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SADC Futures
Developing Foresight Capacity for Climate Resilient Agricultural Development

# Rapid Climate Risk Assessment for the Southern Africa Development Community (SADC) Region

UNIVERSITY OF LEEDS

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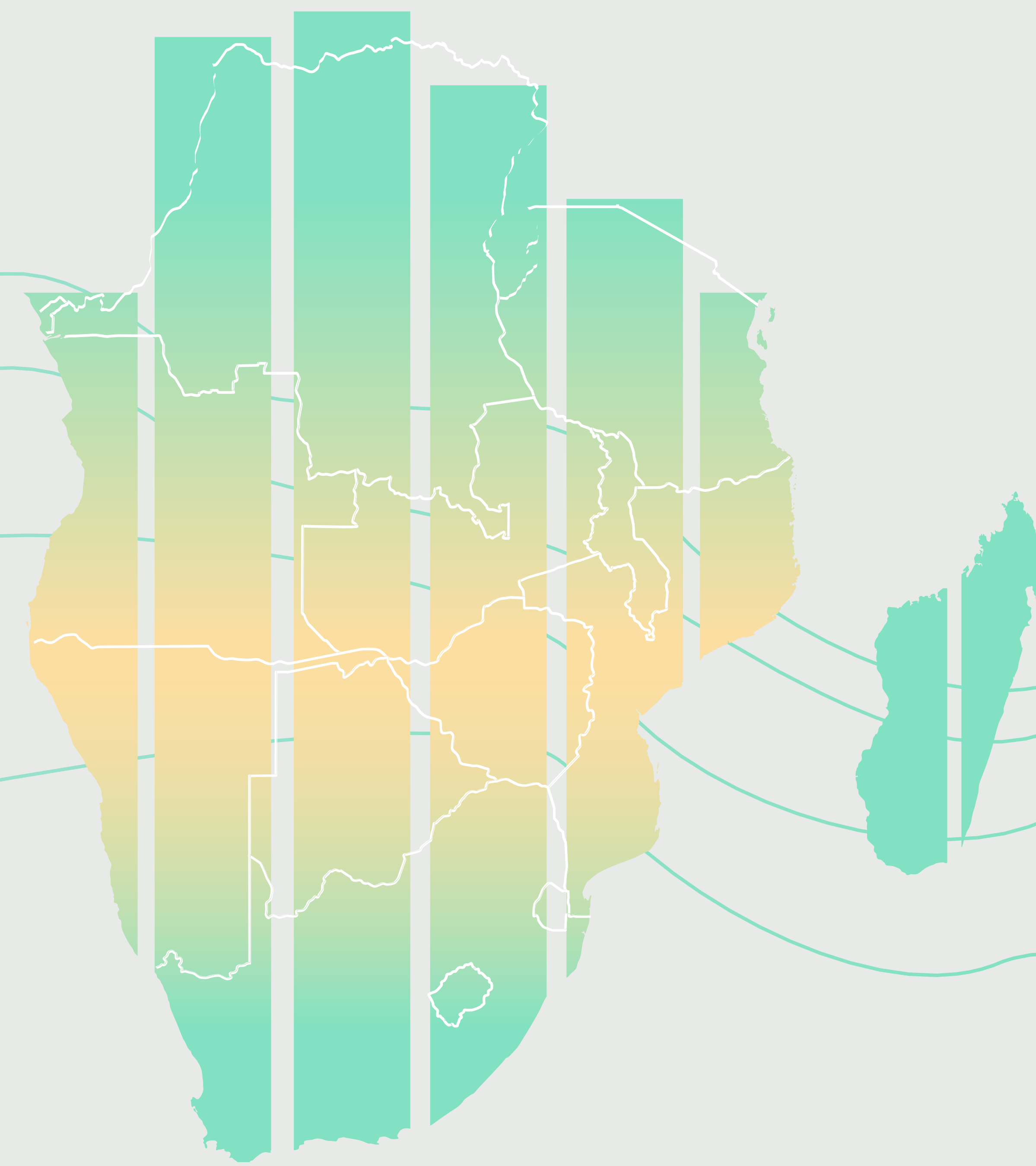

# SADC Futures

Developing Foresight Capacity for Climate Resilient Agricultural Development

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## ABOUT THE SADC FUTURES PROJECT

In these highly uncertain and rapidly changing times, the SADC region, like many regions in Africa, remains fundamentally dependent on a resilient agricultural system and natural resource base. Climate change still poses the greatest threat to the agricultural system and therefore technical capacity is needed to address these future impacts and adapt plans, policies and programs. Taking into account alternative futures, the SADC Futures project has produced tailored supporting materials and documents as part of a wider approach for foresight training in the region. These documents and the associated foresight framework aim to equip users to practically apply the range of foresight tools and methods for innovative strategic planning and policy formulation for climate resilience.

This SADC Futures Project is a joint initiative of the SADC Secretariat's Food, Agriculture and Natural Resources (FANR) Directorate, the Centre for Coordination of Agricultural Research and Development for Southern Africa (CCARDESA), the International Livestock Research Institute (ILRI) through the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) and German Development Cooperation facilitated through the SADC / Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH 'Adaptation to Climate Change in Rural Areas' program (ACCRA), funded by the German Federal Ministry for Economic Cooperation and Development (BMZ).

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CCARDESA Centre for Coordination of Agricultural Research and Development for Southern Africa

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## SADC FUTURES FORESIGHT FRAMEWORK

**Input**
Understanding our context

**Analysis**
What is happening?

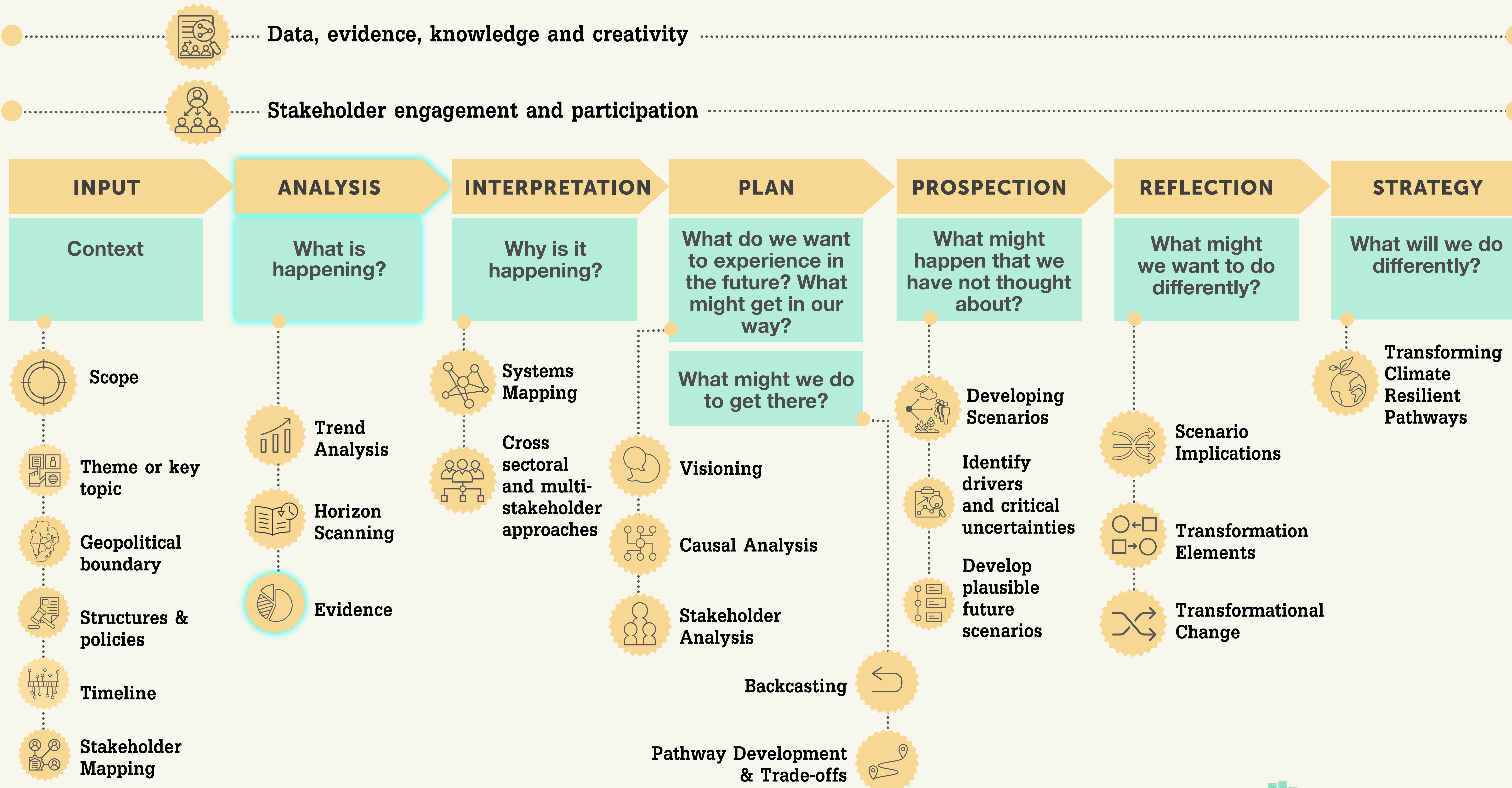
**Interpretation**
Why is it happening?

**Plan**
What do we want to experience in the future? What might get in our way? What might we do to get there?

**Prospection**
What might happen that we have not thought about?

**Reflection**
What might we want to do differently?

**Strategy**
What will we do differently?




SADC Futures
Developing Foresight Capacity for Climate Resilient Agricultural Development

# ABOUT THE SADC FUTURES KNOWLEDGE SERIES

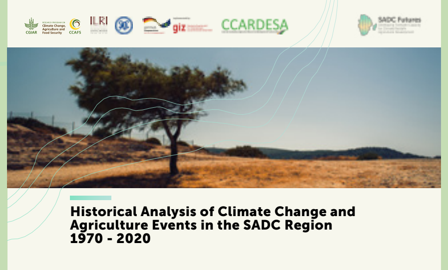
To expand on the foresight and futures capacity building the project has produced a series of accompanying knowledge products and sources. The knowledge series mapped to the SADC Futures foresight framework is shown below.

These can all be found on the SADC Futures webpage https://bit.ly/SADCFuturesForesight.

## INPUT

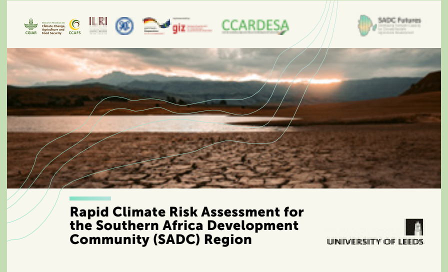

Structures, Policies and Stakeholder Landscape Relevant to Climate Change and Agriculture in the SADC Region

## ANALYSIS




Historical Analysis of Climate Change and Agriculture Related Events in SADC


Mega-trends in the Southern African Region




Rapid Climate Risk Assessment for the Southern Africa Development Community (SADC) Region

## INTERPRETATION


Systems Analysis and Sectoral Linkages Impacting Climate Resilient Development in the SADC Region

## PLAN


Climate Resilient Development Pathways

SADC Futures Foresight Training Toolkit


## PROSPECTION


What Are Scenarios Telling Us About Developing Climate-Resilient Pathways in the Southern African Region?

## REFLECTION

## STRATEGY


Applying Foresight For Enhanced Climate Resilience and Agriculture Policy Development in the SADC Region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# FIGURES AND TABLES CONT



# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| **ACCRA** | Adaptation to Climate Change in Rural Areas |
| **BMZ** | German Federal Ministry for Economic Cooperation and Development |
| **CA** | Conservation Agriculture |
| **CCAFS** | Climate Change, Agriculture and Food Security |
| **CCARDESA** | Coordination of Agricultural Research and Development for Southern Africa |
| **CGIAR** | Consultative Group for International Agricultural Research |
| **DRC** | Democratic Republic of Congo |
| **FANR** | Food, Agriculture and Natural Resources |
| **FAO** | Food and Agriculture Organisation |
| **GCM** | Global Climate Model |
| **GDP** | Gross Domestic Product |
| **GHG** | Greenhouse Gas |
| **GIS** | Geographic Information System |
| **GIZ** | Deutsche Gesellschaft fur Internationale Zusammenarbeit |
| **ILRI** | International Livestock Research Institute |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **MPI** | Multidimensional Poverty Index |
| **PRISMA-P** | Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols |
| **RCM** | Regional Climate Model |
| **RCP** | Representative Concentration Pathway |
| **SADC** | Southern African Development Community |
| **SDG** | Sustainable Development Goal |
| **SPEI** | Standardised Precipitation Evapotranspiration Index |
| **SSA** | Sub-Saharan Africa |
| **USD** | United States Dollar |

# Summary

**This rapid climate risk assessment for the Southern Africa Development Community (SADC) uses the Intergovernmental Panel on Climate Change (IPCC)** 2014 risk analysis framework to assess the distribution of climate hazards and social and biophysical vulnerability to those hazards in order to identify climate risk hotspots.

The assessment uses regional climate models from CORDEX-Africa to map rainfall extremes and drought hazards to 2031–2059. Ten social and biophysical vulnerability indicators are identified from across the capital assets (human, physical, social, financial, natural), using data from the Global Multidimensional Poverty Index (MPI), to develop a vulnerability index. The vulnerability index and distribution of climate hazards are mapped to identify hotspots.

Hotspots of vulnerability to and risk of extreme rainfall are shown in northern Madagascar and in south west Tanzania, under both the RCP4.5 and 8.5 scenarios. Hotspots for drought under these scenarios are shown in Tanzania. However, it is clear that medium-high climate risk (high vulnerability, medium-high climate hazard) is widespread across Angola, Democratic Republic of the Congo (DRC), Tanzania, Mozambique, and Madagascar.

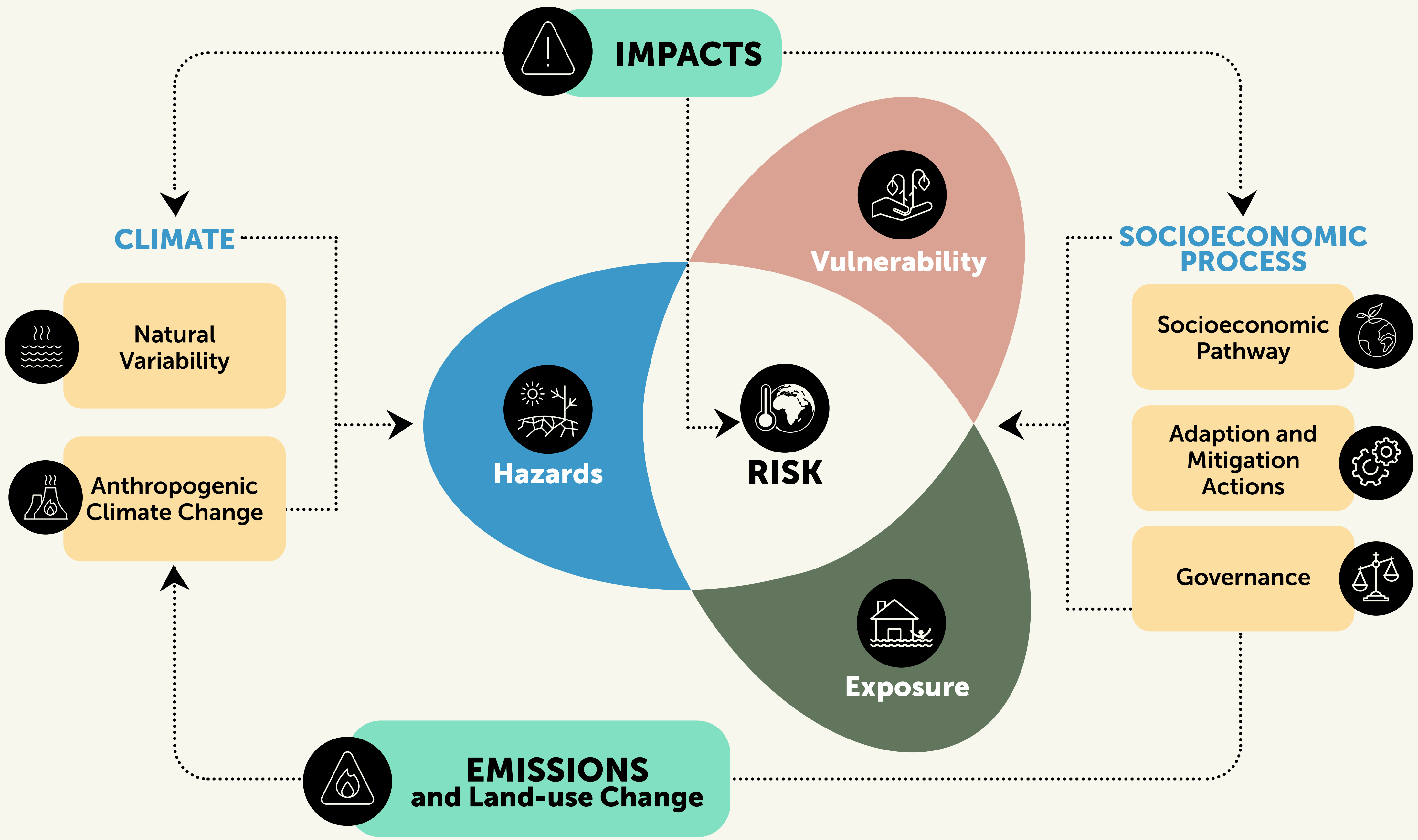
**Photo:** Kon Karampelas-unsplash

## Seven Key Recommendations

1. **Hotspots of vulnerability** to and risk of extreme rainfall and drought occur in northern Madagascar and south west Tanzania, under both medium and high greenhouse gas emission scenarios.
2. Areas of high vulnerability coupled with **medium-high climate hazard** are widespread across Angola, DRC, Tanzania, Mozambique and Madagascar.
3. There is a mismatch between locations with the **highest future climate risk** and where on-the-ground research on climate change impacts and adaptation is currently being undertaken, with potentially serious consequences for testing and implementation of appropriate and robust adaptation options.
4. **Population growth** in these areas is projected to remain high to mid-century – robust targeting and implementation of on-the-ground research for development is needed, based on national policy objectives.
5. **National policy** objectives are required that identify robust and climate resilient pathways for agricultural and economic development to prevent sub-optimal or maladaptive choices now, such as replacing crops like rice with maize in response to current climate change, which is likely to be unproductive under future climate conditions.
6. There is a role and need for **participatory processes** that bring together food system actors in high-risk locations to identify needs and design and implement responses that are tailored to the specific contexts of those locations, there is not a "one size fits all" that will work in all contexts within a country.
7. This work has identified a **lack of data availability** for other climate hazards (e.g. sea level rise), and for vulnerability measurement in small island states, which urgently needs to be addressed.

# Introduction 01

This report presents a **rapid climate risk assessment for the Southern African Development Community (SADC) region**. The goal is to identify climate risk hotspots – locations where climate hazards, exposure and vulnerability coincide to increase the risks of adverse impacts. The 2014 Intergovernmental Panel on Climate Change (IPCC) risk framework is used to structure this analysis (Figure 1) (IPCC 2014).




### KEY TERMS

**Hazard** - possible, future occurrence of natural or human induced physical events that may have adverse effects on vulnerable and exposed elements

**Exposure** – refers to the inventory of elements in an area in which hazard events may occur

**Vulnerability** – the propensity or predisposition of a system to be adversely affected by an event

**Risk** - intersection of hazards, exposure and vulnerability

Figure 1. IPCC climate risk framework (IPCC 2014)

In this framework, natural variability and anthropogenic (human induced) climate change create climate hazards, which are geographically distributed.

### A climate hazard is defined as:

**"The potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources"** (IPCC 2012). Socio-economic processes (e.g., economic activities, livelihoods, decision-making) determine whether communities or economies are exposed to climate hazards and whether they are vulnerable.

### Exposure is defined as:

**"The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected"** (IPCC 2012).

### Vulnerability is defined as:

**"The propensity or predisposition to be adversely affected"** (IPCC 2012).

### Climate risk

Is where hazards, exposure and vulnerability intersect and interact, so that risk is not just about the natural hazard but also about the socio-ecological system where that hazard occurs. For example, the activity of an economy might lead to emissions that drive climate change, which in turn might increase the severity and occurrence of flooding. But an economic system that encourages building houses on higher ground, implements a variety of flood defence and mitigation measures, and invests in economic activities that are not impacted by flooding, can both reduce exposure to the climate hazard, and vulnerability of the economy and communities to flooding hazards, and hence have a lower climate risk. However, a different economy exposed to the same severity and intensity of hazard might face very different climate risks, because of differences in exposure and vulnerability.

