Climate change risk to southern African native wild food plants

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Plagiarism declaration

I, Carina Wessels, know the meaning of plagiarism and declare that the work in the dissertation, save for that which is properly acknowledged, is my own.

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Date: 8 May 2020

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Contents

Abstract

Climate change is a threat to food security. A substantial body of research supports this conclusion for climate change threats to plants with agricultural value, as well as wild-harvested food from animals, such as fish. However, much less is known about climate change threats to wild-harvested food plants despite these species meeting important dietary needs for a large number of households in developing countries, especially when crops fail or during other times of hardship. My study was the first to look at climate change risk to a broad group of wild edible plants and focussed on the wild food plants (WFPs) of southern Africa. The aims of my study were to determine where WFPs occur in southern Africa; whether these WFPs will be threatened by climate change; and how climate change risk for WFPs intersects with climate change risk to staple crops. Species distribution models were used to obtain the historical geographic range of 1190 WFP species and to make projections of range change for 2070 under both low (Representative Concentration Pathway (RCP) 2.6) and high (RCP 8.5) greenhouse gas emissions scenarios. I also mapped percentage change between historical and future yields for maize and sorghum to identify regions where both crops and WFPs, or just one of these are at risk from climate change. WFP species richness in southern Africa generally increases from west to east across the region, with the Eastern Cape, Kwazulu-Natal and Mpumalanga provinces of South Africa having the highest WFP species richness. It is projected that for RCP 2.6, 40% of WFP species will experience a decrease in range extent within southern Africa, increasing to 66% of WFP species for RCP 8.5. For RCP 2.6, the loss of suitable climatic conditions is projected to decrease local WFP species richness most in the north-eastern parts of southern Africa, while increases in WFP species richness are projected in the south and east of South Africa. For RCP 8.5, decreases of more than 200 species are projected for multiple regions in north-eastern South Africa, and local WFP species losses of more than 50% are projected for most of Botswana. Despite these decreases, WFPs could still play an important role in food security during times of low agricultural yield as a result of changing climate conditions, especially in low-income, rural communities that are reliant on smallholder farming. For instance, in parts of the Eastern Cape province of South Africa and northern Namibia, WFP species richness is projected to increase while maize and sorghum yield are projected to decrease. People may be more able to rely on WFPs as a nutritional safety net in these regions into the future. This safety net, however, may be lost in large regions of South Africa's North West and Free State provinces, on the north-eastern border between South Africa and Botswana, as well as parts of northern Namibia, where declines in both crop yield and WFP species richness are projected. This research could prove valuable for climate change adaptation planning, especially in more vulnerable rural regions of southern Africa. Furthermore, by integrating traditional knowledge of WFPs into food security risk assessments and response options, it could provide a more inclusive range of food supply options people can use in order to mitigate risk. However, in order to ensure future food security, more research is needed on WFP uses, nutritional value, responses to climate change, and suitability for cultivation. Still, by looking beyond the farm level and conventional crops to the exceptional diversity of WFPs people obtain from their environment, my research has made a first step towards understanding the linkages between WFPs, agriculture, food security, and climate change.

Introduction

Globally, an estimated two billion people suffer from micronutrient deficiencies (World Health Organisation (WHO), 2007), while 821.6 million people were undernourished in 2019, with over 256 million of those people living in Africa (Food and Agriculture Organization (FAO), 2019). Most literature on food security tends to focus on agricultural foods and fisheries, however, other wild-caught or harvested foods also play a vital role in food security, especially in Africa and other developing country regions (Barnett, 2000; Bennet & Robinson, 2000; Bharucha & Pretty, 2010; Hickey et al., 2016; Rowland et al., 2017). Wild foods, including both plant and animal products, contribute to food security via direct consumption either on a regular basis or in times of shortage, and when sold for income that could be reinvested in other food purchases (FAO, 2019). It is estimated that on a global scale wild foods contribute to the diets of at least one billion people (Burlingame, 2000; Aberoumand, 2009). A more precise global estimate is challenging to determine since wild foods - with the exception of commercial fisheries - are typically collected informally and thus data on wild food consumption are often notably absent from national statistics (Millennium Ecosystem Assessment (MEA), 2005; Bharucha & Pretty, 2010; Schulp et al., 2014). With the value of wild foods typically underrated, the nutritional, medicinal, and cultural value they provide, could easily be lost. For example, in a recent FAO report, it was found that 24% of 4 000 reported wild food species are decreasing in abundance (FAO, 2019). However, numbers of species in decline are likely a gross underestimation as the conservation status of over half of all identified wild food species are currently unknown (FAO, 2019).

Wild foods are a critical contributor to the diets of hundreds of millions of people living in developing countries in Africa, Asia and Latin America (Bennet & Robinson, 2000; Bharucha & Pretty, 2010; Hickey et al., 2016; Coad et al., 2017; Rowland et al., 2017). Wild foods can thus be a potential solution to help overcome food insecurity in these countries (Shaheen et al., 2017), especially because they often contain multiple important micronutrients (Grivetti & Ogle, 2000; Grubben & Denton, 2004; Yang & Keding, 2009; Bharucha & Pretty, 2010; van Huis et al., 2013; Hall et al., 2019). For example, wild-caught fish is not only a source of protein, but also a crucial source of micronutrients such as zinc, often in highly bioavailable form (Golden et al., 2016). In Tanzania, wild foods (plants and animals) acquired from agricultural land in a small-scale farming system contributed 16% of calcium, 19% of iron and 31% of vitamin A to the diets of mothers and children, with the maximum contribution in food insecure seasons (Powell et al. 2013). Wild food plants (WFPs) in particular, provide pronounced dietary diversity and can make an important contribution to micronutrient intake for the people who rely on them (Grivetti & Ogle, 2000). For example, in the arid Ferlo region of Senegal, the specific wild species consumed during seasonal lean periods are crucial contributors of vitamins A, B2 and C (Becker, 1983) and in the Sahel, numerous desert WFPs are sources of essential fatty acids, calcium, iron and zinc (Glew et al., 1997). In rural southern Malawi, households living in areas with high forest cover consumed more WFPs and as a result had significantly improved vitamin A adequacy (Hall et al., 2019). WFPs are not necessarily preferred but can be essential during lean seasons of the year or years when agricultural output is low. For instance, WFPs consumed during the lean dry season in Nigeria were found to have a higher micronutrient and energy content, compared to WFPs used in the productive wet season (Lockett et al., 2000). During the non-agricultural season in the Caprivi region of Namibia, WFPs also provide around 50% of rural household subsistence (Ashley & LaFranchi, 1997). Ethnobotanical surveys indicate that in human history, over 7000 wild plant species have been consumed by humans at some stage (Grivetti & Ogle, 2000; MEA, 2005). In southern Africa alone, a recent inventory revealed that 1740 plant species have food value (Welcome & Van Wyk, 2019).

With the world population soon to reach eight billion people, achieving global food security is a complex challenge. This challenge is exacerbated by climate change. Research describing climate impacts in terms of food security has mostly focused on the effect of climate change on agriculture, mainly on a small number of staple crops (Vermeuelen et al., 2012; Challinor et al., 2014; Rosenzweig et al., 2014; Wu et al., 2014; Springmann et al., 2016). Changes in temperature and rainfall have already negatively impacted crop yields (Carleton & Hsiang, 2016; Ketiem et al., 2017). Future projections indicate substantial reductions in yields and nutritional quality of cereal crops globally for 2°C of global warming, with particularly severe impacts on maize in sub-Saharan Africa (Vermeulen et al., 2012; Porter et al., 2014, Hoegh-Guldberg et al., 2018). For example, Schlenker and Lobell (2010) projected that across Africa by 2050, crop yields are likely to decline by 17-22% for cassava, maize, millet, sorghum and groundnuts, under the Intergovernmental Panel on Climate Change (IPCC) SRES A1B moderate to high warming scenario (Cubasch et al., 2013). By means of a literature review across different emission scenarios, Knox et al. (2012) estimated that by 2050, mean crop yield in Africa would reduce by between 5-17% for maize, millet, sorghum, and wheat. More recent studies in East Africa and southern Africa also projected decreases in crop yield. For example, in central Malawi, mean maize yield losses of 5-11% were projected under different emissions scenarios and with a variety of Global Climate Models (GCMs) (Fiwa et al., 2014; Msowoya et al., 2014; Zinyengere et al., 2014; Zinyengere, 2016). In north-eastern Botswana, mean yield losses for maize and sorghum of 65% and 49% respectively, were projected under the SRES A1B scenario by 2050 (Alemaw & Simalenga, 2015). In semi-arid Botswana, climate change is likely to cause a particularly higher degree of warming which will have serious impacts on cereal crops (Hoegh-Guldberg et al., 2018). Food security in sub-Saharan Africa, a region that is highly reliant on these staple crops, is furthermore anticipated to be hardest hit by climate change due to the region’s unstable economy, in combination with already high temperatures, and its dependence on rain-fed agriculture (Niasse, Afoud & Amani, 2004). Only 5% of all cultivated land in sub-Saharan Africa is irrigated, compared to 37% in Asia and 14% in Latin America (Ringler et al., 2010).

Future climate change conditions could make vulnerable communities that rely on rain-fed agriculture in Africa and other developing country regions much more reliant on WFPs, yet no studies have looked specifically at the projected impacts of climate change on WFPs. For many people in sub-Saharan Africa, WFPs are already an essential livelihood safety net when other sources of food fail, such as during times of drought or other climate impacts (Vinceti et al., 2013; Wunder et al., 2014; Shumsky et al., 2015). For instance, in southern Africa, 60-85% of rural people experience food shortages during three to four months in a year and up to 50% of these people use WFPs to sustain their livelihoods (Akinnifesi et al., 2006). In lean times in Zimbabwe, the quantities of wild fruits consumed and sold to generate income for additional food expenses increases in poor rural households (Mithöfer & Waibel, 2004). In Botswana, when drought leads to crop failure, rural communities rely on WFPs to sustain their livelihoods until conditions improve (Twyman, 2001; Ohiokpehai, 2003; Mojeremane & Tshwenyane, 2004). Furthermore, many wild animal and plant species hold an innate resilience to climate change, which is not always found in domesticated or cultivated species (Fentahun & Hager, 2009). WFPs in particular, are often adapted to grow in poor soils and low rainfall regions and can also have fewer diseases and insect pests than traditional staple crops, providing a yield even when other crops fail (Legwaila et al., 2011). In southern Africa, indigenous fruit trees, which include wild fruit trees, produce more fruits per unit area than a number of exotic fruit trees (Legwaila et al., 2011). These trees also contribute more than 40% to the food basket for most rural people (Akinnifesi et al., 2006). WFPs also have a vast number of other uses, such as medicines and feed for livestock. Despite these indications that WFPs could increase resilience to climate change, limited research has been done on the subject. In Mali, Tanzania, and Zambia, household surveys of climate change adaptation strategies showed that forest products (which includes wild foods) can play a crucial role in reducing household vulnerability by providing alternative sources of food and income during droughts and floods (Robledo et al., 2012). However, this adaptation response may be at risk. For instance in Benin, the impact of climate change on the economic value of three important WFP and export species - *Adansonia digitata* (baobab), *Parkia biglobosa* (African locust bean tree), and *Vitellaria paradoxa* (shea tree) - was investigated. It was found that as much as 50% of the current economic value of these wild tree species may be lost by 2050 under the IPCC SRES A2 scenario, a high warming scenario (Heubes et al., 2012; Cubasch et al., 2013).

Aims & Objectives

Given the projected impact of global climate change on food security, the objective of this research is to assess climate change risk to WFPs.

The aims of my study are to determine:

1. where in southern Africa WFPs occur,
2. if these WFPs will be threatened by climate change,
3. if climate change risk for WFPs intersects with climate change risk to staple crops.

The objective of the third aim specifically, is to assess whether WFPs may provide a coping strategy for vulnerable local communities facing negative impacts on crop yields.

Knowing the projected impact of climate change on WFPs could be useful for climate change adaptation planning, especially in the most vulnerable regions of the world. It could afford valuable time for people to adapt to changing circumstances, especially those communities that already rely on WFPs, or are vulnerable due to crop yield losses, or both. Assessing WFPs as an adaptation strategy is also an important example of the potential for bridging western scientific and traditional knowledge systems to help people adapt to climate change. The use of traditional knowledge for climate change adaptation is potentially a key strength for African communities. This research could also aid in developing advance warning systems that are more inclusive of the full range of food supply options in a region in order to mitigate risk through targeted food security and conservation management actions.

The structure of the thesis

Apart from the Literature Review, the structure of this thesis follows that of a traditional scientific paper, with an Introduction, Materials and Methods, Results, Discussion, Conclusion and Reference section. The Literature Review follows the Introduction, and looks at the importance of wild foods, the impact of climate change on food security and wild foods, and species distribution models.

