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

Alpo Kapuka and Tomáš Hlásny†

Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, Prague 6 - Suchdol 165 00 Czech Republic

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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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† **E-mail** : hlasny@fld.czu.cz

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

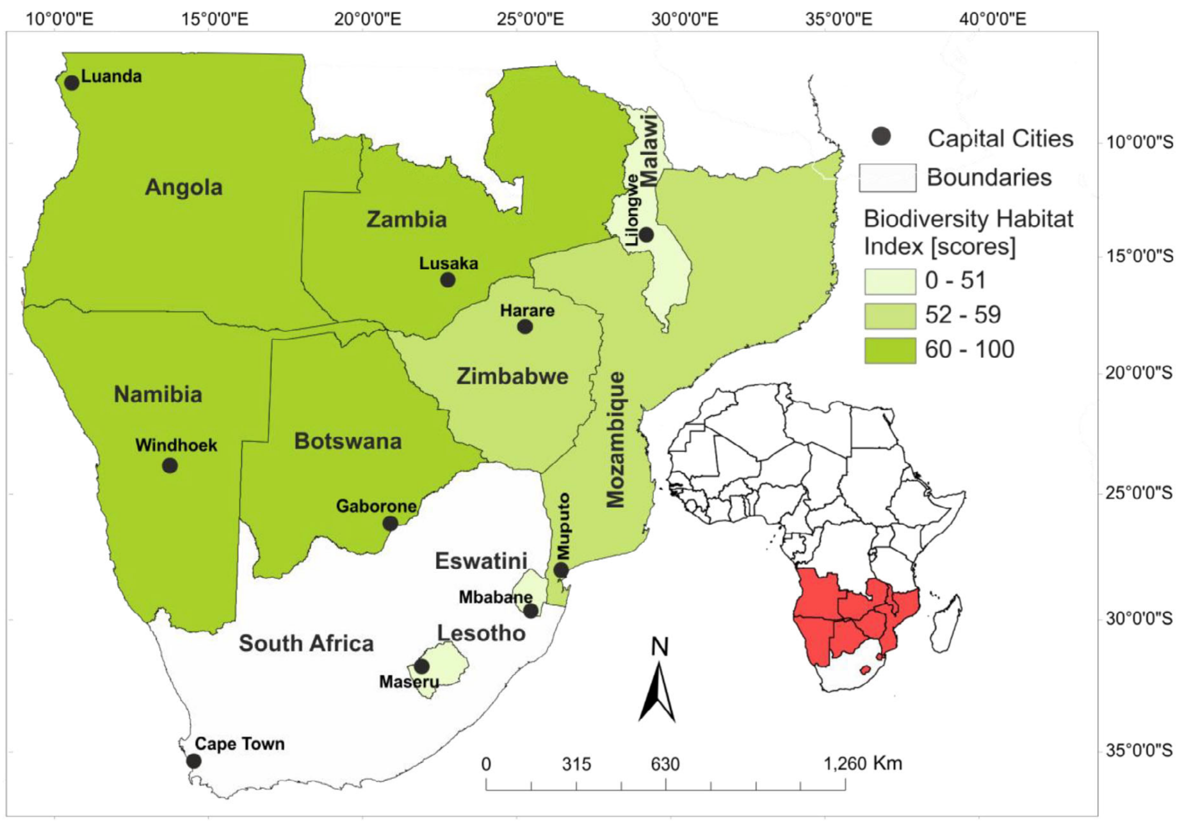

Fig. 1. Southern African countries investigated in this study and their location in Africa. The Biodiversity Habitat Index (Wendling et al. 2020) is shown.

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).