**Photo:** Curioso Photography-unsplash

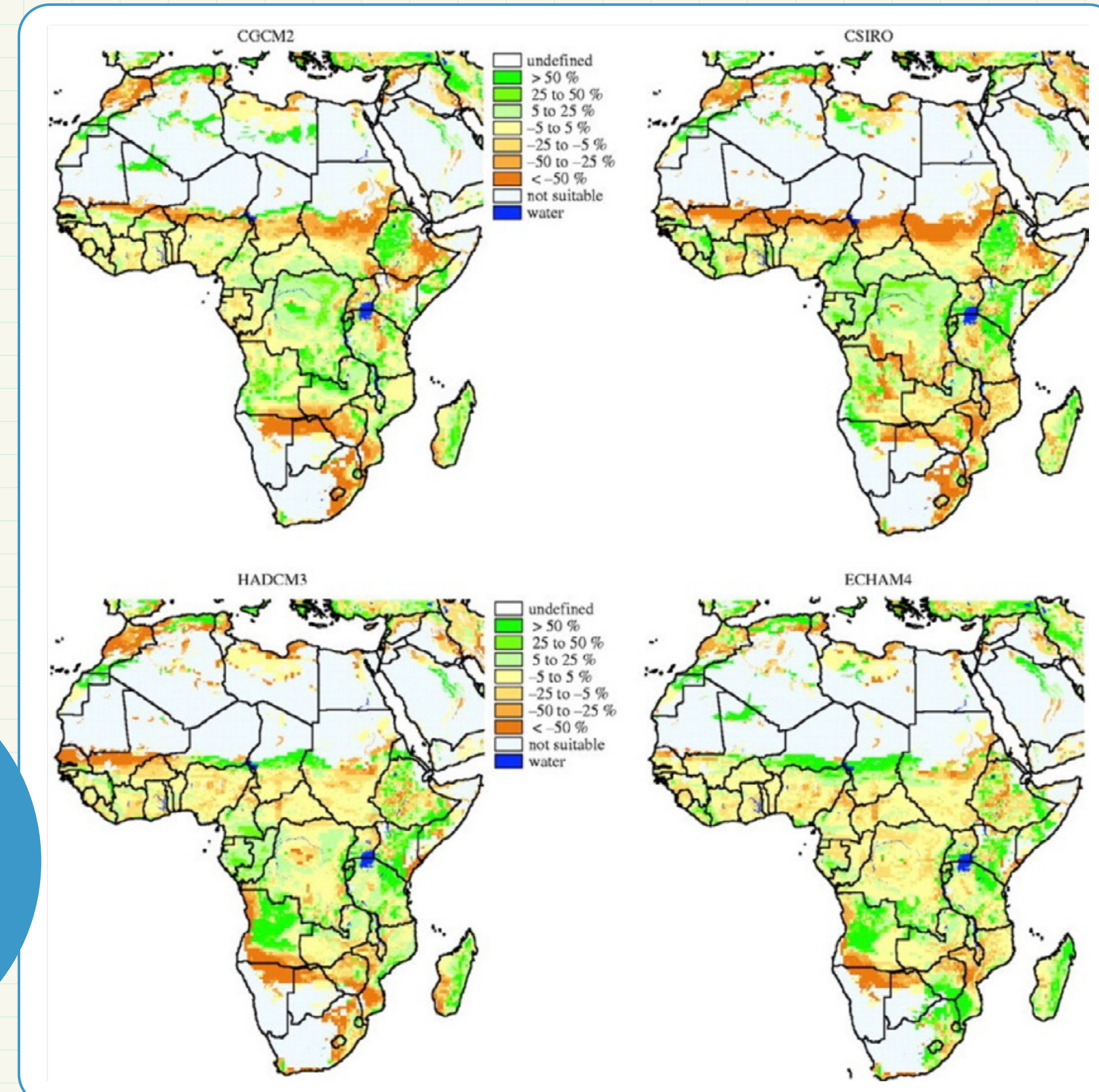
**Climate risk mapping has been widely used to understand the distribution of and interaction between climate and other stressors.** Different studies use different approaches, models and indicators to understand current and future risks. For example, Fischer et al. (2005) used ecological-economic models that linked crops, climate and trade to estimate future impacts on crop production in Africa.

They found that net cereal production potential will fall but with large variations between countries. Similarly, the yield response models produced by Schlenker and Lobell (2010) use crop and weather data alongside farmer responses (i.e. adaptations) to look at the impacts on four different crops (sorghum, millet, maize, groundnuts) across Africa. They found that the impacts on yields of these important and staple food crops are likely to be mostly negative.

Photo: USAID Siegfried Modola

**Net loss overall in agricultural potential in SSA**

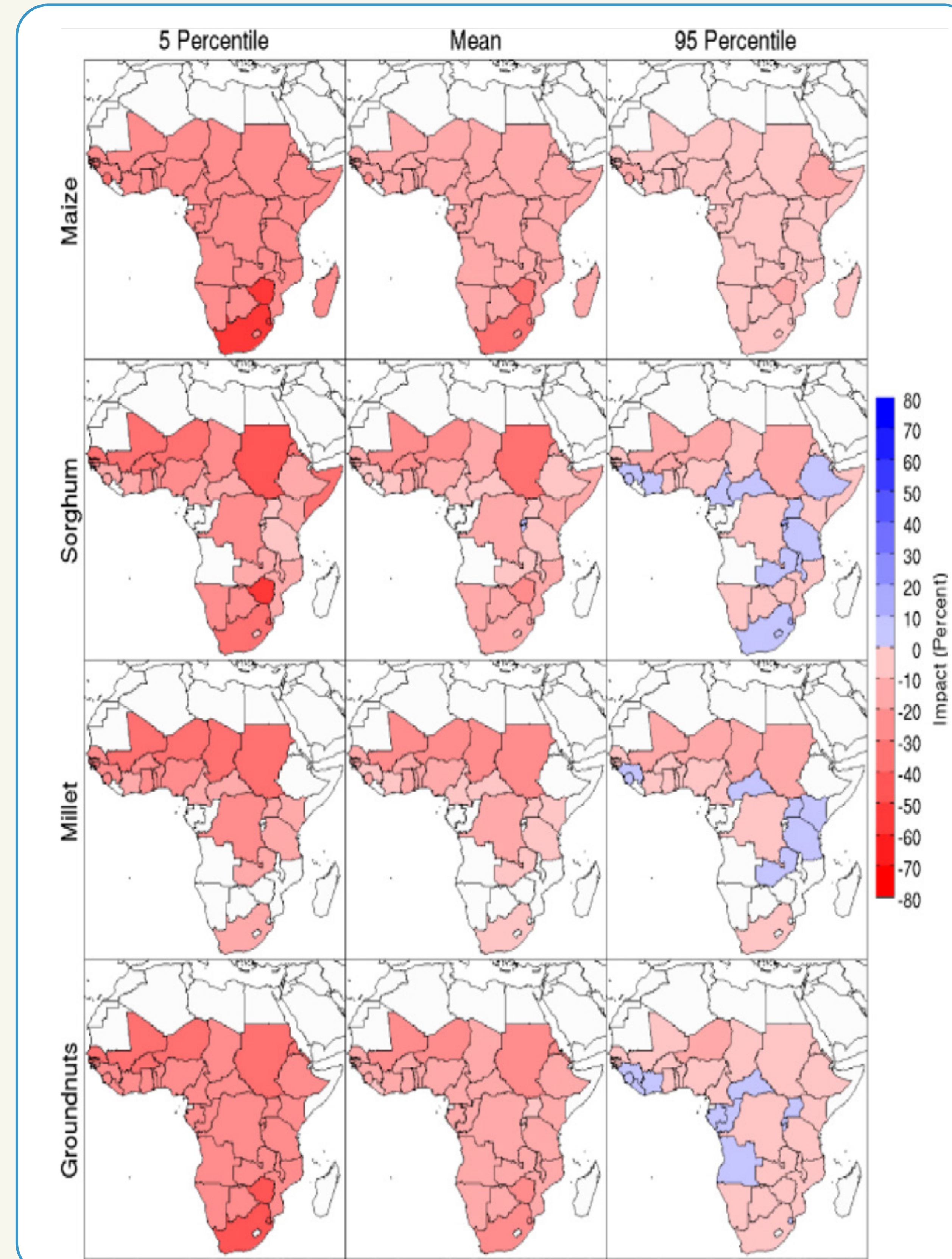
## Future impacts on cereal productivity




Ecological-economic models (Fischer et al. 2005)

## Yield response models

4 staple crops are likely to decline




Yield response models (Schlenker & Lobell 2010)

**Photo:** (Top Left) V. Meadu (CCAFS), (Top Right) USAID, (Bottom Left) USAID Siegfried Modola, (Bottom Right) USAID/Siegfried Modola

## A recent systematic review of 84 studies mapping vulnerability to climate risks (de Sherbinin et al. 2019) identifies key considerations in producing maps for climate risk assessment:

- **a. Coverage** – whether global, regional or national level
- **b. Unit of analysis** – extent to which data can be gathered at particular spatial scales (e.g. county/district, country)
- **c. Goal** – to identify hotspots of climate risk, for risk reduction or adaptation targeting, for planning or monitoring and evaluation of interventions
- **d. Framing** – selection of an appropriate framing of vulnerability and/or climate risks that is fit for purpose
- **e. Indicators** – selection of measurable socio-economic variables
- **f. Climate parameters** – selection of climate variables, e.g. rainfall variability
- **g. Aggregation** – whether weighting of indicators is applied

In this rapid assessment the climate risk assessment has been carried out for the SADC region, with the goal of identifying climate risk hotspots. Where possible the data is at district/county scale or disaggregated to that level. A total of 10 socio-ecological indicators have been selected as measures of vulnerability to natural hazards, and combined, equally weighted, into a single vulnerability index. The natural hazards selected are drought and extreme rainfall events because these are, and are likely to become, significant climate hazards in the SADC region. Hotspots are identified by the intersection between levels of vulnerability and climate hazards.

De Sherbinin et al. (2019) identify four key limitations in many climate vulnerability/risk mapping exercises: a lack of future projections, data availability, uncertainty and policy relevance. We have used climate models from CORDEX-Africa to create climate hazard maps, and so our climate risk mapping does consider future climate projections. However, our vulnerability index is based on current/recent data and is not projected into the future. Projections of future vulnerability are a critical limitation in studies of this kind, but were beyond the scope of this study.

Data availability is also a critical limitation for studies of this type. Data for some countries was either not available or only available at a country level. Where this has been the case the data has been sourced from an alternative database (where possible) and some data has been downscaled to county/district level by assigning each county/district the same value, making the assumption that the country data is representative of every county/district. As a result, these indicators will not differentiate between counties/districts.

Uncertainty is an inherent feature of these studies. What is presented here is not a projection of the future, but presentation of possible futures, and it is unlikely to have identified all possible hotspots in the region. However, it can, in conjunction with other studies at country, region and global scale, contribute to discussions about and planning for climate impacts in the SADC region.

### Using climate risk assessment mapping

**Key considerations**

- Coverage/scale
- Unit of analysis
- Goals for analysis
- Vulnerability framing
- Social/ecological Indicators
- Climate parameters
- Aggregation

**Key limitations**

- Lack of projections
- Uncertainty
- Data availability
- Policy relevance

De Sherbinin et al. (2019) doi: 10.1002/wcc.600

**Photo:** Irene Davila-unsplash

# Approach 02

## CLIMATE HAZARDS

### Introduction to climate hazards

**The SADC region is currently adversely affected by several climate hazards, including heatwaves, unpredictable rainfall, strong winds, drought and extreme rainfall** (Sonwa et al. 2017). Here the focus is on droughts and extreme rainfall, as between 1970 and 2020 these were the most common types of climate hazards in Africa (Centre for Research on the Epidemiology of Disasters 2020).

The region is highly sensitive to droughts due to a dependence on rainfed agriculture (Adejuwon and Olaniyan 2019). Droughts adversely affect water supplies, crop and livestock production and cause food insecurity and conflicts among competing water users (Oguntunde et al. 2017; Adejuwon and Olaniyan 2019). Some crops show more climate resilience than others, but the majority of projected impacts of climate change on rainfed agriculture are negative (Serdeczny et al. 2017). As well as being adversely affected by droughts, much of the SADC region is also negatively impacted by extreme rainfall (Tarhule 2005). Extreme rainfall can lead to landslides and soil erosion, and to floods that can cause direct injury and death to people and livestock, as well as damage infrastructure and fields (Chamani et al. 2018; Tarhule 2005; Tschakert et al. 2010; Sonwa et al. 2017). Extreme rainfall is a necessary but not sufficient condition for damaging floods; land use patterns, drainage and waste management infrastructure are also important, however, with increasing rainfall intensity flood risk increases (Tazen et al. 2019).

Climate change may exacerbate both of these hazards. Previous work has found that the occurrence and severity of droughts in Africa are likely to worsen with climate change due to increases in temperature and changes in rainfall (Adejuwon and Olaniyan 2019; Oguntunde et al. 2017; Gan et al. 2016). There is large uncertainty in the sign and magnitude of climate change impacts on mean rainfall for the region (Rowell and Chadwick 2018), however, extreme rainfall is expected to increase over large parts of the region (Kendon et al. 2019; Sonkoué et al. 2018; Amoussou et al. 2020), and so the associated risk of floods (Tazen et al. 2019).

Previous analyses of climate hazards over Africa have focussed primarily on the CMIP5 ensemble of global climate models. Here we make use of the CORDEX-Africa ensemble of regional climate models, which improve on the representation of climate over global climate models, particularly when it comes to extreme events and precipitation (Paeth and Mannig 2013; Gibba et al. 2018; Diallo et al. 2015).

#### CLIMATE HAZARDS OF CONCERN IN SOUTHERN AFRICA

- Droughts
- Floods
- Extreme weather events
- Salinity intrusion
- Sea level rise
- Temperature changes
- Changes to seasonal patterns

#### THINGS WE TRACK TO UNDERSTAND THE CLIMATE HAZARDS

Magnitude | Extent | Rate of change

**Photo:** Dean Chahim

# CYCLONES

## An Example of Climate Hazards in the SADC Region

Tropical cyclones are intense circular storms that originate over warm tropical oceans, such as the Indian Ocean, and are characterised by low atmospheric pressure, high winds, and heavy rainfall. In comparison with other extreme weather events, storms (including tropical cyclones) result in the most human displacement. For example, in the SADC region approximately 1.7 million people were left homeless between 1980 and 2016 due to storms (Davis-Reddy and Vincent 2017). The associated flooding disproportionately affects communities with poor infrastructure and health services, often resulting in a loss of life, injury, damage to property and infrastructure as well as the spread of disease e.g. malaria and cholera.

- **Madagascar** was affected by five cyclones during the 1993-1994 season. In **1994, Cyclone Geralda** (category 5) destroyed more than 90% of the port city of Toamasina. The damage was estimated at USD 10 million (Davis-Reddy and Vincent 2017).
- In **2000, Cyclone Eline** caused severe flooding in **Mozambique** and to a **lesser extent in South Africa, Zimbabwe, and Botswana**. High winds, torrential rains and high river flows resulted in economic losses and damage to infrastructure, livelihoods, and agricultural crops. In Mozambique alone, around 700 people lost their lives and the GDP growth rate dropped from 10% to 2% (Davis-Reddy and Vincent 2017).
- In **2004, Cyclone Gafilo** (category 5) hit **Madagascar**. It was the most intense tropical cyclone worldwide in 2004. It was estimated that approximately 773,000 people were affected, and it cost USD 250 million in damages (ReliefWeb 2004).
- In **2019, Cyclone Idai hit Beira in Mozambique** and then continued moving across the region. Millions of people were affected in Malawi, Mozambique, and Zimbabwe. Cyclone Idai was the worst natural disaster to hit Southern Africa in around two decades.
- **Six weeks later, Cyclone Kenneth** made landfall in **northern Mozambique**. This was the first occurrence of two strong tropical cyclones hitting the country in the same season. The cyclones caused severe flooding, destroying infrastructure and more than 800,000 hectares of crop land over the three SADC member states (SADC 2019). Approximately, 3.3 million people were affected by the cyclones, requiring immediate humanitarian assistance, including food, shelter, clothing, potable water, sanitation, and medical support. The affected population also faced epidemic threats of cholera, other diarrheal infections, and malaria (UNICEF 2019).

## Methods

We used the regional climate models available from CORDEX-Africa to analyse climate hazards in the SADC region. The CORDEX-Africa models are available at a 0.44° x 0.44° resolution. The multi-model ensemble for RCP8.5 includes 6 RCMs (regional climate models) with 11 different GCMs (global climate models) providing initial and boundary driving conditions, and for RCP4.5 7 RCMs and 9 different GCMs. The matrix of GCM/RCM combinations is presented in Table 1. We used 1971–1999 as the historical period, 2031–2059 as the mid-century period.

| GMC | RCM | | | | | | |
|---|---|---|---|---|---|---|---|
| | SMHI-RCA4 | CLMcom-CCLM4-8-17 | MPI-CSC or GERICS REMO2009 | KNMI-RACMO22T | DMI-HIRHAM5 | CCCma-CanRCM4 | UQAM-CRCM5 |
| HadGEM2-ES | RCP8.5/4.5 | RCP8.5/ 4.5 | RCP8.5 | RCP8.5/ 4.5 | | | |
| EC-EARTH | RCP8.5/4.5 | RCP8.5/ 4.5 | RCP8.5/ 4.5 | RCP8.5/ 4.5 | RCP8.5/ 4.5 | | |
| MPI-ESM-LR | RCP8.5/4.5 | RCP8.5/ 4.5 | RCP8.5/ 4.5 | | | | RCP4.5 |
| CNRM-CM5 | RCP8.5/4.5 | RCP8.5/ 4.5 | | | | | |
| MIROC5 | RCP8.5/ 4.5 | | RCP8.5 | | | | |
| CSIRO-Mk3-6-0 | RCP8.5/ 4.5 | | | | | | |
| IPSL-CM5A-MR | RCP8.5/ 4.5 | | | | | | |
| IPSL-CM5A-LR | | | RCP8.5 | | | | |
| CanESM2 | RCP8.5 | | | | | RCP8.5/ 4.5 | RCP4.5 |
| NOAA-GFDL-ESM2M | RCP8.5/ 4.5 | | | | | | |
| NorESM1-M | RCP8.5/ 4.5 | | | | | | |

Table 1. Available GCM/RCM combinations for CORDEX-Africa RCP8.5 and RCP4.5.

We examined the impact of extreme rainfall by looking at the 95th percentile of daily rainfall (R95 index), and drought by looking at the standardized precipitation evapotranspiration index (SPEI), as defined by Vicente-Serrano et al. (2010), which is a commonly used drought index that performs well compared to alternatives (Labudová et al. 2017) and has been used in Africa (e.g. Abiodun et al. 2018; Adejuwon and Olaniyan 2019; Ghebrezgabher et al. 2016; Oguntunde et al. 2017; Polong et al. 2019; Ujeneza and Abiodun 2015). We used 1955–1970 as the reference period, and looked at droughts over 1 month in duration and used the log-logistic distribution. We performed the calculation using the 'SPEI' package for R statistical software (Begueria and Serrano 2017; R Core Team 2013). Using SPEI, a value of -1 is classified as a drought, and -2 and below is classified as a severe drought.

# VULNERABILITY INDICATORS

## Introduction to vulnerability indicators

In the second stage we characterised underlying social and biophysical vulnerability across the SADC region. Following the methodological approach of Thornton et al. (2008), we developed a set of vulnerability indicators based on the sustainable livelihoods framework capitals:

- Human
- Physical
- Social (Carney 1998)
- Financial
- Natural

A total of 10 indicators were chosen based on data availability and where possible, we identified and used the most recent data sources (Table 2). Below, we give a summary of each indicator and briefly discuss their hypothesised relationships with vulnerability to climate hazards.

### UNDERSTANDING REGIONAL VULNERABILITY

**10 vulnerability indicators**
(equally weighted)

- Crops
- Soils
- Access to Water
- Electricity
- Distance to Markets
- Gross Domestic Product (GDP)
- Poverty
- Gender Equality
- Health
- Education
- Governance

## Human capital

The health poverty headcount indicator represents the percentage of the population considered poor. It measures deprivation of health standards within a given household where a household is considered poor if: a) any adult (under 70 years old) or child within the household is considered undernourished, and b) any child (under 18 years) has died in the five years preceding the survey. The potential impacts from climate change on human health are complex and largely adverse, for example, exacerbating challenges with food and nutrition security (Wolski et al. 2020), manifesting through new distributions in disease vectors (Caminade et al. 2014; Moore et al. 2017) and aggravating underlying health problems (Kapwata et al. 2018). Higher poverty headcounts for health are therefore associated with higher levels of vulnerability.

The education poverty headcount indicator represents two measures of education poverty, where a household is considered poor if: a) no household member above the age of ten has completed at least six years of schooling, and b) children of school age are not attending school up to Class 8. Education is a priority for development, can substantially reduce vulnerability to climate impacts (O'Neill et al. 2020), and is critical for improved adaptation to climate risks (Lutz et al. 2014). We therefore assume that higher poverty headcounts for education are associated with higher levels of vulnerability.

## Physical capital

The standard of living indicator measures deprivation of living standards by combining six indicators. A household is considered poor if:

- **a.** The household cooks with un-improved fuel, e.g. dung, wood, charcoal or coal;
- **b.** Either their sanitation facility is not improved, in accordance with sustainable development goal (SDG) guidelines, or their sanitation facilities are improved but are shared with other households;
- **c.** Either the household has no access to improved drinking water, in line with SDG guidelines, or the distance to safe drinking water exceeds a 30-minute round-trip;
- **d.** The household has no electricity;
- **e.** One or more of the three housing materials (for roof, walls and floor) are made of either rudimentary or natural materials and are therefore considered inadequate; and
- **f.** Household members do not own more than one listed asset (radio, TV, telephone, computer, animal cart, bicycle, motorbike, refrigerator), or a motorised vehicle.

A good standard of living is a prerequisite for human development and wellbeing (Rao and Min 2018). Sturdy infrastructure protects against inclement weather, access to potable water and safe sanitation protects against water-borne diseases, and the use of improved energy sources reduces health burdens (e.g. linked to indoor air pollution), especially for women and children. Thus, a lower standard of living equates to higher levels of underlying vulnerability.