Literature review

The importance of wild foods

Wild foods, or foods acquired from non-domesticated species, contribute to food security via direct consumption either on a regular basis or in times of shortage, and when sold for income that could be reinvested in other food purchases (FAO, 2019). Wild foods may be gathered, hunted, or fished within both agricultural landscapes and other ecosystems (FAO, 2019). A wide diversity of wild foods exist, including: (1) fruits, vegetables, grains, cereals, nuts, saps and gums from plants; (2) fungi; and (3) animals or animal products, such as honey, birds' eggs, insects, shellfish, fish and meat from vertebrates (World Health Organization & Convention on Biological Diversity (WHO & CBD), 2015).

It is estimated that on a global scale wild foods contribute to the diets of at least one billion people (Burlingame, 2000; Aberoumand, 2009). It is challenging to determine a more precise global estimate since wild foods are typically collected informally and thus data on wild food consumption are often omitted in national inventories and economic assessments (Schulp et al., 2014). Although complete global datasets are lacking, approximations are available for specific regions, types, or sectors of wild food. For example, about 20% of the global population's intake of animal protein is supplied by wild-caught aquatic products (fish, molluscs, crustaceans, and other aquatic animals, excluding aquatic mammals and plants) (FAO, 2018). This number is predicted to be even higher in certain developing countries (e.g. Indonesia, Sri Lanka and several small island developing states), where it is estimated that more than 50% of animal protein intake is derived from wild-caught aquatic species (FAO, 2018). Furthermore, recent research suggests that wild-caught fisheries data reported to the FAO underestimate global fish catches. FAO data show that global marine fisheries catches peaked at 86 million tonnes (MT) in 1996 and have declined by 0.38 MT per year since then (FAO, 2011; 2018). However, research by Pauly and Zeller (2016) suggests global marine fisheries catches peaked at 130 MT in 1996 and have been declining by 1.22 MT per year since. Similar discrepancies can be found in global inland fisheries catches. By means of household consumption surveys from 42 low-and middle-income countries, it was estimated that global inland wild-caught fish catch totals reported to the FAO in 2008 as 10.3 MT, were likely closer to 16.6 MT (Fluet-Chouinard et al., 2018). Apart from fisheries, it is estimated that globally no less than 2 billion people eat at least 1000 species of insects on a regular basis (Van Huis et al., 2013). In 2017, a review of the literature totalled 2111 edible insect species globally (Jongema, 2017). In addition, more than 1100 species of wild fungi are consumed globally, with extensive subsistence use in developing countries (Boa, 2004). In central and southern Africa, wild mushrooms are a valuable addition to diets in rural households, especially during times of the year when food from other resources are perilously low. Furthermore, around 300 million people globally obtain plant and animal foods from forests (Bharucha & Pretty, 2010).

Even though information is incomplete, wild foods make a crucial contribution to the diets of hundreds of millions of people living in developing countries and can be a potential solution for overcoming food insecurity in developing countries (Shaheen et al., 2017). A review of 36 studies in 22 countries in Africa and Asia found a mean range of 90-100 wild food species used per forager or agricultural community (Bharucha & Pretty, 2010). Additionally, it was found that in 24 African, Asian and Latin American countries, in communities that live close to or in forests, 77% of households collected wild foods from both forest and non-forest environments (Hickey et al., 2016). Focussing specifically on forest-dependent communities, it was stated that over 53.5% of households in developing countries consumed one or more type of wild forest food (Rowland et al., 2017). Furthermore, a study that looked at 60 developing countries, estimated that fish and bushmeat provide at least 20% of consumed protein in those countries (Bennet & Robinson, 2000). Bushmeat has been part of the staple diet of forest people in developing countries for millennia (Elliott et al., 2002) and it is estimated that per capita bushmeat consumption, where bushmeat is eaten regularly, range from 0.05 to 0.28 kg/person/day (Coad et al., 2017). Approximately 300 species of mammals alone are consumed on a regular basis (Ripple et al., 2016) and species such as duikers, porcupines and primates are among the most hunted bushmeat species in the African tropical forests (Nasi et al., 2011). For many forest dwelling people, when sold, bushmeat is also a significant source of income that can be reinvested in other food purchases (Milner-Gulland et al., 2003).

Micronutrients, including iron, zinc, omega-3 fatty acids, and vitamins, are only needed by the body in very small amounts, but are essential for human health. Micronutrient deficiencies can increase the risks of reduced immune function, perinatal and maternal mortality, child mortality and growth retardation, as well as cognitive deficits (Black et al., 2013). Currently, around 17% of the global population is zinc deficient, approximately one-third of pregnant women worldwide are vitamin-A deficient and one-fifth have iron-deficiency anaemia (Black et al., 2013). The contribution that wild foods make to nutrition and thus also human health has been reviewed in several publications (Vinceti et al., 2013; Powell et al., 2015; WHO & CBD, 2015; Bioversity International, 2017; HLPE, 2017, Ngome et al., 2017; Van Vliet et al., 2017). It has been found that detailed studies of the nutritional composition of wild foods are lacking. Nonetheless, evidence exists that wild foods contain multiple important micronutrients (Grivetti & Ogle, 2000; Grubben & Denton, 2004; Yang & Keding, 2009; Bharucha & Pretty, 2010; van Huis et al., 2013; Hall et al., 2019). For example, fish is not only a source of protein, but also a crucial source of micronutrients such as zinc, often in highly bioavailable form (Golden et al., 2016). In rice fields in Asia, a wide variety of edible plants or aquatic animals, such as frogs, crabs, snails, crayfish and fish are harvested, supplementing traditional rice only diets (Pingali & Roger, 1995; Balzer et al., 2006; Halwart, 2006, 2008). In Tanzania, wild foods (plants and animals) acquired from agricultural land in a small-scale farming system contributed 16% of calcium, 19% of iron and 31% of vitamin A to the diets of mothers and children, with the maximum contribution in food insecure seasons (Powell et al., 2013). In Madagascar, the number of anaemia cases among children would increase by 29% if access to bushmeat was removed, and in the poorest households, a tripling of anaemia cases were found to be likely (Golden et al., 2011). Furthermore, a positive relationship between tree cover and the dietary diversity of children was shown in 21 African countries, indicating the importance of non-timber forest products (NTFPs) in food security and nutrition (Ickowitz et al., 2014). Various studies have also shown a correlation between declines in health and declines in traditional food use in American Indian and Alaskan Native tribes, including increases in health issues such as diabetes, obesity and cancer, which are rare in communities that make use of traditional foods (Boyce & Swinburn, 1993; Ravussin et al., 1994; Kuhnlein & Receveur, 1996; Teufel, 1996; DeGonzague et al., 1999; Norgaard, 2005; Kuhnlein et al., 2009).

Wild food plants (WFPs), in particular, provide dietary diversity and can make an important contribution to micronutrient intake for the people that rely on them (Grivetti & Ogle, 2000). Currently, food security is dependent on a few widely cultivated crop species. More than 50% of worldwide daily nutritional requirements come from maize, wheat, and rice, with only 12 species contributing around 80% of the global dietary intake (FAO, 2009; Bharucha & Pretty, 2010). Compared to cultivated species, studies on the nutritional properties of WFPs are limited (Vincetti et al., 2008). However, some WFPs have been found to contain more nutrients than their cultivated counterparts (Smith et al., 1996; Kobori & Rodriguez Amaya, 2008), hence their importance as genetic resources for crops (Jarvis et al., 2008b). Ethnobotanical surveys indicate that in human history, over 7000 wild plant species have been consumed by humans at some stage (Grivetti & Ogle, 2000; MEA, 2005). In southern Africa alone, a recent inventory revealed that 1740 plant species have food value (Welcome & Van Wyk, 2019) and in India, 600 plant species are known to be used for human consumption (Rathore, 2009). Furthermore, it has been shown that 50% of all plant species in the arid Ferlo region of Senegal have edible parts (Becker, 1983). In this region, particular wild species consumed during seasonal lean periods are crucial contributors of vitamins A, B2 and C (Becker, 1983). In the Sahel, numerous desert WFPs are sources of essential fatty acids, calcium, iron and zinc (Glew et al., 1997). WFPs consumed during the lean dry season in Nigeria also have a higher micronutrient and energy content, compared to WFPs used in the productive wet season (Lockett et al., 2000). Moreover, in rural southern Malawi, it was found that households living in areas with high forest cover consumed more WFPs and as a result had significantly improved vitamin A adequacy (Hall et al., 2019).

Wild food plants also have a vast number of other uses. For example, of 62 WFPs in Nepal, 80% have manifold uses such as medicine, fuelwood, or fodder (Shrestha & Dhillon, 2006). In the Central Vietnamese Highlands and Mekong Delta, several wild edible species are used as medicine, as well as for livestock feed (Ogle et al., 2003). Furthermore, in Tanzania, the Batemi tribe uses 31 plant species as food, six species as thirst quenchers, seven plants for chewing, two as flavourants and one species to make honey beer, while a further 35 WFPs are being cultivated (Johns et al., 1996).

The impact of climate change on food security and wild foods

Achieving global food security is a complex challenge, especially in light of climate change. Research describing climate impacts in terms of food security has primarily focused on the effect of climate change on agriculture, mostly on a small number of staple crops (Vermeuelen et al., 2012; Challinor et al., 2014; Rosenzweig et al., 2014; Wu et al., 2014; Springmann et al., 2016). A large body of research also exists on the observed and projected impacts of climate change on capture fisheries (Cheung et al., 2013; Youn et al., 2014; Cheung et al., 2016, Golden et al., 2016). A much smaller number of studies have focused on crop wild relatives - wild plant species that are genetically related to crops and not necessarily used for food, but rather as a source of genetic diversity for crop improvement (Jarvis et al., 2008a; Aguirre-Gutiérrez et al., 2017; Van Treuren et al., 2017). Despite the important role WFPs play in food security, especially in developing nations, no studies have looked specifically at the projected impacts of climate change on a broad range of WFPs.

Climate change influences food security, nutrition, and thus also human health. For example, changes in patterns of temperature and rainfall have an impact on water availability, crop yield, livestock death, as well as pests and diseases (Vermeulen et al., 2012; Porter et al., 2014; Hoegh-Guldberg et al., 2018). Climate change also changes the frequency of extreme weather events, such as storms, floods or droughts that reduce crop yields and therefore exposes numerous already vulnerable people in developing countries to the risk of malnutrition following these events (Hoegh-Guldberg et al., 2018). Globally, changes in temperature and rainfall have already negatively impacted crop yields (Carleton & Hsiang, 2016). For example, in the United States, relative to optimal growing conditions, current realised temperatures lower annual maize yields by an estimated 48% (Schlenker & Roberts, 2009; Carleton & Hsiang, 2016). Compared to an unchanged climate, observed climate trends up to the end of the 20th century are also estimated to have reduced rice yield in South Asia by up to 0.76% annually (Welch et al., 2010), as well as caused reductions in global maize and wheat yield of 3.8% and 5.5%, respectively (Lobell et al., 2011). Projected impacts of future climate change under moderate to high warming scenarios are in general much larger than impacts that have already occurred. For example, yields for major crops in the United States are expected to decline between 15-20% by 2050 and 63-82% by 2100 (Schlenker & Roberts, 2009; Houser et al., 2015) under the SRES A1F1 high warming scenario (Cubasch et al., 2013). Across Africa, Schlenker and Lobell (2010) projected that by 2050, crop yields are likely to decline by 17-22% for cassava, maize, millet, sorghum, and groundnuts, under the SRES A1B moderate to high warming scenario (Cubasch et al., 2013). By means of a literature review across all emission scenarios, Knox et al. (2012) estimated that by 2050, mean crop yield in Africa would reduce by between 5-17% for maize, millet, sorghum, and wheat. Apart from reducing crop yield, it is also anticipated that climate change would affect the nutritional value of food crops. For example, wheat, rice and maize grown under elevated CO_2 concentrations (546-586 parts per million) contained between 3-9% less zinc, iron and protein, while soybean contained less zinc and iron, but not protein (Myers et al., 2014). It is expected that developing countries, that are already highly reliant on these staple crops, will experience the most severe impacts of climate change, attributable to little adaptation capacity, extreme poverty, and poor infrastructure (Ikeme, 2003; Brooks, Adger & Kelly, 2005; Tschakert, 2007). Comparing all developing regions, sub-Saharan Africa is anticipated to be hardest hit by climate change due to the instability of the region's economy, in combination with already high temperatures and its dependence on rain-fed agriculture (Niasse, Afoud & Amani, 2004). Only 5% of all cultivated land in sub-Saharan Africa is irrigated, compared to 37% in Asia and 14% in Latin America (Ringler et al., 2010). Thus, under future climate change conditions, vulnerable people in developing countries in sub-Saharan Africa could become much more reliant on wild foods.