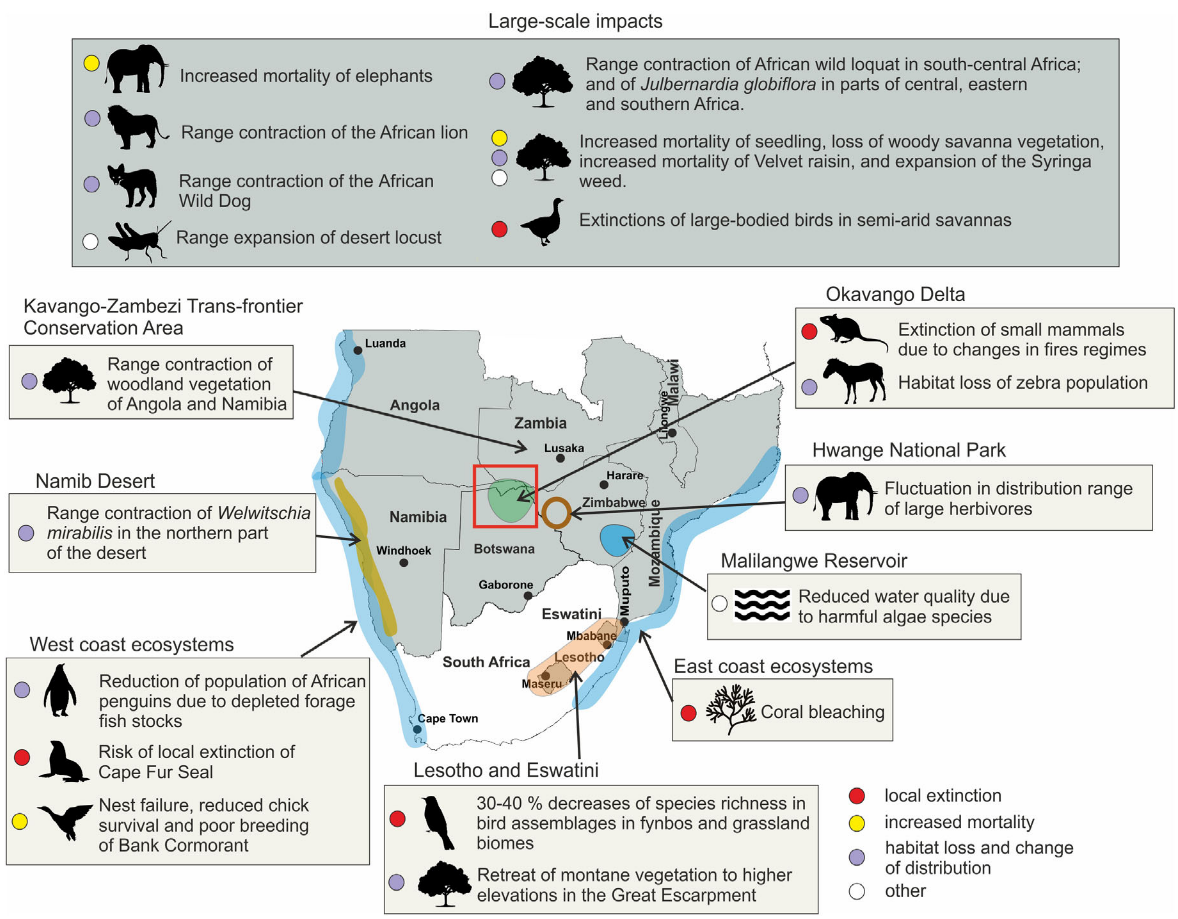

Fig. 2. Impacts of climate change on ecosystems, species, and populations in nine southern African countries identified in the reviewed publications. The silhouettes were obtained from https://silhouette-ac.com.

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,

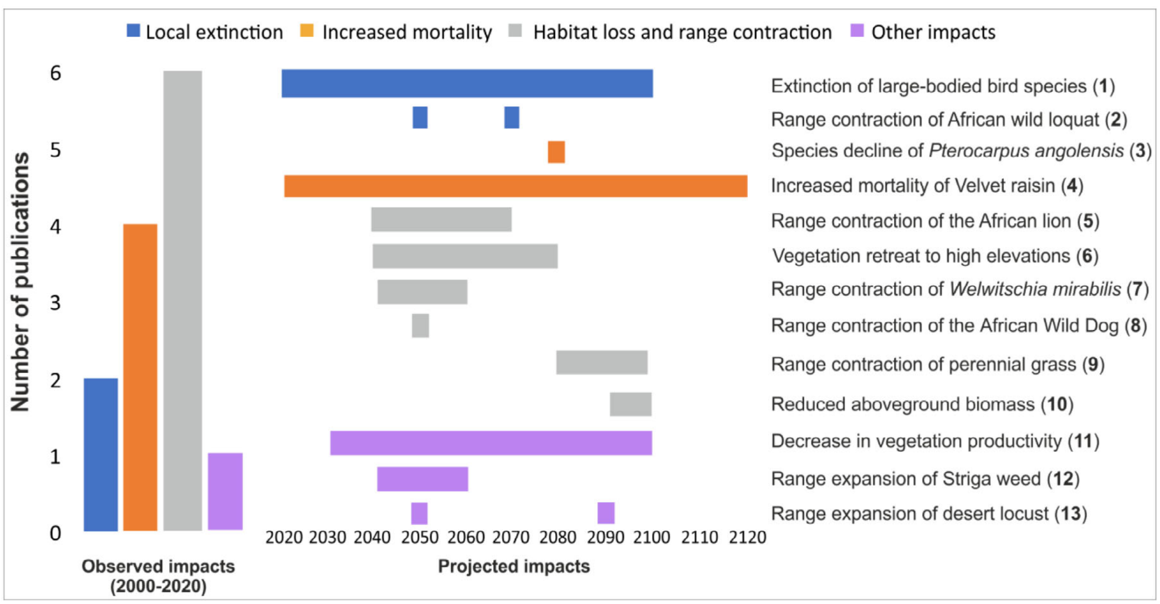

Fig. 3. Observed and projected impacts identified in the reviewed publications. The type of projected impacts and the addressed time horizons are indicated. We note that two papers, which addressed the projected impacts but did not specify the time frame, are not indicated in the figure. Publication 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 (northwestern 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

