. coleosperma* – but not *C. mopane*) were affected the most, rendering this ecosystem service the most vulnerable. The high risks to key timber species of the Miombo woodland in Angola and Zimbabwe were also highlighted by Catarino et al. (2021), and Pelletier et al. (2019). The former authors particularly underscored the vulnerability of *G. coleosperma* due to its restricted distribution and high market value; we identified this species as a regional loser. The major hotspot emerged in the same area as the species retreat hotspot discussed above, and it was significantly larger under RCP8.5 than under RCP4.5. At the same time, the coldspot areas of timber provision were rather unstable under the two RCPs. Interestingly, although the projected changes in land climatic suitability for single species providing food and energy were substantial, they did not form any significant hotspot or coldspot pattern.

Assessments of these impacts did not consider the high species richness in parts of southern Africa and options for the emergent compensatory dynamics (i.e., one species functionally replacing the other) in terms of ecological functions and ES (Gonzalez and Loreau, 2008; Winfree and Kremen, 2008). This could result in a compensation of some losses or certain shifts in the traditional portfolios of ecosystem services (Filgueiras et al., 2021), potentially mitigating some impacts. However, such processes need to be intensively monitored to inform policies and management strategies supporting the use of alternative resources. The compensatory dynamics emerging from species richness, diversity, asynchrony, and complementarity is an important knowledge gap in southern Africa, which can be crucial for informing new adaptation strategies.

5. Conclusions

Climate change alters species distribution and the provision of ES globally, yet, our understanding of these effects remains limited in many regions of southern Africa. These limitations hamper the formulation of knowledge-based adaptation strategies and the provision of adequate guidance for implementing adaptation and mitigation projects. Our projections portrayed distinct regional differences in species range vulnerability, including hotspot and coldspot areas, where climatic suitability for multiple species was projected to decline or persist. Although the coldspot areas may represent opportunities for adaptation planning, their instability between the RCPs questions this option. From the ES perspective, the timber production-related species were most affected, posing a significant risk for local communities and regional economies. Further research should aim to better understand intraspecific variability, including phenotypic plasticity and local adaptation of species, novel interspecific interactions, and possible compensatory dynamics emerging from species and functional diversity, which can mitigate some of the presented impacts. However, this requires improving regional research and monitoring infrastructure and options for using more advanced mechanistic models for identifying future risks.

Data availability

The species occurrence data used for this research have been archived in the Zenodo repository: DOI. https://doi.org/10.5281/zenodo.6586927.

CRediT authorship contribution statement

Alpo Kapuka: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Laura Dobor:** Validation, Writing – original draft, Writing – review & editing. **Tomáš Hlásny:** Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.158006.

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5.4 Social Vulnerability to Natural Hazards in Namibia: A District-Based Analysis

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Social Vulnerability to Natural Hazards in Namibia: A District-Based Analysis

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Abstract: Southern Africa is one of the world's poorest and most vulnerable regions with severe barriers to its sustainable development. We strived to understand here the patterns and drivers of social vulnerability to natural hazards in Namibia, which is the most arid sub-Saharan country with large social inequalities. We used a total of 12 indicators that characterized social, economic and demographic settings of the 14 districts in the country. Further, we evaluated the countrywide pattern of most relevant natural hazards, including wildfires, floods and drought. We identified the main factors driving social vulnerability in the districts, and we evaluated how the socio-economic fitness of populations coincided with the distribution of high-hazard areas. We found that populations with the poorest socio-economic performance were mostly distributed in the country's northern districts, which are also exposed to the highest frequency and severity of natural hazards, particularly to floods and wildfires. This coincidence of highly sensitive populations with high exposure to hazards renders these populations particularly vulnerable. That the frequency of natural hazards increases with climate change, and implementation of programs enhancing the social resilience is insufficient, underscores the urgency of actions targeted at the priority areas identified herein.

Keywords: hazard-prone areas; social inequality; adaptation; southern Africa; vulnerability index

1. Introduction

The world has been experiencing an unprecedented increase in the frequency and intensity of natural hazards that threaten the stability of many human populations [1,2]. These hazards have increasingly affected economies, the environment, infrastructure and human wellbeing and they have caused annual damages amounting to billions of US dollars globally [3]. Understanding the patterns and mechanism of social vulnerability to natural hazards has, thus, become an important part of the research agenda with implications for policy and decision making [4]. It also plays a crucial role in the development of adaptation and resilience strategies enhancing the population's capacity to respond to natural disasters [5].

While the biophysical dimension of vulnerability has been extensively studied [6,7], our understanding of the social dimension remains limited [8]. The increasing size of the population affected by diverse stressors, however, highlights the prominence of this topic [9]. Previous studies have focused, for example, on patterns and drivers of vulnerability to specific hazard types, such as floods [8,10], drought [11] and wildfires [12]. Others shed light on the main drivers of social vulnerability [13,14], including changes in demographic composition [14,15] income and poverty [11,13,15], the proportion of elderly people in the community [16–18] and access to resources, such as information, technologies and knowledge [19].

The concept of vulnerability has been increasingly applied in social science research and management of natural hazards [19,20]. Social vulnerability to hazards is defined as the probability of a population being negatively affected by hazards [15], or as the capacity of a population to cope with and adapt to hazards [21,22]. There is an agreement that the vulnerability is determined by the interaction of three components: exposure, sensitivity and carrying (adaptive) capacity [21,23]. Assessing the vulnerability of any social system thus requires understanding the biophysical (exposure component) as well as the social, economic and demographic settings (sensitivity and adaptive capacity of the system) [24]. In the current study, we defined the overall vulnerability of the population as a property emerging from the level of exposure to natural hazards (based on hazard occurrence or impact) and the level of social vulnerability (i.e., ability to adapt and recover from the impact), which is based on the social, economic and demographic settings of the population.

Social vulnerability is characterized by a large number of factors, which interact and vary in space and over time in manifold ways (e.g., Cutter et al. [18], Rygel [25], Otto et al. [26]). This complexity, however, makes it difficult to measure vulnerability and compare different assessments [27]. Difficulties emerge, for example, from the selection of partial vulnerability indicators, their preprocessing (transformation, dimensionality reduction, etc.) and determination of their relative importance [28,29]. Vulnerability assessments may, for example, use an entire suite of indicators to evaluate vulnerability profiles for different geographical entities (e.g., districts) [30]. Social scientists also strive to formulate composite indices which capture the essence of information provided by the underlying factors (e.g., Cutter & Finch [9], Rygel [25], Cutter et al. [15] and Fekete [31]). The latter approach has recently received increased attention, and different approaches to the construction of vulnerability indices have been developed and tested [15,32–35]. Composite indices are, for example, advised to be used to identify the most vulnerable countries, to assist the adaptation efforts or to obtain an entry point for systemic vulnerability studies [29]. The use of composite indices, however, may lead to an oversimplified understanding of the investigated systems and misplaced overconfidence in the conclusions [35]. For example, qualitatively different combinations of underlying variables, which require different responses, may generate the same index value. We, therefore, combined in this study a composite index approach with an assessment of complex vulnerability profiles.

Human populations that exhibit high social vulnerability to natural hazards often occur in developing parts of the world [36], including Africa [37,38]. The frequency and intensity of natural hazards such as floods and droughts have increased for most of the African continent [12,39,40]. Poor infrastructure development, inadequate adaptative capabilities and high dependence on natural resources are the main factors that exacerbate these populations' vulnerability, and increase, for example, the risk of food insecurity [41–43]. In sub-Saharan Africa, natural hazards are increasingly affecting essential economic sectors such as agriculture [44–46]. It is estimated that more than ten million people in Southern Africa reside within hazard-prone areas, and their livelihoods vitally depend on hazard-exposed agricultural practices [47].

Namibia is one of the countries with the greatest social and economic inequalities in the world [48]. Its semi-arid environment, along with poor socio-economic conditions, often leads to the overexploitation of scarce resources and threatens the stability of human populations [49]. In recent years, the country has increasingly been experiencing erratic rainfall patterns, extreme droughts and wildfires [50,51]. These events have had a major impact on the main sources of livelihood, particularly for the elderly, women, children and those with compromised health conditions [52,53]. Many households have, thus, become unable to secure their essential needs [42]. Social issues, such as HIV/AIDS and unemployment, particularly among the youth, are of great concern too. This social vulnerability is exacerbated by the underdeveloped infrastructure; for example, more than 60% of the population in rural areas depends on firewood and charcoal as a source of energy.

Despite the recurrent incidence of different natural hazards and overall intensification of disturbance regimes, the patterns and drivers of social vulnerability (SV) are not well understood. This hinders implementations of adaptation and resilience strategies and compromises the options for sustainable development of local communities [50,54,55]. In light of these facts, we aim to extend our understanding of SV of the Namibian population and, thus, support the development of knowledge-driven management strategies and policies. In particular, we aim to (i) identify patterns of SV in the country based on a suite of demographic, economic and other indicators; (ii) identify the main drivers that influence the SV and their variability between the administrative districts; and (iii) evaluate the relationship between SV and the distribution of high-hazard areas in the country. Our results are intended to support the development of national and regional management strategies and the formulation of research and investment priorities, and to contribute towards achieving the Sustainable Development Goals [56,57].

2. Materials and Methods

2.1. Study Area

Namibia has an area of 824,292 km^2 and a population of 2.5 million inhabitants. It is one of the most sparsely populated countries in the world and the driest country in sub-Saharan Africa [43,58] (Figure 1). Elevation of the country increases from the coast towards the inland. The north-central part forms the Cuvelai-Etosha Basin, which is shared with southern Angola. The basin is made up of a drainage system that originates from central Angola and enters the north-central part of Namibia. Then, it spreads through the flat areas of the Kalahari sands into the Etosha Pan [59].