Wild foods already provide a critical buffer against climate-related food stress and can be essential livelihood safety nets, especially when other sources of food fail. Even though certain wild foods are consumed continuously, many others are used during times of famine as a reserve food supply. In many of these cases, wild foods are not necessarily preferred, but are essential during lean seasons of the year, years when agricultural output is low, or during other natural disasters, extreme weather or climate impacts (Arnold et al., 2011; Mavengahama et al., 2013; Vinceti et al., 2013; Wunder et al., 2014; Shumsky et al., 2015). For example, Humphry et al. (1993) noted that 83% of surveyed households in Niger reported greater reliance on wild foods in times of drought. In southern Africa, Akinnifesi et al. (2006) reported that 60-85% of rural people experience food shortages during three to four months in a year and up to 50% of these people use WFPs to sustain their livelihoods. During the non-agricultural season in the Caprivi region of Namibia, WFPs provide around 50% of rural household subsistence (Ashley & LaFranchi, 1997). In lean times in Zimbabwe, the quantities of wild fruits consumed and sold to generate income for additional food expenses increases in poor rural households (Mithöfer & Waibel, 2004). In Botswana, when drought leads to crop failure, rural communities rely on WFPs to sustain their livelihoods until conditions improve (Twyman, 2001; Ohiokpehai, 2003; Mojeremane & Tshwenyane, 2004). Wild foods can thus increase resilience to climate change impacts, however, limited research has been done on the subject. Robledo et al. (2012) conducted household surveys to determine climate change adaptation strategies in Mali, Tanzania, and Zambia. It was found that forest products played a crucial role in reducing household vulnerability to climate change by providing alternative sources of food and income during droughts and floods. Heubes et al. (2012) used local surveys to map the economic value of three important wild food and export plant species in Benin, West Africa - *Adansonia digitata* (baobab), *Parkia biglobosa* (African locust bean tree), and *Vitellaria paradoxa* (shea tree). The authors assessed the incomes earned from these species against their current and future probability of occurrence using niche-based models. It was found that due to climate change, as much as 50% of the current economic value of these wild tree species may be lost by 2050 under the SRES A2 scenario, a high warming scenario (Cubasch et al., 2013).

As with all plant species, climate conditions are an important determinant of the distribution of WFPs. Over the past century, climatic change has substantially impacted the distribution, abundance, physiology and phenology of a wide variety of species with numerous studies having already recorded these impacts (Walther et al., 2002; Root et al., 2003; Parmesan, 2006; Jarvis et al., 2008a; Chen et al., 2011; Lenoir & Svenning, 2015; Wiens, 2016; Tomotani et al., 2018; Maire et al., 2019). A study by Thomas et al. (2004) was one of the first to project that globally, due to climate change, ~18% (low emissions scenario) to ~35% (high emissions scenario) of plant, vertebrate and insect species would be threatened with extinction by 2050, with numbers increasing further by 2100. Climate change extinction predictions since this early study vary widely, projecting that anything between 0-54% of species may be lost (Malcolm et al., 2006; Foden et al., 2013; Warren et al., 2013; Urban, 2015). A more recent global study by Warren et al. (2018) projected the effects of limiting global warming to 1.5°C rather than 2°C on 105 000 species of insects, plants, and vertebrates. For global warming of 1.5°C, 4% of vertebrates, 6% of insects and 8% of plants are projected to lose more than 50% of their climatically determined range, compared with 8% of vertebrates, 18% of insects and 16% of plants for global warming of 2°C (Warren et al., 2018). In sub-Saharan Africa, climatically suitable habitat for 81-97% of nearly 5200 plant species is projected to either shift or decrease in size due to climate change by 2085, under the SRES B1 low emissions scenario (McClean et al., 2005). Under the same scenario, 25-42% of the habitat of species is expected to be lost completely (McClean et al., 2005). In addition, it is also predicted that the crop wild relatives of 61% of peanut, 12% of potato and 8% of cowpea species could be extinct within as little as 50 years (Jarvis et al., 2008a). This is due to these species losing over 50% of their climatically determined range size under a high emissions scenario (Jarvis et al., 2008a). Climate related changes in distribution, abundance, physiology, or phenology, can also be expected for wild food species. American Indian and Alaskan Native tribal harvesters have already noticed changes in harvest times for traditional WFPs (Lynn et al., 2013). A recent assessment by the FAO (2019) used reports submitted by 91 countries on the state and management of their biodiversity that contributes to food and agriculture. A number of country reports included threats from climate change that would also impact wild foods. For example, in the Amazon, it was communicated that climate change is projected to bring about "savannisation" of forest habitats, which could have an effect on the supply of WFPs. Peru reported that shifts in fruiting seasons are anticipated to reduce availability of certain wild fruits. Finland noted that due to the country's northern position, poleward movement of the coniferous zone would lead to changes in the availability of berries and wild mushrooms. Finland also reported that earlier flowering may also negatively impact wild berry availability, due to a risk of frost exposure. In the case of Eswatini, it was reported that erratic rainfall and altered precipitation patterns are projected to inhibit seed germination of WFPs.

Although wild food species are at risk from climate change, many wild animal and plant species may hold an innate resilience to climate variability and change, which is not always found in domesticated or cultivated species (Fentahun & Hager, 2009). WFPs in particular, are often adapted to grow in poor soils and low rainfall regions, and can also have fewer diseases and insect pests than traditional staple crops, providing a yield even when other crops fail (Legwaila et al., 2011). Indigenous fruit trees, which include wild fruit trees, contribute more than 40% to the food basket for many rural people in southern Africa (Akinnifesi et al., 2006). These trees also produce more fruits per unit area than a number of exotic fruit trees (Legwaila et al., 2011). Therefore, wild food species could play a progressively more important role in times of low agricultural yield as a result of changing climate conditions, especially in low income communities. Given the projected impact of global climate change on food security, assessing climate change risks to WFPs in order to inform conservation and adaptation responses, are key actions to assist with food security in the most vulnerable societies of the world.

Species distribution models

For many species, distribution changes are the primary response to climate change. For example, with increasing temperature, species that are able to move will generally seek out suitable habitat at higher altitudes and latitudes. To predict species responses to climate change, researchers make use of biodiversity modelling at either the species level or the ecosystem level. Species distribution models (SDMs) are commonly used for these predictions. SDMs use species distribution records or abundances (current observations of where species occur) and correlate it with present environmental conditions (reviewed in Guisan & Zimmerman, 2000; Guisan & Thuiller, 2005; Elith et al., 2006). Possible future climate conditions are then entered into a statistical model and it will calculate probable species distribution under those future climate conditions.

Popular uses of SDMs include: conservation planning to support conservation prioritization and reserve design, and to guide reintroduction of endangered species (Pearson, 2007); to assess the impacts of climate and land-use change on species movement (e.g. Berry et al., 2002; Yates et al., 2010; Guerin & Lowe, 2013; Warren et al., 2013; Newbold, 2018; Warren et al., 2018); to predict distributions of known and unknown species (e.g. Raxworthy et al., 2003); or to predict spreading of invasive species (e.g. Thuiller et al., 2005).

A limitation of SDMs is that forecasting is in part based on assumptions. It assumes that a species is occupying its fundamental niche (the environment a species *can* occur in under ideal conditions), this rarely happens in nature (Pearson, 2007). In reality, species distribution typically reflects the realized niche (the environment a species *does* occur in) (Pearson, 2007). In addition, other factors such as predation and competition also play a role in limiting where species can occur – SDMs does not take this into account. SDMs also tend to fall short if a species has recently been introduced to an area and is still expanding in its new range (Pearson, 2007).

It is not within the scope of this thesis to describe the theory, advantages and disadvantages of a large number of SDMs. However, it will be useful to mention one of the most popular methods, MaxEnt. This algorithm is commonly used where only presence data are available (Phillips et al., 2006). As input, MaxEnt takes a list of species presence locations (presence-only data), and a set of environmental predictors (e.g. temperature or precipitation) across a user-defined landscape which is split up into grid cells (Merow et al., 2013). MaxEnt then extracts a sample of background locations from this user-defined landscape, which it contrasts against the presence locations (Merow et al., 2013). At these background locations, presence is unknown (Merow et al., 2013). The Inhomogeneous Poisson Point Process models (Warton & Shepherd, 2010; Renner et al., 2015) that are used in this study to estimate the historical range of species and subsequently to make spatial projections for future climate scenarios, are a generalisation of the MaxEnt algorithm.

Materials & Methods

My study investigates climate change risk to a broad group of WFPs and focusses on the WFPs of southern Africa. The aims of my study are to determine where WFPs occur in southern Africa; whether these WFPs will be threatened by climate change; and how climate change risk for WFPs intersects with climate change risk to staple crops.

Species distribution models were used to obtain the historical geographic range of 1190 WFP species and to make projections of range change for 2070 under both low (RCP 2.6) and high (RCP 8.5) greenhouse gas emissions scenarios. I also mapped percentage change between historical and future yields for maize and sorghum to identify regions where both crops and WFPs, or just one of these are at risk from climate change.

Wild food plant species

To identify WFPs I used a recently published list of 1740 southern African edible plant species (Welcome & Van Wyk, 2019). The list includes food plants from Botswana, Eswatini (formerly Swaziland), Lesotho, Namibia, and South Africa. It is the most comprehensive inventory of wild edible plants in southern Africa to date, and one of the most comprehensive globally for known usage of WFPs by local communities. I removed all plant species from the list that are non-indigenous, in order to focus only on the WFPs that are native to southern Africa. In order to do this I used the classification of species as either indigenous or not that was provided by Welcome and Van Wyk (2019). All native WFP species (n=1479) were run through The Taxonomic Name Resolution Service (http://tnrs.iplantcollaborative.org), a web service that corrects spelling errors, checks for alternative spellings, and converts synonyms to the current accepted name. The inventory by Welcome and Van Wyk (2019) also includes information on what part of the plant is used, how it is used, as well as the plant species used by a selection of indigenous language/ethnic groups for which adequate information was available. I used this additional information to show WFP species range changes according to categories of use, as well as species used by different ethnolinguistic groups.

Species occurrence records

Wild food plant occurrence records were obtained from the Botanical Information and Ecology Network (BIEN) (http://bien.nceas.ucsb.edu/bien/). Occurrence records passed BIEN's geovalidation filters to remove records with errant coordinates and check that the latitude and longitude of a recorded observation falls within its specific declared political divisions (http://bien.nceas.ucsb.edu/bien/biendata/bien-3/validation/). A number of steps were performed to prepare occurrence records before modelling. Firstly, for species with more than 20 occurrences, occurrences were thinned to ensure that all retained records were at least 20km from one another in order to reduce spatial autocorrelation (Aiello-Lammens et al., 2015). Secondly, outliers in geographic and environmental space were determined based on a Grubb's outlier test with p=0.0001 (Grubbs, 1950) (implemented with the *R* package outliers (Komsta, 2011)). We chose this small p-value to make sure that only fairly obvious outliers were removed. All outliers were discarded. Finally, presences were clustered into five folds spatially stratified for cross-validation. The basic idea of spatial cross validation is to repeatedly split a dataset into test and training sets whereby the training data can be used to fit a model which is then applied to a test set. Only species with 10 or more records were retained and used in subsequent analyses (n=1190, representing 80% of identified native WFPs in the southern African region).

Historical climate and environmental data

Environmental predictors included six climate and five soil layers. 30-year time-averages of historical climate data were downloaded from WorldClim version 2.0, at a spatial resolution of 10 km, for the period 1970-2000 (Fick & Hijmans, 2017). To reduce collinearity among climate variables in the species distribution models, four bioclim variables were chosen from the full set of 19 bioclim variables, based on their low correlation with each other ($r < 0.7$): mean annual temperature, mean diurnal temperature range, annual precipitation, and precipitation seasonality. Two additional variables were added based on expert recommendation and since they also had a correlation coefficient of $r < 0.7$ with the four selected bioclim predictors. These were aridity, calculated as the maximum accumulated water deficit, and precipitation in the warmest quarter divided by the sum of precipitation in the warmest quarter and precipitation in the coldest quarter. Five soil layers were obtained from https://soilgrids.org. These were bedrock depth, mean bulk density, mean pH, proportion silt, and proportion clay in the first four soil horizons. To generate the soil layers, the 250m resolution layers available on soilgrids.org were aggregated to the 10km grid defining the climate layers. These aggregated layers correlated at $r < 0.7$ with the climate layers. Soil moisture may be an additional important variable but it was not used in this study.