For countries lacking MPI data (i.e. Botswana, Mauritius and the Seychelles), a related measure of poverty was sought. This resulted in the combined use of World Bank indicators for percentage of people/homes living on less than USD 1.90, with access to clean cooking fuels, access to basic sanitation and drinking water, and access to electricity (N.B. rationale for the inclusion of these data is provided within the Section on Creating risk maps Page 19).The access to market indicator measures travel time to the nearest urban area in excess of 20,000 people. Markets are important for reducing vulnerability as they stimulate livelihood and income diversification, particularly into off-farm sectors (Haggblade et al. 2010). Households nearer markets also tend to have better access to services (e.g. education, health and extension). We therefore assume that better market access is associated with reduced vulnerability.

| CAPITAL | INDICATORS | DESCRIPTORS | DATA SOURCE |
|---|---|---|---|
| HUMAN | Education | The national poverty headcount for the 'education' dimension (MPI-1)a | OPHI (2019a) |
| | Health | The national poverty headcount for the 'health' dimension (MPI-2)a | OPHI (2019a) |
| PHYSICAL | Standard of living | The national poverty headcount for the 'standard of living' dimension (MPI-3)a, b | OPHI (2019a) |
| | Accessibility to markets | A continuous index based on travel time to urban areas with populations exceeding 20,000 | IFPRI (2016) |
| SOCIAL | Gender inequality | National-level index based on gender inequalities across 3 aspects, namely: Reproductive health, Empowerment and Economic status, taken from the Human Development Index (HDI) | UNDP (2018) |
| | Governance | National-level data on voice and accountability, and government effectiveness | World Bank (2019) |
| FINANCIAL | Per capita GDP | National-level data for per capita GDP, in USD | World Bank (2020) |
| | Agricultural GDP | National-level data for agricultural GDP as percentage of total GDP | World Bank (2020) |
| NATURAL | Crop production suitability | Categorised from 1-8, where pixels scored 8 are considered areas with high crop suitability. | FAO (2007) |
| | Soil erosion | An assessment of soil loss for 2012 (Pg yr-1), normalised for the SADC region into quantiles. | ESDAC (2019) |

Table 2. Vulnerability indicators identified and used in the analysis (adapted from Thornton et al. 2008).

- **a.** No data available for Botswana, Mauritius and the Seychelles.
- **b.** All MPI data (for health (MPI-1), education (MPI-2) and standard of living (MPI-3) indices) were taken from the 2019 Global Multidimensional Poverty Index (MPI) and, due to a lack of district level data for South Africa and inconsistencies in district names between datasets, are at a national level (OPHI 2019b).

Photo: Dimitry-unsplash

## Social capital

The **gender inequality indicator** measures disparities between men and women in three areas of development:

a. Reproductive health,
b. Empowerment, and
c. Economic status.

Reproductive health quantifies maternal mortality ratios and adolescent birth rate. Empowerment encompasses both the proportion of parliamentary seats occupied by women, and the percentage women and men (above the age of 25) with secondary education. Economic status measures the labour force participation rates of men and women over the age of 15. The majority of the world's poor are women[1] and women typically experience the most severe impacts from climate change in situations of poverty. For example, in the aftermath of a disaster, women are more likely than men to be displaced and be victims of violence (Cutter 2017). Women have less access to, and control over, resources, which undermines their ability to cope with and adapt to climate impacts. Subsequently, women also have fewer capabilities than men, limiting their contributions to decision-making processes (World Bank 2009). Higher gender inequality therefore represents higher levels of vulnerability.

The governance indicator uses data from the World Bank, based on a study by Kaufmann et al. (2005). Following (Thornton et al. 2008), we use two of the six dimensions:

a. Voice and accountability
b. Government effectiveness

Because all six indicators cannot be meaningfully combined for a given country. Scores for the two indicators were normalised into quintiles at national level. Good governance creates enabling environments for investment, job creation and effective implementation of regulations, such as those related to climate adaptation, and is associated with higher adaptive capacity at the national level (Brooks et al. 2005). We therefore assume that better governance equates to lower levels of vulnerability.

[1]https://www.oxfam.org/en/why-majority-worlds-poor-are-women

## Financial capital

**Per capita GDP** provides a measure for estimating the economic prosperity of a country, where income is associated with access to resources. Whilst economic indicators such as GDP have been found to be poor indicators of mortality as a result of climate-related disasters (Brooks et al. 2005), losses in GDP have been used to measure national vulnerability to climate impacts (Formetta and Feyen 2019), and per capita GDP has also been used as a measure for economic security (Li et al. 2019). We assume that higher per capita GDP is associated with lower levels of vulnerability, although we note that this also assumes that resources are distributed equally amongst the population.

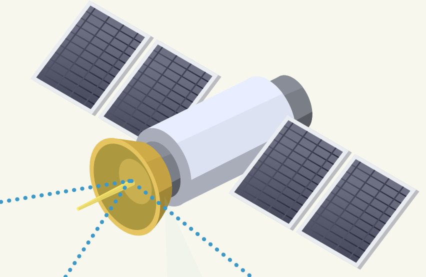
The agricultural sector is highly vulnerable to the effects of climate change (Mase et al. 2017), particularly in rainfed systems across much of the SADC region (Cooper et al. 2008). National economies more dependent on agriculture are therefore more susceptible to climate impacts and expected changes. Countries with higher economic dependency on agriculture may also be less diverse (Thornton et al. 2008). Higher contributions of agricultural GDP to total GDP is therefore assumed to be associated with higher vulnerability.

## Natural capital

The **crop production suitability indicator** considers the known and calculated rainfed pasture and crop requirements, the dominant soil conditions of a given area, and soil management practices used, under intermediate input scenarios, as stipulated by FAO (2007). Whilst rainfed agriculture is highly vulnerable to the effects of climate change, areas with higher crop suitability provide greater diversification options for rural populations (e.g. growing different, or a range of crops), offering opportunities for risk spreading, thus increasing resilience (Lin 2011; Speranza et al. 2014). We thus assume that higher cropping suitability is associated with lower vulnerability.

The soil erosion indicator assesses human-induced soil erosion resulting from land use/land cover change. The modelled data do not include short-term impacts from land use (e.g. fire and wood harvesting), overgrazing and climate change effects. Soil erosion rates are divided into seven classes (ranging from 0–350 t/25km cell sample), according to the European Soil Bureau classifications. Soil degradation, which can be exacerbated by climate change and extreme events, undermines agricultural productivity and reduces water quality (FAO 2015). Extreme rainfall events and flooding can also trigger landslides. Areas with higher levels of soil erosion are therefore considered to be more vulnerable.

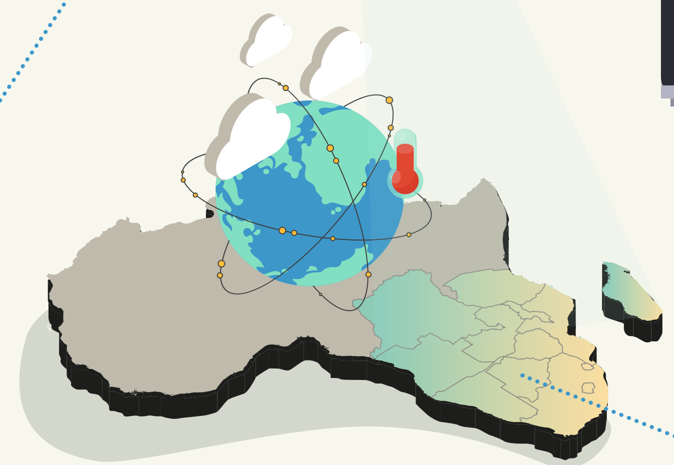
## CREATING RISK MAPS



01

To **visualise the range of vulnerability indicators across the SADC region** and to assist eventual identification of hotspots, **all data were mapped using a Geographic Information System (GIS)**. Initially, all data were imported into the GIS (ArcGIS 10.6) either in its raw tabulated form (e.g. for the MPI data) or, where available, in its original GIS format (e.g. the Distance to Market and Soil Erosion data are provided as raster map layers by data authors).

To present data in the regional context, national boundaries for each of the member nations of the SADC and the respective first and second level district boundaries were also imported into the mapping environment. Using the Join – Relate function of the GIS, data for the Human, Physical, Financial and Social capital indicators was assigned to their respective national boundary. This duly produced a suite of ten maps for each vulnerability indicator at a national scale (not shown here).



02

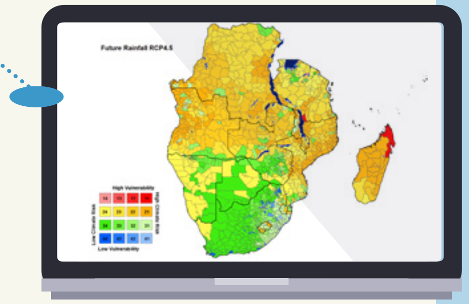
To further visualise and understand the vulnerability of each nation, indicator values were normalised to make them comparable before combining them into an index of average vulnerability. To achieve this, the separate map layers for each vulnerability indicator were combined into a single database and exported to Excel. Within Excel the quartile range for each indicator was determined and values were reassigned to a quartile depending on whether they fell within the 1st, 2nd, 3rd or 4th quartile of all values.

The assignment of values, whether to the 1st or 4th quartile, was based on whether a high figure for a given indicator was deemed to be good or bad, and vice versa (e.g. for Soil Loss, high loss was deemed to be bad and was consequently assigned a value of 1, i.e. the 1st quartile; conversely high GDP was deemed to be good if falling within the upper 25% of values and assigned a value of 4, i.e. the 4th quartile). Following data processing each indicator quartile, within each nation, was summed and divided by the number of total indicators for each country to provide an average (mean) level of vulnerability on a continuous scale of 1.0–4.0 (representing each quartile), with 1.0 being highly vulnerable and 4.0 being less vulnerable.

03

The data gap for Botswana was filled using alternative data (section on Vulnerability indicators Page 16) before calculating the combined average vulnerability for each county. Representative World Bank indicators for physical capital were identified and used to represent ‘Living Standards’ within Botswana, as well as Mauritius and the Seychelles (albeit fewer comparable indicators were found for the latter two countries).

Though similar, it is acknowledged that the World Bank data is not a direct replacement for the MPI measures of standard of living. However, inclusion was deemed preferable to exclusion of countries without MPI data.



04

The normalised indicator data for each country, and the combined average indicator value for each country, were imported back into the GIS as a data table and, using the Join – Relate function, reassigned to the boundary map of each SADC country. This facilitated the production of a choropleth (or ‘thematic’) map showing the vulnerability index for each country across SADC allowing direct comparisons to be made across the region (Section on Vulnerability maps Page 24), though not with other countries and regions.

To achieve greater resolution and accuracy within the vulnerability maps, the data allocation and normalisation exercise was repeated for each country’s first and second level districts. For the tabulated data, this involved reassigning national values to districts (district level data was not available for several countries and/or there were significant inconsistencies in names of districts). For the raster and vector vulnerability data (i.e. Crop Suitability, Soil Loss and Distance to Market), however, this involved converting the map layers to data points and assigning them individually to each district using the Join – Relate function (where multiple points existed within a geographic area, the mean of values was assigned to the district). Though this procedure effectively adds weighting to these latter indicators, it provides the combined vulnerability maps with greater nuance in terms of identifying potential ‘hotspots’ and lessens the impact of data for key indicators, such as roads to markets, being effectively lost in a large country’s national data (e.g. within the DRC) and Angola where there are fewer good quality roads to markets in the interior).

Simple raster layers were produced for each climate rainfall and drought scenario (RCP4.5 and RCP8.5) and overlaid onto the vulnerability map. Bivariate maps were also produced where the climate data raster layers were converted to data points and normalised in the manner described above for raster vulnerability data. The point data for climate risks was then assigned to the relevant districts (and averaged where multiple points fell within one district). As such, it should be noted that to produce the discrete figures required to produce a bivariate map (i.e. 1, 2, 3, 4 rather than 1.0–4.0) both the average climate risk and vulnerability data was rounded up or down to its nearest significant figure. This serves to heighten the severity, good or bad, of indicators, which should be noted in respect to interpretation of the maps, but also brings greater resolution and emphasise to potential hotspots of risk (relative to the wider SADC).

# SYSTEMATIC EVIDENCE REVIEW

A **systematic literature review** was undertaken to compile evidence about regional SADC climate risks, adaptation and vulnerability. Systematic reviews seek to synthesise existing knowledge about a topic through a review of the literature focussed on specific research questions. The approach increases methodological transparency and rigour in the process of synthesising research by requiring that methods used are explicitly outlined and reproducible, and that document selection and review meets pre-defined and defensible eligibility criteria (Cooper et al. 2019; Fink 2020). A number of methodological guidelines exist (Pullin and Stewart 2006; Moher et al. 2009; Berrang-Ford et al. 2015), often tailored to particular disciplinary perspectives.

**Systematic reviews require similar specific components to be reported and generally include the following steps:**

1. Define the research question and scope of the study
2. Select documents, including development of inclusion and exclusion criteria
3. Critically appraise study quality
4. Analyse and synthesise evidence
4. Present results (Berrang-Ford et al. 2015)

We adhered to the general methodological guidelines for systematic reviews (Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) (Moher et al. 2009), and report below the items specified by Berrang-Ford et al. (2015), who tailor requirements to the epistemologically complex and methodologically diverse literature base that comprises climate research.

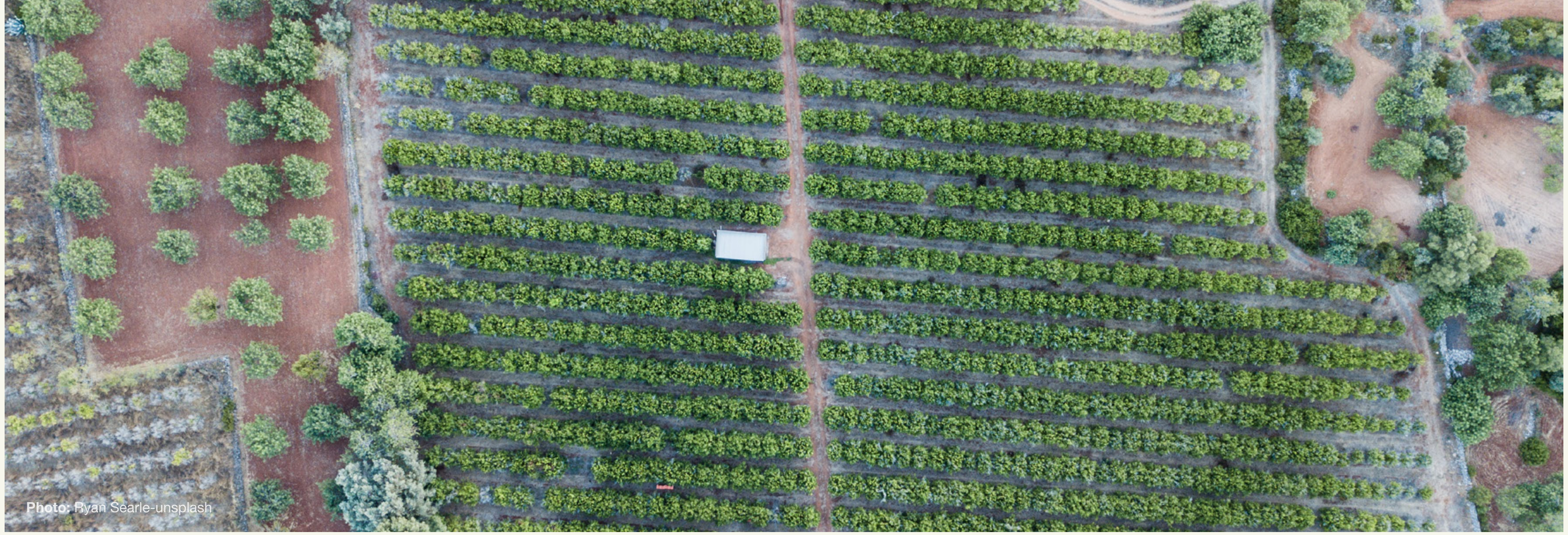


Photo: Ryan Searle-unsplash

## Aim of the review and key questions

### Explicit aim/objectives and prevailing literature/concepts:

Our review is located in the context of vulnerability, climate hazards and risk mapping outlined above, and aimed to identify what underpins agricultural climate risk in the SADC region.

### We were guided by the following questions:

1. **What are the key climate hazards linked to agriculture?**
2. **How and where do they interact with agricultural vulnerability and adaptations to create climate risk hotspots?**

## Data source and document selection

### Literature source (justification and description):

We searched SCOPUS and Web of Knowledge databases because they contain a substantial collection of relevant research, and because they perform precisely and reproducibly when using an extensive Boolean search string, such as the one we used (Gusenbauer and Haddaway 2020). The search was limited to peer-reviewed literature, published since 2016 that included research conducted in SADC countries to enable compilation of the most recent evidence on climate risk and vulnerability across the region. Time constraints limited our ability to include research published prior to 2016. Only literature written in the English language was included.

### Search terms and process and selection criteria:

Literature was selected, screened, and then coded following the process and criteria outlined in Figure 2, which also details the search string and database fields used and the numbers of studies rejected at each step. The initial search was undertaken on May 5th 2020 by one researcher. Three researchers completed subsequent screening and coding.

For quality control, all abstracts were double-screened, and retained for full review in the event of disagreement. Our initial search produced 759 research articles, which was reduced to a final set of 275 (Appendix A). Articles were generally excluded because they either did not focus on the SADC region, did not include empirical data (e.g. they were review papers), and/or did not identify findings or use data about the specified climate-related topics linked to agriculture (Figure 2).

# Analysis and presentation of results

## Methods of analysis:

We developed a **set of questions and a corresponding coded Excel spreadsheet** to extract and store information from the papers. The same three researchers performed the coding exercise after piloting the questions and coded template. The final output was an Excel spreadsheet providing information about the location of the research, the focal agricultural system and climate hazards, and whether the research was vulnerability- and/or adaptation-oriented.

## Information quality:

We included only **peer-reviewed data** in our review in an attempt to assure research included was rigorous. More rigorous controls on information quality were precluded by time constraints. However, greater consideration of data quality was given to research included as climate-risk hotspot case studies.

# Summary of literature

**With the exception of 2018, research in the SADC countries about climate-related hazards and exposure of agricultural systems has increased year on year between 2016 and 2019** (Figure 2). The 23 articles published to April in 2020 and that met our review criteria, suggest a continuing trend. More research was conducted in Tanzania than any other SADC country, featuring in nearly one quarter (22%) of articles (Figure 2). South Africa, Zimbabwe, Malawi and Zambia were also frequently the geographic focus (occurring in between 14-18% of articles). The remaining 11 SADC countries received less attention. Only two studies were conducted in Lesotho and one in Mauritius and Comoros, and we did not find any research meeting our criteria conducted in the Seychelles. Fifty-five papers had a regional or global focus. Drought, temperature and precipitation were the hazards most frequently linked to agricultural systems. Sea-level rise and hazards linked to salinization were seldom the focus of investigation. Most (87%) of the articles reviewed included analysis of food crops. Livestock systems were considered in approximately one third of articles, whilst non-food crops, aquaculture and agroforestry systems received much less attention. The majority of studies focussed on agricultural system vulnerability to climate hazards. However, nearly half researched adaptation, and nearly one quarter (23%) were concerned with both.