The climate is hot and dry, with uneven rainfall. The average annual air temperature ranges from 16 °C along the coast to 22 °C in the north-central and northeastern part of the country [58]. In the interior, the climate is continental with high summer temperatures and cold winters. Mean annual rainfall ranges from 25 mm in the southern and coastal areas to 600 mm in the Northeast. The most erratic rainfall (inter-annual range >35%) occurs in the transition between the south-western coastal areas and the inland regions. Rainfall is more stable and predictable in the North and Northeast. The wettest period of the year is December to March.

Despite the country's harsh weather, it harbors a remarkable number of species of fauna and flora. The country is divided into three vegetation zones: desert (16%), savannah (64%), dry woodlands and forests (20%). The country comprises four biomes: tree and shrub savanna (60%), Nama Karoo (dominated by grass, shrubland and quiver trees *Aloidendron dichotomum*) (24%), the Namib Desert and the Succulent Karoo (mainly dominated by succulents, dwarf shrubs and quiver trees) (2%) (Figure 1). The latter biome is acknowledged as a biodiversity hotspot and the only arid hotspot in the world [60].

The largest ethnic group is Owambo (50%), which mainly occupies the north-central part of the country. Kavangos (9%) are mostly found in the Northeast and Hereros (7%) in the central-east and north-west parts. Damaras (7%) and Namas (5%) mainly occupy the southern part, and Caprivians (4%) the Zambezi district in the far East. The San people (3%), who are one the most marginalized and disadvantaged groups of the population, mostly occupy the northern and central-eastern territories [61]; they are assumed to be the oldest inhabitants of Southern Africa [62]. Other ethnicities include Whites 6%, Basters 2% and Tswanas 5% [63].

The distribution of ethnic groups has been mainly influenced by historical migrations and, to some extent, the dislocation of groups such as the Ovaherero, Damaras and Nama. The dislocations were happening particularly in the eastern, central, and southern parts of the country during the colonial era [64,65]. Moreover, the distribution of some ethnic groups was influenced by the apartheid regime, which, for example, introduced the controversial "redline", the veterinary cordon fence, that separates communal and commercial farming lands [66]. In the North, the abundance of natural resources such as arable land was the main factor attracting the early settlers. Extensive indigenous knowledge of ethnics such as Owambo, Kavangos and Caprivians allowed them to adapt and persist here even under harsh environmental conditions [67].

More than 54% of the Namibian population reside in rural areas [58], where rainfall-dependent subsistence farming is the main source of livelihood. Namibia has extreme income inequality [48,50], with about 30% of the population living below the poverty line [68,69]. The socio-economic system has been influenced by the apartheid system, which largely compromised all spheres of development.

The main sources of income for most of the population in urban areas are small informal businesses. Other sources of income include tourism, mining, agriculture and construction. Poverty is extreme, particularly in rural underdeveloped areas [70]. The most vulnerable groups of the population are female-headed households, the San community, the youth, the elderly and people with disabilities. Poor and severely poor populations account for 29% and 15% of the total population, respectively [70], with poverty hotspots being located in the northern districts (Figure 1).

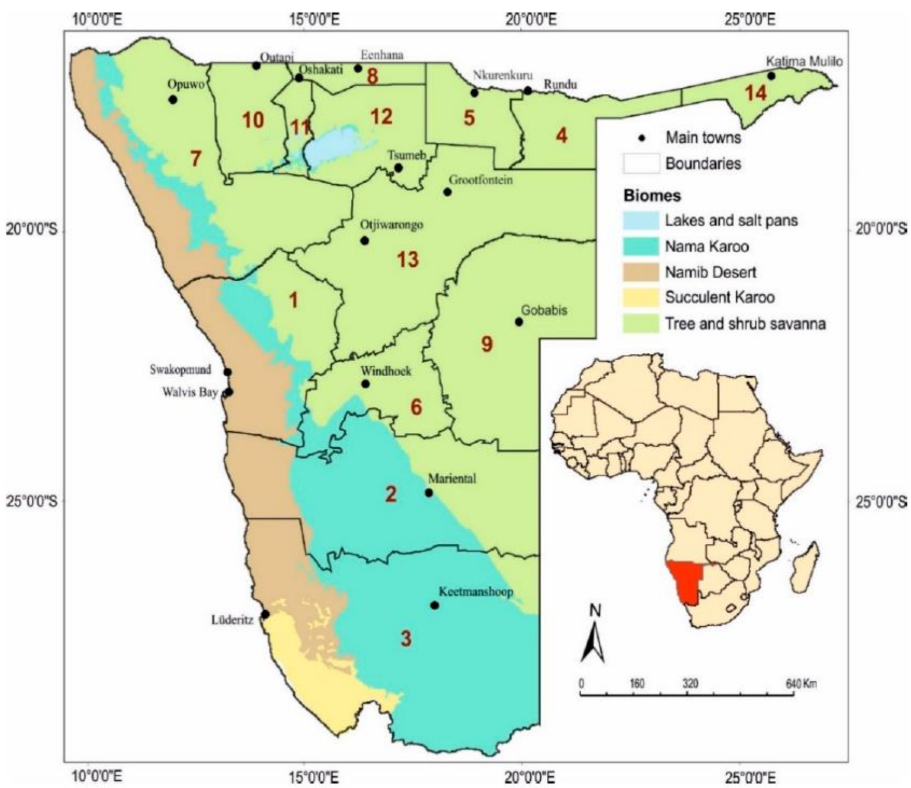

Figure 1. Administrative districts, main towns and biomes of Namibia. District codes: 1—Erongo, 2—Hardap, 3—Karas, 4—Kavango East, 5—Kavango West, 6—Khomas, 7—Kunene, 8—Ohangwena, 9—Omaheke, 10—Omusati, 11—Oshana, 12—Oshikoto, 13—Otjozondjupa, 14—Zambezi. The inset figure shows the location of Namibia in the African continent. Map of biomes [71].

2.2. Natural Hazard Regime

Flood frequency has increased in recent years in Namibia, affecting around 70,000 people annually [68]. Floods triggered by seasonal torrential rains, often amplified by deforestation, have particularly affected the northern part of the country [68]. For example, the 2011 flood affected here nearly 500,000 people, with over 60,000 displaced, 19,000 in relocation camps and 65 flood-related deaths [72]. North-central Namibia experiences seasonal floods, which relate to the hydrological regime of the Cuvelai Basin. It accumulates water from central Angola during heavy rains and spreads further through the floodplains of Namibia [73]. Floods in north-eastern Namibia mainly relate to the hydrological regime of the Okavango river system (Kavango East and Kavango West) and to the Zambezi river in the far Northeast. The floods are less frequent here than in the north-central part of the country [74]. The far Northeast is part of the Zambezi basin, where floods typically occur during the rainfall season in January and February [75]. The floods, for example, disrupt water supplies, damage sewerage systems in the cities and trigger outbreaks of water-borne diseases such as cholera and malaria (e.g., 2008 flood season) [76].

Recurrent droughts affect most of the Namibian territory and cause livestock deaths, crop failures, poverty and food insecurity [77]. Droughts related to erratic rainfall patterns and increasing evaporation demand occur in most of the country. These effects are further modulated by the El Niño–Southern Oscillation (ENSO), as was the case in the 2015/2016 season [53]. For example, drought events in the period 2013–2016 affected about 450,000 people and caused massive food insecurity [78]. During the season 2018/2019, below-average rainfall caused one of the worst drought events over the previous 40 years, which caused deaths of over 80,000 livestock, and largely compromised household food security [77,79].

Wild and man-induced fires have important impacts on the Namibian ecosystems and economies and, at the same time, have indispensable ecological functions [80]. It is estimated that more than 1 million hectares of forest and open land is burned every year, though the area burned fluctuates depending on weather and actual fuel loads (e.g., 1.1 million hectares in 2016, 2.1 million hectares in 2017) [81]. Most of the fires occur in the fire-driven savanna ecosystems in northern Namibia, which were found to be resilient to a wide range of fire regimes [82]. Most of the fires (90%), particularly in the north-central and north-eastern parts, are anthropogenic and relate, for example, to slash-and-burn agriculture practices [83] or are ignited accidentally [84]. The use of fire in agriculture, however, often leads to uncontrollable spread with undesired consequences [85]. Fires mostly occur during the dry and windy seasons of May–July (early dry season: low intensity fires) and August–September (late dry season: high-intensity fires) [80]. The most fire-prone areas are the communal lands in the north-central and north-eastern parts of the country [85]. Depending on the intensity and timing, wildfires may cause environmental degradation and loss of biodiversity, which impact the livelihood of local communities, national and regional economies [53]. Adverse effects include, for example, the disruption of plant regeneration and damage to commercially valuable tree species such as *Burkea pterocarpus* and *Baikiaea plurijuga* in the northern woodlands [80,83].

2.3. Material and Methods

2.3.1. Social Vulnerability Indicators

We used a set of 29 candidate variables (see Supplementary material, Table S1) that characterized the social, economic and demographic conditions of districts in the country (Figure 1). The data were obtained from the Namibia Inter-censal Demographic Survey of 2016 conducted by the Namibia Statistics Agency (NSA). We refined this initial set of variables based on several criteria to arrive at the final list of twelve variables listed in Table 1. Rather than using factors or other analyses for dataset reduction [15,31], we preferred to select a subset of original variables that adequately represented the entire initial dataset (e.g., Sebesvari et al. [6], Rufat et al. [10] and Fatemi et al. [32]). Such an approach allowed for a more straightforward and intuitive interpretation of the final findings.