The set of 11 predictor variables was the starting point for modelling the distribution of each species. Within each species-specific model domain, however, the 11 predictors were further subset to ensure they had $r < 0.7$ within the modelling domain by retaining the largest subset of predictors below this correlation level. This emphasis on removing correlated predictors for each species was done to reduce the influence of correlations among predictor variables on the fitted models, when projecting the future range of each species.

Future climate scenarios

Future climate data for 20-year time averages were downloaded from WorldClim version 1.4 (https://worldclim.org/data/v1.4/cmip5.html), at a spatial resolution of 10km, for the period 2061-2080. Future climate projections from seven Coupled Model Intercomparison Project

(CMIP5) Global Climate Models (GCMs), that were downscaled and calibrated by WorldClim (Hijmans et al., 2005), were used in this study (Table 1). Temperature and precipitation for future climates have been downscaled and bias-corrected by WorldClim using a change factor approach where the difference in the GCM output between the simulated historical and future period is calculated, resulting in climate anomalies which are then applied to the 10 km resolution observed historical dataset. This approach makes the assumption that the change in climate is relatively stable across space (that is, has high spatial autocorrelation). We note that this may result in less accurate downscaling than when using dynamical downscaling methods, particularly in mountainous areas.

Data were downloaded for two future greenhouse gas scenarios: representative concentration pathway (RCP) 2.6 and RCP 8.5 (van Vuuren et al., 2011). RCP 2.6 is a low emissions scenario, likely keeping global warming below 2°C by 2081-2100 compared to 1850-1900, whereas RCP 8.5 has been characterised as an extreme high emissions scenario representing more than 4°C of global warming by 2081-2100 (Cubasch et al., 2013).

Table 1. The seven Global Climate Models (and their abbreviations) from which data on future climate projections were used for this study.

Global Climate Model	**Abbreviation**	**Reference**
Beijing Climate Center, Climate System Model, version 1.1	BCC-CSM1.1	Xin et al., 2013
Community Climate System Model, version 4	CCSM4	Gent et al., 2011
Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5	CNRM-CM5	Voldoire et al., 2013
Geophysical Fluid Dynamics Laboratory Climate Model, version 3	GFDL CM3	Griffies et al., 2011
Hadley Centre Global Environment Model, version 2, Earth System	HadGEM2-ES	Collins et al., 2011
Model for Interdisciplinary Research on Climate, Earth System Model	MIROC-ESM	Watanabe et al., 2011
Max Planck Institute Earth System Model, low resolution	MPI-ESM-LR	Giorgetta et al., 2013

Species distribution modelling

Inhomogeneous Poisson Point Process (PPM) models (Warton & Shepherd, 2010; Renner et al., 2015) were used to estimate the historical range of species and subsequently to make spatial projections for future climate scenarios. Future distributions, under RCP 2.6 and RCP 8.5, were predicted for every species for each of the seven different GCMs.

PPMs are a generalisation of the MaxEnt algorithm, which is commonly used where only presence data are available (Phillips et al., 2006). PPM settings were chosen to balance underfitting (that is, excessively smooth models that over predict range size) with overfitting that would underestimate species range sizes. PPM models were fitted using regularized down-weighted Poisson regression (Renner et al., 2015) in the *R* package *glmnet* (Friedman et al., 2010). Different feature classes of increasing complexity were added, depending on the number of occurrence records available for each species: linear and quadratic for all species, product for species with more than 100 records, and hinge for species with more than 200 records. When models failed to converge with more complex feature classes the next simpler feature set in this hierarchy was used. Linear and quadratic features were always paired together to ensure modal responses were always included as an option, in order to reflect that species often exhibit modal responses to environmental gradients. In cases where linear and quadratic features failed, the number of predictor variables was reduced by selecting the five (or three, if five failed) predictors with the highest univariate correlations with presence data, in order to generate linear and quadratic features. This sequential approach of applying simpler features increases the robustness of the modelling approach to idiosyncrasies in data for individual species. This is in order to ensure that models could be fit for each species with 10 or more presence records.

The regularisation parameter was determined based on 5-fold cross-validation with each fold, choosing a value one standard deviation below the minimum deviance (Hastie et al., 2009). The resulting five models for each species were combined in an unweighted ensemble, which is interpreted as a relative occurrence rate (ROR) (Fithian & Hastie, 2013; Merow et al., 2013). Continuous predictions of ROR were converted to binary absence/presence predictions for each species by choosing a threshold based on the fifth percentile of training presence locations.

When projecting species occurrences using future climate scenarios, extrapolation in the species distribution model was limited to one standard deviation beyond the data range of the observed occurrence records for each predictor variable. This approach was used to allow for a small amount of extrapolation beyond the modelled limits of the observed species niche, while also limiting the influence of monotonically increasing marginal responses. The latter can lead to statistically unsupported and likely biologically unrealistic projections of species responses to climate change.

Due to lack of data on dispersal distances, species-specific dispersal capacity was not included in modelling changes in species range in response to future climate change scenarios. Instead, spatial predictions of future occurrences were constrained to be in the WWF ecoregions (Olson et al., 2001) where a species occurs currently, and the immediate neighbours of those ecoregions. Although ecoregions differ in size, this approach prevents predictions of future occurrences being extreme distances away from the current range of each species. It is preferred to a strict spatial rule, because it integrates the high degree of biome-level niche conservatism found in southern African plant species ranges (Crisp et al., 2009) into the modelled dispersal constraint.

Analysis of model outputs

For every species, I made majority consensus maps for future species distributions under RCP 2.6 and RCP 8.5. This was done by only assigning a species as present if a majority (four out of seven) of the species distribution models from the GCMs agreed on the species being present in a given 10km grid cell. I calculated the projected change in species richness for each grid cell under each scenario, by adding up the number of species presences in each grid cell for the historical time period (1970-2000) and each future scenario, and then subtracting the historical value from the future value.

For each species, I also calculated the percentage change in geographic range extent between future and historical modelled geographic ranges using the BIOMOD RangeSize function in *R* (Thuiller et al., 2019). I calculated the mean range change for each species across the seven GCMs, and additionally calculated the range change by category of plant use, as well as by ethnolinguistic group use.

Crop yields and wild food plants

In order to determine whether the projected change in WFP species richness overlaps with regions where agricultural crop yield losses are expected due to climate change, I downloaded crop yield data for maize (*Zea mays*) and sorghum (*Sorghum bicolor*) from The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (www.isimip.org). Data were downloaded under the ISIMIP Fast Track simulation protocol, as this was the only protocol with RCP 8.5 data available. I chose maize and sorghum because these are two of the most important agricultural crops for small scale farmers in southern Africa (Zinyengere et al., 2014). Crop yield raster maps were downloaded for historical, as well as future climate conditions, under RCP 2.6 and RCP 8.5, at 0.5°x0.5° regular global grid resolution, with CO_2 fertilisation, and Shared Socioeconomic Pathway (SSP) scenario two. SSP2 is a "middle of the road" scenario of projected socioeconomic global change up to 2100, where trends are expected to follow their historical patterns, with medium challenges to adaptation and mitigation (Riahi et al., 2017). In addition, a no irrigation scenario was chosen, as most small-holder farmers in southern Africa depend only on rain for crop production and would likely include those communities that make use of WFPs in times of hardship.

Maize yield data were downloaded for four crop models, and sorghum yield data for two crop models (Table 2). Each crop model had projections for five different GCMs (Table 2), totalling 20 model runs for maize and 10 model runs for sorghum, for each of the historical conditions, RCP 2.6 and RCP 8.5. I retained only annual crop yield projections in years that matched historical

(1970-2000) and future (2061-2080) climate time periods available for WFPs. For each crop model, I first calculated the mean of the yield data for the five available GCMs, and then the mean across crop models to get the overall mean crop yield for maize and sorghum for historical conditions, RCP 2.6, and RCP 8.5. To enable comparison of projected changes in crop yield and WFP species richness, WFP projections were re-gridded using nearest neighbour interpolation to match the lower 0.5° spatial resolution of the crop yield data. I mapped the percentage change between future and historical crop yield and used these maps, together with maps of percentage change in WFP species richness, to identify regions where both crops and WFPs, or just one of these are at risk. For this analysis, only WFPs that are used as a snack, fresh or in situ (n=686), cooked vegetables (n=407), ground as flour (n=91), and famine food (n=64) were included (Welcome & van Wyk, 2019) . This selection of WFPs represents 81% of the total number of species used in this study. Wild food plants in these categories of use were chosen as they are the most likely to replace staple crops, such as maize and sorghum, when these crops fail.

Table 2. The four crop models and five Global Climate Models used to project future crop yield change under RCP 2.6 and RCP 8.5. All models were used in projections for maize and sorghum, except GEPIC and LPJ-GUESS that were not available for sorghum.

Crop model	**Abbreviation**	**Reference**
Environmental Policy Integrated Climate model, run by the University of Natural Resources and Life Sciences Vienna (BOKU)	EPIC-BOKU	Kiniry et al., 1995
Geographic Information System-based Environmental Policy Integrated Climate Model	GEPIC	Folberth et al., 2012
Integrated Model to Assess the Global Environment	IMAGE	Bouwman et al., 2006
Lund Potsdam Jena General Ecosystem Simulator	LPJ-GUESS	Lindeskog et al., 2013
Global Climate Model	**Abbreviation**	**Reference**
Geophysical Fluid Dynamics Laboratory Earth System Model with MOM, version 4 component	GFDL-ESM2M	Dunne et al., 2012; 2013
Hadley Centre Global Environment Model, version 2, Earth System	HadGEM2-ES	Collins et al., 2011
L'Institut Pierre-Simon Laplace Coupled Model, version 5A, low resolution	IPSL-CM5A-LR	Dufresne et al., 2013
Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry Coupled	MIROC-ESM-CHEM	Watanabe et al., 2011
Norwegian Earth System Model, version 1 (intermediate resolution)	NORESM1-M	Bentsen et al., 2013

Results

WFP species richness in southern Africa generally increases from west to east across the region with the Eastern Cape, Kwazulu-Natal and Mpumalanga provinces of South Africa having the highest species richness (Figure 1A). Within the western part of the region, there is a north-south gradient of increasing WFP species richness from more arid habitats in Namibia to the Cape Floristic Region in the Mediterranean climate zone of South Africa. These spatial patterns in WFP species richness stay the same when looking at individual categories of the uses of particular WFPs most important for food security and as nutritional supplements (Figure 1B-E).

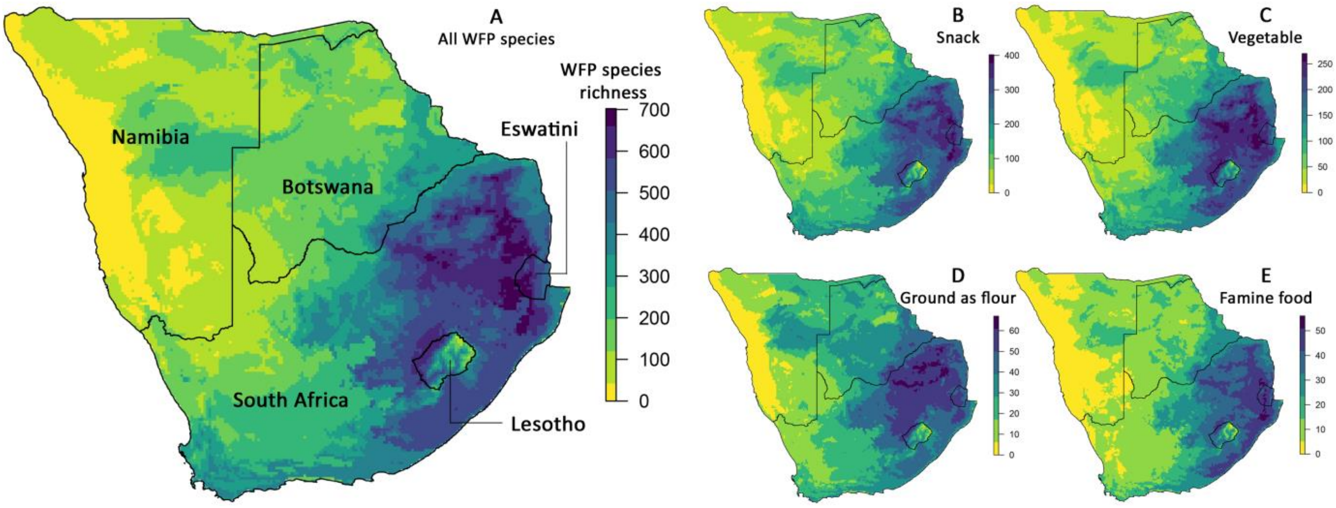

Figure 1. Wild food plant (WFP) species richness in five southern African countries: Botswana, Eswatini, Lesotho, Namibia, and South Africa. A – all WFP species modelled in this study (n=1190); B – species eaten as snack, fresh or in situ (n=686); C – species eaten as cooked vegetables (n=407); D – species that are ground as flour (n=91); E – species used as famine food in times of hardship (n=64).