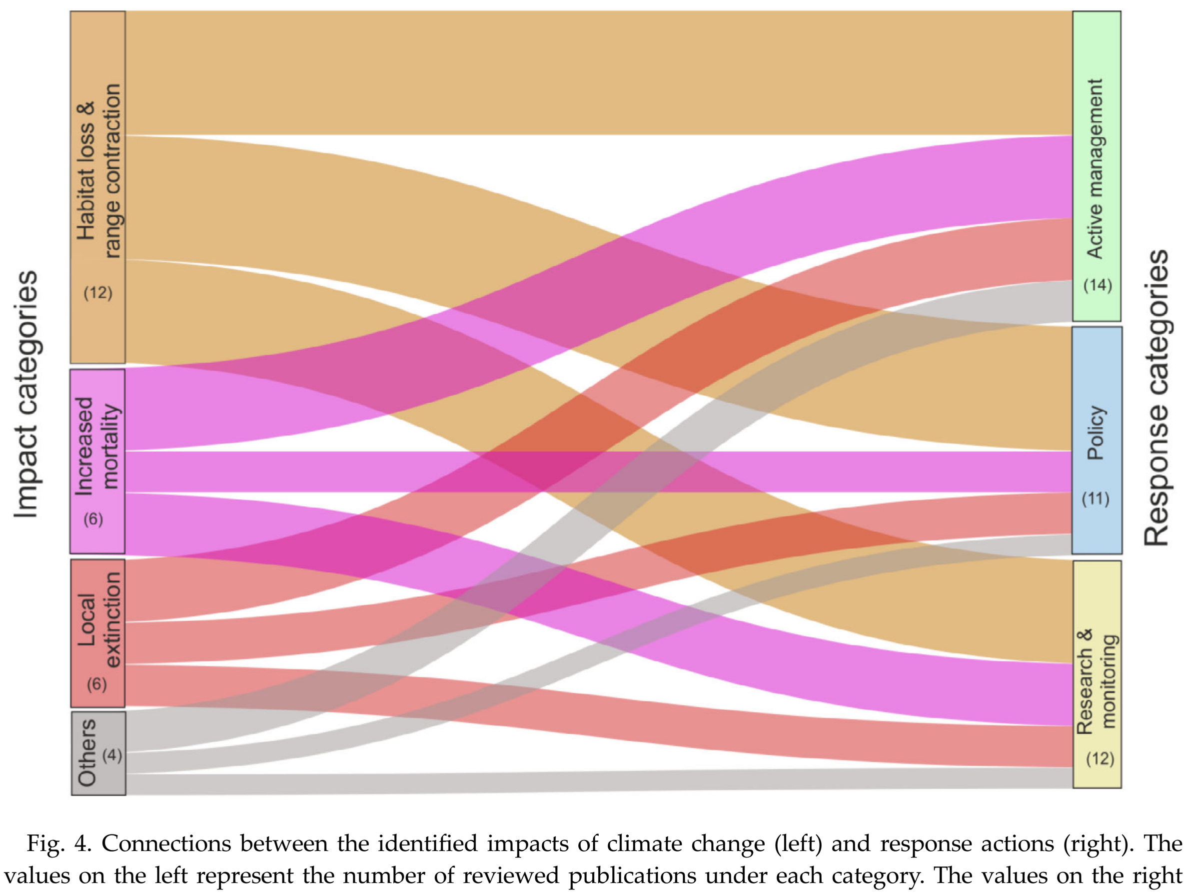

Fig. 4. Connections between the identified impacts of climate change (left) and response actions (right). The values on the left represent the number of reviewed publications under each category. The values on the right represent the number of identified responses under each category. The belts represent 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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Literature Cited

Abson, D. J., A. J. Dougill, and L. C. Stringer. 2012. Using Principal Component Analysis for information-rich socio-ecological vulnerability mapping in Southern Africa. Applied Geography 35:515–524.

Allen, C. D., D. D. Breshears, and N. G. McDowell. 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere 6:1–55.

Andersson, L., P. Samuelsson, and E. Kjellström. 2011. Assessment of climate change impact on water resources in the Pungwe river basin. Tellus, Series A: Dynamic Meteorology and Oceanography 63:138–157.