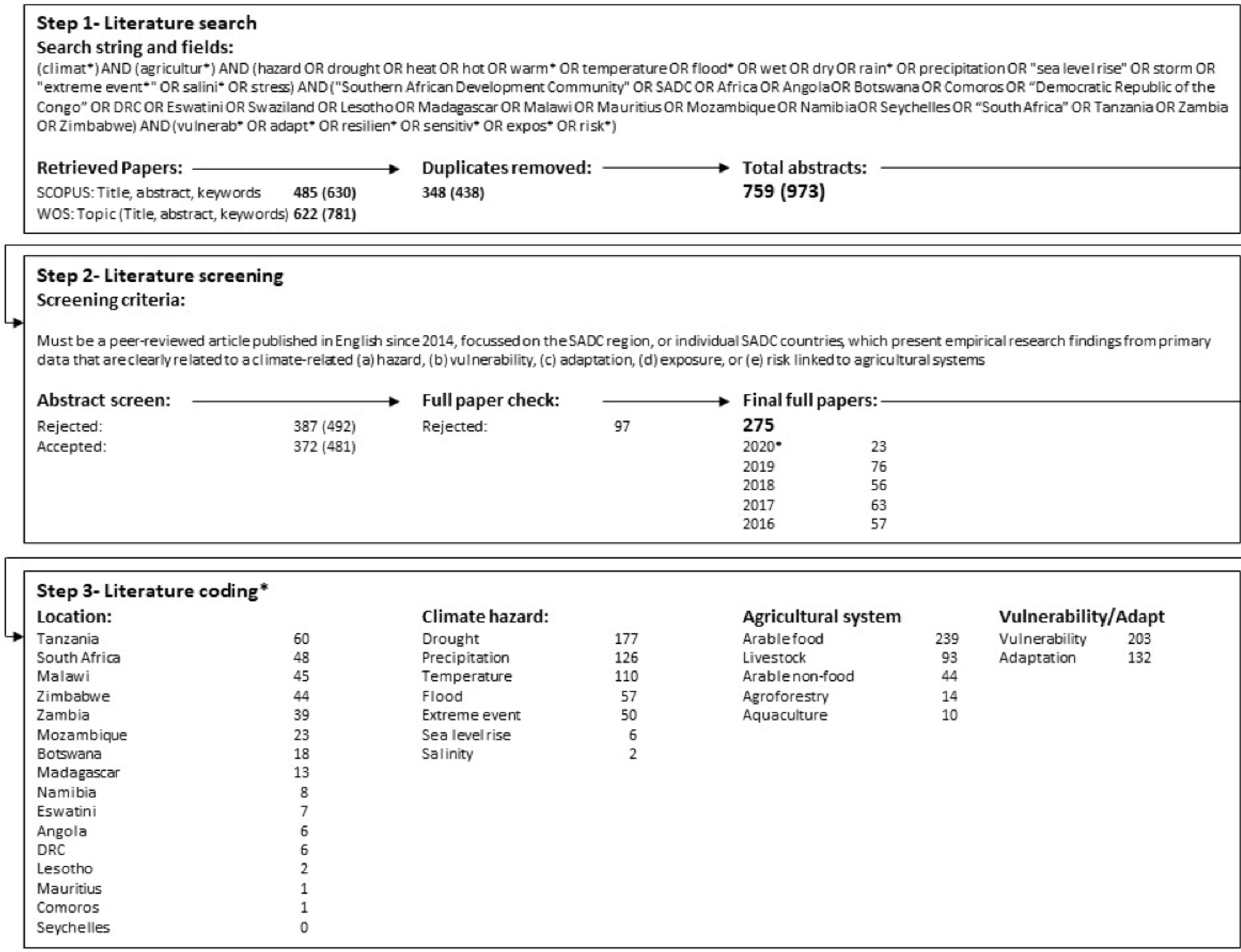


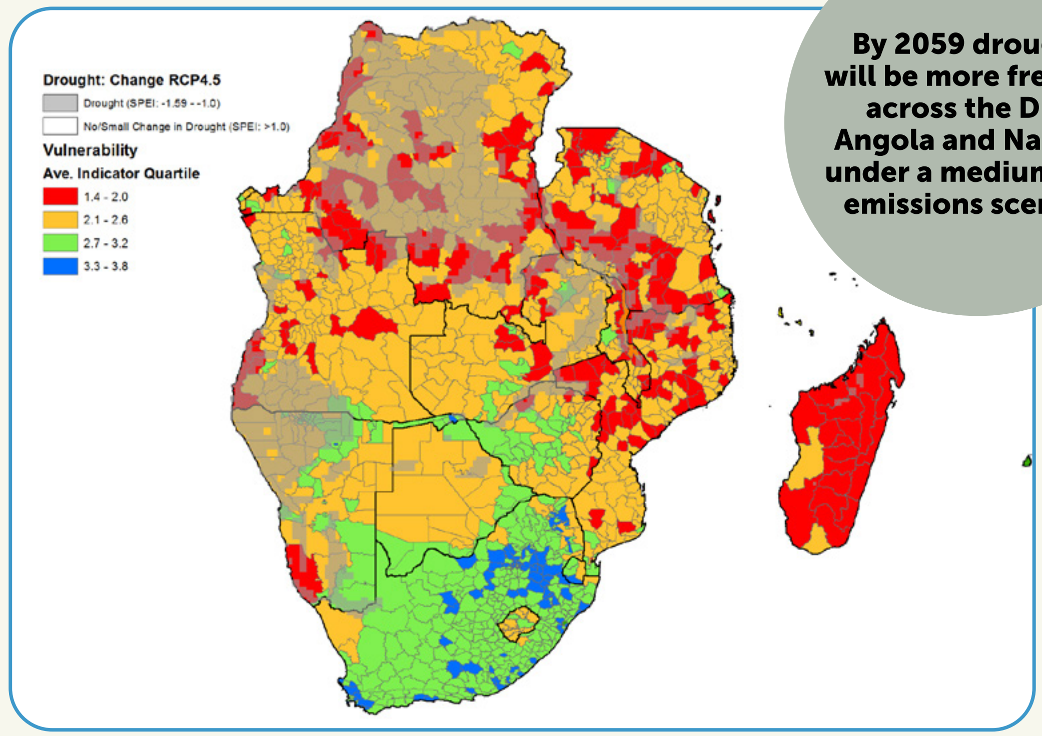

Figure 2. Search, screening and coding process and results for the systematic literature review. Numbers refer to the number of papers.* In 2020, articles were only retrieved for January-April. Coding sub-categories are not mutually exclusive. Articles can occur in multiple sub-categories.

# 03 Outcomes of the Climate Risk Analysis and Mapping

## CLIMATE HAZARD MAPS

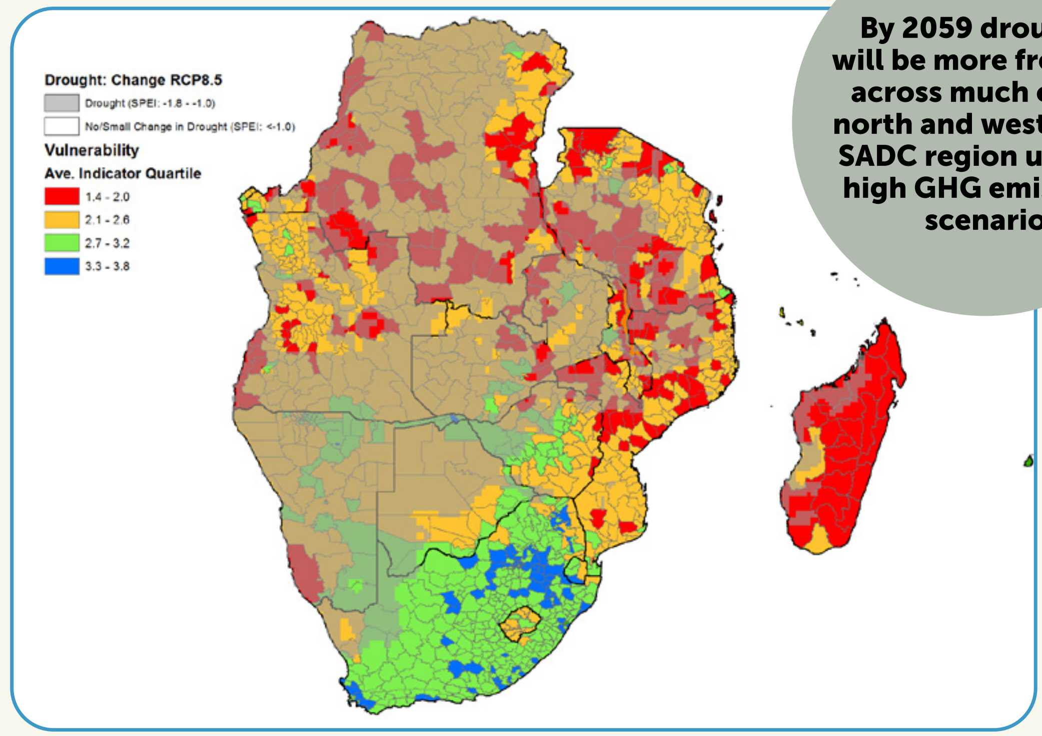
### Droughts

By mid-century, the likelihood of droughts increases in both RCP4.5 and 8.5 scenarios (Figure 3 and Figure 4). In RCP8.5, drought risk increases across most of the region, while in RCP4.5, droughts become more common primarily in the DRC, parts of East Africa, Angola and Namibia. The result of these changes in droughts is that in both RCP4.5 and 8.5 by mid-century droughts are common in most of the SADC region (Figure 5 and Figure 6). However, droughts are more severe in RCP8.5 than 4.5, although the most severe droughts remain rare.



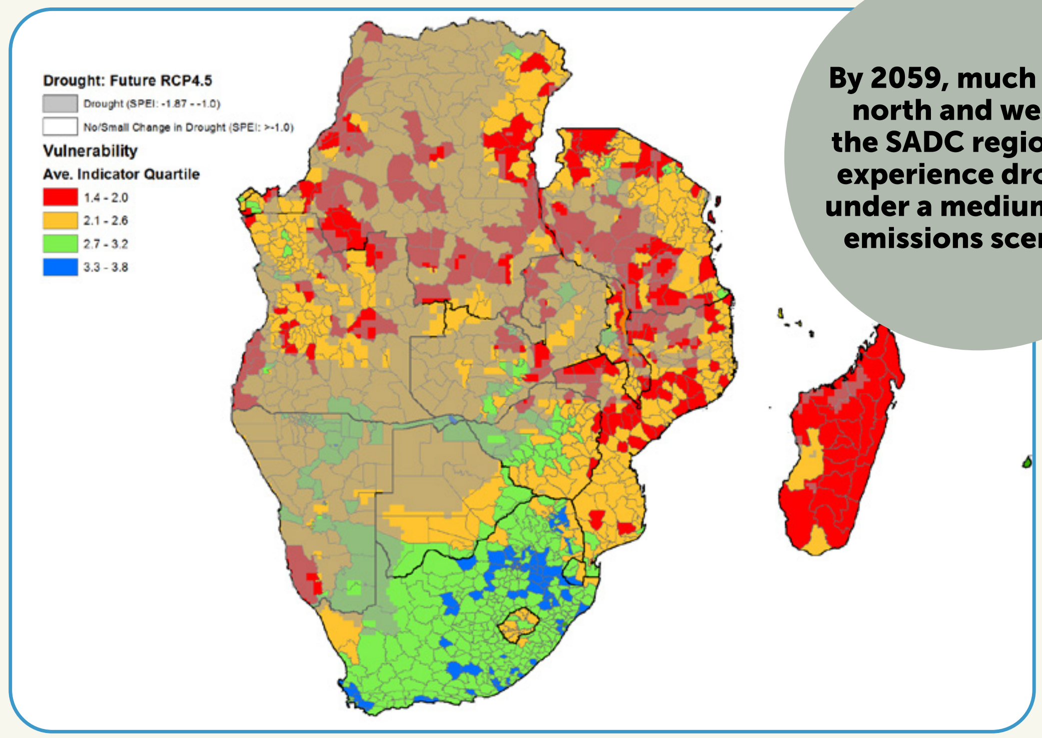

**By 2059 droughts will be more frequent across the DRC, Angola and Namibia under a medium GHG emissions scenario**

Figure 3. Multi-model ensemble mean of change in frequency of 1-month droughts by mid-century in RCP4.5 (2031–2059), as compared to the historical time period (1971–1999). Drought change of greater than 1 only shown in shading. Overlaid on vulnerability map where red = more vulnerable, blue = less vulnerable.



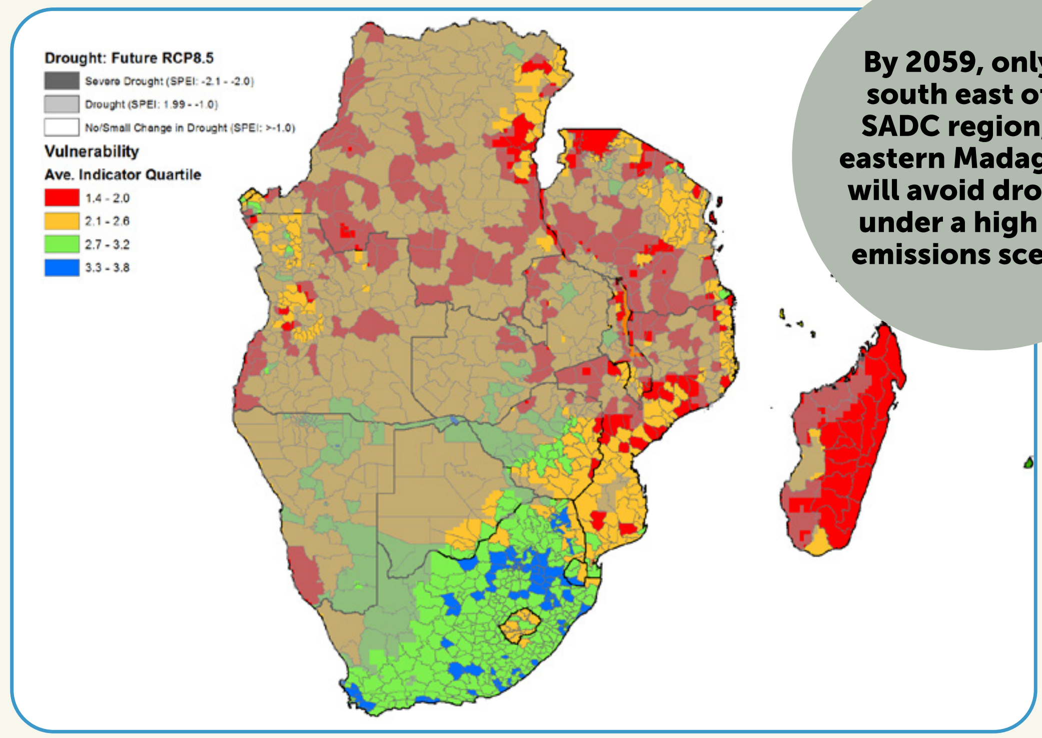

**By 2059 droughts will be more frequent across much of the north and west of the SADC region under a high GHG emissions scenario**

Figure 4. Multi-model ensemble mean of change in frequency of 1-month droughts by mid-century in RCP8.5 (2031–2059), as compared to the historical time period (1971–1999). Drought change of greater than 1 only shown in shading. Overlaid on vulnerability map where red = more vulnerable, blue = less vulnerable.




**By 2059, much of the north and west of the SADC region will experience drought under a medium GHG emissions scenario**

Figure 5. Multi-model ensemble mean 1-month droughts (SPEI <= -1) in mid-century in RCP4.5 (2031–2059). Overlaid on vulnerability map where red = more vulnerable, blue = less vulnerable.




**By 2059, only the south east of the SADC region, and eastern Madagascar, will avoid droughts under a high GHG emissions scenario**

Figure 6. Multi-model ensemble mean 1-month droughts in mid-century in RCP8.5 (2031–2059). SPEI <= -1 used to indicated droughts, and SPEI <= -2 indicates severe droughts. Overlaid on vulnerability map where red = more vulnerable, blue = less vulnerable.

## Extreme rainfall

Extreme rainfall increases by mid-century in both RCP4.5 and 8.5 in most of the northern SADC region. The increases in extreme rainfall are larger in RCP8.5 than in 4.5, and more widespread (Figure 7 and Figure 8).
R95 is an indicator of an extreme that occurs on a yearly basis. Figure 9 and Figure 10 show that by mid-century, rainfall between 12–25 mm/day should be a yearly occurrence in the northern SADC region under RCP4.5 and 8.5.

Recent research in East Africa has shown that there is a risk of landslides in susceptible areas (susceptibility depends on topography, land cover and soil type) with antecedent rainfall between 9.2 and 22 mm (Monsieurs et al. 2019). Research in the Sahel region has also shown floods are associated with 5-day rainfall totals of 30mm or more (Tazen et al. 2019). Rainfall at these levels could therefore be associated with risks of landslides and floods.

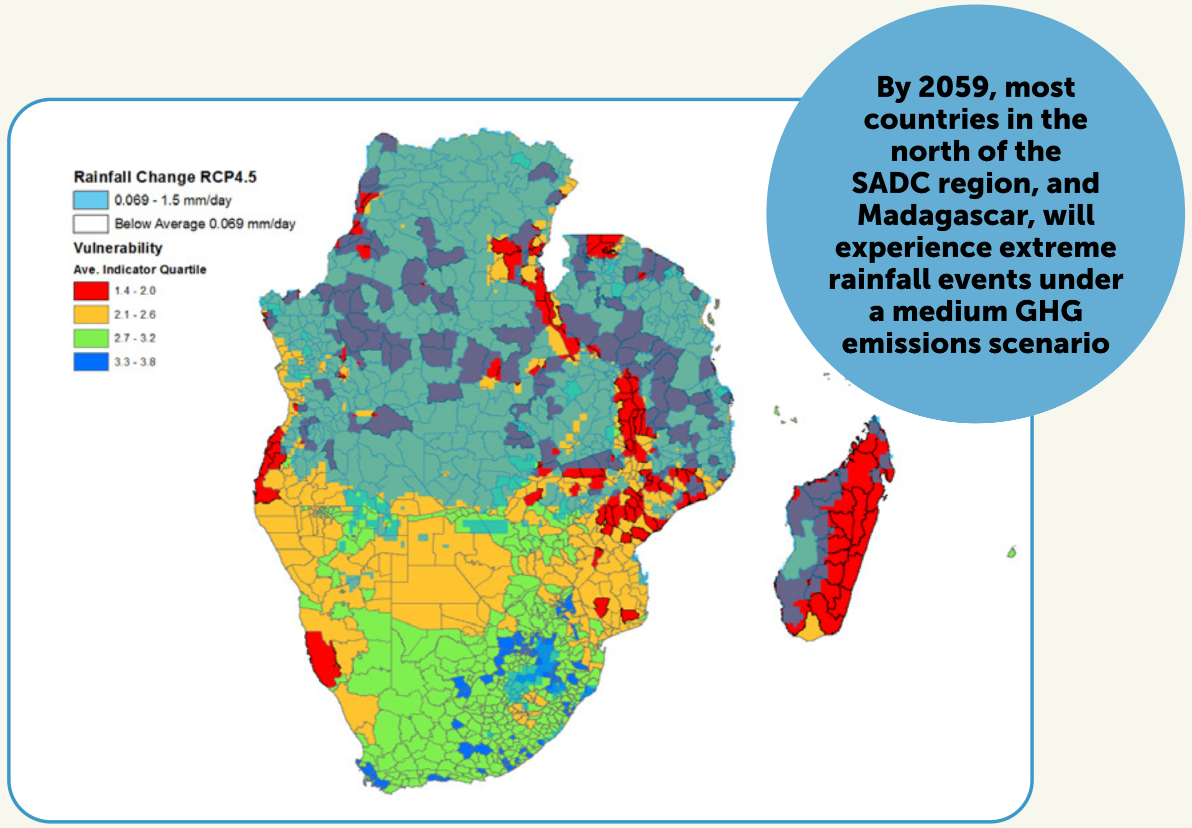



Figure 7. Multi-model ensemble mean of change in 95th percentile of rainfall (R95) by mid-century in RCP4.5 (2031–2059), as compared to the historical time period (1971–1999). Overlaid on vulnerability map where red = more vulnerable, blue = less vulnerable.

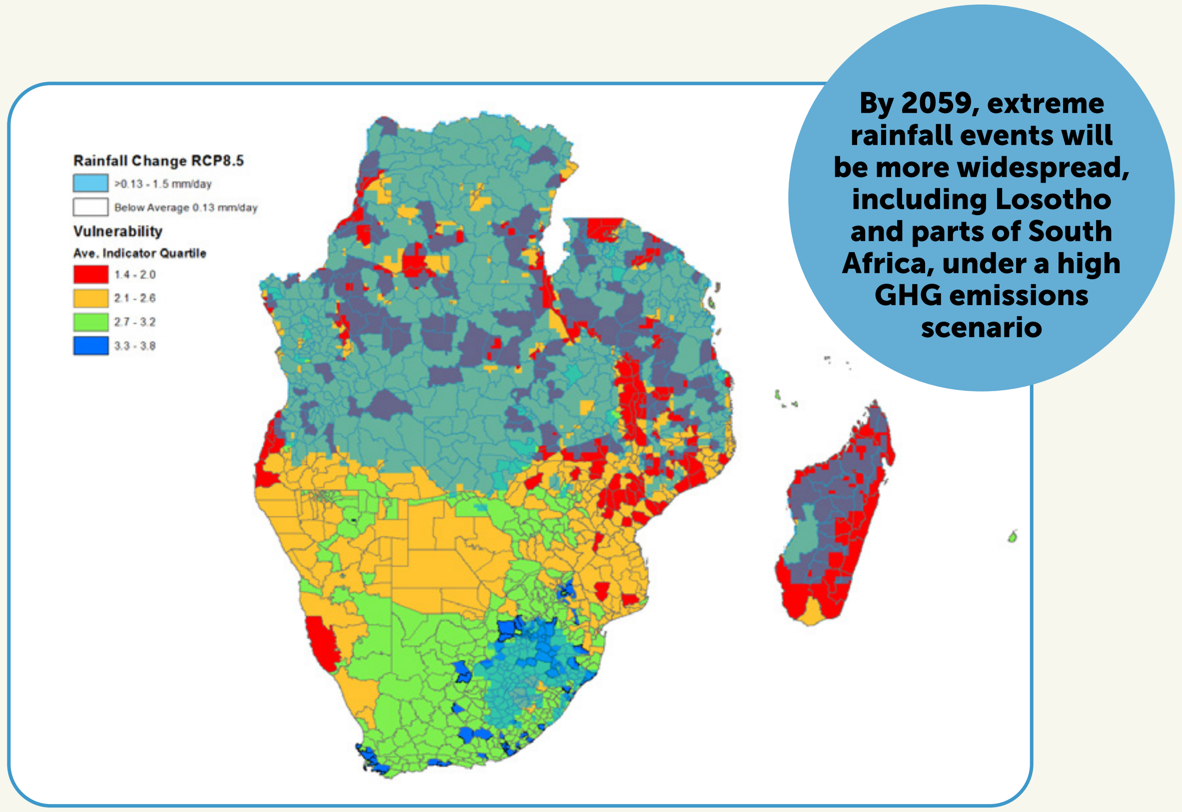



Figure 8. Multi-model ensemble mean of change in 95th percentile of rainfall (R95) by mid-century in RCP8.5 (2031–2059), as compared to the historical time period (1971–1999). Overlaid on vulnerability map where red = more vulnerable, blue = less vulnerable.