Of the 1190 native WFP species with 10 or more occurrence records available, it is projected that under RCP 2.6, a low warming scenario, 40% of species will experience a decrease in range extent within southern Africa (Figure 2A). Of these species, 38% are expected to lose up to 25% of their range, 3% lose more than 25%, and only 1% lose more than 50% of their range (Figure 2A). However, species gaining range extent outnumber those projected to have range losses, with a total of 60% expected to experience a range increase under RCP 2.6 (Figure 2A). Of these species, 40% are expected to gain up to 25% in range, while 20% of species gain more than 25% in range (Figure 2A). No regional species extinctions, estimated as more than 90% range loss, were projected under RCP 2.6.

In contrast, under RCP 8.5, the extreme warming scenario, the pattern of projected range change is reversed, with a majority (66%) of native WFP species projected to suffer a decrease in range extent within southern Africa (Figure 2B). Of these species, 44% are expected to lose up to 25% of their range, while 22% lose more than 25%, and 4% lose more than 50% in range extent (Figure 2B). Only

34% of species are projected to experience a range increase under RCP 8.5, of which 19% are expected to gain up to 25%, and 15% gain more than 25% in range (Figure 2B). Five regional species extinctions, estimated as more than 90% range loss, were projected under RCP 8.5. These species are *Combretum engleri*, used as a snack; *Euphorbia inermis*, used as a snack and cooked vegetable; *Grewia schinzii,* used as a snack and non-alcoholic beverage; *Searsia horrida*, used as a snack and to curdle milk; *Vachellia hebeclada*, used as a snack.

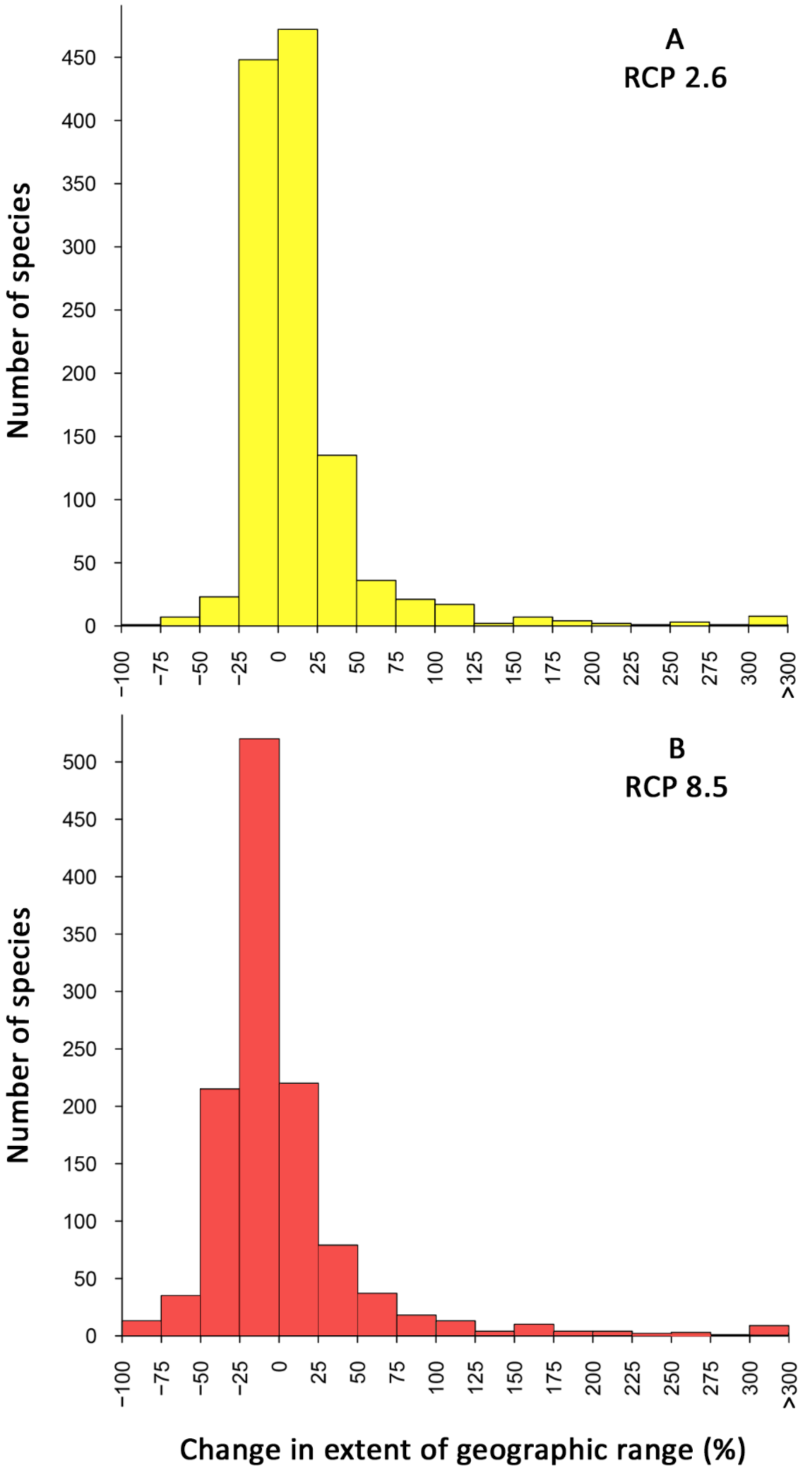

Figure 2. The mean change in extent of geographic range (%) for 1190 southern African native wild food plant species calculated from seven Global Climate Models under RCP 2.6 (A) and RCP 8.5 (B).

Under RCP 2.6 the loss of suitable climatic conditions is projected to decrease species richness of WFPs most in the north-eastern parts of southern Africa with local extinctions of more than 100 species (Figures 3A and B). This pattern is intensified under RCP 8.5 with multiple regions in north-eastern South Africa projected to have decreases of more than 200 species and local species losses of more than 50% of WFPs are projected for most of Botswana (Figures 3E and F). In contrast, increases in local species richness are projected in more southern and eastern regions due to species shifting their ranges southward and into cooler montane regions under both RCP 2.6 and RCP 8.5 (Figures 3B and F). The largest relative local species richness increases are projected in the western parts of southern Africa, with increases of more than 270% on the west coast of Namibia, although this represents a small change in absolute numbers of species - 12 species under RCP 2.6 and 14 species under RCP 8.5 (Figures 3A and E). Further large increases of between 25-125% are projected in the south to south-eastern regions of South Africa (Figures 3A and E).

Most categories of WFP use are projected to have more species undergo increases than decreases in range extent under RCP 2.6 (Figure 4). Specifically, all categories are projected to have more than 50% of species experience range increases, except for species used to curdle milk, as syrup, and as yeast (Table 3). However, under RCP 8.5 overall range decreases are projected for over 50% of species in every use category except alcoholic beverages (45% of species), with some categories projected to be more negatively affected than others (Figure 4; Table 3). For example, overall range decreases are projected for over 70% of species used as milk curdlers (74%), sources of moisture/thirst quenchers (77%), preservatives (73%), thirst or appetite suppressants (91%), syrup (83%), tea substitutes (80%), and as yeast (78%) (Table 3). When looking at the categories of use of WFPs most important for food security and as nutritional supplements, 59-69% of species are projected to experience decreases in range under RCP 8.5. These include species used as cooked vegetables (69%), as famine food (59%), ground as flour (67%), and eaten as snacks, fresh or in situ (63%) (Table 3).

Most WFPs used by each ethnolinguistic group are projected to undergo range extent increases under RCP 2.6 (Figure 5). More than 50% of species are projected to experience range increases for all ethnolinguistic groups, except for species used by the Xóõ ethnolinguistic group, from the dry Kalahari region of Namibia, Botswana, and South Africa (49% of species) (Table 4). However, under RCP 8.5, range decreases are projected for more than 50% of species in every ethnolinguistic group, except the Lozi from the Caprivi Strip in Namibia and northern Botswana (47% of species), with some ethnolinguistic groups expected to be more negatively affected than others (Figure 5; Table 4). For example, overall range decreases are projected for over 70% of species used by the Southern Sotho (76%), the Xhosa (71%), and Xóõ (74%) ethnolinguistic groups.

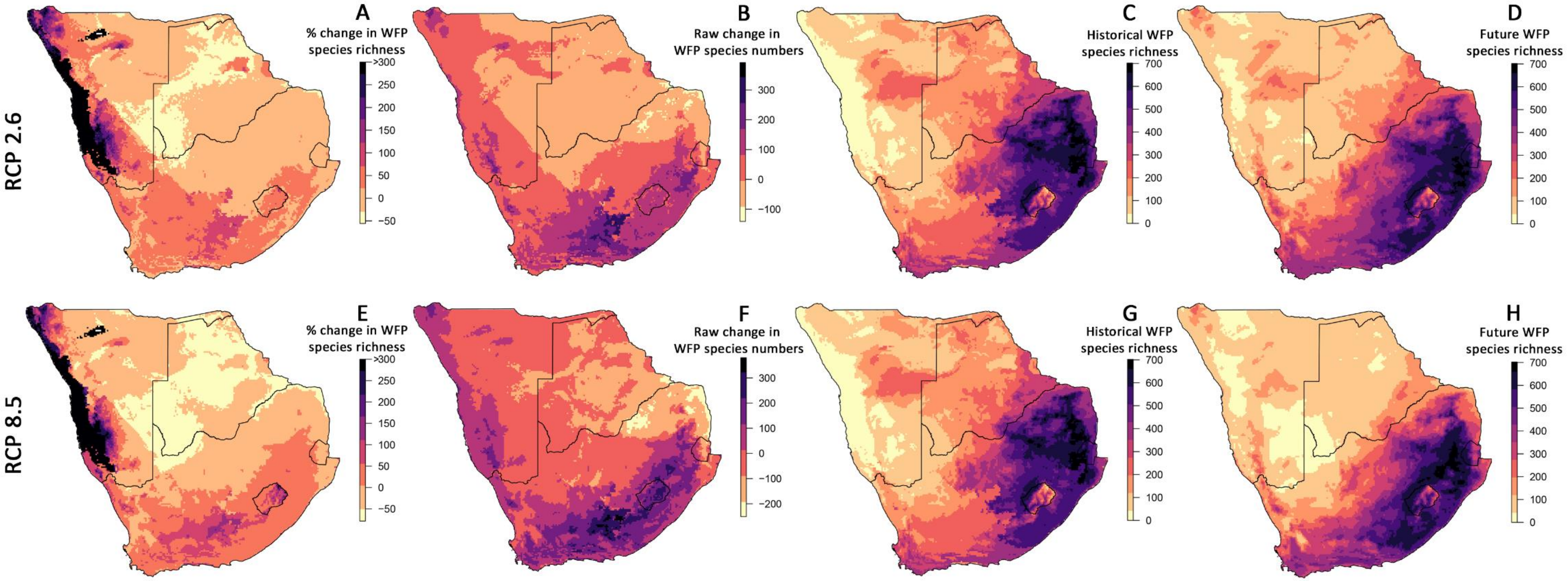

Figure 3. The % change in wild food plant (WFP) species richness for RCP 2.6 (A) and RCP 8.5 (E), the raw change in WFP species numbers for RCP 2.6 (B) and RCP 8.5 (F), WFP species richness modelled for historical (1970-2000) (C,G) and future (2061-2080) climate conditions, under RCP 2.6 (D) and RCP 8.5 (H).