Andersson, L., J. Wilk, M. C. Todd, D. A. Hughes, A. Earle, D. Kniveton, R. Layberry, and H. H. G. Savenije. 2006. Impact of climate change and development scenarios on flow patterns in the Okavango River. Journal of Hydrology 331:43–57.

Archer, E. R. M., W. Adolf, M. Alexander, J. Malherbe, H. Weepener, P. Maluleke, and F. Maxwell. 2017. Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: key lessons. Climate Risk Management 16:22–28.

Arvai, J., et al. 2006. Adaptive management of the global climate problem: bridging the gap between climate research and climate policy. Climatic Change 78:217–225.

Baltazar, C. S., and E. V. Rossetto. 2020. Mozambique Field Epidemiology and Laboratory Training Program as responders workforce during Idai and Kenneth cyclones: a commentary. Pan African Medical Journal 36:36.

Bartlam-Brooks, H. L. A., M. C. Bonyongo, and S. Harris. 2013. How landscape scale changes affect ecological processes in conservation areas: external factors influence land use by zebra (*Equus burchelli*) in the Okavango Delta. Ecology and Evolution 3:2795–2805.

Bauer, S., and I. Scholz. 2010. Adaptation to climate change in Southern Africa: new boundaries for sustainable development? Climate and Development 2:83–93.

Beck, L., and T. Bernauer. 2011. How will combined changes in water demand and climate affect water availability in the Zambezi river basin? Global Environmental Change 21:1061–1072.

Bellard, C., C. Bertelsmeier, P. Leadley, W. Thuiller, and F. Courchamp. 2012. Impacts of climate change on the future of biodiversity. Ecology Letters 15:365–377.

Bentley, L. K., M. P. Robertson, and N. P. Barker. 2019. Range contraction to a higher elevation: the likely future of the montane vegetation in South Africa and Lesotho. Biodiversity and Conservation 28:131–153.

Bezeng, B. S., K. Yessoufou, P. J. Taylor, and S. G. Tesfamichael. 2020. Expected spatial patterns of alien woody plants in South Africa's protected areas under current scenario of climate change. Scientific Reports 10:1–12.

Biggs, R., H. Simons, M. Bakkenes, R. J. Scholes, B. Eickhout, D. van Vuuren, and R. Alkemade. 2008. Scenarios of biodiversity loss in southern Africa in the 21st century. Global Environmental Change 18:296–309.

Bombi, P. 2018. Potential impacts of climate change on Welwitschia mirabilis populations in the Namib Desert, southern Africa. Journal of Arid Land 10:663–672.

Bond, W. J., and G. F. Midgley. 2000. A proposed CO2-controlled mechanism of woody plant invasion in grasslands and savannas. Global Change Biology 6:865–869.

Bond, W. J., and G. F. Midgley. 2012. Carbon dioxide and the uneasy interactions of trees and savannah grasses. Philosophical Transactions of the Royal Society B: Biological Sciences 367:601–612.

Boshoff, N. 2010. South-South research collaboration of countries in the Southern African Development Community (SADC). Scientometrics 84:481–503.

Bramer, W. M., M. L. Rethlefsen, J. Kleijnen, and O. H. Franco. 2017. Optimal database combinations for literature searches in systematic reviews: a prospective exploratory study. Systematic Reviews 6:1–12.

Brian, C. O., et al. 2017. IPCC reasons for concern regarding climate change risks. Nature Climate Change 7:28–37.

Burke, A. 2006. Savanna trees in Namibia - Factors controlling their distribution at the arid end of the spectrum. Flora: morphology. Distribution, Functional Ecology of Plants 201:189–201.

Butt, N., A. L. M. Chauvenet, V. M. Adams, M. Beger, R. V. Gallagher, D. F. Shanahan, M. Ward, J. E. M. Watson, and H. P. Possingham. 2021. Importance of species translocations under rapid climate change. Conservation Biology 35:775–783.

Cahill, A. E., et al. 2013. How does climate change cause extinction? Proceedings of the Royal Society B: Biological Sciences 280:20121890.

Chamaillé-Jammes, S., H. Fritz, and F. Murindagomo. 2007. Climate-driven fluctuations in surface-water availability and the buffering role of artificial pumping in an African savanna: potential implication for herbivore dynamics. Austral Ecology 32:740–748.

Chari, F., B. S. Ngcamu, and C. Novukela. 2021. Supply chain risks in humanitarian relief operations: a case of Cyclone Idai relief efforts in Zimbabwe. Journal of Humanitarian Logistics and Supply Chain Management 11:29–45.

Chidumayo, E. N. 2008. Implications of climate warming on seedling emergence and mortality of African savanna woody plants. Plant Ecology 198:61–71.