Table 1. Variables characterizing social, economic and demographic settings of the Namibian districts. The variables were selected to represent a broader set of 29 variables listed in Supplementary material, Table S1.

Category	Variable	Unit	Abbrev.	Mean	Median	Min	Max.	Var. Coef.
Demographic	Population density	inhabitants/km^2	PopD	6.81	4.30	0.50	23.90	107.49
	Population in rural area	%	PopRur	61.50	64.50	5.00	99.00	44.21
	Female population	%	FemPop	50.23	49.45	46.70	55.00	5.51
	<4 years old	%	Age < 5	14.36	13.60	12.30	20.10	15.26
	>60 years old	%	Age > 60	6.42	6.35	3.30	9.90	23.81
Social	Total unemployment	%	Unemp	36.06	37.05	21.90	52.20	24.51
	Population with disabilities	%	Disab	4.77	4.60	2.30	7.60	32.92
	HIV level	%	HIV	13.34	12.45	7.30	23.70	29.78
	Literacy rate	%	LitR	85.66	85.55	66.50	96.70	9.86
Economic	Pension dependent	%	Pens$	16.14	14.00	4.00	31.00	49.72
	Average household income (2015)	USD	House$	1210	867	560	3506	63.49
	Farming dependent	%	Farm	20.86	21.50	1.00	60.00	74.07

First, we discarded variables that were obviously redundant (e.g., income per household vs. income per capita). From each group of redundant variables, we preserved a single variable, which had better support in the literature as an indicator of SV (Supplementary material, Table S1). The retained variables were grouped into the categories "social", "economic" and "demographic". Within each category, we evaluated the redundancy of variables using Spearman's rank correlation coefficient with a threshold value of 0.7. From each pair of correlated variables, we retained the variable that showed a greater inter-district variability, i.e., it better discriminated between the districts (Table 1).

Alongside evaluating the districts' SV profiles using the entire set of variables listed in Table 1, we also calculated the SV index (SVI) for each district by aggregating these variables. We first normalized the values of each variable into the unit range using the following formula:

$$Z_i = \frac{x_i - min(x)}{max(x) - min(x)} \quad (1)$$

where Z_i is the normalized ith value of the variable Z, x_i is the ith value of the variable Z, and $min(x)$ and $max(x)$ are the minimum and maximum values of the variable Z.

Rescaling was conducted so that a value of 1 indicated the highest vulnerability, and vice versa. Such an approach required reverting the normalized values of some variables. This applied for average household income and literacy rate, where the highest value indicated the lowest vulnerability (in contrast to, for example, HIV level, where the highest value indicates the highest vulnerability). The SVI was calculated as the weighted median of the normalized variables. Because normalization based on the Equation (1) unified the variability of variables, we used the variation coefficient (Table 1) as the weight. This allowed for downweighing variables with a small inter-district variability, such as the percent of female population, and attaching a greater importance to variables that strongly discriminated between the districts.

2.3.2. Natural Hazard Indicators

We explored various sources of data to collect a number of indicators related to flood, wildfire and drought incidence in the districts (Supplementary material, Table S2). Because of limited data availability, the data covered different periods of time or were available for a single year only. This can seriously limit use of these data as indicators of the long-term disturbance regime in the districts. We, therefore, critically assessed each of the available indicators using previous studies and statistics (Section 2.2; Appendix A). Based on this, we retained seven indicators that were found to represent the characteristic regime of natural hazards in a given district or a broader region (i.e., the recorded events were not isolated episodic occurrences) (Table 2).

Table 2. Variables characterizing the incidence of the most prominent natural hazards in the Namibian districts. Weights are used to calculate a composite indicator of natural hazards for each district.

Hazard	Variable	Period	Unit	Abbrev.	Mean	Median	Min	Max	Weight
Fire	Average area burned	2007–2017	km^2	AreaB	2160	701	0.0	9108	0.33
Drought	Livestock deaths	2018–2019	number of livestock	LivestD	6301	3590	0.0	17,955	0.165
	Food insecure population	2013	number of people	FInsP	29,403	20,497	4928	80,720	0.165
Floods	Human mortality	2009	number of people	HumM	7.5	0.0	0.0	48.0	0.083
	Schools affected	2008	number of schools	ScholA	7.5	0.0	0.0	44.0	0.083
	People displaced by floods	2017	number of people	PopDis	238	0.0	0.0	2,655	0.083
	Estimated damages	2009	millions of US $	EstDam	10.7	6.6	0.0	37.2	0.083

Apart from investigating district-specific hazard profiles based on the whole set of indicators, we also calculated a composite hazard indicator by averaging the underlying indicators rescaled to the unit range. Because the three hazard categories (fire, drought and floods) were represented by a different number of variables (Table 2), we applied weights to equally model the effect of each group of hazards on the final indicator value (column Weight in Table 2). This weighting was applied to compensate for the different data availability on different hazard types rather than to model their equal impact.

2.3.3. District-Based Vulnerability Assessment

Finally, we evaluated the vulnerability of the Namibian population based on the interaction between socio-economic conditions approximated by the SVI and the level of exposure to natural hazards approximated by the introduced hazard index. Based on district positions in the space defined by the SVI and the aggregate hazard index, we categorized the districts into three vulnerability classes using the K-means clustering technique. In the final evaluation, we conducted the analysis based on composite indices with socio-economic or hazard profiles constructed for each district using the full set of underlying variables.

All presented analyses were conducted in Statistica 13.4 [86], R-Language [87] and ArcGIS Desktop [88].

3. Results

3.1. District-Based Pattern of Social Vulnerability

The SVI reached its highest values in the northern districts of the country, with maximums in the Omusati and Ohangwena districts (Figure 2a). While all categories of indicators (i.e., social, economic and demographic) were nearing their maximum in Ohangwena, the vulnerability of populations in Omusati was mainly driven by economic and demographic factors (Figure 3).

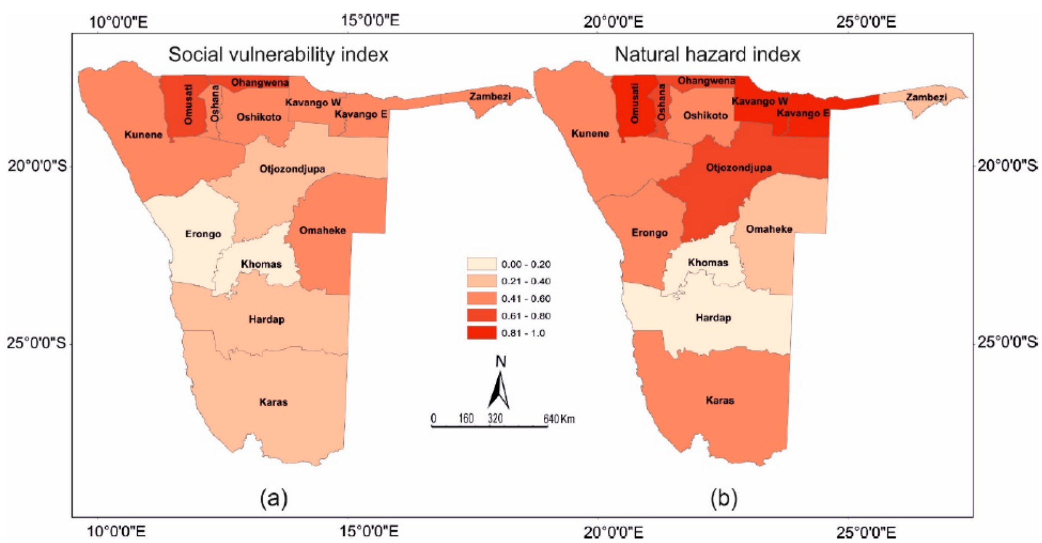

Figure 2. Spatial distribution of the composite index of social vulnerability (**a**) and natural hazards (**b**) within the districts of Namibia.

The effect of underlying indicators was variable in a group of districts with medium SVI values (Oshikoto to Zambezi, Figure 3). A common pattern was that a small subset of indicators drove the overall SV rather than being equally affected by a large number of factors. The remaining four districts (Hardap to Khomas, Figure 3) with low SV formed a cluster located in the central and west-central parts of the country. The least vulnerable districts were Khomas and Erongo (Figures 2 and 3). In summary, there was no common pattern of SV pattern applicable for all Namibian districts, and the districts' vulnerability profiles were highly variable.

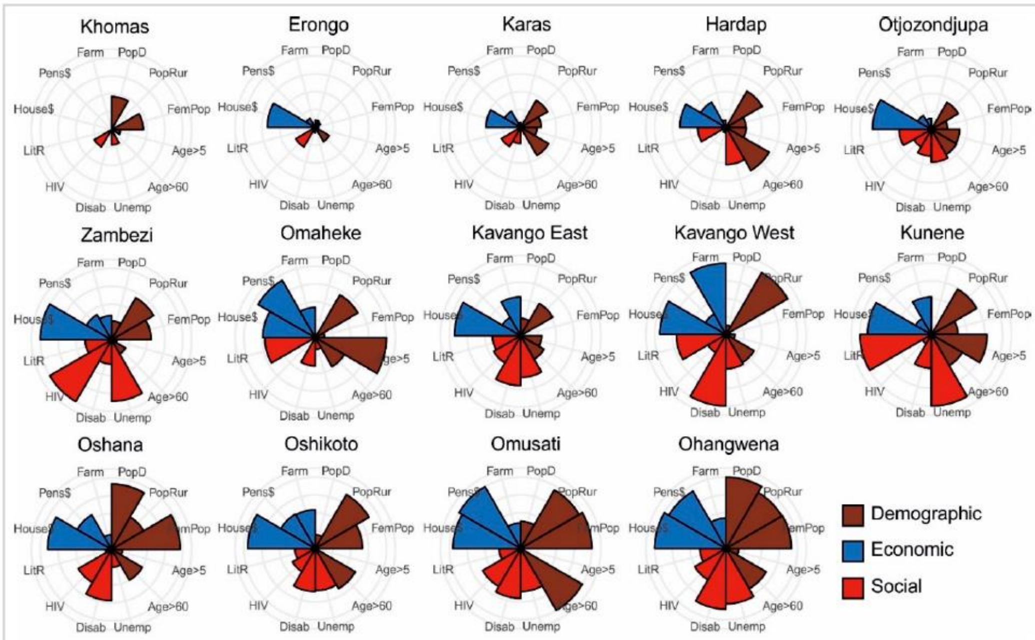

Figure 3. Relative contribution of twelve indicators to the overall level of social vulnerability in the Namibian districts. The districts are ordered by the magnitude of the composite index of social vulnerability based on all underlying variables. Colors indicate three groups of variables—social, demographic and economic. Abbreviations of the variables are explained in Table 1.