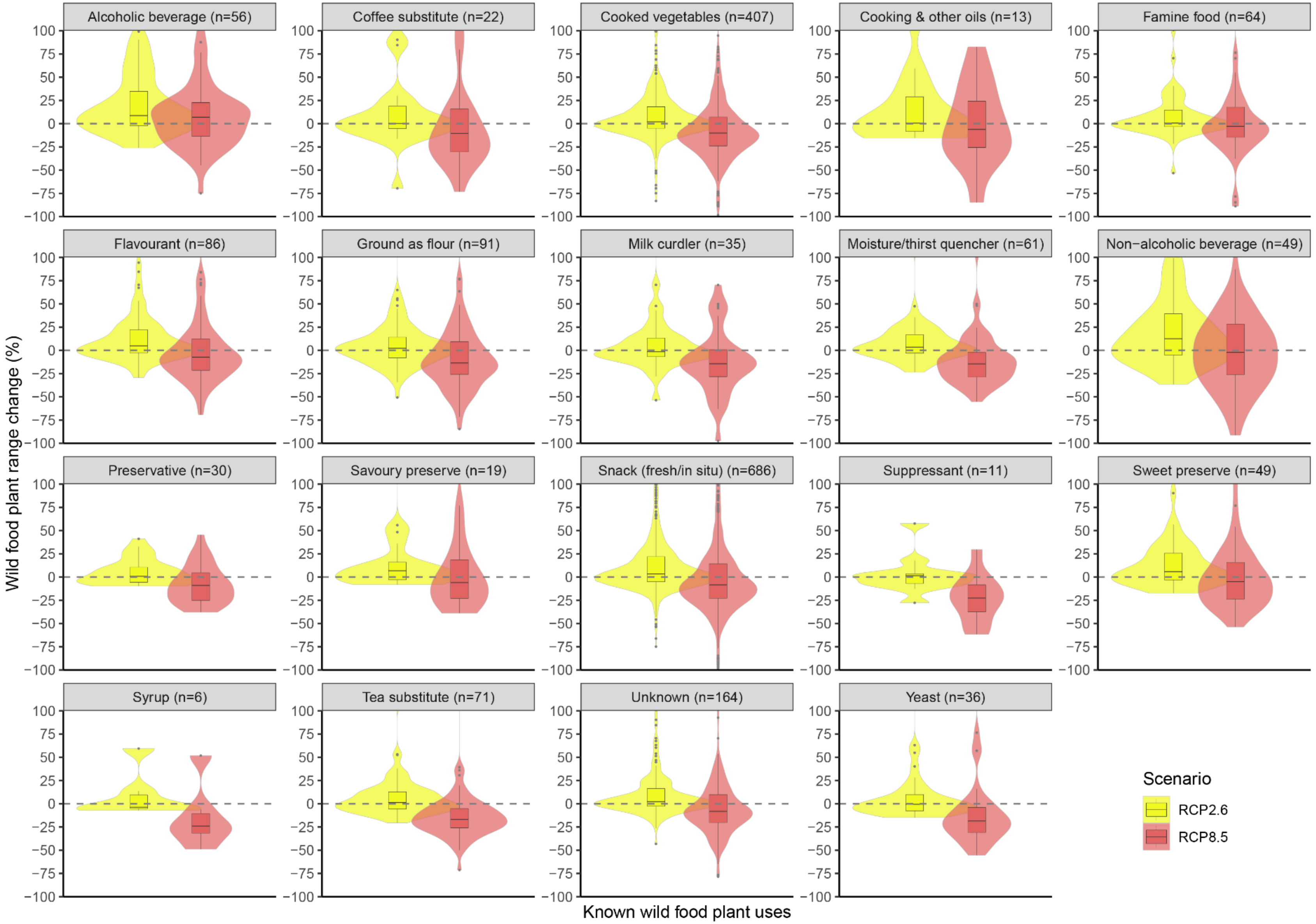

Figure 4. Projected percentage change in wild food plant range extent by category of plant use for RCP 2.6 (yellow) and RCP 8.5 (red). Only range increases of up to 100% are shown, as most of the species range change lies within this limit (see figure 2). The median, 25th and 75th percentiles are shown by box plots within the violin plots. Potential outliers are indicated by grey dots. The numbers of species (n) are shown for each category of use. Categories of use are those described in Welcome and Van Wyk (2019).

Table 3. The percentages of wild food plant species, for each of 19 categories of plant use, that are projected to either experience a range loss or gain under RCP 2.6 and RCP 8.5. The numbers of species (n) are shown for each category of plant use. Where the total percentage of species with range loss or range gain for a given scenario is greater than 50%, this is shown in bold.

	% of species with range loss				**% off species with range gain**			
	RCP 2.6 range loss (%)		**RCP 8.5 range loss (%)**		**RCP 2.6 range gain (%)**		**RCP 8.5 range gain (%)**	
	0-25%	**>25%**	**0-25%**	**>25%**	**0-25%**	**>25%**	**0-25%**	**>25%**
All species (n=1190)	37	3	**44**	**22**	**40**	**20**	18	16
Categories of use important during famine:								
Famine food (n=64)	39	2	**45**	**14**	**38**	**22**	22	19
Ground as flour (n=91)	37	5	**40**	**27**	**40**	**18**	18	15
Cooked vegetables (n=407)	39	4	**44**	**24**	**40**	**18**	17	14
Snack (fresh/in situ) (n=686)	37	3	**41**	**22**	**38**	**23**	19	18
Other categories of use:								
Alcoholic beverage (n=56)	30	2	30	14	**36**	**32**	**34**	**21**
Coffee substitute (n=22)	44	5	**27**	**36**	**33**	**18**	18	18
Cooking & other oils (n=13)	38	0	**23**	**31**	**31**	**31**	23	23
Flavourant (n=86)	35	2	**43**	**22**	**40**	**23**	19	16
Milk curdler (n=35)	**51**	**6**	**46**	**29**	26	17	11	14
Moisture/thirst quencher (n=61)	34	0	**46**	**31**	**49**	**16**	16	7
Non-alcoholic beverage (n=49)	33	6	**22**	**29**	**24**	**37**	22	27
Preservative (n=30)	49	0	**47**	**27**	**38**	**13**	20	7
Savoury preserve (n=19)	37	0	**42**	**21**	**42**	**21**	16	21
Suppressant (n=11)	36	9	**55**	**36**	**45**	**9**	0	9
Sweet preserve (n=49)	37	0	**35**	**24**	**35**	**29**	22	18
Syrup (n=6)	**67**	**0**	**50**	**33**	17	17	0	17
Tea substitute(n=71)	45	0	**54**	**27**	**44**	**11**	14	6
Unknown (n=164)	38	1	**47**	**18**	**45**	**16**	21	14
Yeast (n=36)	**53**	**0**	**42**	**36**	33	14	11	11

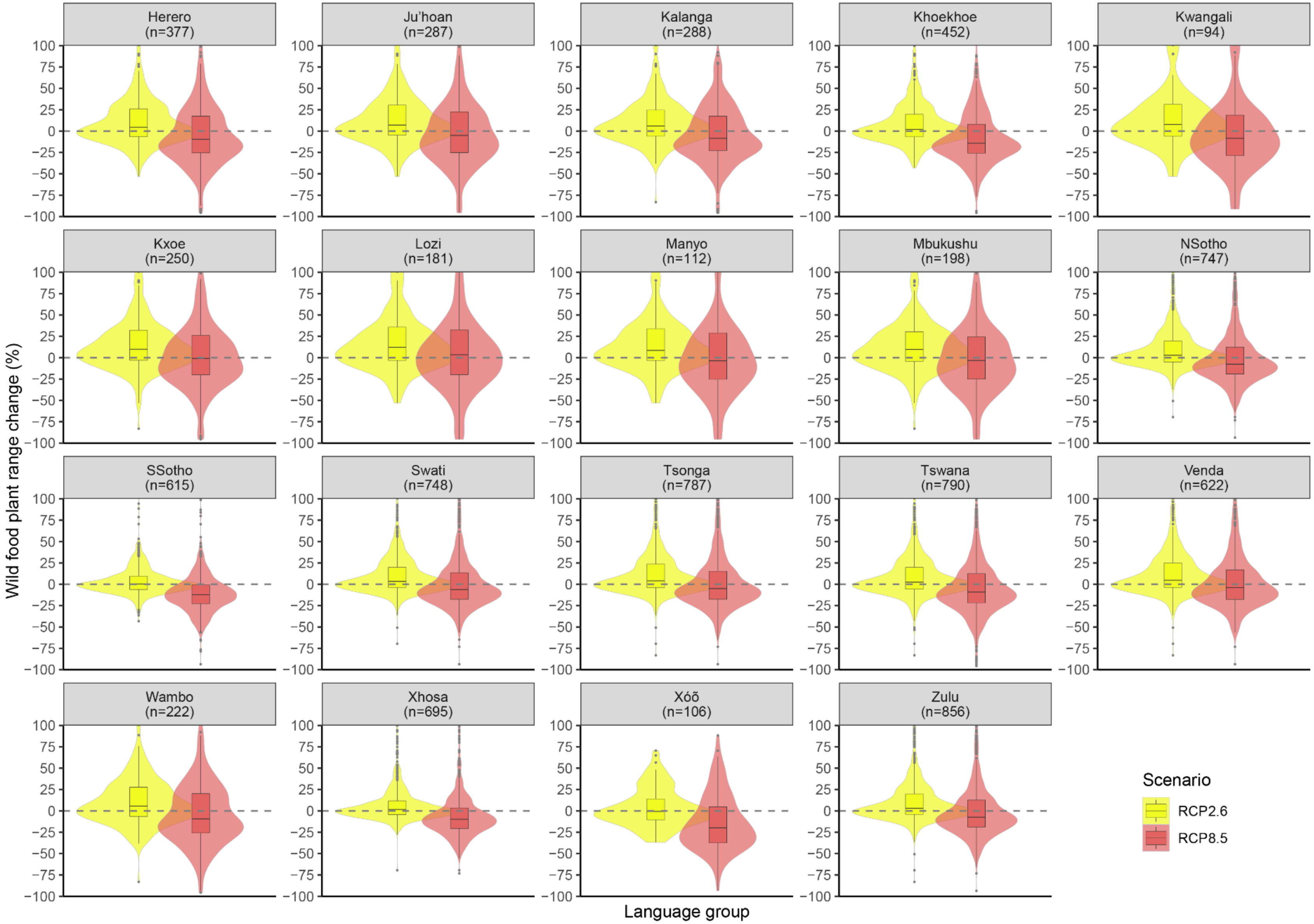

Figure 5. Projected percentage change in wild food plant range extent by category of known ethnolinguistic group use for RCP 2.6 (yellow) and RCP 8.5 (red). Only range increases of up to 100% are shown, as most of the species range change lies within this limit (see figure 2). The median, 25th and 75th percentiles are shown by box plots within the violin plots. Potential outliers are indicated by grey dots. The numbers of species (n) are shown under each category of use. Categories of use are those described in Welcome and Van Wyk (2019).

Table 4. The percentages of wild food plant species used by each of 19 ethnolinguistic groups that are projected to either experience a range loss or a range gain, under RCP 2.6 and RCP 8.5. The numbers of species (n) are shown for each ethnolinguistic group. Where the total percentage of species with range loss or range gain for a given scenario is greater than 50%, this is shown in bold.

	% of species with range loss				**% off species with range gain**			
	RCP 2.6 range loss (%)		**RCP 8.5 range loss (%)**		**RCP 2.6 range gain (%)**		**RCP 8.5 range gain (%)**	
	0-25%	>25%	0-25%	>25%	0-25%	>25%	0-25%	>25%
Herero (n=377)	34	5	**34**	**26**	**34**	**27**	19	20
Ju’hoan (n=287)	28	6	**30**	**25**	**37**	**29**	22	23
Kalanga (n=288)	31	5	**36**	**23**	**40**	**25**	20	20
Khoekhoe (n=452)	39	4	**41**	**28**	**36**	**21**	16	15
Kwangali (n=94)	28	6	**29**	**30**	**35**	**31**	23	18
Kxoe (n=250)	26	4	**31**	**20**	**37**	**32**	23	26
Lozi (n=181)	23	6	27	20	**35**	**36**	**24**	**29**
Manyo (n=112)	24	6	**28**	**26**	**36**	**34**	21	26
Mbukushu (n=198)	28	5	**28**	**25**	**36**	**31**	22	25
NSotho (n=747)	38	2	**47**	**16**	**39**	**20**	21	16
SSotho (n=615)	47	2	**53**	**23**	**42**	**10**	18	6
Swati (n=748)	37	1	**48**	**13**	**41**	**20**	22	16
Tsonga (n=787)	37	1	**46**	**13**	**39**	**23**	22	19
Tswana (n=790)	38	3	**43**	**21**	**38**	**21**	20	15
Venda (n=622)	36	2	**44**	**13**	**38**	**25**	23	20
Wambo (n=222)	32	7	**32**	**27**	**34**	**28**	21	20
Xhosa (n=695)	42	0	**53**	**18**	**44**	**14**	19	10
Xóõ (n=106)	**42**	**8**	**28**	**45**	30	19	13	13
Zulu (n=856)	38	1	**46**	**16**	**40**	**20**	22	16