Chidumayo, E. N. 2017. Biotic interactions, climate and disturbance underlie the distribution of two

Julbernardia tree species in miombo woodlands of Africa. Journal of Tropical Ecology 33:1–11.

Chirwa, P. W., S. Syampungani, and C. J. Geldenhuys. 2008. The ecology and management of the Miombo woodlands for sustainable livelihoods in southern Africa: the case for non-timber forest products. Southern Forests: A Journal of Forest Science 70:237–245.

Conradi, T., J. A. Slingsby, G. F. Midgley, H. Nottebrock, A. H. Schweiger, and S. I. Higgins. 2020. An operational definition of the biome for global change research. New Phytologist 227:1294–1306.

Dai, A. 2011. Drought under global warming: A review. Wiley Interdisciplinary Reviews: Climate Change 2:45–65.

Dalu, T., and R. J. Wasserman. 2018. Cyanobacteria dynamics in a small tropical reservoir: Understanding spatio-temporal variability and influence of environmental variables. Science of the Total Environment 643:835–841.

Darkoh, M. B. K. 2009. An overview of environmental issues in Southern Africa. African Journal of Ecology 47:93–98.

de Cauwer, V., C. J. Geldenhuys, R. Aerts, M. Kabajani, and B. Muys. 2016. Patterns of forest composition and their long term environmental drivers in the tropical dry forest transition zone of southern Africa. Forest Ecosystems 3. https://doi.org/10.1186/s40663-016-0080-9

de Cauwer, V., B. Muys, R. Revermann, and A. Trabucco. 2014. Potential, realised, future distribution and environmental suitability for *Pterocarpus angolensis* DC in southern Africa. Forest Ecology and Management 315:211–226.

Dewees, P. A., B. M. Campbell, Y. Katerere, A. Sitoe, A. B. Cunningham, A. Angelsen, and S. Wunder. 2010. Managing the Miombo Woodlands of Southern Africa: policies, Incentives and Options for the Rural Poor. Journal of Natural Resources Policy Research 2:57–73.

Dinerstein, E., et al. 2019. A Global Deal for Nature: guiding principles, milestones, and targets. Science Advances 5:1–18.

England, M. I., A. J. Dougill, L. C. Stringer, K. E. Vincent, J. Pardoe, F. K. Kalaba, D. D. Mkwambisi, E. Namaganda, S. Afionis, and K. E. Vincent. 2018. Climate change adaptation and cross-sectoral policy coherence in southern Africa. Regional Environmental Change 18:2059–2071.

Foden, W., G. F. Midgley, G. Hughes, W. J. Bond, W. Thuiller, M. T. Hoffman, P. Kaleme, L. G. Underhill, A. Rebelo, and L. Hannah. 2007. A changing climate is eroding the geographical range of the Namib Desert tree Aloe through population declines and dispersal lags. Diversity and Distributions 13:645–653.

Ford, J. D., L. Berrang-Ford, A. Bunce, C. McKay, M. Irwin, and T. Pearce. 2015. The status of climate change adaptation in Africa and Asia. Regional Environmental Change 15:801–814.

Fox, J. T., M. E. Vandewalle, and K. A. Alexander. 2017. Land cover change in Northern Botswana: the influence of climate, fire, and elephants on Semi-Arid Savanna Woodlands. Land 6:73.

Global Drought Observatory. 2019. GDO Analytical Report: drought in Southern Africa–January 2019.

Guo, D., J. L. Arnolds, G. F. Midgley, and W. B. Foden. 2016. Conservation of quiver trees in Namibia and South Africa under a changing climate. Journal of Geoscience and Environment Protection 04:1–8.

Haselip, J., and M. Hughes. 2018. Africa-Europe collaborations for climate change research and innovation: What difference have they made? Pages 81–97 *in* A. Cherry, J. Haselip, G. Ralphs, and I. E. Wagner, editors. Africa-Europe research and innovation cooperation: Global challenges, bi-regional responses. Springer International Publishing, Cham, Switzerland.

Heller, N. E., and E. S. Zavaleta. 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. Biological Conservation 142:14–32.

Helmschrot, J., S. Thompson, S. Kralisch, and F. Zander. 2018. The SASSCAL data and information portal. Pages 112–113 *in* R. Revermann, K. M. Krewenka, U. Schmiedel, J. M. Olwoch, J. Helmschrot, and N. Jürgens, editors. Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions. Klaus Hess Publishers, Göttingen, Germany, Windhoek, Namibia.

Hoegh-Guldberg, O., et al. 2019. The human imperative of stabilizing global climate change at 1.5°C. Science 365:eaaw6974.

Hruska, T., L. Huntsinger, M. Brunson, W. Li, N. Marshall, J. L. Oviedo, and H. Whitcomb. 2017. Rangelands as social-ecological systems. Pages 263–302 *in* D. D. Briske, editor. Rangeland systems: processes, management and challenges. Springer International Publishing, Cham, Switzerland.