3.2. Exposure to Natural Hazards

The highest exposure to natural hazards was in the northern districts of the country, where multiple hazard indicators culminated (Figure 2b). On the contrary, the lowest level of exposure occurred in the central and southern districts of Khomas and Hardap, where all indicators were zero (Figure 4), i.e., no hazard was recorded here during the period covered by the used data (Table 2). The risk of hazard was typically driven by two out of three main hazard types, with floods and drought being the most frequent combination. The main hazard categories, i.e., drought, fire and floods, showed a differential spatial pattern across the country (Appendix A). While fire incidence was highest in the northern districts (Kavango East and Kavango West), flood risk was mainly pronounced in the north-central and northeastern districts [72]. Drought exposure was highest in the South and Northwest of the country, while central districts Khomas and Hardap exhibited relatively low drought impacts.

3.3. Vulnerability Assessment

The final vulnerability assessment showed a positive relationship between most of the used hazard indicators and the level of SV indicated by the SVI (Figure 5). This applied to all hazard indicators except for drought-induced livestock mortality, where the relationship was negative (Figure 5).

Investigation of the district positions in a space defined by the SVI and the composite hazard indicator showed that the districts formed three distinct categories characterized by different levels of SV and exposure to hazards (Figure 6a). These groups of districts displayed a distinct South–North zonal pattern, with most vulnerable populations being distributed in the North of the country (Figure 6b). These districts covered 10% of the country's area but included 32% of the total population. Districts with the lowest vulnerability were in the southern part of the country (Erongo, Khomas, Hardap, Karas) and covered 45% of the Namibian territory (Figure 6b). At the same time, they included 33% of the total population. These districts are also the economic, social and political centers, with major cities of the country (see Figure 1). The remaining six districts, which form the medium vulnerability cluster, showed relatively low levels of exposure (0.1–0.25). The only exception was Otjozondjupa, where the level of exposure was 0.32.

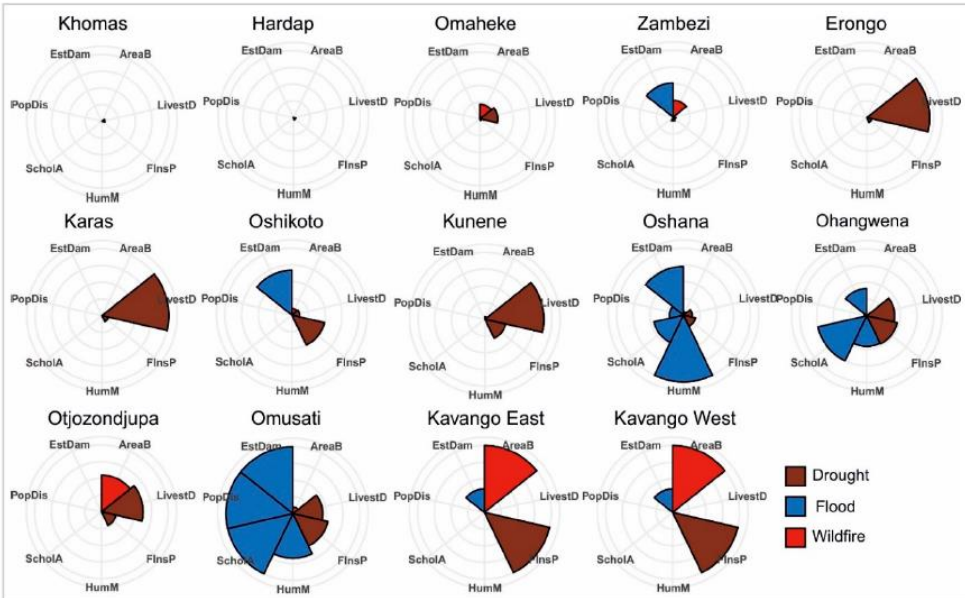

Figure 4. Relative magnitude of different indicators of natural hazards in the Namibian districts. The districts are ordered from lowest to highest exposure based on the composite index of natural hazards. The greater the area of the segment the greater the effect of the given hazard type.

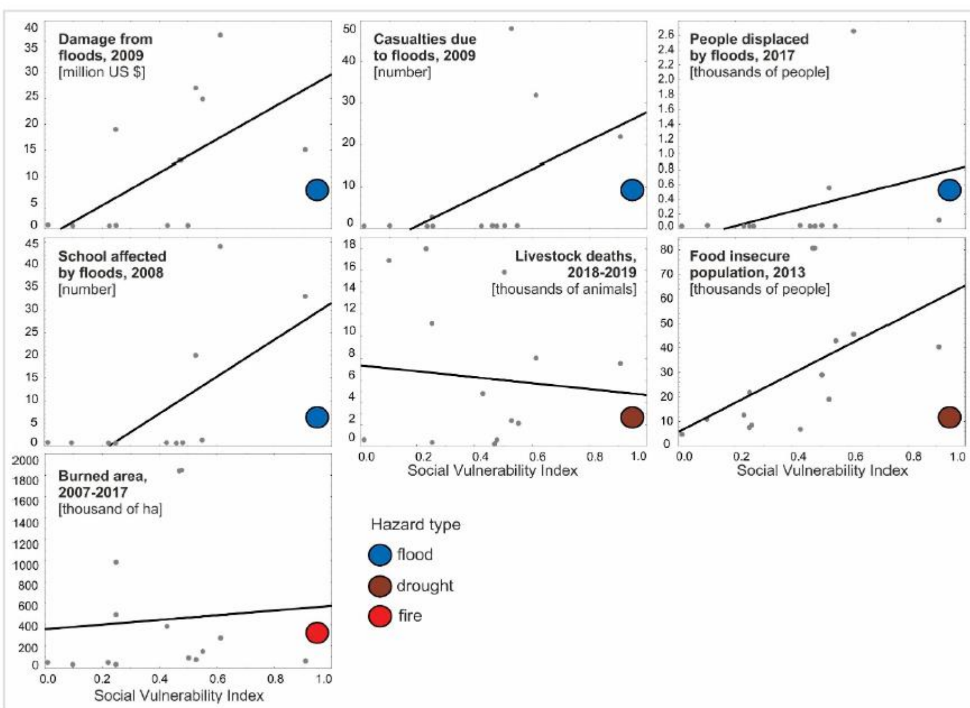

Figure 5. Response of individual indicators of natural hazards to the composite index of social vulnerability calculated for the Namibian districts.

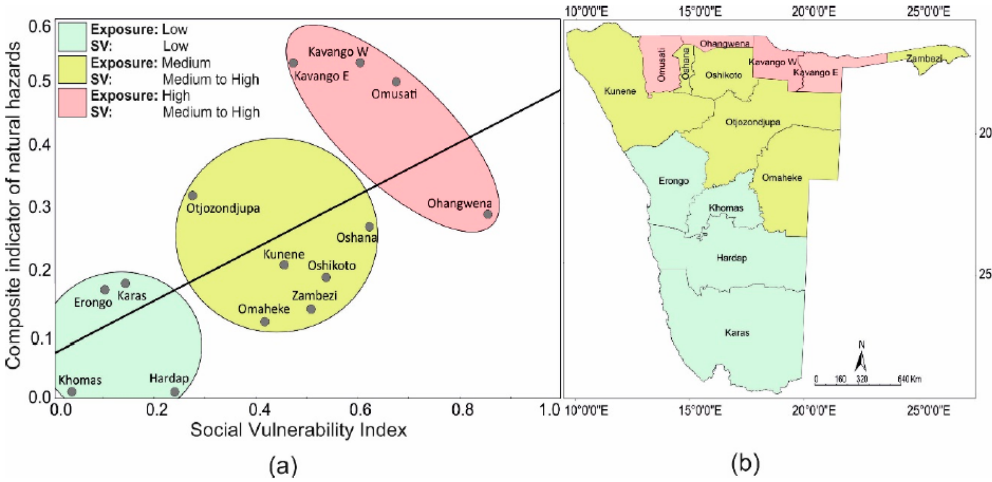

Figure 6. Position of the Namibian districts in space defined by the socio-economic conditions of populations and their exposure to natural hazards (**a**). The groups of districts were identified using the K-means clustering technique. The map indicates spatial distribution of the identified vulnerability classes (**b**).