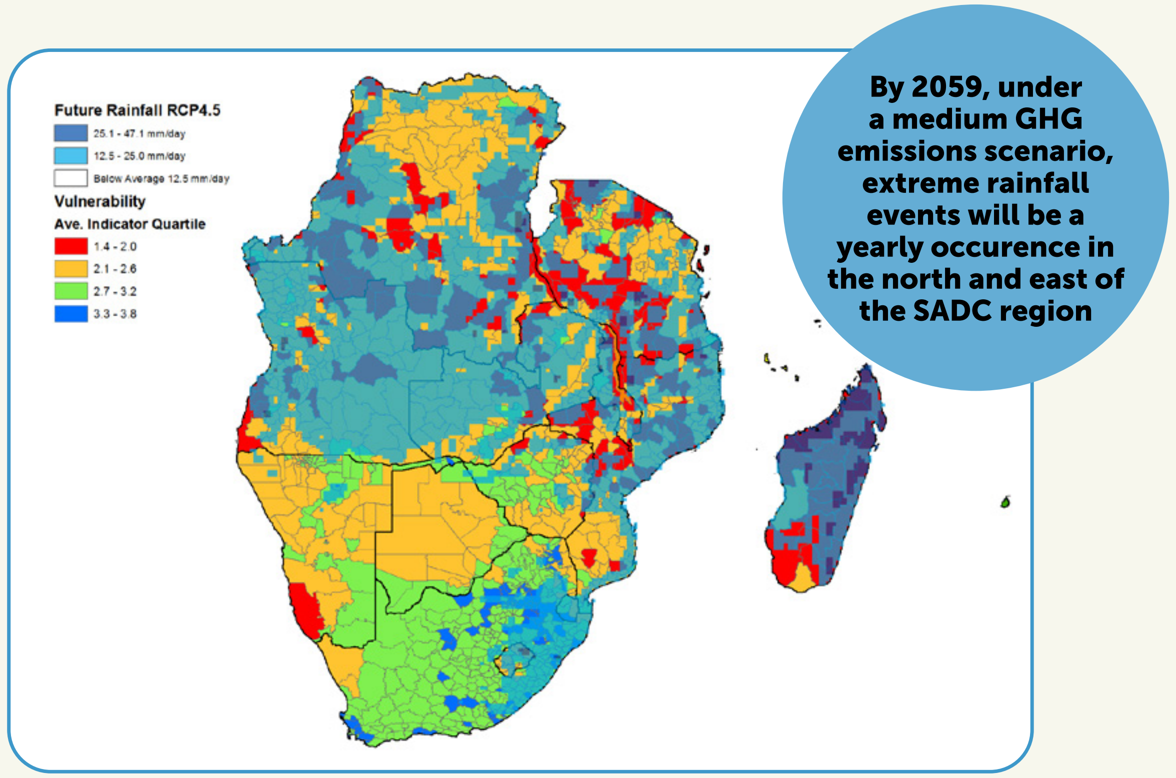



Figure 9. Multi-model ensemble mean 95th percentile of rainfall (R95) by mid-century in RCP4.5 (2031–2059). Overlaid on vulnerability map where red = more vulnerable, blue = less vulnerable.

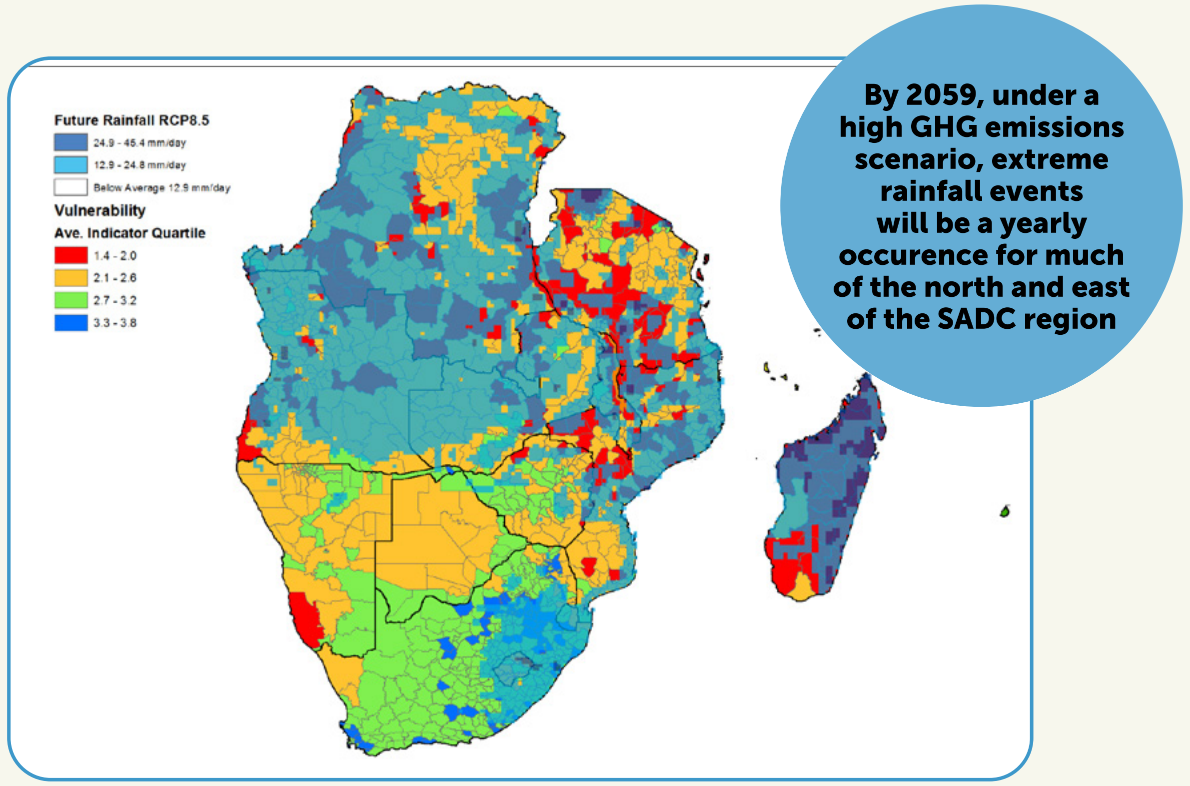



Figure 10. Multi-model ensemble mean 95th percentile of rainfall (R95) by mid-century in RCP8.5 (2031–2059). Overlaid on vulnerability map where red = more vulnerable, blue = less vulnerable.


## VULNERABILITY MAPS

Figure 11 represents the combined vulnerability index at national (inset) and district level. Vulnerability across the SADC region varies, with higher national-level vulnerability found in northern and eastern countries, including the DRC, Tanzania, Mozambique and Madagascar. There is a greater degree of variability between districts with, for example, countries such as Madagascar and areas such as northern Mozambique and south-western Angola demonstrating higher vulnerability. South Africa exhibits lowest overall levels of vulnerability, though urban districts (e.g. surrounding Pretoria and Johannesburg and in the south-western tip near to Cape Town) demonstrate the lowest vulnerability at a sub-national level.

**Looking across all of the indicators, red shows the areas of greatest vulnerability and blue the areas of least vulnerability**

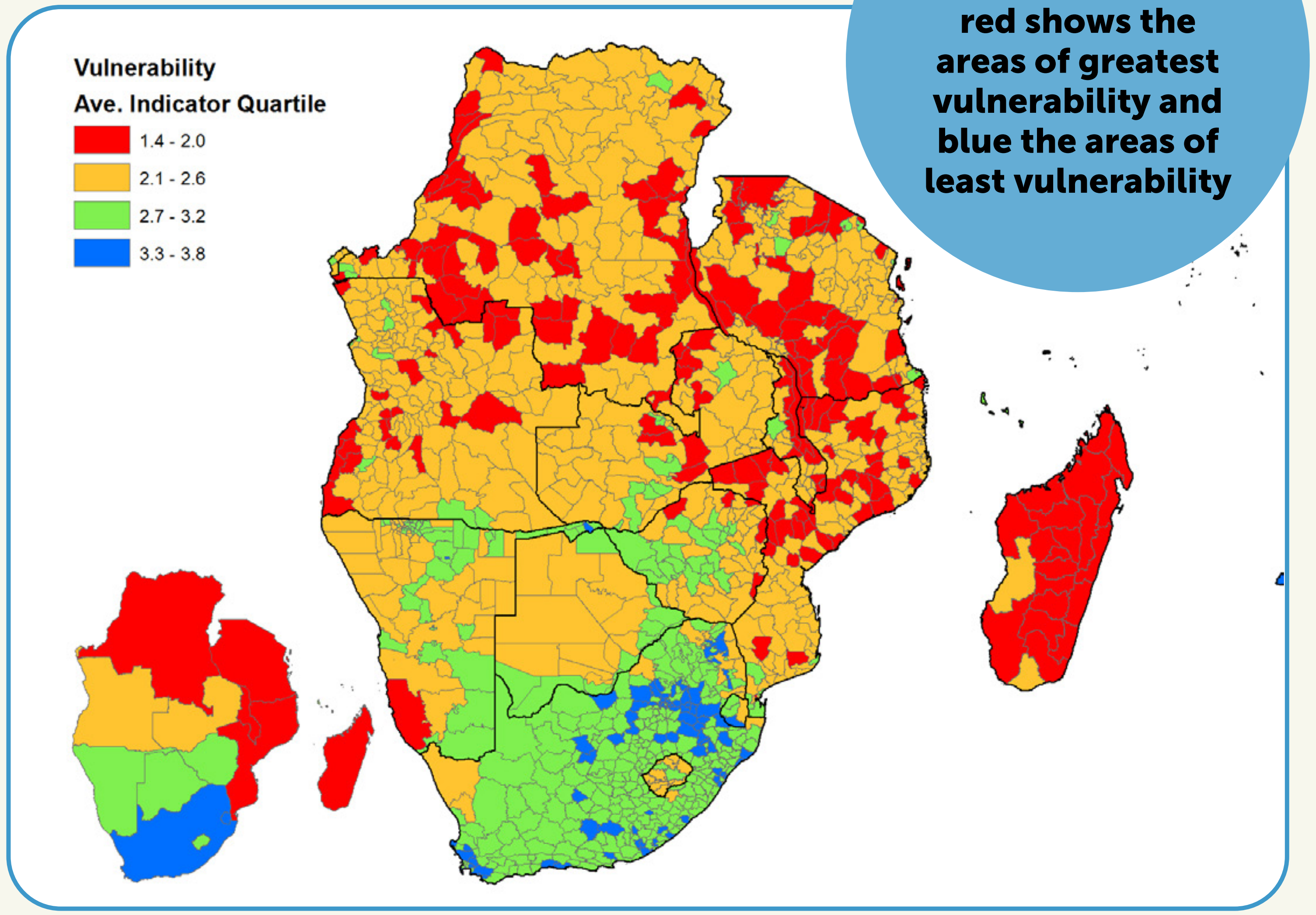
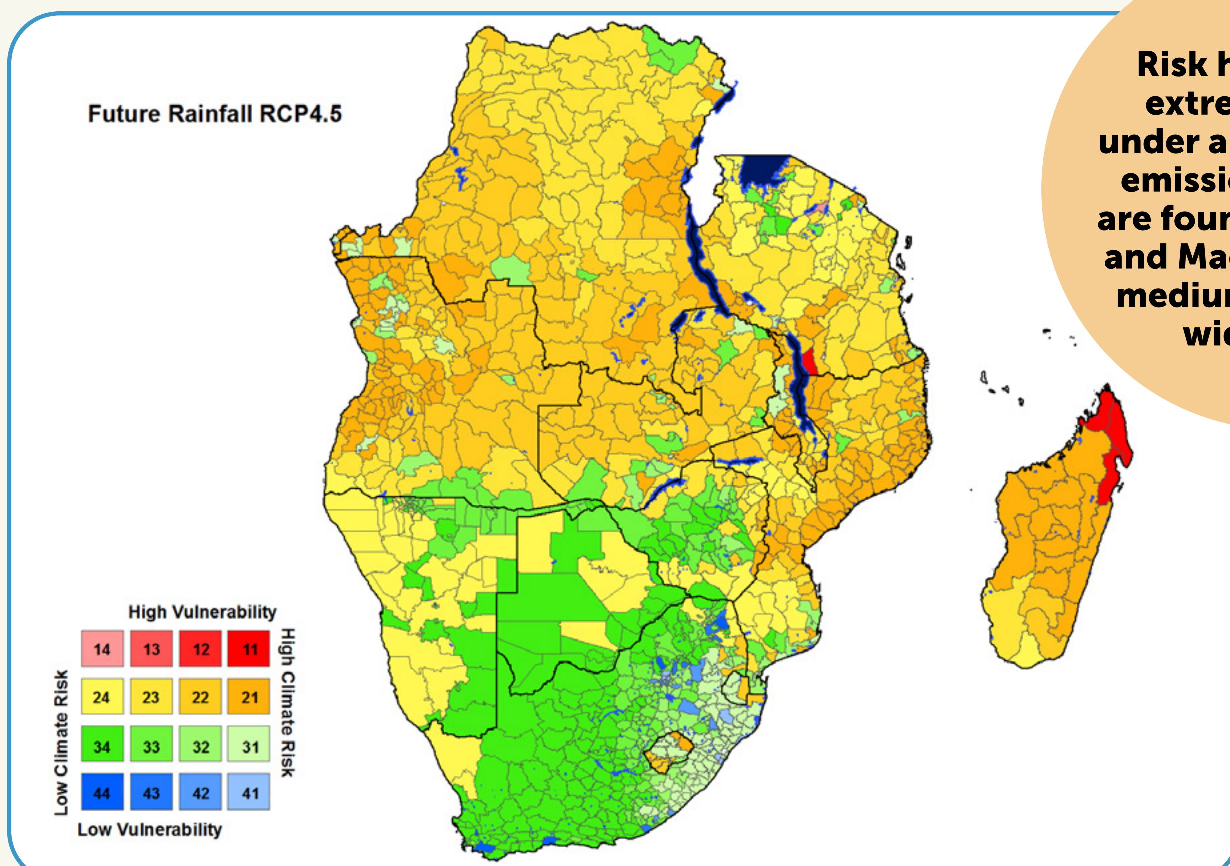



Figure 11. Vulnerability status of districts and countries (inset) across the SADC region. Quartiles represent the combined (10 indicators) relative vulnerability levels, whereby quartile 1 (red) = more vulnerable, quartile 4 (blue) = less vulnerable.

# CLIMATE RISK HOTSPOTS

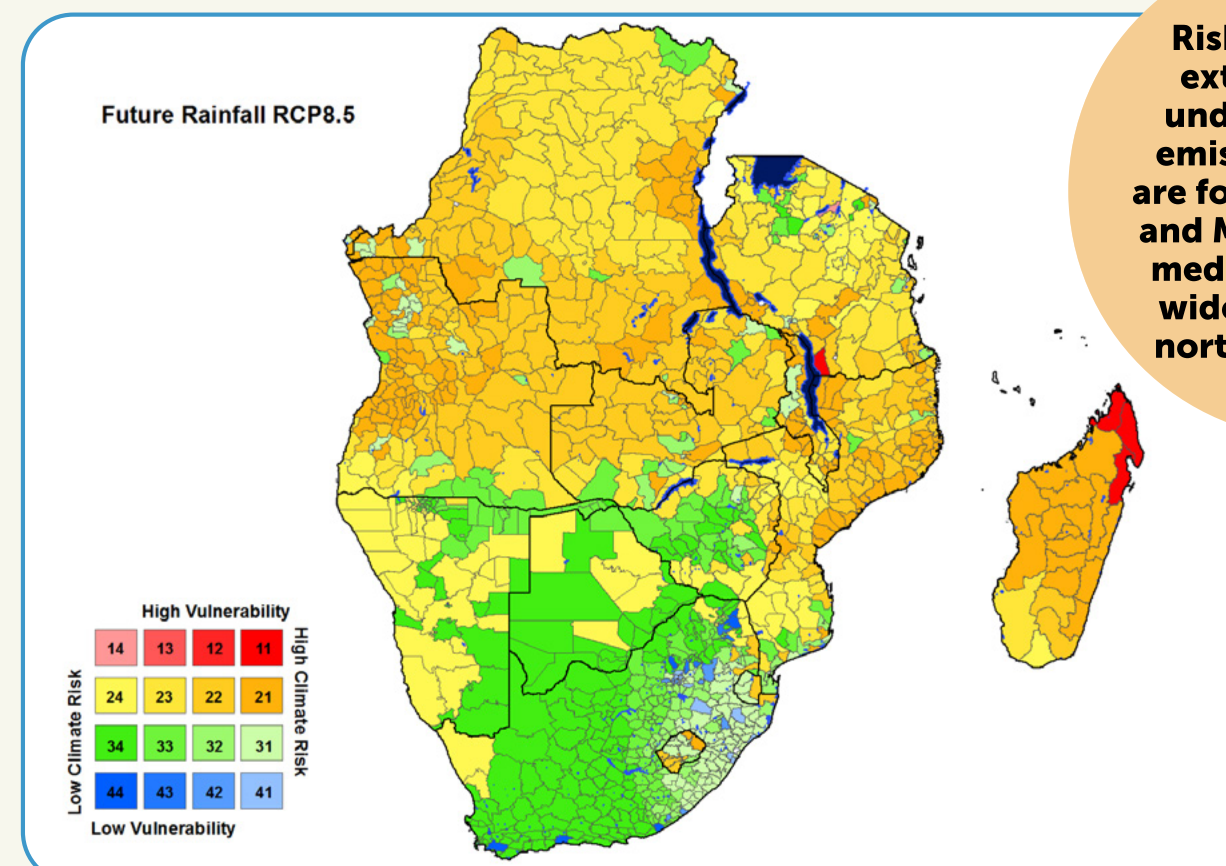
So far an overlay method has been used to provide a visual description of the impact of climate change across the SADC region, and where areas of greater vulnerability are located. However, the locations where the extremes in both climate hazard and vulnerability (i.e. hotspots) are located are difficult to identify. Bivariate choropleth maps enable the range of climate hazard to be combined with vulnerabilities within the same districts so that potential hotspots of concern can be identified.

Presented are the bivariate maps for combined current vulnerability within districts and future rainfall and drought under the RCP4.5 and RCP8.5 scenarios. Vulnerability is represented from high (red), medium high (orange), medium low (green) and low (blue), while climate hazards are represented by colour shading from high (darker) to low (lighter) risk. Figure 12 suggests that there are hotspots of high rainfall and high vulnerability, therefore climate risk hotspots, along the northern coast of Madagascar (particularly Antsiranana and Toamasina) and along the coast of Lake Nyasha/Malawi (particularly the east coast around Ruvuma in Tanzania). Some further potential hotspots can also be seen along the eastern border of the DRC and the coasts of Angola and Mozambique. In comparison to the RCP.4.5 scenario, under RCP.8.5 there is little change between potential hotspots (Figure 13).




**Risk hotspots for extreme rainfall under a medium GHG emissions scenario are found in Tanzania and Madagascar, but medium high risk is widespread**

Figure 12. Bivariate map showing hotspots of vulnerability to and risk of extreme rainfall within the districts of each SADC region for the RCP4.5 scenario. The first number within each matrix colour represents the normalised and rounded mean vulnerability value for the district, with the second number representing the rounded climate hazard value (i.e. 34 equates to 'medium low vulnerability', 'low climate hazard).

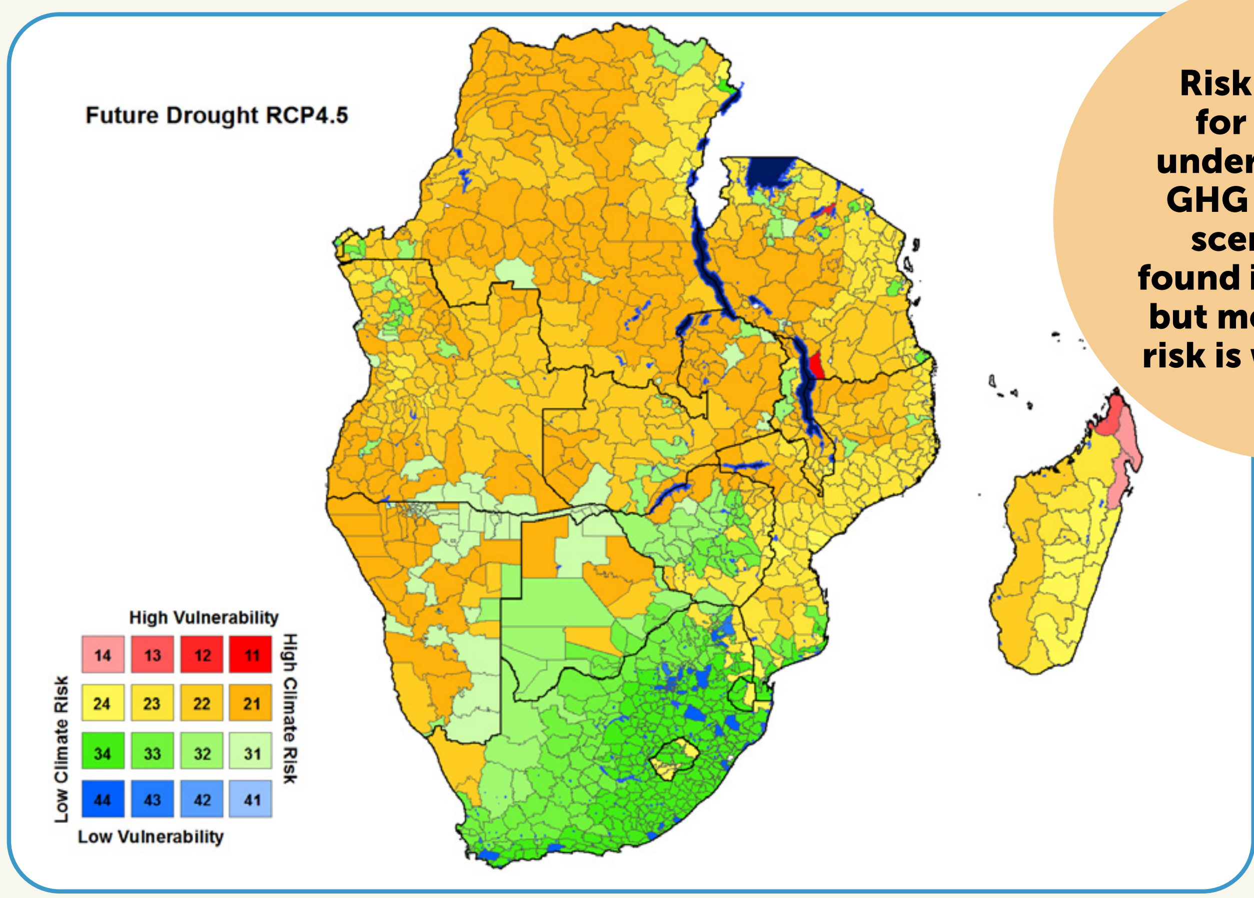



**Risk hotspots for extreme rainfall under a high GHG emissions scenario are found in Tanzania and Madagascar, but medium high risk is widespread across northern countries**

Figure 13. Bivariate map showing hotspots of vulnerability to and risk of extreme rainfall within the districts of each SADC region for the RCP8.5 scenario. The first number within each matrix colour represents the normalised and rounded mean vulnerability value for the district, with the second number representing the rounded climate hazard value (i.e. 34 equates to 'medium low vulnerability', 'low climate hazard).