Huntley, B., and P. Barnard. 2012. Potential impacts of climatic change on southern African birds of fynbos and grassland biodiversity hotspots. Diversity and Distributions 18:769–781.

Inman, E. N., R. J. Hobbs, and Z. Tsvuura. 2020. No safety net in the face of climate change: the case of pastoralists in Kunene Region, Namibia. PLoS Medicine 15:e0238982.

IPCC. 2019. Summary for policymakers. *In* P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, and J. Malley, editors. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, *in press*.

Janetos, A. C. 2020. Why is climate adaptation so important? What are the needs for additional research? Climatic Change 161:171–176.

Jinga, P., J. Palagi, J. P. Chong, and E. D. Bobo. 2020. Climate change reduces the natural range of African wild loquat (*Uapaca kirkiana* Müll. Arg., Phyllanthaceae) in south-central Africa. Regional Environmental Change 20:108.

Jones, B., and B. C. O'Neill. 2016. Spatially explicit global population scenarios consistent with the Shared Socioeconomic Pathways. Environmental Research Letters 11:1–10.

Jones, M., L. D. Bertola, and O. Razgour. 2016. Predicting the effect of interspecific competition on habitat suitability for the endangered African wild dog under future climate and land cover changes. Hystrix 27:1–8.

Kaspar, F., et al. 2015. The SASSCAL contribution to climate observation, climate data management and data rescue in Southern Africa. Advances in Science and Research 12:171–177.

Kirkman, S. P., W. H. Oosthuizen, M. A. Meÿer, S. M. Seakamela, and L. G. Underhill. 2011. Prioritising range-wide scientific monitoring of the Cape fur seal in southern Africa. African Journal of Marine Science 33:495–509.

Kupika, O. L., E. Gandiwa, S. Kativu, and G. Nhamo. 2017. Impacts of Climate Change and Climate Variability on Wildlife Resources in Southern Africa: experience from Selected Protected Areas in Zimbabwe. https://doi.org/10.5772/intechopen.70470

Kusangaya, S., M. L. Warburton, E. Archer van Garderen, and G. P. W. Jewitt. 2014. Impacts of climate change on water resources in southern Africa: a review. Physics and Chemistry of the Earth 67–69:47–54.

Kuyah, S., G. W. Sileshi, J. Njoloma, S. Mng'omba, and H. Neufeldt. 2014. Estimating aboveground tree biomass in three different miombo woodlands and associated land use systems in Malawi. Biomass and Bioenergy 66:214–222.

Lawal, S., C. Lennard, and B. Hewitson. 2019. Response of southern African vegetation to climate change at 1.5 and 2.0° global warming above the pre-industrial level. Climate Services 16:100134.

Lohmann, D., B. Tietjen, N. Blaum, D. F. Joubert, and F. Jeltsch. 2012. Shifting thresholds and changing degradation patterns: climate change effects on the simulated long-term response of a semi-arid savanna to grazing. Journal of Applied Ecology 49:814–823.

López-Carr, D., N. G. Pricope, J. E. Aukema, M. M. Jankowska, C. Funk, G. Husak, and J. Michaelsen. 2014. A spatial analysis of population dynamics and climate change in Africa: potential vulnerability hot spots emerge where precipitation declines and demographic pressures coincide. Population and Environment 35:323–339.

Malhi, Y., J. Franklin, N. Seddon, M. Solan, M. G. Turner, C. B. Field, and N. Knowlton. 2020. Climate change and ecosystems: threats, opportunities and solutions. Philosophical Transactions of the Royal Society B: Biological Sciences 375:20190104.

Mapaura, A., K. Canavan, D. M. Richardson, V. R. Clark, and S. L. Steenhuisen. 2020. The invasive grass genus Nassella in South Africa: a synthesis. South African Journal of Botany 135:336–348.

Mavhura, E. 2020. Learning from the tropical cyclones that ravaged Zimbabwe: policy implications for effective disaster preparedness. Natural Hazards 104:2261–2275.

Mcclanahan, T. R., J. M. Maina, and N. A. Muthiga. 2011. Associations between climate stress and coral reef diversity in the western Indian Ocean. Global Change Biology 17:2023–2032.

Meynard, C. N., P. E. Gay, M. Lecoq, A. Foucart, C. Piou, and M. P. Chapuis. 2017. Climate-driven geographic distribution of the desert locust during recession periods: subspecies' niche differentiation and relative risks under scenarios of climate change. Global Change Biology 23:4739–4749.

Midgley, G. F., and W. Thuiller. 2011. Potential responses of terrestrial biodiversity in Southern Africa to anthropogenic climate change. Regional Environmental Change 11:127–135.