4. Discussion

We conducted our investigation in Namibia, a sub-Saharan country where many ecosystems and populations persist at their social and ecological margins [89,90]. These conditions can be further exacerbated by climate change, which may cause the social-ecological resilience limits to be exceeded [91]. We strived to extend our understanding of SV to natural hazards in the country by exploiting a large set of heterogeneous, and often incomplete, information available from public sources. Consistently with national strategic materials, such as the National Disaster Risk Management Plan [56] and the National Disaster Risk Management Policy [76], we found that macro-regions with specific magnitudes of vulnerability exist in the country, which require different treatment and management responses [56,76]. We also highlighted large differences among the districts in their overall vulnerability, as well as in the relative contributions of underlying social factors and hazard types. Most importantly, we found that socially the most vulnerable populations, which cannot take effective emergency and adaptation actions, occurred in high-hazard areas of the country. This fact further underscores the vulnerability of the entire region.

4.1. Population Vulnerability Patterns

We found that although SV and hazard exposure varied between the districts, there were characteristic large-scale patterns that deserve attention in strategic planning. Social vulnerability reached its highest values in the northern districts and culminated in Ohangwena and Omusati. Due to the prominence of these districts, they also received increased attention in previous studies [48,50,92–94]. Vulnerability profiles in the northern districts, however, did not show any common pattern, and the overall SV was driven by different combinations of factors. This suggests that one-size-fits-all solutions are not applicable, and tailor-made systems of measures are required for different districts. For example, a high prevalence of the elderly population (10%) is a key contributing factor in Omusati, while high HIV/AIDS levels (24%) drive social vulnerability in Zambezi. High levels of populations with disabilities are typical of the Kavango West and Ohangwena districts, while low household income drives social vulnerability in the entire north-central and northeastern parts of Namibia. On the contrary, the southern districts Khomas, Erongo, Karas and Hardap were found to have, relative to the remaining parts of the country, good capacities to cope with and respond to natural hazards (see also Angula and Menjono [54], Namibia Statistics Agency [70], Angula [95]). This is related to factors such as high employment and literacy rates and lower numbers of young, elderly and disabled persons in the population.

Exposure to natural hazards showed a distinct geographical pattern too. While flood- and fire-prone districts occurred in two non-overlapping clusters in the North, drought risk was high across the entire country. Lower drought risk in the central districts Khomas and Hardap should be interpreted with caution due to the limited temporal coverage of the used data. The most frequent combination of hazards was drought and flood, while the combination of drought and fire occurred in Otjozondjupa, Kavango East and Kavango West only. The latter two districts also showed a minor exposure to floods, which makes them the most hazard-prone districts in the country from the view of both magnitude of the impact and the number of participating hazards. For example, drought here affects both crop and livestock farming and local populations; thus, they frequently experience food insecurity [96]. Although the flood and fire hazard patterns identified herein are relatively robust (Appendix A), limitations related to data availability still need to be considered.

The previous patterns imply that a large part, socially, of the highly vulnerable population (32%) occurred in high-hazard areas of the country, and vice versa. This pattern was mainly driven by flood risk, which showed the tightest positive relationship with the level of social vulnerability. Reasons of such a situation likely stem from the historical attraction of communities to water resources (i.e., migration along rivers in Namibia), which facilitated the agriculture expansion, yet also increased the size of the population and infrastructure exposed to floods [97]. Moreover, the rapid development of cities such as Oshakati in the flood-prone regions triggers immigration, which, along with lacking infrastructure and poor planning, increases the pressure on natural resources and exacerbates population vulnerability [75].

In the case of drought, the relationship with the SVI was tight for the number of food insecure people but not for drought-induced livestock mortality. The reason is that livestock farming is mainly used in Erongo, Karas, and Kunene, which have relatively good socio-economic conditions. Moreover, the high level of livestock mortality needs to be thought of as a legacy of previous years with sufficient rains, which may have caused overstocking. These facts, thus, highlight the need for broader contextual considerations in the assessment of social vulnerability to hazards, which may not have been obvious in our investigation.

The total burned area during the period 2007–2017 was associated with the SVI only loosely. The most exposed districts were Kavango East and West, where the level of social vulnerability was moderate. The frequency of wildfires decreased southward mainly due to the decreasing management intensity and the presence of the desert [85,98]. We note that although the pattern of fire-prone districts was rather robust, the used dataset did not differentiate between the causes and impacts of the fire (i.e., only the burned area was reported). Most of the fires occurred in the fire-driven savanna ecosystem, where they formed a characteristic disturbance regime [84]; however, the social impacts were not sufficiently documented. Still, previous studies indicate substantial effects of fire on human wellbeing (Section 2.2), which justifies the use of this dataset as a proxy of social exposure to fire hazards.

In total, 32% of the total population of Namibia was found to be distributed in four districts belonging to the highest vulnerability class. Although being geographically close, the social and hazard profiles showed substantial differences between these districts. This situation represents a rather complex challenge to adaptation and resilience management, which needs to cope with highly diverse local contexts, high population density, exposure to multiple concurrent hazards and social barriers to implementation [90,99]. For example, some ethnic groups with strong cultural and religious beliefs are often unwilling to take adaptive measures, such as to reduce the livestock herd size during droughts. The reasons are, for example, low market prices and problematic access to the markets but also a fear of losing prestige in the community [93,100]. Such a cultural background further exacerbates the overall vulnerability of this region.

The coincidence of high social vulnerability and exposure to hazards generates a chain of other issues that puts additional pressure on human and infrastructure resources. These include, for example, aggravating conflicts between agriculture development and nature conservation, risks to biodiversity and tourism, food insecurity and exposure to water-borne diseases [101,102]. For example, the most vulnerable districts identified here overlapped with areas harboring exceptional biodiversity values such as the Etosha National Park. On the other hand, the spatially restricted size of these priority areas can be thought of as an opportunity as it may allow for better concentration of resources, which can generate synergies and thus amplify the final effect [50].

The presented patterns of vulnerability were based on data from previous decades, when different social-ecological systems have already experienced effects of changing climate [103,104]. These effects may further increase in the future as the studied systems are sensitive to climate. For example, natural hazard regimes can be intensified under climate change and trigger a chain of social responses [105]. This requires consideration of the presented assessment in the context of transient ecological and social conditions, including limitations related to the static nature of the data used herein.

4.2. Methodological Aspects

Our analysis used a coarse resolution of administrative districts, which was determined by the availability of used data. Although such a scale of assessment can support strategic planning, including targeting of investments from external sources, finer-scale studies addressing the diversity of local contexts are needed for efficient implementation [27,101]. The scale of districts is particularly limiting if inhabitants are unevenly dispersed across their territory, and within-district variation in social and biophysical vulnerability is large. Moreover, districts in Namibia are influenced by the colonial era, where indigenous people were being largely relocated, without respect to their cultural, ethnic and historical background [64]. Use of district-specific data in vulnerability and other studies has, therefore, obvious limitations and findings should be interpreted with caution. However, as census and other data are typically available for districts, this scale will remain important in the future. To obtain a more complex picture of social vulnerability in Namibia, our assessment can be confronted with previous finer-scale studies, such as Hegga et al. [92], aiming at climate change adaptation in the Omusati district, or Angula and Kaundjua [93] aiming at north-central Namibia (Ohangwena, Oshana and Omusati).

We characterized SV using a number of social, economic and demographic indicators, which is a frequent practice in social vulnerability research (e.g., Cutter et al. [7], Chakraborty et al. [106] and Dwyer [107]). There are, however, other aspects of SV not considered here, such as the broader institutional context, quality of governance, law enforcement, dependence on humanitarian donations [96], level of rural development or existing international collaborative networks [108]. Such district-specific data were not available in the current study though these factors obviously determine SV in Namibia. For example, factors such as institutional development, match between the level of regional development and actual needs of the regions, and participation of vulnerable populations in hazard management largely vary between the districts, thus depicting another dimension of SV.

One factor affecting our analyses was temporal mismatch between SV and natural hazard indicators. While social, economic and demographic data were collected in the census in 2016, the natural hazard data came from different sources and covered different periods. While snapshot data should not be limiting in the case of social attributes (see, e.g., Rufat et al. [10]) (although volatile political and market environment may trigger rapid social changes), this may not be the case for natural hazard data, which often characterize episodic events with erratic temporal fluctuations.

We evaluated relative differences in districts' exposure to natural hazards by combining several hazard indicators (see, e.g., [109,110]).The most robust data were available for wildfires, which covered a 10-year period of time. These data thus differentiated well between fire-prone and the remaining districts in the country. Moreover, the high fire incidence in the northern districts (Appendix A) was also corroborated by previous studies [80,84,85,98]. In the case of flood risk, we mitigated the limited temporal coverage of data by aggregating different flood indicators from different years (2007, 2008 and 2009) and thus obtained a more robust estimate of the overall flood risk. Moreover, flood incidence is generally driven by the hydrological conditions of the country (Section 2.2); this fact, along with numerous previous studies (e.g., [72,74,75,77]), supports the flood risk pattern identified herein (Appendix A). Drought impacts were approximated by livestock mortality (2018–2019) and the food insecure population (2013), which limits the robustness of this dataset. Moreover, interpreting the livestock mortality as an indicator of drought should be taken with caution, as there are also other factors, most prominently diseases [111], that lead to livestock death. Still, the source statistical reports indicated drought as the main reason for livestock mortality in the season 2018–2019, without referring to any disease outbreak, which supports the use of this indicator. Although further extension of the used dataset would be a great asset in assessing the patterns and drivers of natural hazards, dealing with low-resolution or incomplete data will remain one of the important challenges in research and management planning in many parts of Africa (e.g., Hosegood & Madhavan [112]).

Finally, recent research has increasingly emphasized the importance of resilience as a prerequisite for sustainable development [113]. Resilience goes beyond the vulnerability framework and considers the complex abilities of populations to reduce the severity of impacts and recover rapidly from losses [114]. Further research can use the data and approaches presented here to address the resilience of the Namibian population and, thus, provide more comprehensive support in decision and policy making.