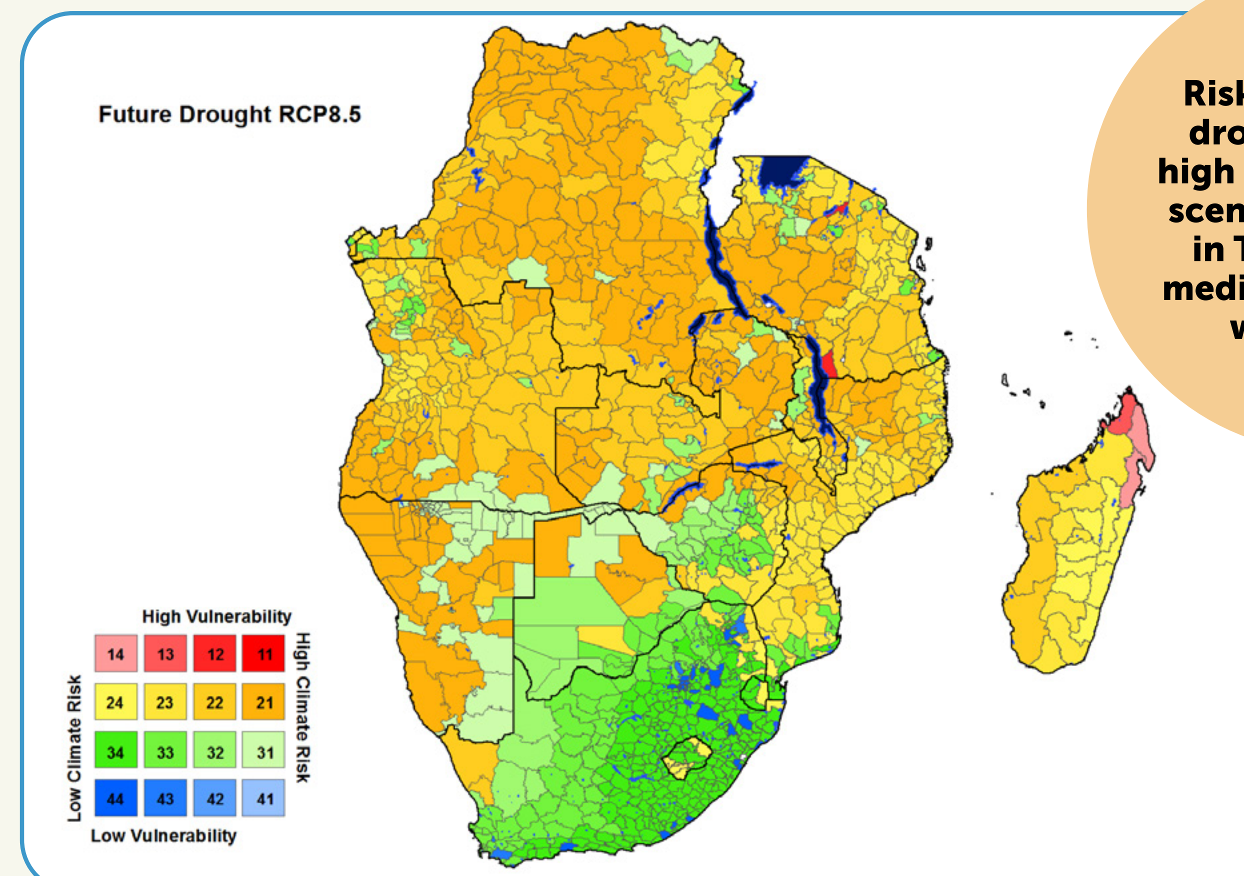
Potential hotspots of vulnerability to and risk of extreme droughts can be seen under the RCP4.5 scenario along Lake Nyasha/Malawi with medium high vulnerability, and high drought risk seen across extensive areas of Namibia, northern Zambia, inland Tanzania, and across large areas of the DRC (Figure 14). Under the RCP8.5 scenario the hotspots do not change significantly, with some climate risk reduced along the coast of Lake Nyasha/Malawi, and some increase in the area of the hotspot along the coast of Namibia (particularly IIKaras) (Figure 15).

It is clear across all the hotspot bivariate maps that medium-high climate risk (high vulnerability, medium-high climate hazard) is widespread under both future scenarios (RCP4.5 and 8.5) and for extreme rainfall and droughts across Angola, DRC, Tanzania, Mozambique and Madagascar.


**Risk hotspots for drought under a medium GHG emissions scenario are found in Tanzania, but medium high risk is widespread**

Figure 14. Bivariate map showing hotspots of vulnerability to and risk of extreme drought within the districts of each SADC region for the RCP4.5 scenario. The first number within each matrix colour represents the normalised and rounded mean vulnerability value for the district, with the second number representing the rounded climate hazard value (i.e. 34 equates to 'medium low vulnerability', 'low climate hazard).




**Risk hotspots for drought under a high GHG emissions scenario are found in Tanzania, but medium high risk is widespread**

Figure 15. Bivariate map showing the vulnerability and risk of extreme drought within the districts of each SADC region for the RCP8.5 scenario. The first number within each matrix colour represents the normalised and rounded mean vulnerability value for the district, with the second number representing the rounded climate hazard value (i.e. 34 equates to 'medium low vulnerability', 'low climate hazard).

04

# Comparing the climate risk maps with some previous studies

**Three studies were identified that have taken a broadly similar approach to climate risk mapping and the identification of climate risk hotspots across a broadly similar set of countries in Southern Africa:** Thornton et al (2008) who examined poverty and climate change for sub-Saharan Africa;  Midgley et al (2011) who mapped climate risk and vulnerability for Southern Africa, and Herding for Health (2020) who conducted a climate vulnerability assessment for Southern Africa's rangelands (excluding Tanzania, Malawi and DRC).

In the **Thornton et al (2008) study hotspots of climate hazard** were identified using Global Climate Models (GCMs) to calculate changes to the length of the growing season, combined with an agricultural system classification. This enabled agricultural systems at risk to be identified. Hotspots of vulnerability were identified by mapping 14 vulnerability indicators from across the capital assets, including soils, distance to markets, governance, incidence of malaria, etc. A principle components analysis was used to create four factors, explaining 63% of the variance, which were combined using the percentage variance explained to weight each factor, normalised and then quartiled. A qualitative synthesis of the results identified hotspots of vulnerability to climate change in the mixed rainfed crop-livestock systems of the Sahel, and in the great lakes region and mixed agricultural systems of East Africa. Livestock and mixed rainfed systems were considered most vulnerable to future changes in climate.

In their study mapping climate risk hotspots, **Midgley et al (2011) used an earlier IPCC vulnerability model compared to the one used in this study**, where vulnerability is a function of exposure, sensitivity and adaptive capacity. They developed a set of 11 exposure indicators for current (rainfall variation, risk of cyclones, fires, etc) and future (using GCMs) climate. Their 16 sensitivity indicators included land under irrigation, soil moisture and net primary productivity and their 19 adaptive capacity indicators included measures of conflict, contribution of agriculture to GDP, governance and education. They used a weighted overlay method to identify hotspots of vulnerability in northern and central Tanzania, Madagascar, south and central Mozambique, Malawi, Zimbabwe and Zambia, south and central Angola, and south and west DRC.

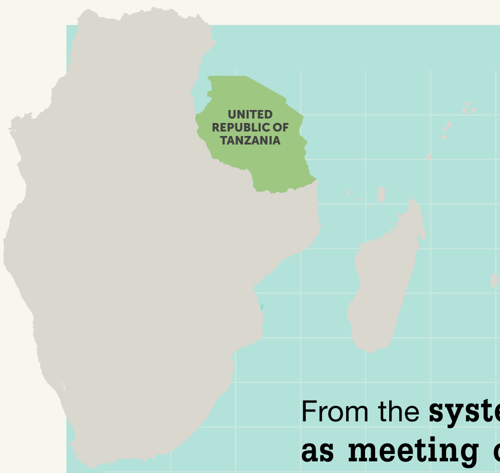
The work by **Herding for Health (2020) focused on rangelands, used the same IPCC climate risk model as this study**. They used both observed data, future indices and GCMs to map climate hazards including aridity, heatwaves, deforestation and land degradation. Their six vulnerability indicators included measures of access to markets, gender and the Human Development Index (including education, income and health), while their exposure index included measures of population density and the distribution of rangelands. The indices of hazard, vulnerability and exposure were equally weighted in a combined index of climate risk. Hotspots of climate risk were identified in Zambia and Mozambique.

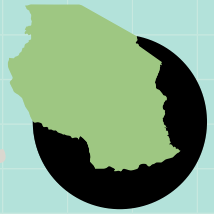
**Direct comparisons are difficult because of differences in spatial coverage**. The creation of indices, and the use of quartiles to aggregate the data mean that areas and countries identified as high climate risk are done so in comparison to the other areas and countries included in the analysis. Each study has also used a different combination of climate models, with our study using the CORDEX-Africa ensemble rather than CMIP5 ensembles used in the other studies.. These models will have evolved in accuracy over time, from 2008 when the earliest study was undertaken (Thornton et al, 2008) to this study and that by Herding for Health in 2020. The data underlying the vulnerability and exposure indices used in all the studies will also have been updated over time.

Nevertheless, **all four studies identify comparatively higher climate risks for the areas further north and east in their study regions, from parts of Zambia and Mozambique for Herding for Health (2020); parts of Angola, DRC, Zambia, Zimbabwe, Malawi, Mozambique, Tanzania and Madagascar for Midgley et al (2011); parts of Angola, DRC, Tanzania, Mozambique and Madagascar in this study, to the Sahel and parts of East Africa for Thornton et al (2008)**. This highlights the importance of considering vulnerabilities (in agricultural and social systems) as well as climate hazards (i.e. droughts or extreme rainfall events). Vulnerability in particular is likely to be behind the spatial patterns of increasing climate risk found in all these studies. As a result, all of these studies suggest that efforts to reduce climate risk should be targeted particularly to areas (and countries) in the north and north-east of the SADC region where vulnerabilities are highest.

# 4 Hotspot Case Studies 05

Only two of the 23 studies identified by our systematic literature review were carried out in the hotspots identified through the mapping of climate hazard and vulnerability outlined above. This suggests a possible mismatch between locations where climate risk is likely to be highest and where research on impacts of and adaptation to climate change is being conducted. Here we outline what we know from the research that has been undertaken in our hotspots, but also more broadly in the countries where the hotspots occur.



## TANZANIA

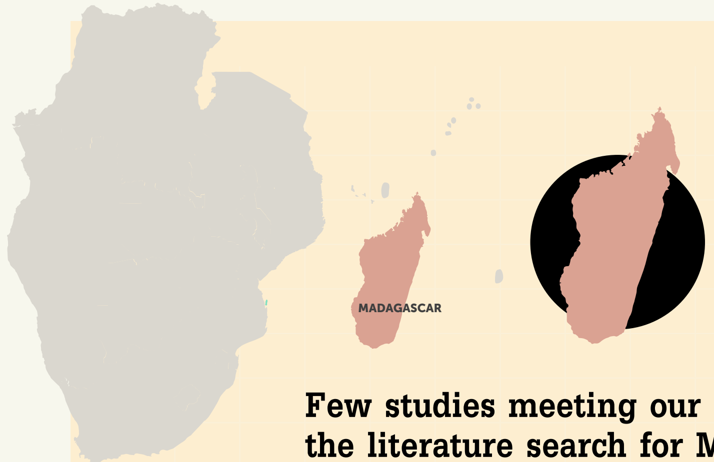
From the **systematic review 60 papers were identified as meeting our criteria for Tanzania,** with 10 having conducted research in medium high vulnerability and medium high climate hazard areas for both extreme rainfall events and drought (Figure 12 to Figure 15), including two in the hotspot identified in the plateau region in the south west of the country near lake Nyasa/Malawi (Kangalawe 2017; Luhunga 2017).

Luhunga (2017) undertook an assessment of the impacts of climate change on maize yields in the southern highlands and plateau region of southern Tanzania. They used a climate crop model, using CORDEX-Africa climate models, to simulate maize yields under different future scenarios. They found that maize yields may decrease by up to 10% (under RCP8.5) in the hotspot region (Figure 15) due to increased temperatures and a shortening of the growing season caused by reductions in rainfall.

Kangalawe (2017) conducted participatory rural assessments to understand perceptions of changing climate in Mbinga District, within the hotspot identified by our bivariate mapping (Figure 12 to Figure 15). Here, villagers report decreasing river flows and decreasing water availability for both agriculture and domestic purposes, in line with our hotspots for drought (Figure 14 and Figure 15). These reductions in available water have led to expansion of agriculture into wetland areas with subsequent losses of diversity, but also the shrinkage of wetland areas as river flows decrease and water use increases. A trebling of the population in this region (up to 120 people per square kilometers) indicates increasing exposure of the population to increasing drought. These findings are supported by Kassain et al. (2017) whose participatory research in the Iringa region also found perceptions of a decline in river flows over the last 20 years following declines in rainfall. This has led to impacts on water levels in irrigation channels, over-utilisation of available water, and reductions in yields. Both Kangalawe (2017) and Kassain et al. (2017) found that farmers were likely to implement measures such as deepening wells, expanding irrigation channels, or expanding agriculture into wetland areas that would be considered maladaptive. While some adaptation measures, such as tree planting for water conservation, are understood, they are not widely undertaken. There is a clear need for more work to understand, and implement, adaptation options in this region.

In addition to research in the southern highlands and plateau region, research has been undertaken in the northern highlands, specifically on Mount Kilimanjaro in northern Tanzania. This area also falls under the medium high vulnerability and medium to medium high climate hazard. Here the focus is very much on coffee production, given the importance of these highlands to producing this important export crop. The work by Rahan et al. (2018) developed a coffee crop model, linked to climate and soils data, to understand the effect of changing climate on yields. They found that increasing temperatures and drought stress are likely to reduce yields by as much as 32%, although increased carbon dioxide concentrations may go some way towards mitigating this effect. Their work suggests that a common strategy of using shade plants may not be beneficial under conditions of water stress. In addition, Azrag et al. (2018) predicted the distribution of an important coffee pest, Antestiopsis thunbergii, under climate change on Mount Kilimanjaro. Their work suggests that the risks of pest infestation at lower elevations are likely to decrease under climate change, but would be offset by increased risks occurring at higher elevations.

Finally, a set of 3 papers were identified by our systematic review covering the alluvial plans and semi-arid regions found in central Tanzania, an area of medium high vulnerability and medium to medium high climate hazards. Näschen et al. (2019) used the CORDEX-Africa climate models to examine the impact of climate change on water resources in the Kilombero region. They found increasing temperatures, and particularly intensification of the season with extreme flooding and drought, along with shifts in peak river flows will become more pronounced. Some farmers are already aware of changes to climate in the region, with rainfall becoming more unpredictable (Balama et al. 2016). Here, farmers are already implementing adaptation strategies through changes to planting calendars, uptake of agricultural technologies, crop diversification and the use of non-timber forest products to supplement incomes and household consumption. Osewe et al. (2020) have also found evidence of farmer led adaptation schemes, particularly farmer led irrigation schemes. However, more research is needed on these autonomous strategies to assess how robust and climate smart they are.




# MADAGASCAR

**Few studies meeting our criteria were retrieved from the literature search for Madagascar, and none were conducted in the areas identified as climate risk hotspots along the northern coast** (Figure 12 to Figure 15). However, locations subject to medium-high vulnerability and rainfall or drought related hazards have received research attention. Eight studies in these locations explored local agricultural practices and related knowledge, and adaptation options to reduce climate-related production risks.

The Lake Alaotra region in north eastern Madagascar currently experiences variable wet and dry episodes during the rainy season (Bruelle et al. 2017), and is at high risk of future extreme rainfall events, and moderately-highly vulnerable under both RCP 4.5 and 8.5 projections (Figure 12 and Figure 13) Rain-fed rice production, which characterises and is expanding on the hillsides as a result of the increasing food needs of the growing local population, is highly susceptible to rainfall variability, and resulting water stress and impoverished soils (Bruelle et al. 2017; Penot et al. 2018). Research using simulated water × soil × rice interactions indicates the use of conservation agriculture (CA) in these areas mainly increased water loss because of drainage in the majority of conditions, and that crop growth was least affected when sown in November regardless of other interactions. Simulations and findings suggest mulching widened the favourable sowing window towards early dates, reduced associated risks by enhancing water capture and storage during the first erratic rains of the season, and increased crop yields (Bruelle et al. 2017). However, Penot et al. (2018), highlight high abandonment rates by upland rice farmers adopting CA in the same region over a 10-year period, partly because of difficulties implementing technologies including mulching, and perceived risk of crop failure, especially when disappointed by losses or yields early on. Abandonment was lower by those farming colluvial land because costs were often offset by yields. However, findings overall indicate >5–7 years of practice was needed for CA to persist. Despite high drop-out, the use of CA technologies was sustained by farmers fully convinced of their benefits, albeit in diversified forms reflecting innovation that tailored cropping systems to individual circumstances.

Rainfall in Madagascar's mid-west is also erratic, with droughts alternating with intense rainfall events (Randrianjafizanaka et al. 2018), which are forecast to pose high future risk to moderately or highly vulnerable farming communities (Figure 12 and Figure 13). Here, rice-maize rotations predominate in upland areas on impoverished soils that attract weeds, including Striga asiatica, which suppress yields and increases labour demand. Randrianjafizanaka et al. (2018) present evidence that illustrates how different combinations of zero-tillage, intercropping and mulching CA strategies promoted as adaptations to soil and climatic constraints, can also delay and reduce (although not eradicate) the impact of S. asiatica parasitism in rice and maize crops, particularly when partially-resistant rice varieties are integrated into the system. Methods to assess accessibility of insurance to compensate for losses associated with climate hazards, have also been researched in this region. Focussing on rice cultivation, Möllmann et al. (2020) found that remotely-sensed vegetation health indices provided considerably higher explanatory power for credit risk related to the variability of borrowers' yields, than indices derived from the more often used meteorological data which is scarce, and hence less reliable in regions like this. Lower credit risk, and thus predicted default rates, allow lending institutions to reduce interest rates, potentially enhancing farmers' access to the credit often critical for elevating and sustaining production.

In the semi-arid south, maize composite varieties have been developed from local landraces to produce higher-yielding plants more tolerant of local climatic and agronomic conditions than the old landraces or obsolete hybrid varieties smallholder farmers often rely on (Masoni et al. 2020). The authors emphasise that maize has become Madagascar's second staple food in recent years, and highlight its potential contribution to future food security because it has lower water demand than rice. On the southeast coast, the high risk of extreme rain events in the future looms large for a potentially vulnerable farming community (Figure 12 and Figure 13) already prone to flooding and drought (Kruger 2016). During interviews and focus groups, farmers described early and late-planting, and using short-cycle cassava and yam varieties to increase resilience to hazards. In certain areas however, farmers have been unable to mitigate the lack of infrastructure to store water, and floods that destroy crops every year. In the southwest, drought is projected to be a greater hazard (Figure 14 and Figure 15), and conditions are already harsh. Very low amounts of rainfall on the Mahafaly plateau, and famine regularly affects those dependent on rain-fed production (Neudert et al. 2015).

Knowledge accumulated and transmitted locally related to climatic extremes and changing resource use is presented by Fritz-Vietta et al. (2017) to identify principles for inherent sustainable land management: management based on context specific values, socio-cultural norms, and the knowledge and perceptions of the local population, to enable future adaptation to environmental change. A different approach to facilitating adaptation to the dry and drying climate in the southeast is provided by Fust and Schlecht (2018), who developed a spatially explicit agent-based model to simulate livestock production systems, with the objective of sustaining the economic and food security of livestock keepers faced with impoverished forage yields and variable pasture quality. The model integrates metabolic energy costs due to pastoral herd movements in search of forage, incorporates seasonal dynamics in forage quality in terms of feed digestibility, and relates forage availability and quality to climatic conditions.