Moher, D., A. Liberati, J. Tetzlaff, and D. G. Altman. 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Medicine 6:e1000097.

Muche, G., et al. 2018. SASSCAL WeatherNet: present state, challenges, and achievements of the regional climatic observation network and database. Pages 34–43 *in* R. Revermann, K. M. Krewenka, U. Schmiedel, J. M. Olwoch, J. Helmschrot, and N. Jürgens, editors. Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions. Klaus Hess Publishers, Göttingen, Germany, Windhoek, Namibia.

Mudereri, B. T., E. M. Abdel-Rahman, T. Dube, T. Landmann, Z. Khan, E. Kimathi, R. Owino, and S.

Niassy. 2020. Multi-source spatial data-based invasion risk modeling of Striga (*Striga asiatica*) in Zimbabwe. Giscience and Remote Sensing 57:553–571.

Muller, M. 2018. Scale and consequences: Does the distribution of formal powers and functions affect water management outcomes in federal contexts in Southern Africa? Regional Environmental Change 18:1693–1706.

Muntifering, J. R., A. J. Dickman, L. M. Perlow, T. Hruska, P. G. Ryan, L. L. Marker, and R. M. Jeo. 2005. Managing the matrix for large carnivores: a novel approach and perspective from cheetah (*Acinonyx jubatus*) habitat suitability modelling. Animal Conservation 9:103–112.

Nalau, J., and B. Verrall. 2021. Mapping the evolution and current trends in climate change adaptation science. Climate Risk Management 32:100290.

Ndlela, S., T. Manyangadze, A. Sachisuko, S. van der Lingen, and I. A. Makowe. 2018. The distribution and management of two invasive pests of eucalyptus: the red gum Lerp Psyllid, *Glycaspis brimblecombei* (Hemiptera: Psylloidae), and the Blue Gum Chalcid Wasp, Leptocybe invasa (Hymenoptera: Eulophidae), in Zimbabwe. African Entomology 26:104–115.

Nikolau, D. K., C. D. Macamo, S. O. Bandeira, A. Tajú, and H. A. Mabilana. 2017. Mangrove change detection, structure and condition in a protected area of eastern Africa: the case of Quirimbas National Park, Mozambique. WIO Journal of Marine Science 16:47–60.

Osborne, C. P., T. Charles-Dominique, N. Stevens, W. J. Bond, G. Midgley, and C. E. R. Lehmann. 2018. Human impacts in African savannas are mediated by plant functional traits. New Phytologist 220:10–24.

Palazzo, A., et al. 2017. Linking regional stakeholder scenarios and shared socioeconomic pathways: quantified West African food and climate futures in a global context. Global Environmental Change 45:227–242.

Pecl, G. T., et al. 2017. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. Science 355:1–9.

Pereira, H. M., et al. 2010. Scenarios for global biodiversity in the 21st century. Science 330:1496–1501.

Peterson, A. T., T. Radocy, E. Hall, J. C. Kerbis Peterhans, and G. G. Celesia. 2014. The potential distribution of the Vulnerable African lion Panthera leo in the face of changing global climate. Oryx 48:555–564.

Plavsic, M. J. 2014. Proximate and ultimate drivers of small-mammal recolonization after fire: microhabitat conditions, rainfall and species traits. Animal Conservation 17:573–582.

Rosendo, S., L. Celliers, and M. Mechisso. 2018. Doing more with the same: A reality-check on the ability of local government to implement Integrated Coastal Management for climate change adaptation. Marine Policy 87:29–39.

Runting, R. K., B. A. Bryan, L. E. Dee, F. J. F. Maseyk, L. Mandle, P. Hamel, K. A. Wilson, K. Yetka, H. P. Possingham, and J. R. Rhodes. 2017. Incorporating climate change into ecosystem service assessments and decisions: a review. Global Change Biology 23:28–41.

Ryan, C. M., R. Pritchard, I. McNicol, M. Owen, J. A. Fisher, and C. Lehmann. 2016. Ecosystem services from southern African woodlands and their future under global change. Philosophical Transactions of the Royal Society B: Biological Sciences 371:20150312.

SADC. 1992. The declaration and treaty of the southern African development community. SADC, Windhoek, Namibia.

SADC. 2008. Southern African development community: regional biodiversity strategy. SADC, Gaborone, Botswana.

Saito, M., S. Luyssaert, B. Poulter, M. Williams, P. Ciais, V. Bellassen, C. M. Ryan, C. Yue, P. Cadule, and P. Peylin. 2014. Fire regimes and variability in aboveground woody biomass in miombo woodland. Journal of Geophysical Research: Biogeosciences 119:1014–1029.