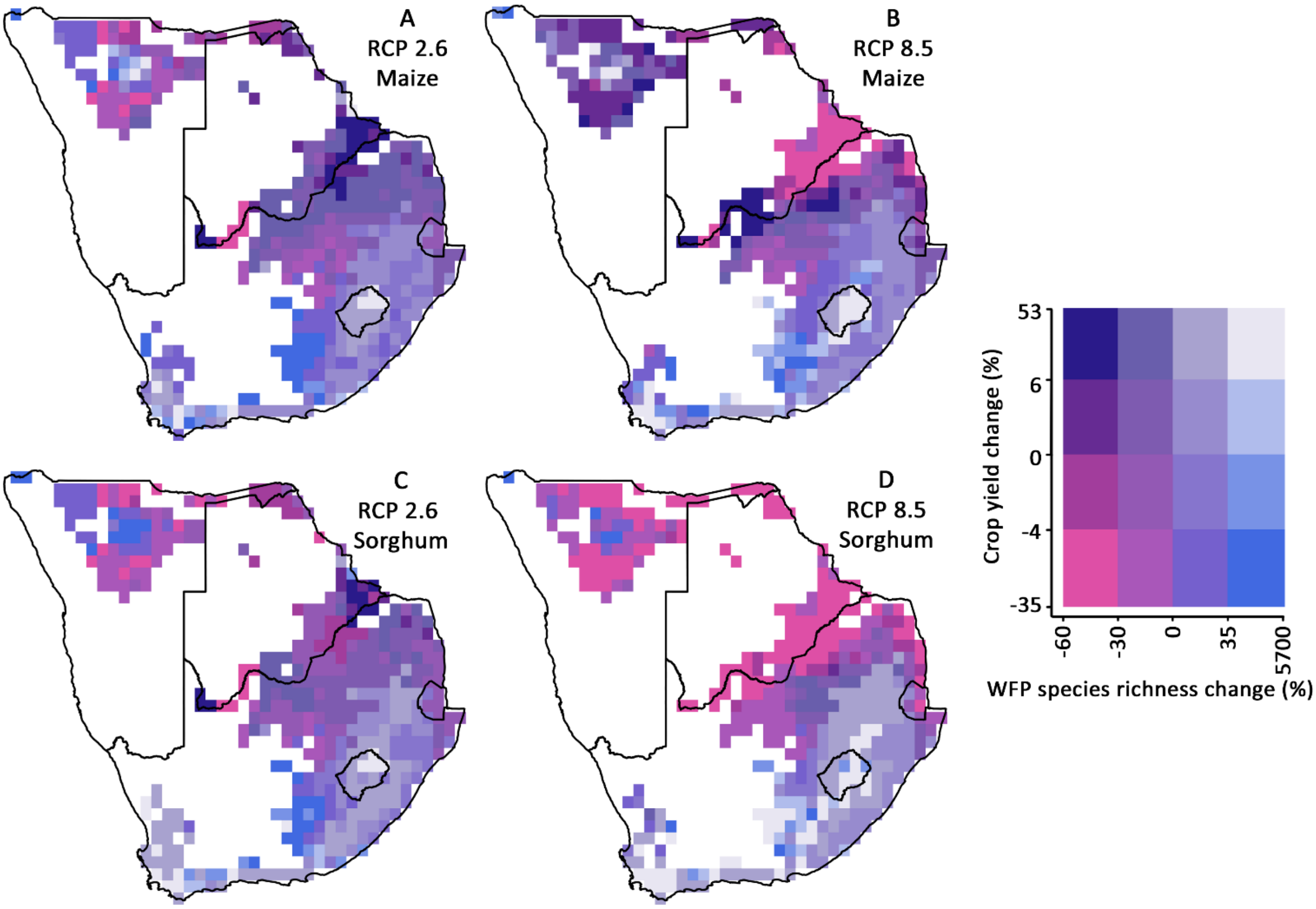

Figure 6. Projected crop yield change (%) combined with wild food plant (WFP) species richness change (%) for a low emissions (RCP 2.6) and high emissions (RCP 8.5) scenario in 2060-2080 compared to historical climate (1980-2000). White regions are projected as unsuitable for maize and sorghum both in historical and future warming scenarios. Pink colours show regions where both crop yields and WFP species richness are projected to decrease. Only WFPs that are used as snacks, fresh or in situ (n=686), cooked vegetables (n=407), ground as flour (n=91), or as famine food (n=64) were included in this analysis as they are the most likely to replace staple crops, such as maize and sorghum, when these crops fail.

People living in rural areas use WFPs to supplement their diets, especially during times of hardship when staple crops such as maize and sorghum fail. Thus, to identify regions where both crop yields and WFPs, or just one of these could be at risk from climate change, I compared climate change risks for maize and sorghum yields with risks for a selection of WFPs that are most likely to replace staple crops when these crops fail. This selection constituted 81% of the total number of WFPs. My approach identified large regions of southern Africa where both crop yields and WFPs are at risk under both RCP 2.6 and RCP 8.5 (Figure 6). South Africa’s North West and Free State provinces, as well as parts of northern Namibia are projected to experience declines in both crop yield and WFP species richness. Under RCP 8.5, the highest risk to maize, sorghum, and WFPs are on the north-eastern border between South Africa and

Botswana (Figures 6B and D), as well as for sorghum and WFPs in northern Namibia and Eswatini (Figure 6D). In contrast, regions where increases are projected for both crop yield and WFP species richness follow earlier projections of WFP increases in the southern and eastern parts of southern Africa, including Lesotho and parts of the Western Cape, Eastern Cape, Kwazulu-Natal and Mpumalanga provinces of South Africa. Under RCP 2.6, a small region on the northernmost border of South Africa and Botswana is projected to experience an increase in crop yield with a decrease in WFPs (Figures 6A and C). A decrease in crop yield with an increase in WFPs are projected for maize (Figures 6A and B), and sorghum in the south of South Africa (Eastern Cape province), as well as for sorghum in the north of Namibia (Figure 6C and D).

Discussion

WFP species richness in southern Africa generally increases from west to east across the region with the Eastern Cape, Kwazulu-Natal and Mpumalanga provinces of South Africa having the highest species richness (Figure 1A). This pattern of diversity differs from overall plant diversity patterns in Southern Africa. The Cape Floristic Region (CFR) is the plant biodiversity hotspot for South Africa, but not a hotspot for WFP diversity. This could be due to under sampling of WFPs in the CFR and the loss of traditional ecological knowledge for this region, however, it is also likely that the CFR has less food plants, as many species in this region are unpalatable shrubs.

Within southern Africa, large variations in WFP species responses under both RCP 2.6 and RCP 8.5 are projected, with range decreases expected for some species and range increases for others. Overall, under RCP 2.6, the less than 2°C warming scenario, range reductions are expected for 40% of WFP species, while under RCP 8.5, the greater than 4°C warming scenario, 66% of species are projected to experience range reductions (Figure 2). These projections of range decrease are less than what has been reported previously for wild plants in southern Africa, the wider sub-Saharan African region, and globally. Broennimann et al. (2006) modelled the climatically suitable habitat of 975 endemic plant species in four southern African countries (Eswatini, Lesotho, Namibia, and South Africa) and projected that species ranges would reduce by 39% on average by 2050 under the SRES B1 scenario. This scenario was the most optimistic at the time, comparable to RCP 4.5, which projects likely global warming of up to 2.6°C by 2100 (Cubasch et al., 2013). McClean et al. (2005) projected that climatically suitable habitat for 81–97% of 5197 plant species in sub-Saharan Africa will decrease in size by 2085, also under the SRES B1 scenario, with many species shifting to higher altitudes. This study also projected that 25-42% of the habitat of plant species in sub-Saharan Africa is expected to be lost completely by 2085, compared to the only 0.5% of species extinctions projected for WFPs in our study under RCP 8.5. At the global scale it has been projected that 16% of plants could lose more than 50% of their climatically determined range under 2°C global warming (Warren et al., 2018), compared to our 1% of WFP under RCP 2.6 and 4% under RCP 8.5. For crop wild relatives, 61% of peanut and 12% of potato relatives (both in Latin America), and 8% of cowpea relatives in sub-Saharan Africa are projected to lose more than 50% of their climatically determined ranges under a high emissions scenario (Jarvis et al., 2008a). Compared to these studies on wild plant species more generally, WFPs are projected to lose less of their ranges under both RCP 2.6 and RCP 8.5. Potential explanations for this could be that WFPs are often adapted to lower rainfall and growing in poor soils (Legwaila et al., 2011), affording them a higher resilience to climate change.

Changes in WFP species richness are projected to vary regionally. Under RCP 8.5, local species losses of more than 200 species are projected in the north-eastern parts of southern Africa, and more than 50% of WFP losses are projected for most of Botswana (Figure 3). Over these semi-arid regions of southern Africa, high warming rates and an increase in aridity are projected, with already water-stressed countries like Botswana and Namibia likely to get even hotter, drier and more water-stressed (Hoegh-Guldberg et al., 2018). In contrast, increases in local species richness are projected in more southern and eastern regions due to species shifting their ranges southward and into cooler montane regions under both RCP 2.6 and RCP 8.5 (Figure 3). Wetter conditions are also projected in these regions, which includes the Drakensberg mountain range, a dominant feature in South Africa's landscape, with an elevation of over 3000 meters (Hewitson & Crane, 2006; Engelbrecht et al., 2009). Interestingly, the largest relative increases in local WFP species richness are projected in the western parts of southern Africa, particularly in Namibia, although this represents a small change in absolute numbers (Figure 3). Native species in the hot and arid regions of southern Africa, such as Namibia, already have a high degree of stress tolerance (Midgley & Thuiller, 2007) and it might be that WFP growth forms in these regions have a higher resilience to climate change as a result. These species are projected to persist under climate change thereby maintaining current species numbers and leading to an increase in species richness under future climate conditions, as other species shift their ranges into more coastal regions of Namibia.

Increases in WFP species richness is also projected in the south to southeast of South Africa (Figure 3). Previous studies have projected that this region, which consists of mainly the Albany thicket, Grassland and shrubland semi-arid Nama Karoo biomes, will likely undergo substantial future changes in dominant plant growth forms in response to climate change (Masubelele et al., 2015).

Although projected changes in geographic ranges for WFP species in this study do not include the effect of future increases in atmospheric CO_2 concentration, experimental work and model projections suggest that increased CO_2 levels may moderate the effect of changing climate conditions, especially for C3 photosynthesizing species, with consequences for future species and biome distributions. For example, in response to a combination of increasing atmospheric CO_2 and aridification, the Nama Karoo biome is projected to shift to the east into the Grassland biome (Ellery et al., 1991; Rutherford et al., 1996; Midgley et al., 2002; Midgley et al., 2008). For plants of drier climates, such as those that occur in the Nama Karoo, positive changes in water use efficiency, positive responses to increasing CO_2 concentrations, or the potential for CO_2 fertilisation, may be especially beneficial (Cowling, 1999; Cowling & Sykes, 1999; Thuiller et al., 2006). Despite few publications available on species richness for the Nama Karoo flora, it has been found that Nama Karoo mountainous regions harbour both Succulent Karoo and Nama Karoo type vegetation. These include succulent endemics, as well as an assortment of Succulent Karoo species, well out of their previously known distribution range (Desmet, 2000). Therefore, it is possible that the Nama Karoo could be home to a much larger species diversity than we know, of which more WFPs could be shrubs, trees, succulents, or geophytes than grasses. These WFP species could persist under climate change, similar to species in the hot and arid Namibian regions, and/or shift their ranges into the Grassland biome as conditions in that region become more suitable for their specific growth forms.

Of the 19 southern African ethnolinguistic groups examined in this study, the Zulu language is the most common language in South Africa, followed closely by the Xhosa ethnolinguistic group. The Zulu and Xhosa people live predominantly in the Kwazulu Natal and Eastern Cape provinces respectively, in the south and south-eastern regions of southern Africa. This is also where the highest overall WFP species richness (as well as maize and sorghum yield) increases are projected to occur (Figure 3; Figure 6). However, for WFP species specifically used by these two ethnolinguistic groups, range decreases for 39% (Zulu) and 43% (Xhosa) of species are projected under RCP 2.6, and 62% (Zulu) and 71% (Xhosa) under RCP 8.5 (Table 4). These projected losses, especially under RCP 8.5, stresses the urgency of documenting traditional knowledge on WFP use. The loss of traditional ecological knowledge in sub-Saharan Africa, is one of the greatest challenges among indigenous rural communities for accomplishing sustainable natural resource management and retaining cultural continuity (Rim-Rukeh et al., 2013; Bruyere et al., 2016; Ketlhoilwe & Jeremiah, 2016; Maroyi & Cheikhyoussef, 2017). Van Wyk and Gericke (2000) emphasised that in southern Africa knowledge of indigenous plant use requires urgent scientific documenting to not be lost irretrievably to future generations. My study projects that multiple WFPs can be expected to persist under moderate or near-term global warming levels. If we take into consideration the projected shifts in WFP species ranges, some ethnolinguistic groups that have not traditionally used particular species may now be able to do so as new WFPs move into their region. For other ethnolinguistic groups, valuable species may be lost. It is thus imperative that traditional knowledge on the use of WFPs are documented, as it can be used in climate change policies, which could lead to development of cost-effective adaptation strategies that are sustainable and participatory (Robinson & Herbert, 2001).