5. Conclusions

Understanding the interactions between the social conditions of human populations and the dynamics of natural hazards is one of the key preconditions for sustainable development. This particularly applies for populations living at their social margins, which can be driven to collapse by minor fluctuations in resource availability. We showed that the pattern of natural hazards was highly variable among the districts of Namibia, as were the factors determining the social and economic fitness of the population. Adaptation strategies, therefore, need to consider the diversity of regional contexts, which is high even between adjacent districts with similar natural and cultural conditions. We found that macro-regions exist in the country, where multiple adverse effects coincided, including critically low socio-economic performance, high population density and the concurrent incidence of different hazard types. The increasing risk of natural disasters, which is often mediated by climate change, implies that tipping points can be exceeded in such environments and social and ecological harm can be beyond repair. Our findings can inform national and regional policies on how to develop better targeted management actions that recognize the diversity of the social and hazard-related conditions described herein.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/12/4910/s1, Table S1: Description of candidate indicators of social vulnerability, Table S2: Description of candidate indicators of natural hazards.

Author Contributions: Conceptualization, T.H.; data curation, A.K.; formal analysis, A.K. and T.H.; investigation, A.K. and T.H.; methodology, T.H.; supervision, T.H.; writing—original draft, A.K.; writing—review & editing, T.H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. District-Based Patterns of Main Hazard Types

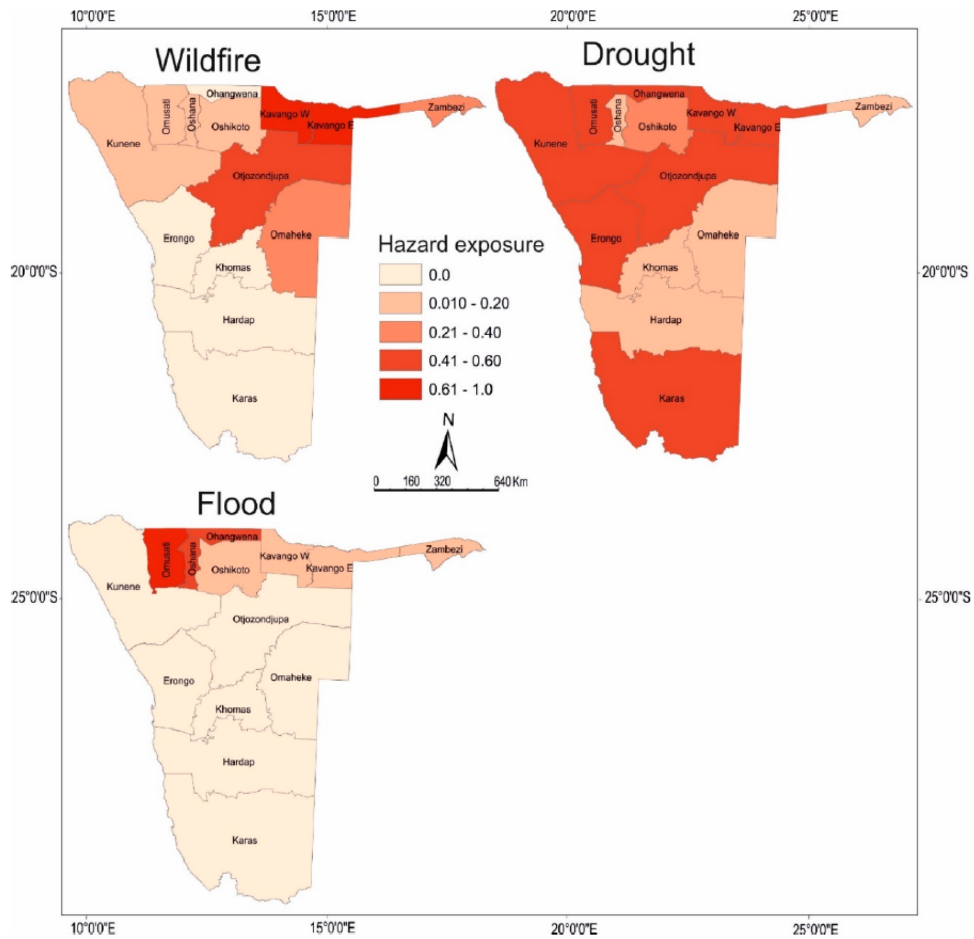

Figure A1. District-based pattern of the main hazard types in Namibia based on hazard indicators listed in Table 2. Average standardized indicator values for each hazard category are shown.

The collected hazard indicators characterize the most prominent natural hazards in Namibia. The patterns in Figure A1 are based on several often heterogenous indicators with limited temporal coverage. Because these patterns are vital to the vulnerability assessment presented in this study, we provide here an additional justification of the relevance of these patterns.

- Wildfire: Wildfire data are derived from the regular monitoring conducted by the Remote Sensing Department of the Ministry of Agriculture, Water and Forestry of Namibia, based on satellite imagery. This assessment is rather robust as it based on 10 years of observations. Identical patterns of fires were also identified in previous studies, particularly Sheuyange et al. [84] for the northeastern districts, Pricope et al. [53] and Siljander [80] for the Zambezi district, and Verlinden et al. [85] for the northern districts.
- Floods: Flood impact patterns were based on different indicators from flood seasons 2008, 2009 and 2017. The most flood-prone districts are Oshikoto, Oshana, Omusati and Ohangwena, which belong to the Cuvelai Basin floodplains. High flood incidence was documented here also by [68,73,77]. The remaining districts Kavango East, Kavango West and Zambezi, which belong to the Kavango and Zambezi river basins, showed high levels of risk too, though lower than the

previous region [74]. The current dataset does not indicate any flood impact in the remaining districts, although authors in [115] indicate infrequent floods, for example, in the Kuiseb catchment in the Namib Desert. In summary, the flood pattern identified based on the used indicators is highly consistent with previous studies.

- Drought: Drought impacts were characterized based on the records from two drought seasons, 2013 and 2018–2019. These data indicate that the entire country was affected to a certain degree, though differences between districts existed. A lower level of drought impacts was observed in the central districts Khomas, Hardap and Omahake with relatively good social-economic conditions. The lower impact of drought here was therefore likely related to the higher adaptive capacity of the population relative to the remaining districts. With regard to the underlying data, drought patterns are the least robust and need to be interpreted with caution. Given the large-scale drivers of drought, which often affects multiple countries in southern Africa [116,117], all districts in Namibia need to be thought of as highly drought-exposed.

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6 Discussions

6.1 Summary of addressed knowledge gaps and objectives

Southern Africa is particularly vulnerable to the impacts of climate change due to the populations' high dependence on climatically vulnerable natural resources, high levels of poverty, and low adaptive capacity. This thesis contributed to the knowledge of the dynamics of southern African social-ecological systems exposed to climate change in. The thesis particularly focused on:

(i) understanding the temporal development of climate change research, its geographical differences, coverage of different thematic areas, and level of research internationalization southern African countries, and how international collaboration and the role of African authors in climate change research have been developing between 2000-2019. The thesis further evaluated how publication performance was associated with different demographic, economic, and other characteristics of the investigated countries;

(ii) understanding observed and projected impacts of climate change on various species, populations, and ecosystems, with management and policy recommendations aiming to mitigate these impacts in southern African countries;

(iii) investigating how climate change threatens major woody species' potential current and future distributions and identify regional winner and loser species, i.e., species gaining and losing areas with climatically suitable conditions, and assess the implications for providing crucial ecosystem services by identifying areas where conditions for one or several species providing various ecosystem services are projected to persist, decline, or expand, and

(iv) identifying patterns of social vulnerability of the Namibian population based on a number of demographic, economic and other indicators, identify the main drivers that influence the social vulnerability and their variability between the administrative districts of Namibia, and evaluate the relationship between social vulnerability and the distribution of high-hazard areas in the country.

The thesis' objectives were addressed through the original set of studies published in scientific journals with Impact Factors. The publications were in line with the topic of the dissertation, focusing on various aspects of climate change impacts and adaptation in southern Africa.

6.2 Summary of used methodological approaches

Integrative and interdisciplinary approaches are required to understand the impacts of climate change on social-ecological systems and to support the formulation of effective adaptation mechanisms. This thesis therefore utilized such interdisciplinary research which explores the concept of social-ecological systems, with the main aim of enhancing the understanding of dynamics of social-ecological systems under climate change in southern Africa. Transdisciplinary research approaches were used to examine the characteristics of selected southern African social-ecological under climate change. The thesis employed various research approaches, including systematic literature review of publications extracted from Scopus and Web of Science databases based on the PRISMA framework, vulnerability assessment based on the concept of "exposure-sensitivity-adaptive capacity", and ecosystem modelling based on the MaxEnt algorithm. The social-ecological system approach is a useful framework for understanding the interaction between social and ecological systems in the face of climate change. The social-ecological framework was used to answer the main question addressed by the dissertation: "*How different social-ecological systems are influenced by climate change in southern Africa and how the societies respond to these challenges*?" The dissertation was guided by the following key activities:

i. collection of social-economic, natural conditions, including climate and other data on southern Africa.
ii. creation of geodatabases in MS access and Arc GIS for the whole of southern African region to address specific research objectives.
iii. statistical analyses of the collected data using STATISTICA software and spatial analysis in ArcGIS.
iv. study trips aimed at the presentation of research findings and developing international collaborations.
v. publication of research findings and their presentations on different media.