# REFERENCES


Abiodun BJ, Makhanya N, Petja B, Abatan AA, Oguntunde PG. 2018. Future Projection of Droughts over Major River Basins in Southern Africa at Specific Global Warming Levels. Theoretical and Applied Climatology 137:1785–99. https://doi.org/10.1007/s00704-018-2693-0

Adejuwon JO, Olaniyan SB. 2019. Drought Occurrence in the Sub-Humid Eco-Climatic Zone of Nigeria. Theoretical and Applied Climatology 137(3–4):1625–36. https://doi.org/10.1007/s00704-018-2670-7

Amoussou E, Awoye H, Vodounon HST, Obahoundje S, Camberlin P, Diedhiou A, Kouadio K, Mahé G, Houndénou C, Boko M. 2020. Climate and Extreme Rainfall Events in the Mono River Basin (West Africa): Investigating Future Changes with Regional Climate Models. Water 12(3). https://doi.org/10.3390/w12030833

Azrag AGA, Pirk CWW, Yusuf AA, Pinard F, Niassy S, Mosomtai G, Babin R. 2018. Prediction of insect pest distribution as influenced by elevation: Combining field observations and temperature-dependent development models for the coffee stinkbug, Antestiopsis thunbergii (Gmelin). PLoSONE 13(6). https://doi.org/10.1371/journal.pone.0199569

Balama C, Augustino S, Eriksen S, Makonda FBS. 2016. Forest adjacent households' voices on their perceptions and adaptation strategies to climate change in Kilombero District, Tanzania. Springerplus 5:792. https://doi.org/10.1186/s40064-016-2484-y

Begueria S, Serrano V. 2017. SPEI: Calculation of Standardised Precipitation-Evapotranspiration Index.

Berrang-Ford L, Pearce T, Ford JD. 2015. Systematic review approaches for climate change adaptation research. Regional Environmental Change 15:755–769. https://doi.org/10.1007/s10113-014-0708-7

Brooks N, Adger WN, Kelly PM. 2005. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Global Environmental Change 15(2):151–163. https://doi.org/10.1016/j.gloenvcha.2004.12.006

Bruelle G, Affholder F, Abrell T, Ripoche A, Dusserre J, Naudin K, Tittonell P, Rabeharisoa L, Scopel E. 2017. Can conservation agriculture improve crop water availability in an erratic tropical climate producing water stress? A simple model applied to upland rice in Madagascar. Agricultural Water Management 192:281–293. https://doi.org/10.1016/j.agwat.2017.07.020

Caminade C, Kovats S, Rocklov J, Tompkins AM, Morse AP, Colón-González FJ, Stenlund H, Martens P, Lloyd SJ. 2014. Impact of climate change on global malaria distribution. Proceedings of the National Academy of Sciences of the United States of America 111(9):3286–3291. https://doi.org/10.1073/pnas.1302089111

Carney D. 1998. Sustainable rural livelihoods : what contribution can we make? (Vol. 10). Department for International Development.

Centre for Research on the Epidemiology of Disasters. 2020. "EM-DAT." Brussels, Belgium: UCLouvain.

Chamani R, Monkam D, Djomou ZY. 2018. Return Times and Return Levels of July–September Extreme Rainfall over the Major Climatic Sub-Regions in Sahel. Atmospheric Research 212:77–90. https://doi.org/10.1016/j.atmosres.2018.04.026

Cooper PJM, Dimes J, Rao KPC, Shapiro B, Shiferaw B, Twomlow S. 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? Agriculture, Ecosystems and Environment 126(1–2):24–35. https://doi.org/10.1016/j.agee.2008.01.007

Cooper H, Hedges LV, Valentine JC. 2019. The handbook of research synthesis and meta-analysis. 3rd ed. Russell Sage Foundation, New York.

Cutter S L. 2017. The forgotten casualties redux: Women, children, and disaster risk. Global Environmental Change 42:117–121. https://doi.org/10.1016/j.gloenvcha.2016.12.010

Davis-Reddy, C.L., Vincent, K., 2017. Climate risk and vulnerability: A handbook for Southern Africa (2nd Ed), CSIR, Pretoria, South Africa. https://www.csir.co.za/sites/default/files/Documents/SADC%20Handbook_Second%20Edition_full%20report.pdf

de Sherbinin A, Bukvic A, Rohat G, Gall M, McCusker B, Preston B, Apotsos A, Fish C, Kienberger S, Muhonda P, Wilhelmi O, Macharia D, Shubert W, Sliuzas R, Tomaszewski B, Zhang S. 2019. Climate vulnerability mapping: A systematic review and future prospects. WIREs Climate Change. https://doi.org/10.1002/wcc.600

Diallo I, Giorgi F, Sukumaran S, Stordal F, Giuliani G. 2015. Evaluation of RegCM4 Driven by CAM4 over Southern Africa: Mean Climatology, Interannual Variability and Daily Extremes of Wet Season Temperature and Precipitation. Theoretical and Applied Climatology 121(3–4):749–66. https://doi.org/10.1007/s00704-014-1260-6

ESDAC. 2019. Global soil erosion. European Soil Data Centre (ESDAC), esdac.jrc.ec.europa.eu, European Commission, Joint Research Centre. https://esdac.jrc.ec.europa.eu/content/global-soil-erosion

FAO. 2007. Combined Suitability of Currently Available Land for Pasture and Rainfed Crops [Dataset]. Rome, Italy: Food and Agricultural Organisation (FAO).

FAO. 2015. Status of the World's Soil Resources. In Intergovernmental Technical Panel on Soils. Food and Agricultural Organisation (FAO).

Fink A. 2020. Conducting research literature reviews. From the internet to the paper. 5th ed. SAGE, Los Angeles.

Fischer G, Shah M, Tubiello FN, van Velhuizen H. 2005. Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. Philosophical Transactions B 360:2067–2083. https://doi.org/10.1098/rstb.2005.1744

Formetta G, Feyen L. 2019. Empirical evidence of declining global vulnerability to climate-related hazards. Global Environmental Change 57. https://doi.org/10.1016/j.gloenvcha.2019.05.004

Fritz-Vietta NVM, Tahirindraza HS, Stoll-Kleemann S. 2017. Local people's knowledge with regard to land use activities in southwest Madagascar – Conceptual insights for sustainable land management. Journal of Environmental Management 199:126–138. https://doi.org/10.1016/j.jenvman.2017.05.034Gan TY, Ito M, Hülsmann S, Qin X, Lu XX, Liong SY, Rutschman P, Disse M, Koivusalo H. 2016. Possible Climate Change/Variability and Human Impacts, Vulnerability of Drought-Prone Regions, Water Resources and Capacity Building for Africa. Hydrological Sciences Journal 61(7):1209–26. https://doi.org/10.1080/02626667.2015.1057143

Fust P, Schlecht E. 2018. Integrating spatio-temporal variation in resource availability and herbivore movements into rangeland management: RaMDry—An agent-based model on livestock feeding ecology in a dynamic, heterogeneous, semi-arid environment. Ecological Modelling 369:13–41. https://doi.org/10.1016/j.ecolmodel.2017.10.017Ghebrezgabher MG, Yang T, Yang X. 2016. Long-Term Trend of Climate Change and Drought Assessment in the Horn of Africa. Advances in Meteorology 2016. https://doi.org/10.1155/2016/8057641

Gibba P, Sylla MB, Okogbue EC, Gaye AT, Nikiema M, Kebe I. 2018. State-of-the-Art Climate Modeling of Extreme Precipitation over Africa: Analysis of CORDEX Added-Value over CMIP5. Theoretical and Applied Climatology 137:1041–1057. https://doi.org/10.1007/s00704-018-2650-y

# REFERENCES


Gusenbauer M, Haddaway NR. 2020. Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources. Research Synthesis Methods 11:181–217. https://doi.org/10.1002/jrsm.1378

Haggblade S, Hazell P, Reardon T. 2010. The Rural Non-farm Economy: Prospects for Growth and Poverty Reduction. World Development 38(10):1429–1441. https://doi.org/10.1016/j.worlddev.2009.06.008

Herding for Health, 2020: Climate Vulnerability Assessment. Published by the Herding for Health Programme, an programme of Conservation International and the Peace Parks Foundation, funded by the Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ) GmbH ACCRA Programme.

IFPRI. 2016. Travel Time to Markets in Africa South of the Sahara. International Food Policy Research Institute (IFPRI). https://doi.org/10.7910/DVN/YKDWJD, Harvard Dataverse, V2

IPCC. 2012. Glossary of terms. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner GK, Allen SK, Tignor M, Midgley PM. (eds.). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA. p. 555-564.

IPCC. 2014. Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Field CB, Barros V, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL. (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. p. 1-32.

Kangalawe YM. 2017. Climate change impacts on water resource management and community livelihoods in the southern highlands of Tanzania. Climate and Development 3:191-201 https://doi.org/10.1080/17565529.2016.1139487

Kapwata T, Gebreslasie MT, Mathee A, Wright CY. 2018. Current and potential future seasonal trends of indoor dwelling temperature and likely health risks in rural Southern Africa. International Journal of Environmental Research and Public Health 15(5). https://doi.org/10.3390/ijerph15050952

Kassian L, Tenywa M, Liwenga ET, Wellard Dyer K, Bamutaze Y. 2017. Implication of climate change and variability on stream flow in Iringa region, Tanzania. Journal of Water and Climate Change 8(2):336–347. https://doi.org/10.2166/wcc.2016.238

Kaufmann D, Kraay A, Mastruzzi M. 2005. Governance Matters IV : Governance Indicators for 1996-2004. Policy Research Working Paper; No. 3630.

Kendon EJ, Stratton R, Tucker S, Marsham JH, Berthou S, Rowell DP, Senior CA. 2019. Enhanced Future Changes in Wet and Dry Extremes over Africa at Convection-Permitting Scale. Nature Communications 10. https://doi.org/10.1038/s41467-019-09776-9

Kruger L. 2016. The timing of agricultural production in hazard-prone areas to prevent losses at peak-risk periods: A case of Malawi, Madagascar and Mozambique. Jamba Journal of Disaster Risk Studies 8:1–9. https://doi.org/10.4102/jamba.v8i2.179

Labudová L, Labuda M, Takáč J. 2017. Comparison of SPI and SPEI Applicability for Drought Impact Assessment on Crop Production in the Danubian Lowland and the East Slovakian Lowland. Theoretical and Applied Climatology 128(1–2):491–506. https://doi.org/10.1007/s00704-016-1870-2

Li L, Cao R, Wei K, Wang W, Chen L. 2019. Adapting climate change challenge: A new vulnerability assessment framework from the global perspective. Journal of Cleaner Production 217. https://doi.org/10.1016/j.jclepro.2019.01.162

Lin BB. 2011. Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change. BioScience 61(3):183–193. https://doi.org/10.1525/bio.2011.61.3.4

Luhunga PM. 2017. Assessment of the Impacts of Climate Change on Maize Production in the Southern and Western Highlands Sub-agro Ecological Zones of Tanzania. Frontiers in Environmental Science 5:51. https://doi.org/10.3389/fenvs.2017.00051

Lutz W, Muttarak R, Striessnig E. 2014. Universal education is key to enhanced climate adaptation. Science 346(6213):1061–1062. https://doi.org/10.1126/science.1257975

Mase AS, Gramig BM, Prokopy LS. 2017. Climate change beliefs, risk perceptions, and adaptation behavior among Midwestern U.S. crop farmers. Climate Risk Management 15:8–17. https://doi.org/10.1016/j.crm.2016.11.004

Masoni A, Calamai A, Marini L, Benedettelli S, Palchetti E. 2020. Constitution of Composite Cross Maize (Zea mays L.) Populations Selected for the Semi-Arid Environment of South Madagascar. Agronomy 10. https://doi.org/10.3390/agronomy10010054

Midgley, S.J.E., Davies, R.A.G. and Chesterman, S. 2011. Climate Risk and Vulnerability Mapping in Southern Africa: Status quo (2008) and future (2050). For the Regional Climate Change Programme for Southern Africa (RCCP), UK Department for International Development (DFID). OneWorld Sustainable Investments, Cape Town.

Moher D, Liberati A, Tetzlaff J, Altman DG. 2009. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. British Medical Journal. 339:332–336. https://doi.org/10.1136/bmj.b2535

Möllmann J, Buchholz M, Kölle W, Musshoff O. 2020. Do remotely-sensed vegetation health indices explain credit risk in agricultural microfinance? World Development 127. https://doi.org/10.1016/j.worlddev.2019.104771

Monsieurs E, Dewitte O, Demoulin A. 2019. A Susceptibility-Based Rainfall Threshold Approach for Landslide Occurrence. Natural Hazards and Earth System Sciences 19(4):775–789. https://doi.org/10.5194/nhess-19-775-2019

Moore SM, Azman AS, Zaitchik BF, Mintz ED, Brunkard J, Legros D, Hill A, McKay H, Luquero FJ, Olson D, Lessler J. 2017. El Niño and the shifting geography of cholera in Africa. Proceedings of the National Academy of Sciences of the United States of America 114(17):4436–4441. https://doi.org/10.1073/pnas.1617218114

Näschen K, Diekkrüger B, Leemhuis C, Seregina LS, van der Linden R. 2019. Impact of Climate Change on Water Resources in the Kilombero Catchment in Tanzania. Water 11:859. https://doi.org/10.3390/w11040859

Neudert R, Goetter JF, Andriamparany JN, Rakotoarisoa M, 2015. Income diversification, wealth, education and well-being in rural south-western Madagascar: Results from the Mahafaly region. Development Southern Africa 32:758–784. https://doi.org/10.1080/0376835X.2015.1063982

O'Neill BC, Jiang L, KC S, Fuchs R, Pachauri S, Laidlaw EK, Zhang T, Zhou W, Ren X. 2020. The effect of education on determinants of climate change risks. Nature Sustainability 3(7),520–528. https://doi.org/10.1038/s41893-020-0512-y

Oguntunde PG, Abiodun BJ, Lischeid G. 2017. Impacts of Climate Change on Hydro-Meteorological Drought over the Volta Basin, West Africa. Global and Planetary Change 155:121–132. https://doi.org/10.1016/j.

# REFERENCES


gloplacha.2017.07.003

OPHI. 2019a. 2019 global MPI resources. Oxford Poverty and Human Development Initiative (OPHI). https://ophi.org.uk/2019-global-mpi-resources/

OPHI. 2019b. Multidimensional Poverty Index 2019: Illuminating Inequalities. http://hdr.undp.org/sites/default/files/mpi_2019_publication.pdf

Osewe M, Liu A, Njagi T. 2020. Farmer-Led Irrigation and Its Impacts on Smallholder Farmers' Crop Income: Evidence from Southern Tanzania. International Journal of Environmental Research and Public Health 17:1512. https://doi.org/10.3390/ijerph17051512

Paeth H, Mannig B. 2013. On the Added Value of Regional Climate Modeling in Climate Change Assessment. Climate Dynamics 41(3–4):1057–66. https://doi.org/10.1007/s00382-012-1517-7

Penot E, Fevre V, Flodrops P, Razafimahatratra HM. 2018. Conservation Agriculture to buffer and alleviate the impact of climatic variations in Madagascar: Farmers' perception. Cahiers Agricultures 27. https://doi.org/10.1051/cagri/2018009

Polong F, Chen H, Sun S, Ongoma V. 2019. Temporal and Spatial Evolution of the Standard Precipitation Evapotranspiration Index (SPEI) in the Tana River Basin, Kenya. Theoretical and Applied Climatology 138(1–2):777–92. https://doi.org/10.1007/s00704-019-02858-0

Pullin AS, Stewart GB. 2006. Guidelines for systematic review in conservation and environmental management Conservation Biology 20(6):1647–1656. https://doi:10.1111/j.1523-1739.2006.00485.x

R Core Team. 2013. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. http://www.r-project.org/

Rahn E, Vaast P, Läderach P, van Asten P, Jassogne L, Ghazoul J. 2018. Exploring adaptation strategies of coffee production to climate change using a process-based model. Ecological Modelling 371:76-89. https://doi.org/10.1016/j.ecolmodel.2018.01.009

Randrianjafizanaka MT, Autfray P, Andrianaivo AP, Ramonta IR, Rodenburg J. 2018. Combined effects of cover crops, mulch, zero-tillage and resistant varieties on Striga asiatica (L.) Kuntze in rice-maize rotation systems. Agriculture, Ecosystems and Environment 256:23–33. https://doi.org/10.1016/j.agee.2017.12.005

Rao ND, Min J. 2018. Decent Living Standards: Material Prerequisites for Human Wellbeing. Social Indicators Research 138:225–244. https://doi.org/10.1007/s11205-017-1650-0

Reliefweb, 2004. Madagascar: Cyclone Gafilo- Mar 2004. https://reliefweb.int/disaster/2004-0103

Rowell DP, Chadwick R. 2018. Causes of the Uncertainty in Projections of Tropical Terrestrial Rainfall Change: East Africa. Journal of Climate 31(15):5977–95. https://doi.org/10.1175/JCLI-D-17-0830.1

SADC, 2019. 39th SADC summit towards inclusive, sustainable industrial development. Southern Africa Today. SADC Today Vol. 21 No. 5 August 2019. https://www.tralac.org/news/article/14187-39th-sadc-summit-towards-inclusive-sustainable-industrial-development.html

Schlenker W, Lobell DB. 2010. Robust negative impacts of climate change on African agriculture Environmental Research Letters 5. https://iopscience.iop.org/article/10.1088/1748-9326/5/1/014010/meta

Serdeczny O, Adams S, Baarsch F, Coumou D, Robinson A, Hare W, Schaeffer M, Perrette M, Reinhardt J. 2017. Climate Change Impacts in Sub-Saharan Africa: From Physical Changes to Their Social Repercussions. Regional Environmental Change 17(6):1585–1600. https://doi.org/10.1007/s10113-015-0910-2

Sonkoué D, Monkam D, Fotso-Nguemo TC, Yepdo ZD, Vondou DA. 2018. Evaluation and Projected Changes in Daily Rainfall Characteristics over Central Africa Based on a Multi-Model Ensemble Mean of CMIP5 Simulations. Theoretical and Applied Climatology 137:2167–86. https://doi.org/10.1007/s00704-018-2729-5

Sonwa DJ, Dieye A, El Houssine El Mzouri, Majule A, Mugabe FT, Omolo N, Wouapi H, Obando J, Brooks N. 2017. Drivers of Climate Risk in African Agriculture. Climate and Development 9(5):383–98. https://doi.org/10.1080/17565529.2016.1167659

Speranza CI, Wiesmann U, Rist S. 2014. An indicator framework for assessing livelihood resilience in the context of social-ecological dynamics. Global Environmental Change 28:109–119. https://doi.org/10.1016/j.gloenvcha.2014.06.005

Tarhule A. 2005. Damaging Rainfall and Flooding: The Other Sahel Hazards. Climatic Change 72(3):355–77. https://doi.org/10.1007/s10584-005-6792-4

Tazen F, Diarra A, Kabore RFW, Ibrahim B, Bologo/Traoré M, Traoré K, Karambiri H. 2019. Trends in Flood Events and Their Relationship to Extreme Rainfall in an Urban Area of Sahelian West Africa: The Case Study of Ouagadougou, Burkina Faso. Journal of Flood Risk Management 12(S1):1–11. https://doi.org/10.1111/jfr3.12507

Thornton PK, Jones PG, Owiyo T, Kruska RL, Herrero M, Orindi V, Bhadwal S, Kristjanson P, Notenbaert A, Bekele N, Omolo A. 2008. Climate Change and Poverty in Africa: Mapping Hotspots of Vulnerability. African Journal of Agricultural and Resource Economics 2(1):1–21. https://doi.org/10.22004/ag.econ.56966

Tschakert P, Sagoe R, Ofori-Darko G, Codjoe SN. 2010. Floods in the Sahel: An Analysis of Anomalies, Memory, and Anticipatory Learning. Climatic Change 103(3):471–502. https://doi.org/10.1007/s10584-009-9776-y

Ujeneza EL, Abiodun BJ. 2015. Drought Regimes in Southern Africa and How Well GCMs Simulate Them. Climate Dynamics 44(5–6):1595–1609. https://doi.org/10.1007/s00382-014-2325-z

UNDP. 2018. Gender Inequality Index (GII) Data. http://hdr.undp.org/en/content/gender-inequality-index-gii

UNICEF, 2019. Cyclone Idai and Kenneth cause devastation and suffering in Mozambique. https://www.unicef.org/ mozambique/en/cyclone-idai-and-Kenneth

Vicente-Serrano SM, Beguería S, López-Moreno JI. 2010. A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. Journal of Climate 23(7):1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Wolski P, Lobell D, Stone D, Pinto I, Crespo O, Johnston P. 2020. On the role of anthropogenic climate change in the emerging food crisis in southern Africa in the 2019–2020 growing season. Global Change Biology. https://doi.org/10.1111/gcb.15047

World Bank. 2009. The Social Dimensions of Climate Change. In: New Frontiers of Social Policy. The World Bank. https://doi.org/doi:10.1596/978-0-8213-7887-8

World Bank. 2019. Worldwide Governance Indicators (www.govindicators.org). The World Bank. https://datacatalog.worldbank.org/dataset/worldwide-governance-indicators

World Bank. 2020. World Development Indicators. The World Bank. https://datacatalog.worldbank.org/dataset/world-development-indicators