Increases in WFPs are projected along the west coast of southern Africa, partly into the Kalahari Desert, as well as into the Nama Karoo of South Africa (Figure 3). Among other ethnolinguistic groups, the Khoesaan people, which includes the Ju’hoan, Khoekoe, Kxoe and Xóõ ethnolinguistic groups, can be found in isolated locations around the dry Kalahari region of Namibia, Botswana, and South Africa (Welcome & Van Wyk, 2019). This region does not have a high number of WFPs, and only the hardiest of vegetation can survive here. An increase in WFPs may be beneficial to these groups, as the region is unsuitable for crop production now and into the future (Figure 6). Traditional Khoesaan people mostly rely on WFP roots. Native geophyte species that do occur in these hot and arid regions have a high degree of stress tolerance (Midgley & Thuiller, 2007) and may thus have a higher resilience to climate change. However, WFPs used by two ethnolinguistic groups within the Khoesaan are projected to experience considerable range decreases under RCP 8.5. These are the Xóõ and Khoekhoe, with 74% and 69% of species projected to experience range decreases (Table 4). The Xóõ is also the only group where more than 50% of species are expected to experience range decreases under RCP 2.6 (Table 4). Considering that already water-stressed countries like Botswana and Namibia are likely to get even hotter, drier and more water-stressed (Hoegh-Guldberg et al., 2018), people from these two ethnolinguistic groups should be prioritised for climate change adaptation strategies.

For the majority of other ethnolinguistic groups residing in the north of southern Africa, varying degrees of WFP range change are projected, with increases in species richness projected under RCP 2.6 and decreases under RCP 8.5. The Southern Sotho ethnolinguistic group, however, which resides mostly in Lesotho and the Free State province of South Africa, are at risk even under RCP 2.6. My study projected range decreases for WFPs used specifically by the Southern Sotho ethnolinguistic group for 48% of species under RCP 2.6 and 76% of species under RCP 8.5 (Table 4). Furthermore, in the Free State region, under RCP 2.6, my study projected species richness decreases for those WFPs most likely to replace staple crops (species used as cooked vegetables, ground as flour, famine foods, and species eaten fresh and in situ as snacks), as well as maize and sorghum yield losses (Figure 6A and C). Maize is the most important grain crop in South Africa, and the Free State province produces the largest percentage of maize of all provinces in the country (42% in the 2018 harvesting season) (The Southern African Grain Laboratory NPC, 2019). In the Free State, a recent study projected mean maize yield losses from two crop models of 26% under RCP 4.5 and 29% under RCP 8.5 for the period 2051-2080 (Mangani et al., 2019). Therefore, in the Free State province, the Southern Sotho ethnolinguistic group may be at risk of future climate change even under the less than 2°C warming scenario and should also be prioritised for climate change adaptation strategies. In contrast, in Lesotho, the Southern Sotho ethnolinguistic group seems much less vulnerable, as my study projected WFP species richness increases, as well as maize and sorghum yield increases, under both RCP 2.6 and RCP 8.5 (Figure 6). In Lesotho, Zinyengere et al. (2014) projected a mean yield increase under the SRES B1 (low emissions) and SRES A2 (high emissions) scenarios respectively, of 6% and 11% for maize and 51% and 52% for sorghum, for the period 2046-2065. Lesotho is located in a high-altitude region of southern Africa, which is prone to cold related crop yield losses historically (Zinyengere et al., 2014). The country thus has the advantage that warming temperatures, in combination with increased rainfall from February to April, will create more favourable maize and sorghum growth conditions (Zinyengere et al., 2014). Sorghum will also benefit even more from a wetter and warmer climate in Lesotho, as this crop is already more tolerant to water and heat stress than maize (Zinyengere et al., 2014).

The impact of climate change on agricultural crops will threaten food security by affecting the affordability and availability of nutritious food, especially in developing countries (Lloyd et al., 2011). Across sub-Saharan Africa, rates of undernutrition are already high, with global warming of 1.2-1.7°C projected to increase the undernourished proportion of the population by 25–90% by 2050 (Lloyd et al., 2011). My study projected that in some regions of southern Africa, both crop yield losses and species richness decreases of those WFPs most important for food security and as nutritional supplements can be expected under RCP 2.6 and RCP 8.5 (Figure 6). Large regions of South Africa's North West and Free State provinces, as well as parts of northern Namibia, are projected to experience declines in both crop yield and WFP species richness (Figure 6). Under RCP 8.5, the highest risk to both crops and WFPs are on the north-eastern border of South Africa and Botswana (Figures 6B and D), as well as for sorghum and WFPs in northern Namibia and Eswatini (Figure 6D). As people will not be able to rely on WFPs when crops fail under future climate conditions in these regions, more help from governments might be needed to adapt to climate change, such as shifting away from smallholder farming, or other adaptations to make crops more resilient. It has been shown that certain agronomic practices can be used to reduce the negative impact of climate change on maize yields, such as changing planting dates, appropriate fertilizer use, changing cultivar, and conservation agriculture (Ngwira et al., 2014; Zinyengere et al., 2014; Zinyengere, 2016). Therefore, adaptation practices, combined with the potential advantages CO_2 fertilisation offers, could possibly reduce negative impacts of climate change, and help reverse projected crop yield losses.

In contrast to the above, for some regions in southern Africa my research indicates that limiting global warming to below 2°C may enable WFPs to continue to form part of a critical nutritional buffer against climate change for vulnerable rural communities. For example, in parts of the Eastern Cape province of South Africa, maize and sorghum yield are projected to decrease, and in northern regions of Namibia, sorghum yield losses are projected (Figure 6). In these same regions, WFPs are projected to increase (Figure 6). WFPs can thus supplement the diets of rural people or farm households and provide them with essential micronutrients. Some WFPs even contain more nutrients than their cultivated counterparts (Smith et al., 1996; Kobori & Rodriguez Amaya, 2008), and could be important genetic resources for developing future crops (Jarvis et al., 2008b). For many people in sub-Saharan Africa, wild foods are already an essential livelihood safety net when other sources of food fail, such as during times of drought or other natural disasters (Vinceti et al., 2013; Wunder et al., 2014; Shumsky et al., 2015). However, if we follow an RCP 8.5 global warming pathway, WFPs are more at risk and may not be able to help people adapt to climate change.

Given the projected persistence of multiple WFPs under moderate or near-term global warming levels, encouraging the cultivation of WFPs could also be a useful strategy to enhance food security, adapt to and mitigate climate change, and provide cash income for rural communities (Legwaila et al., 2011). A variety of native wild fruit tree species have already been domesticated in several eastern and southern Africa countries (Taylor et al., 1996; Akinnifesi et al., 2004, 2006, 2008; Leakey, 2005; Kalaba et al., 2009) along with some medicinal plants (Mander et al., 1996). In these countries, it is also customary for farmers to leave native wild fruit trees when they clear land for growing crops (Legwaila et al., 2011). In Botswana, wild fruit tree planting in backyard gardens is quite common in both rural and urban areas (Taylor et al., 1996). In contrast, cultivation of wild vegetables has not received as much attention. Their cultivation could be constricted by their availability in the wild, but also due to a lack of knowledge in propagation techniques and husbandry skills (Legwaila et al., 2011). Furthermore, the monetary value of WFP harvests is also not well known (High & Shackleton, 2000). In a case study of a rural village in the Mpumalanga province of South Africa, it was found that each household harvested four to five WFP species (High & Shackleton, 2000). In this village, WFPs represented 31% of total dietary intake, and the mean monetary value of WFPs per household was approximately 50% of that of cultivated crops: around R520 per household for WFPs and around R1170 per household for crops (High & Shackleton, 2000). Thus, WFPs can be a significant source of income for rural people in southern Africa and may be even more so if cultivated. Furthermore, apart from providing food and cash income, WFPs, especially wild fruit trees, have the added benefit of capturing and storing atmospheric carbon.

Conclusion

Key findings

WFP species richness in southern Africa generally increases from west to east across the region, with the Eastern Cape, Kwazulu-Natal and Mpumalanga provinces of South Africa having the highest WFP species richness. It is projected that for RCP 2.6, 40% of WFP species will experience a decrease in range extent within southern Africa, increasing to 66% of WFP species for RCP 8.5. For RCP 2.6, the loss of suitable climatic conditions is projected to decrease local WFP species richness most in the north-eastern parts of southern Africa, while increases in WFP species richness are projected in the south and east of South Africa. For RCP 8.5, decreases of more than 200 species are projected for multiple regions in north-eastern South Africa, and local WFP species losses of more than 50% are projected for most of Botswana. Despite these decreases, WFPs could still play an important role in food security during times of low agricultural yield as a result of changing climate conditions, especially in low-income, rural communities that are reliant on smallholder farming. For instance, in parts of the Eastern Cape province of South Africa and northern Namibia, WFP species richness is projected to increase while maize and sorghum yield are projected to decrease. People may be more able to rely on WFPs as a nutritional safety net in these regions into the future. This safety net, however, may be lost in large regions of South Africa's North West and Free State provinces, on the north-eastern border between South Africa and Botswana, as well as parts of northern Namibia, where declines in both crop yield and WFP species richness are projected.

Limitations of the study

Crop yield data were downloaded under the ISIMIP Fast Track simulation protocol, as this was the only protocol with RCP 8.5 data available. However, the Global Climate Models used for projections of crop yield changes available in the ISIMIP Fast Track protocol were not the same as those used for the WFP modelling, apart from one model, HadGEM2-ES, resulting in a limitation of this research.

Although the projections of crop yield changes included CO_2 fertilisation effects, a limitation to this study is that the projections of climate change impacts on presence of WFP species did not. Many WFP species in this study are C3 photosynthesising and may benefit from increased atmospheric CO_2 concentrations, especially species used for their fruits or underground storage organs (e.g., bulbs and tubers) may have high potential to increase carbohydrate availability at higher CO_2 levels. For example, *Oxalis pes-caprae*, a species native to southern Africa and harvested by humans for its bulbs, almost doubled the mass of bulbs when grown at current versus glacial atmospheric CO_2 concentrations (Faltein et al., 2020). As such, with increased atmospheric CO_2 and climate change in future, some WFPs may present more of a nutritional safety net in some areas than we project here, still, many WFP species may not show these benefits, leading to large uncertainty in species responses.

A limitation to this study is also that exotic species were excluded from the study. Exotic species make up 15% of the edible plant species listed for the study region (e.g., naturalised weeds used as vegetables), however, I had to exclude these species due to limitations in modelling the global range extent of exotic species.

Recommendations for future research

Future work on WFP responses to climate change should consider CO_2 fertilisation effects in more detail, in addition to the climate change risk to naturalised exotic WFP species. In order to ensure future food security, more research is also needed on WFP uses, nutritional value, responses to climate change, and suitability for cultivation.

The importance of this study

Knowing the potential impact of climate change on WFPs could afford valuable time for people to adapt to changing food security circumstances, especially for those communities that are already vulnerable due to crop yield losses. My research indicated that WFPs could play a progressively more important role in times of low agricultural yield as a result of changing climate conditions, especially in low income rural communities that are reliant on smallholder farming, and under global warming levels below 2°C. In addition, my research highlighted regions that may be able to rely on WFPs as a nutritional safety net into the future, such as in parts of the Eastern Cape province of South Africa and parts of northern Namibia, where maize and sorghum yield are projected to decrease. My research also highlighted where in southern Africa this safety net may be lost, such as in South Africa's North West and Free State provinces, on the north-eastern border between South Africa and Botswana, and certain parts of northern Namibia.

Developing advance warning systems in order to adapt to climate change, or mitigate risk through targeted conservation or management actions, can add value in local and regional climate change strategies or policies (Robinson & Herbert, 2001), such as through the cultivation of WFPs. My research could prove valuable for climate change adaptation planning, especially in the most vulnerable regions of southern Africa. However, in order to ensure future food security, more research is needed on WFP uses, nutritional value, responses to climate change, including CO_2 fertilisation effects, suitability for cultivation, and the climate change risk to naturalised exotic WFP species. By looking beyond the farm level and conventional crops to the exceptional diversity of WFPs people obtain from their environment, this research is a step towards the goal of understanding the linkages between WFPs, food security, climate change, and agriculture.

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