6.2.1 Limitations of the methodological approaches

Despite the use of application of integrative and interdisciplinary approaches in our analyses, the methodological approaches still had their shortcomings. The systematic review of the impacts of climate change on ecosystems utilized the search outputs from the two bibliographic databases, which suggest that a large proportion of relevant papers could have been identified (Bramer et al., 2017). Still, the number of studies that met all the defined criteria was surprisingly low, given the broadly recognized vulnerability of African ecosystems and large-scale impacts reported by different global assessments (Dai, 2011; Sintayehu, 2018). This undoubtedly accounts for the strict criteria for the inclusion of papers that was applied in this analysis, that is, the clear identification of the addressed species or ecosystem, attribution of the impact to climate change, and the provision of management and policy recommendations. Moreover, we considered only papers published in English, which could have discriminated countries where English is not commonly used (e.g., Mozambique and Angola). In our review, we also did not consider publications related to South Africa, where science production outperforms the remaining region (Sooryamoorthy, 2018). However, South Africa shares numerous species, ecosystems, and management practices with the rest of the southern African countries, therefore, highlighting the importance of knowledge transfer and transnational collaboration in narrowing the existing knowledge gaps (Boshoff, 2010).

Another limitation in the applied methodology involved the use of correlative models (i.e. models predicting species distribution as a function of environmental conditions) such as MaxEnt. Such models assume that species occurrence data characterize species fundamental niche adequately, i.e., the entire range of conditions where species can survive was sampled (Booth, 2014). This is not true for many species because the sampling often does not cover their current distribution entirely, and their current distribution often does not correspond with their fundamental niche (Botella et al., 2020). The quality of climate data and choice of a dataset are other aspects affecting the presented predictions (Abdulwahab et al., 2022; Datta et al., 2020). For example, the used AFRICLIM contains an RCM-based climate change signal (Platts et al., 2015), making it superior to Worldclim, which uses GCM-based anomaly values. On the other hand, the used version of AFRICLIM uses Worldclim 1.4 as a baseline, though Worldclim 2.1 based on a denser station network has already been released (Fick & Hijmans, 2017). Further, the 30′ resolution of the used climate data limits smaller scale assessment such as the identification of microclimatic refugia (Barrows et al., 2020), yet this limitation should not be severe in the presented large-scale assessment. Using higher-resolution data that better captures the effects of terrain-induced climate transitions, water bodies, and other features would increase these projections' applicability at smaller scales. However, effective resolution that depends on the density of underlying station data (Daly, 2006) is particularly limited in sub-Saharan Africa, where monitoring infrastructure is largely underdeveloped (Haselip & Hughes, 2018; Posada et al., 2018).

Our analysis considered two Representative Concentration Pathway (RCP) scenarios to capture the variability of future developments. However, we used the average ensemble of climate projections produced by different combinations of General Circulation Models (GCMs) and Regional Climate Models (RCMs) driven by each RCP. This averaging likely underestimated future projections' variability, particularly concerning precipitation-related variables, which typically vary between the RCM-GCM pairs more than between the RCPs (Saini et al., 2015).

The proposed methodology for mapping species distribution vulnerability hotspots and coldspots by identifying areas where climatic conditions for multiple species were projected to persist or decline. Although this approach is straightforward, the interpretations should be cautious. This approach, for example, assumes that the baseline species pool is equal across the study region and that the social or ecological impact of different species retreats is similar. However, compensatory dynamics emerging from species diversity and functional asynchrony, which may involve species not included in this analysis, can potentially mitigate some impacts, and stabilize the provision of ecosystem services (Gonzalez & Loreau, 2008; Winfree & Kremen, 2008). This is particularly relevant for highly diverse and species-rich ecosystems such as the Miombo and Mopane woodlands, where such dynamics can be anticipated (Gonçalves et al., 2017). Therefore, the identified hotspot and coldspot areas need to be interpreted with respect to the baseline distribution of the eight addressed species, which is obviously limiting. We strived to mitigate this limitation by carefully selecting ecologically and socially relevant species, which could thus approximate the overall pattern of future risks.

Finally, the scale of the districts used in the analysis of social vulnerability of the Namibian population is particularly limiting if inhabitants are unevenly dispersed across their territory, and within-district variation in social and biophysical vulnerability is large. Moreover, districts in Namibia are influenced by the colonial era, where indigenous people were being largely relocated, without respect to their cultural, ethnic and historical background. Use of district specific data in vulnerability and other studies has, therefore, obvious limitations and findings should be interpreted with caution.

6.3 Key findings

This thesis is presented as a set of original scientific articles, each containing detailed discussions on the researched issue. Here, we briefly discuss the key findings of the presented scientific articles.

6.3.1 Knowledge gaps in current understanding of climate change impact and adaptation options in Sub-Saharan Africa

Progress in climate change research in Southern Africa

While climate change research is increasing globally, geographical differences in our understanding of major impacts, drivers, and responses remain large (Arnell et al., 2019; Blicharska et al., 2017). Southern Africa represents one of the world's most understudied regions with poor research infrastructure and human resources (Kusangaya et al., 2014). Literature review of the progress in climate change research demonstrated that the region has experienced remarkable progress between 2000-2019. The identified increase in climate change research corresponds with the findings from Zinyengere et al., (2013) and Ford et al., (2015). The latter authors demonstrated that research on adaptation to climate change in southern and eastern Africa outperformed the remaining African regions. This is good news for the southern African region and Africa in general, as this development complies with the continent's strategic framework, the Africa 2063 Agenda. It also corresponds with the increasing involvement of the African governments in global discussions, including those leading to the formulation of strategic documents such as the Paris Agreement adopted at "The 2015 United Nations Climate Change Conference in Paris" (United Nations 2015), and the "Sustainable Development Goals" adopted by the United Nations in 2015.

However, geographical differences in research performances still prevail, with South Africa being the most researched country, accounting for more than half of the publications in the reviewed period. The results show that climate change research focused on social impacts and populations' responses to these impacts have received more attention since 2015. Climate change research in southern Africa have also seen an increase in research collaborations (i.e., mixed of African and non-African affiliated authors) since 2008, increasing between 33 and 38% after 2013. More than half of these publications had a first author with an African affiliation. A remarkable finding is that the main driver of publication performances was the level of social and political globalization rather than, for example, expenditures on education. This finding should be considered in regional development policies. This analysis can play an important role in better understanding of the patterns and drivers of the regional research, which are critical entries to informed decisions about research investments, infrastructure development, and education transformation.

Climate change impacts on ecosystems and management responses in Southern Africa

Climate change increasingly threatens global biodiversity (Malhi et al., 2020), however, information about the direction and magnitude of impacts in southern Africa is still lacking. The underdeveloped research infrastructure and human resources in the southern African region limits our understanding and hamper the implementation of knowledge-based adaptation strategies (Wangai et al., 2016).

The analysis showed that there is a high diversity of climate change-related impacts on human society, species, and various ecosystems in southern Africa. Observed and projected climate change-related impacts in the region included, for example, local extinctions, increased mortality, and species range shifts in terrestrial, marine, and freshwater ecosystems. Habitat loss and range contraction were the most frequently reported processes, potentially leading to the loss of keystone species such as predators (e.g., the African Wild Dog) and pollinators (e.g., *Promerops cafer, Nectarinia famosa,* and *Anthobaphes violacea*). This agrees with Sintayehu, (2018), who noted that the impacts of climate change have resulted in significant shifts in species' geographical ranges in many parts of Africa. We found a relatively high geographical imbalance in the number of identified publications, with the dominance of Namibia (28% of all cases) and Zimbabwe (21%). However, it is worth noting that such a pattern should not be interpreted in terms of the higher vulnerability of these countries but rather in terms of their size and research environment that outperforms the remaining countries.

Our analysis showed that most of the reviewed publications addressed vegetation (50%) and were mainly focused on increased mortality and range shift. This is consistent with other previous research, such as (Midgley & Thuiller, 2011), who suggested that research on plant species in southern Africa is currently further developed than that on animals. On the other hand, aquatic (marine and freshwater) systems were the least addressed in the reviewed publications. This finding conforms with that of Pereira et al., (2010), who found that quantitative scenarios focusing on the impacts of global change on freshwater and marine organisms are lacking. The impacts identified in this analysis represent only some of the climate change effects documented in the literature. This is likely related to the limited science production in the target region and our strict selection criteria to identify studies that addressed both impacts and management and policy responses. We also found that many of the reviewed studies (57%) addressed the projected impacts of climate change, while the remaining papers addressed actual observed impacts. This suggests an increasing recognition of model-based approaches and the use of climate projections in research in the region, which was previously found marginal (Kusangaya et al., 2014).

The review of active management measures demonstrated the high diversity of approaches which need to be considered, including building artificial nesting spots and water points, revising fire management approaches, reintroducing threatened species, or regulating industrial fishing. Although these cases were somewhat fragmented and challenging to synthesize, they may inspire the development of adaptive management plans elsewhere in the region. The reviewed publications repeatedly indicated a limited understanding of climate change impacts and vulnerability of different species and ecosystems as a factor hampering adaptation actions. Therefore, the authors mostly recommended further intensive and coordinated monitoring of vegetation and animal populations, which seems to be particularly needed for marine and freshwater ecosystems (Kirkman et al., 2011; Sherley et al., 2012).

The implementation of active management measures needs to be embedded within an efficient policy framework, which is often missing in southern Africa. Therefore, some of the reviewed publications suggested targeted policy improvements to facilitate the operational mitigation of climate change impacts (Huntley & Barnard, 2012). The policy recommendations highlighted the need to incorporate transient ecosystem dynamics into nature conservation and management planning, coordinate transboundary conservation policies, and strengthen and coordinate different monitoring systems. These recommendations are well consistent with the emergent concepts on biodiversity conservation under climate change (Heller & Zavaleta, 2009).

We found an increasing tendency in the number of publications addressing the interface of climate change and management and policy. Such an increase corresponds with the global recognition of climate change-related threats and the urgency of coordinated actions (Ford et al., 2015; Siders, 2019).