Scherer, C., F. Jeltsch, V. Grimm, and N. Blaum. 2016. Merging trait-based and individual-based modelling: an animal functional type approach to explore the responses of birds to climatic and land use changes in semi-arid African savannas. Ecological Modelling 326:75–89.

Sherley, R. B., K. Ludynia, B. M. Dyer, T. Lamont, A. B. Makhado, J. P. Roux, K. L. Scales, L. G. Underhill, and S. C. Votier. 2017. Metapopulation tracking juvenile penguins reveals an ecosystem-wide ecological trap. Current Biology 27: 563–568.

Sherley, R. B., K. Ludynia, L. G. Underhill, R. Jones, and J. Kemper. 2012. Storms and heat limit the nest success of Bank Cormorants: implications of future climate change for a surface-nesting seabird in southern Africa Richard. Journal of Ornithology 153:441–455.

Shrader, A. M., S. L. Pimm, and R. J. van Aarde. 2010. Elephant survival, rainfall and the confounding effects of water provision and fences. Biodiversity and Conservation 19:2235–2245.

Siders, A. R. 2019. Adaptive capacity to climate change: a synthesis of concepts, methods, and findings in a fragmented field. Wiley Interdisciplinary Reviews: Climate Change 10:1–18.

Sintayehu, D. W. 2018. Impact of climate change on biodiversity and associated key ecosystem services in Africa: a systematic review. Ecosystem Health and Sustainability 4:225–239.

Sintayehu, D. W., A. Egeru, W.-T. Ng, and E. Cherenet. 2020. Regional dynamics in distribution of *Prosopis juliflora* under predicted climate change in Africa. Tropical Ecology 61:437–445.

Sirami, C., C. Seymour, G. Midgley, and P. Barnard. 2009. The impact of shrub encroachment on savanna bird diversity from local to regional scale. Diversity and Distributions 15:948–957.

Sooryamoorthy, R. 2018. The production of science in Africa: an analysis of publications in the science disciplines, 2000–2015. Scientometrics 115:317–349.

Swart, R., R. Biesbroek, and T. C. Lourenço. 2014. Science of adaptation to climate change and science for adaptation. Frontiers in Environmental Science 2:1–8.

Tews, J., A. Esther, S. J. Milton, and F. Jeltsch. 2006. Linking a population model with an ecosystem model: Assessing the impact of land use and climate change on savanna shrub cover dynamics. Ecological Modelling 195:219–228.

Thiaw, I. 2015. Is the changing climate changing African ecosystems? Ecosystem Health and Sustainability 1:1–3.

Vogel, C., A. Steynor, and A. Manyuchi. 2019. Climate services in Africa: re-imagining an inclusive, robust and sustainable service. Climate Services 15:100107.

Waldron, A., D. C. Miller, D. Redding, A. Mooers, T. S. Kuhn, N. Nibbelink, J. T. Roberts, J. A. Tobias, and J. L. Gittleman. 2017. Reductions in global biodiversity loss predicted from conservation spending. Nature 551:364–367.

Walther, G. R. 2010. Community and ecosystem responses to recent climate change. Philosophical Transactions of the Royal Society B: Biological Sciences 365:2019–2024.

Wang, C. J., J. Z. Wan, H. Qu, and Z. X. Zhang. 2017. Modelling plant invasion pathways in protected areas under climate change: implication for invasion management. Web Ecology 17:69–77.

Wangai, P. W., B. Burkhard, and F. Müller. 2016. A review of studies on ecosystem services in Africa. International Journal of Sustainable Built Environment 5:225–245.

Warren, R., J. Price, J. VanDerWal, S. Cornelius, and H. Sohl. 2018. The implications of the United Nations Paris Agreement on climate change for globally significant biodiversity areas. Climatic Change 147:395–409.

Watson, J. E. M., M. Rao, A. L. Kang, and Y. Xie. 2012. Climate change adaptation planning for biodiversity conservation: a review. Advances in Climate Change Research 3:1–11.

Wendling, Z. A., et al. 2020. Environmental Performance Index. Yale Center for Environmental Law & Policy, New Haven, Connecticut, USA.

Wisely, S. M., K. Alexander, T. Mahlaba, and L. Cassidy. 2018. Linking ecosystem services to livelihoods in southern Africa. Ecosystem Services 30:339–341.

Zhu, T., and C. Ringler. 2012. Climate change impacts on water availability and use in the Limpopo River Basin. Water (Switzerland) 4:63–84.

Ziervogel, G., M. New, E. Archer van Garderen, G. Midgley, A. Taylor, R. Hamann, S. Stuart-Hill, J. Myers, and M. Warburton. 2014. Climate change impacts and adaptation in South Africa. Wires Climate Change 5:605–620.

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