6.3.2 Climate change impact on trees species distribution and ecosystem services provision in Sub-Saharan Africa

Climate change is a global phenomenon that is currently affecting human populations and the environment around the world. In southern Africa, woody vegetation provides essential ecological, regulation, and cultural ecosystem services (ES), yet many species and ecosystems are increasingly threatened by climate change and land-use transformations. Therefore, this analysis can inform targeted adaptation and conservation actions and strategies, which are currently lacking in most parts of Africa.

Species perspective

Our investigation showed that climate change is projected to have significant impacts on the vegetation in the region under different climatic scenarios. The results portrayed distinct regional differences in species range vulnerability. The projection highlighted remarkable differences in climatic sensitivity of species distribution, rendering a specific pattern of winners and losers and the distinct geographical pattern of multi-species vulnerability. Generally, the distribution of species with a small baseline range, such *as B. plurijuga*, and *G. coleosperma*, were found to be the most threatened by climate change, i.e., the climatic suitability within their baseline range declined, and future gains were insignificant. At the same time, species with large baseline distributions, such as *S. rautanenii, C. imberbe, and C. mopane*, benefited from climate change in terms of (i) the persistence of suitable conditions within their baseline range and (ii) large future gains. Our assessment indicated that *C. mopane* is a regional winner, which is particularly important regarding the broad range of ES the species provides, including timber, food, medicine, and energy (Makhado et al., 2014; Sekonya et al., 2020). While the baseline range of *G. coleosperma* declined entirely rendering the species a regional loser.

The investigation identified several distinct hotspots of species range vulnerability, where climatic suitability for multiple species was projected to decline, and coldspots of potential species persistence. Interestingly, while coldspot were unstable under the two RCPs, and their area shrunk significantly under RCP8.5, the hotspot areas exhibited high stability. The central hotspot area was located at the borders of Angola, Zambia, Namibia, and Botswana in the Miombo and Mopane woodlands. This finding is alarming because of the potential loss of vital ecological functions over the large areas of the woodlands, which support the livelihood of ca 10 million rural people and 50 million urban dwellers. The findings of our analysis on high vulnerability of these woodlands has is consistent with previous studies, including risks such as phenological disruption and species turnover driven by a shorter and shifted growing season, reduced water availability, and fire regime shift (Prichard et al., 2017).

Ecosystem services perspective

Climate change is also projected to result in the decline in the provision of key ecosystem services for the local communities of southern Africa, with the provision of timber projected to be the most affected (Kapuka et al., 2022). The analysis identified the hotspots and coldspots of ecosystem services provision based on the decline and persistence of land climatic suitability for species providing specific ecosystem service. Species important for timber production (*B. plurijuga, P. angolensis,* and *G. coleosperma* – except for *C. mopane*) were affected the most, rendering this ecosystem service the most vulnerable. The high risks to key timber species of the Miombo woodland in Angola and Zimbabwe were also highlighted by other previous analysis, e.g., Catarino et al., (2021), and Pelletier et al., (2019). The former authors particularly underscored the vulnerability of *G. coleosperma* due to its restricted distribution and high market value; we identified this species as a regional loser. The major hotspot emerged in the same area as the species retreat hotspot discussed above, and it was significantly larger under RCP8.5 than under RCP4.5. At the same time, the coldspot areas of timber provision were rather unstable under the two RCPs. Interestingly, although the projected changes in land climatic suitability for single species providing food and energy were substantial, they did not form any significant hotspot or coldspot pattern.

6.3.3 Patterns of socio-economic vulnerability in Namibia

The social vulnerability to natural hazard assessment shows that social vulnerability and exposure to natural hazards varied between the districts. We found that macro-regions with specific magnitudes of vulnerability exist in the country, which require different treatment and management responses. The results shows that populations with the poorest socio-economic performance in the country are mostly distributed in areas with highest frequency and severity of natural hazards, rendering these populations as the most vulnerable to climate change related impacts. Social vulnerability reached its highest values in the northern districts and culminated in Ohangwena and Omusati. These districts have previously received increased research attention due to their prominence (Angombe, 2012; Lendelvo et al., 2018; O'Brien et al., 2009). The southern districts such as Khomas, Erongo, Karas, and Hardap, on the other hand were found to have good capacities to cope with and respond to natural hazards.

The social vulnerability was mainly driven by a combination of various factors, including the high number of elderly populations, populations with disabilities, and household income. Exposure to natural hazards also showed a distinct geographical pattern. While flood- and fire-prone districts occurred in the northern parts of the country, drought risks were high across the entire country. Results show lower drought risk in the central districts such as Khomas and Hardap. The most frequent combination of hazards was drought and flood, while the combination of drought and fire occurred in Otjozondjupa, Kavango East and Kavango West only. The latter two districts also showed a minor exposure to floods, which makes them the most hazard-prone districts in the country from the view of both magnitude of the impact and the number of participating hazards. The results of this analysis are intended to support the development of national and regional management strategies and the formulation of research and investment priorities, and to contribute towards achieving the Sustainable Development

7 Recommendations for practice and policy

To narrow the major knowledge gaps in climate change risks in southern Africa, we suggest that knowledge transfer from South Africa should be increasingly considered in regional adaptation planning. The South African experience can, for example, help address the knowledge gaps identified herein concerning the control of biological invasions and infrastructure and capacity building.

We found that the current level of understanding of climate change risks is incomplete in many aspects, and further systematic research and monitoring is needed. Therefore, we recommend future studies considering different selection criteria (e.g., without requiring the connection to management responses) to investigate the impacts on ecosystems more comprehensively.

Improving regional research and monitoring infrastructure, including investments in research, innovation, technology transfer as well as options for using more advanced mechanistic models for identifying future risks are crucial for promoting effective adaptation to climate change in southern Africa. Implementing new curricula of climate change–related subjects in masters and doctoral studies could be a solid incentive to improving climate change research and awareness. Improved education could be an essential step towards increasing the proportion of interdisciplinary studies and broader use of advanced technologies and climate model outputs.

Improving research infrastructure and availability of climate data, including bias-corrected climate projections, would significantly enhance the current options for process-based understanding of climate change impacts in the region and formulation of adaptation strategies.

Despite advanced climate change research in southern Africa, further investments are needed to reach a fully operational stage to boost the existing research. Policy and institutional frameworks play a crucial role in improving research performance, which is another field that requires attention in southern Africa. An improved policy and institutional environment would be conducive to joint activities of academia, the private sector, citizen science, and policy, as well as to the search for additional resources to support African publishers and scientists. The countries should, for example, establish national agencies such as the National Research Foundation in South Africa (NRF) or the National Commission on Research Science and Technology (NCRST) in Namibia, which were instrumental in overseeing and coordinating research activities.

We further advise maintaining the database of so-focused publications and update it regularly to support future, more comprehensive synthetic studies. A review of gray literature conducted by the local scientists would also be a valuable input increasing our understanding of climate change impacts and adaptation options in the region.

Further research on the emergent biotic interactions and implications for ecosystem services is needed in southern Africa to reduce some of the most pronounced known uncertainties in assessing future impacts of climate change. Although our analysis considered climate predictors only, other predictors such as land-use, soil conditions, and nonenvironmental constraints should be considered, particularly at smaller scales and for species with azonal and man-altered distributions (Pelletier et al., 2019; Sieben, 2019). We further suggest that future research on the impacts of climate change on species distribution should consider all or a subset of the underlying climate projections, which, even if combined with different Species Distribution Models (SDMs), can capture the future uncertainty of vegetation responses more comprehensively (Jiang et al., 2012).

Our analysis on social vulnerability of human population in Namibia used a coarse resolution of administrative districts, which was determined by the availability of used data. Although such a scale of assessment can support strategic planning, including targeting of investments from external sources, finer-scale studies addressing the diversity of local contexts are needed for efficient implementation.

8 Conclusions

The thesis highlights the patterns and drivers of regional climate change research, which are critical entries to informed decisions about research investments, infrastructure development, and education transformation in southern Africa. Despite significant advances in the field of climate change research in the last 15 years, mainly in terms of the number of publications, the role of African researchers in author teams, and international collaboration, regional inequalities remain.

Our analyses highlighted that vulnerabilities and climate change risks to human population and ecosystems in southern Africa exhibit distinct spatial patterns, which may need to be considered by managers, policymakers, funding organizations, and individual donors seeking science-based guidance.

Our assessments revealed that despite a wide range of identified and projected climate change-related impacts threatening the diverse natural and cultural environment of southern Africa, and the availability of various possible response measures to these impacts, there is limited or fragmented knowledge about their directions and magnitudes. This limitation hampers the formulation of knowledge-based adaptation strategies in the region and highlights the need for further synthetic studies aiming to collate the available and often fragmented knowledge.

The study further showed that the pattern of natural hazards and social vulnerability were highly variable among the districts of Namibia, as were the factors determining the social and economic fitness of the population. Adaptation strategies, therefore, need to consider the diversity of regional contexts, which is high even between adjacent districts with similar natural and cultural conditions. We found that macro-regions exist in the country, where multiple adverse effects coincided, including critically low socio-economic performance, high population density and the concurrent incidence of different hazard types. The increasing risk of natural disasters, which is often mediated by climate change, implies that tipping points can be exceeded in such environments and social and ecological harm can be beyond repair.

The results of this thesis have important implications for practice. The findings can inform national and regional climate change and biodiversity conservation policies. Support targeted adaptation and conservation actions and strategies, which are currently lacking in many African regions. Inform donors and funders about priorities, knowledge gaps and climate change hotspot regions. Increase the visibility of research on Africa in the scientific community.

9 References

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