# APPENDIX A: LITERATURE FROM SYSTEMATIC REVIEW


Adhikari, U., Nejadhashemi, A.P., Herman, M.R., Messina, J.P., 2017. Multiscale assessment of the impacts of climate change on water resources in Tanzania. J. Hydrol. Eng. 22. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001467

Adisa, O.M., Botai, C.M., Botai, J.O., Hassen, A., Darkey, D., Tesfamariam, E., Adisa, A.F., Adeola, A.M., Ncongwane, K.P., 2018. Analysis of agro-climatic parameters and their influence on maize production in South Africa. Theor. Appl. Climatol. 134, 991–1004. https://doi.org/10.1007/s00704-017-2327-y

Adisa, O.M., Botai, J.O., Adeola, A.M., Botai, C.M., Hassen, A., Darkey, D., Tesfamariam, E., Adisa, A.T., Adisa, A.F., 2019. Analysis of drought conditions over major maize producing provinces of South Africa. J. Agric. Meteorol. 75, 173–182. https://doi.org/10.2480/agrmet.D-18-00049

Akinyemi, F.O., 2017. Climate change and variability in semiarid palapye, eastern Botswana: An assessment from smallholder farmers' perspective. Weather. Clim. Soc. 9, 349–365. https://doi.org/10.1175/WCAS-D-16-0040.1

Akinyemi, F.O., Abiodun, B.J., 2019. Potential impacts of global warming levels 1.5 °C and above on climate extremes in Botswana. Clim. Change 154, 387–400. https://doi.org/10.1007/s10584-019-02446-1

Alemu, W.G., Henebry, G.M., 2017. Land surface phenology and seasonality using cool earthlight in croplands of Eastern Africa and the Linkages to crop production. Remote Sens. 9. https://doi.org/10.3390/rs9090914

Amadu, F.O., McNamara, P.E., Miller, D.C., 2020. Yield effects of climate-smart agriculture aid investment in southern Malawi. Food Policy 92. https://doi.org/10.1016/j.foodpol.2020.101869

Amjath-Babu, T.S., Krupnik, T.J., Kaechele, H., Aravindakshan, S., Sietz, D., 2016. Transitioning to groundwater irrigated intensified agriculture in Sub-Saharan Africa: An indicator based assessment. Agric. Water Manag. 168, 125–135. https://doi.org/10.1016/j.agwat.2016.01.016

Amondo, E., Simtowe, F., Bahadur Rahut, D., Erenstein, O., 2019. Productivity and production risk effects of adopting drought-tolerant maize varieties in Zambia. Int. J. Clim. Chang. Strateg. Manag. 11, 570–591. https://doi.org/10.1108/IJCCSM-03-2018-0024

Araujo, J.A., Abiodun, B.J., Crespo, O., 2016. Impacts of drought on grape yields in Western Cape, South Africa. Theor. Appl. Climatol. 123, 117–130. https://doi.org/10.1007/s00704-014-1336-3

Arnell, N.W., Brown, S., Gosling, S.N., Gottschalk, P., Hinkel, J., Huntingford, C., Lloyd-Hughes, B., Lowe, J.A., Nicholls, R.J., Osborn, T.J., Osborne, T.M., Rose, G.A., Smith, P., Wheeler, T.R., Zelazowski, P., 2016. The impacts of climate change across the globe: A multi-sectoral assessment. Clim. Change 134, 457–474. https://doi.org/10.1007/s10584-014-1281-2

Arslan, A., Belotti, F., Lipper, L., 2017. Smallholder productivity and weather shocks: Adoption and impact of widely promoted agricultural practices in Tanzania. Food Policy 69, 68–81. https://doi.org/10.1016/j.foodpol.2017.03.005

Arslan, A., Cavatassi, R., Alfani, F., Mccarthy, N., Lipper, L., Kokwe, M., 2018. Diversification Under Climate Variability as Part of a CSA Strategy in Rural Zambia. J. Dev. Stud. 54, 457–480. https://doi.org/10.1080/00220388.2017.1293813

Asfaw, S., Maggio, G., 2018. Gender, Weather Shocks and Welfare: Evidence from Malawi. J. Dev. Stud. 54, 271–291. https://doi.org/10.1080/00220388.2017.1283016

Asfaw, S., McCarthy, N., Lipper, L., Arslan, A., Cattaneo, A., 2016. What determines farmers' adaptive capacity? Empirical evidence from Malawi. Food Secur. 8, 643–664. https://doi.org/10.1007/s12571-016-0571-0

Asfaw, S., Scognamillo, A., Caprera, G.D., Sitko, N., Ignaciuk, A., 2019. Heterogeneous impact of livelihood diversification on household welfare: Cross-country evidence from Sub-Saharan Africa. World Dev. 117, 278–295. https://doi.org/10.1016/j.worlddev.2019.01.017

Aukema, J.E., Pricope, N.G., Husak, G.J., Lopez-Carr, D., 2017. Biodiversity areas under threat: Overlap of climate change and population pressures on the world's biodiversity priorities. PLoS One 12. https://doi.org/10.1371/journal.pone.0170615

Azrag, A.G.A., Pirk, C.W.W., Yusuf, A.A., Pinard, F., Niassy, S., Mosomtai, G., Babin, R., 2018. Prediction of insect pest distribution as influenced by elevation: Combining field observations and temperature-dependent development models for the coffee stink bug, antestiopsis thunbergii (gmelin). PLoS One 13. https://doi.org/10.1371/journal.pone.0199569

Bahta, Y.T., Jordaan, A., Muyambo, F., 2016. Communal farmers' perception of drought in South Africa: Policy implication for drought risk reduction. Int. J. Disaster Risk Reduct. 20, 39–50. https://doi.org/10.1016/j.ijdrr.2016.10.007

Bailey, K.M., McCleery, R.A., Barnes, G., McKune, S.L., 2019. Climate-driven adaptation, household capital, and nutritional outcomes among farmers in Eswatini. Int. J. Environ. Res. Public Health 16. https://doi.org/10.3390/ijerph16214063

Balama, C., Augustino, S., Eriksen, S., Makonda, F.B.S., 2016. Forest adjacent households' voices on their perceptions and adaptation strategies to climate change in Kilombero District, Tanzania. Springerplus 5. https://doi.org/10.1186/s40064-016-2484-y

Bareki, N.P., Antwi, M.A., 2017. Drought preparedness status of farmers in the Nguni cattle development project and the sire subsidy scheme in north West Province, South Africa. Appl. Ecol. Environ. Res. 15, 589–603. https://doi.org/10.15666/aeer/1504_589603

Baudoin, M.-A., Vogel, C., Nortje, K., Naik, M., 2017. Living with drought in South Africa: lessons learnt from the recent El Niño drought period. Int. J. Disaster Risk Reduct. 23, 128–137. https://doi.org/10.1016/j.ijdrr.2017.05.005

Beyer, M., Wallner, M., Bahlmann, L., Thiemig, V., Dietrich, J., Billib, M., 2016. Rainfall characteristics and their implications for rain-fed agriculture: a case study in the Upper Zambezi River Basin. Hydrol. Sci. J. 61, 321–343. https://doi.org/10.1080/02626667.2014.983519

Bezner Kerr, R., Kangmennaang, J., Dakishoni, L., Nyantakyi-Frimpong, H., Lupafya, E., Shumba, L., Msachi, R., Boateng, G.O., Snapp, S.S., Chitaya, A., Maona, E., Gondwe, T., Nkhonjera, P., Luginaah, I., 2019. Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. Agric. Ecosyst. Environ. 279, 109–121. https://doi.org/10.1016/j.agee.2019.04.004

Bezner Kerr, R., Nyantakyi-Frimpong, H., Dakishoni, L., Lupafya, E., Shumba, L., Luginaah, I., Snapp, S.S., 2018. Knowledge politics in participatory climate change adaptation research on agroecology in Malawi. Renew. Agric. Food Syst. 33, 238–251. https://doi.org/10.1017/S1742170518000017

Biber-Freudenberger, L., Ziemacki, J., Tonnang, H.E.Z., Borgemeister, C., 2016. Future risks of pest species under changing climatic conditions. PLoS One 11. https://doi.org/10.1371/journal.pone.0153237

Biffis, E., Chavez, E., 2017. Satellite Data and Machine Learning for Weather Risk Management and Food Security. Risk Anal. 37, 1508–1521. https://doi.org/10.1111/risa.12847

# APPENDIX A: LITERATURE FROM SYSTEMATIC REVIEW


Black, E., Tarnavsky, E., Maidment, R., Greatrex, H., Mookerjee, A., Quaife, T., Brown, M., 2016. The use of remotely sensed rainfall for managing drought risk: A case study of weather index insurance in Zambia. Remote Sens. 8. https://doi.org/10.3390/rs8040342

Boillat, S., Jew, E.K.K., Steward, P.R., Speranza, C.I., Whitfield, S., Mkwambisi, D., Kiteme, B., Wambugu, G., Burdekin, O.J., Dougill, A.J., 2019. Can smallholder farmers buffer rainfall variability through conservation agriculture? On-farm practices and maize yields in Kenya and Malawi. Environ. Res. Lett. 14. https://doi.org/10.1088/1748-9326/ab45ad

Bornemann, F.J., Rowell, D.P., Evans, B., Lapworth, D.J., Lwiza, K., Macdonald, D.M.J., Marsham, J.H., Tesfaye, K., Ascott, M.J., Way, C., 2019. Future changes and uncertainty in decision-relevant measures of East African climate. Clim. Change 156, 365–384. https://doi.org/10.1007/s10584-019-02499-2

Bruelle, G., Affholder, F., Abrell, T., Ripoche, A., Dusserre, J., Naudin, K., Tittonell, P., Rabeharisoa, L., Scopel, E., 2017. Can conservation agriculture improve crop water availability in an erratic tropical climate producing water stress? A simple model applied to upland rice in Madagascar. Agric. Water Manag. 192, 281–293. https://doi.org/10.1016/j.agwat.2017.07.020

Brüssow, K., Gornott, C., Faße, A., Grote, U., 2019. The link between smallholders' perception of climatic changes and adaptation in Tanzania. Clim. Change 157, 545–563. https://doi.org/10.1007/s10584-019-02581-9

Byakatonda, J., Parida, B.P., Kenabatho, P.K., Moalafhi, D.B., 2019. Prediction of onset and cessation of austral summer rainfall and dry spell frequency analysis in semiarid Botswana. Theor. Appl. Climatol. 135, 101–117. https://doi.org/10.1007/s00704-017-2358-4

Byakatonda, J., Parida, B.P., Kenabatho, P.K., Moalafhi, D.B., 2018a. Influence of climate variability and length of rainy season on crop yields in semiarid Botswana. Agric. For. Meteorol. 248, 130–144. https://doi.org/10.1016/j.agrformet.2017.09.016

Byakatonda, J., Parida, B.P., Moalafhi, D.B., Kenabatho, P.K., 2018b. Analysis of long term drought severity characteristics and trends across semiarid Botswana using two drought indices. Atmos. Res. 213, 492–508. https://doi.org/10.1016/j.atmosres.2018.07.002

Cai, X., Haile, A.T., Magidi, J., Mapedza, E., Nhamo, L., 2017. Living with floods – Household perception and satellite observations in the Barotse floodplain, Zambia. Phys. Chem. Earth 100, 278–286. https://doi.org/10.1016/j.pce.2016.10.011

Carrão, H., Naumann, G., Barbosa, P., 2016. Mapping global patterns of drought risk: An empirical framework based on sub-national estimates of hazard, exposure and vulnerability. Glob. Environ. Chang. 39, 108–124. https://doi.org/10.1016/j.gloenvcha.2016.04.012

Chagumaira, C., Rurinda, J., Nezomba, H., Mtambanengwe, F., Mapfumo, P., 2016. Use patterns of natural resources supporting livelihoods of smallholder communities and implications for climate change adaptation in Zimbabwe. Environ. Dev. Sustain. 18, 237–255. https://doi.org/10.1007/s10668-015-9637-y

Challinor, A.J., Koehler, A.-K., Ramirez-Villegas, J., Whitfield, S., Das, B., 2016. Current warming will reduce yields unless maize breeding and seed systems adapt immediately. Nat. Clim. Chang. 6, 954–958. https://doi.org/10.1038/nclimate3061

Chemura, A., Kutywayo, D., Chidoko, P., Mahoya, C., 2016. Bioclimatic modelling of current and projected climatic suitability of coffee (Coffea arabica) production in Zimbabwe. Reg. Environ. Chang. 16, 473–485. https://doi.org/10.1007/s10113-015-0762-9

Chitongo, L., 2019. Rural livelihood resilience strategies in the face of harsh climatic conditions. The case of ward 11 Gwanda, South, Zimbabwe. Cogent Soc. Sci. 5. https://doi.org/10.1080/23311886.2019.1617090

Cobbing, J., Hiller, B., 2019. Waking a sleeping giant: Realizing the potential of groundwater in Sub-Saharan Africa. World Dev. 122, 597–613. https://doi.org/10.1016/j.worlddev.2019.06.024

Conradie, B., Piesse, J., 2016. Ranking perceived risk to farmers: How important is the environment? African J. Agric. Resour. Econ. 11, 263–276.

Conradie, B., Piesse, J., Stephens, J., 2019. The changing environment: Efficiency, vulnerability and changes in land use in the South African Karoo, 2012–2014. Environ. Dev. 32. https://doi.org/10.1016/j.envdev.2019.07.003

Corbeels, M., Berre, D., Rusinamhodzi, L., Lopez-Ridaura, S., 2018. Can we use crop modelling for identifying climate change adaptation options? Agric. For. Meteorol. 256–257, 46–52. https://doi.org/10.1016/j.agrformet.2018.02.026

d'Amour, C.B., Wenz, L., Kalkuhl, M., Steckel, J.C., Creutzig, F., 2016. Teleconnected food supply shocks. Environ. Res. Lett. 11. https://doi.org/10.1088/1748-9326/11/3/035007

Dalin, C., Conway, D., 2016. Water resources transfers through southern African food trade: water efficiency and climate signals. Environ. Res. Lett. 11. https://doi.org/10.1088/1748-9326/11/1/015005

Dassanayake, W., Mohapatra, S., Luckert, M.K., Adamowicz, W., 2018. Households' responses to climate change: Contingent behavior evidence from rural South Africa. Environ. Dev. Econ. 23, 37–62. https://doi.org/10.1017/S1355770X17000328

de Jalón, S., Iglesias, A., Neumann, M.B., 2018. Responses of sub-Saharan smallholders to climate change: Strategies and drivers of adaptation. Environ. Sci. Policy 90, 38–45. https://doi.org/10.1016/j.envsci.2018.09.013

De Pauw, E., Ramasamy, S., 2020. Rapid detection of stressed agricultural environments in Africa under climatic change 2000?2050 using agricultural resource indices and a hotspot mapping approach. Weather Clim. Extrem. 27. https://doi.org/10.1016/j.wace.2019.100211

De Pinto, A., Smith, V.H., Robertson, R.D., 2019. The role of risk in the context of climate change, land use choices and crop production: Evidence from Zambia. Clim. Res. 79, 39–53. https://doi.org/10.3354/cr01581

de Villiers, M., Kriticos, D.J., Veldtman, R., 2017. Including irrigation in niche modelling of the invasive wasp Vespula germanica (Fabricius) improves model fit to predict potential for further spread. PLoS One 12. https://doi.org/10.1371/journal.pone.0181397

De Vrese, P., Hagemann, S., Claussen, M., 2016. Asian irrigation, African rain: Remote impacts of irrigation. Geophys. Res. Lett. 43, 3737–3745. https://doi.org/10.1002/2016GL068146

Dellink, R., Lanzi, E., Chateau, J., 2019. The Sectoral and Regional Economic Consequences of Climate Change to 2060. Environ. Resour. Econ. 72, 309–363. https://doi.org/10.1007/s10640-017-0197-5

Descheemaeker, K., Zijlstra, M., Masikati, P., Crespo, O., Homann-Kee Tui, S., 2018. Effects of climate change and adaptation on the livestock component of mixed farming systems: A modelling study from semi-arid Zimbabwe. Agric. Syst. 159, 282–295. https://doi.org/10.1016/j.agsy.2017.05.004

Dorward, P., Osbahr, H., Sutcliffe, C., Mbeche, R., 2020. Supporting climate change adaptation using historical climate analysis. Clim. Dev. 12, 469–480. https://doi.org/10.1080/17565529.2019.1642177

# APPENDIX A: LITERATURE FROM SYSTEMATIC REVIEW

Dube, T., Mlilo, C., Moyo, P., Ncube, C., Phiri, K., 2018. Will adaptation carry the future? Questioning the long-term capacity of smallholder farmers' adaptation strategies against climate change in Gwanda District, Zimbabwe. J. Hum. Ecol. 61, 20–30. https://doi.org/10.1080/09709274.2018.1452866

Dunning, C.M., Black, E.C.L., Allan, R.P., 2016. The onset and cessation of seasonal rainfall over Africa. J. Geophys. Res. 121, 11405–11424. https://doi.org/10.1002/2016JD025428

Ebrahim, G.Y., Villholth, K.G., Boulos, M., 2019. Integrated hydrogeological modelling of hard-rock semi-arid terrain: supporting sustainable agricultural groundwater use in Hout catchment, Limpopo Province, South Africa. Hydrogeol. J. 27, 965–981. https://doi.org/10.1007/s10040-019-01957-6

Elum, Z.A., Modise, D.M., Marr, A., 2017. Farmer's perception of climate change and responsive strategies in three selected provinces of South Africa. Clim. Risk Manag. 16, 246–257. https://doi.org/10.1016/j.crm.2016.11.001

Elum, Z.A., Nhamo, G., Antwi, M.A., 2018. Effects of climate variability and insurance adoption on crop production in select provinces of South Africa. J. Water Clim. Chang. 9, 500–511. https://doi.org/10.2166/wcc.2018.020

Enenkel, M., Osgood, D., Anderson, M., Powell, B., McCarty, J., Neigh, C., Carroll, M., Wooten, M., Husak, G., Hain, C., Brown, M., 2019. Exploiting the convergence of evidence in satellite data for advanced weather index insurance design. Weather. Clim. Soc. 11, 65–93. https://doi.org/10.1175/WCAS-D-17-0111.1

Eze, S., Dougill, A.J., Banwart, S.A., Hermans, T.D.G., Ligowe, I.S., Thierfelder, C., 2020. Impacts of conservation agriculture on soil structure and hydraulic properties of Malawian agricultural systems. Soil Tillage Res. 201. https://doi.org/10.1016/j.still.2020.104639

Fallon, A.L., Villholth, K.G., Conway, D., Lankford, B.A., Ebrahim, G.Y., 2019. Agricultural groundwater management strategies and seasonal climate forecasting: Perceptions from Mogwadi (Dendron), Limpopo, South Africa. J. Water Clim. Chang. 10, 142–157. https://doi.org/10.2166/wcc.2018.042

Fer, I., Tietjen, B., Jeltsch, F., Wolff, C., 2017. The influence of El Niño-Southern Oscillation regimes on eastern African vegetation and its future implications under the RCP8.5 warming scenario. Biogeosciences 14, 4355–4374. https://doi.org/10.5194/bg-14-4355-2017

Flatø, M., Muttarak, R., Pelser, A., 2017. Women, Weather, and Woes: The Triangular Dynamics of Female-Headed Households, Economic Vulnerability, and Climate Variability in South Africa. World Dev. 90, 41–62. https://doi.org/10.1016/j.worlddev.2016.08.015

Frischen, J., Meza, I., Rupp, D., Wietler, K., Hagenlocher, M., 2020. Drought Risk to Agricultural Systems in Zimbabwe: A Spatial Analysis of Hazard, Exposure, and Vulnerability. Sustainability 12. https://doi.org/10.3390/su12030752

Fritz-Vietta, N.V.M., Tahirindraza, H.S., Stoll-Kleemann, S., 2017. Local people's knowledge with regard to land use activities in southwest Madagascar – Conceptual insights for sustainable land management. J. Environ. Manage. 199, 126–138. https://doi.org/10.1016/j.jenvman.2017.05.034

Fust, P., Schlecht, E., 2018. Integrating spatio-temporal variation in resource availability and herbivore movements into rangeland management: RaMDry—An agent-based model on livestock feeding ecology in a dynamic, heterogeneous, semi-arid environment. Ecol. Modell. 369, 13–41. https://doi.org/10.1016/j.ecolmodel.2017.10.017

Gebrechorkos, S.H., Bernhofer, C., Hülsmann, S., 2019. Impacts of projected change in climate on water balance in basins of East Africa. Sci. Total Environ. 682, 160–170. https://doi.org/10.1016/j.scitotenv.2019.05.053

Gelcer, E., Fraisse, C.W., Zotarelli, L., Stevens, F.R., Perondi, D., Barreto, D.D., Malia, H.A., Ecole, C.C., Montone, V., Southworth, J., 2018. Influence of El Niño-Southern oscillation (ENSO) on agroclimatic zoning for tomato in Mozambique. Agric. For. Meteorol. 248, 316–328. https://doi.org/10.1016/j.agrformet.2017.10.002

Gomes, A.M.F., Rodrigues, A.P., António, C., Rodrigues, A.M., Leitão, A.E., Batista-Santos, P., Nhantumbo, N., Massinga, R., Ribeiro-Barros, A.I., Ramalho, J.C., 2020. Drought response of cowpea (Vigna unguiculata (L.) Walp.) landraces at leaf physiological and metabolite profile levels. Environ. Exp. Bot. 175. https://doi.org/10.1016/j.envexpbot.2020.104060

Grothmann, T., Petzold, M., Ndaki, P., Kakembo, V., Siebenhüner, B., Kleyer, M., Yanda, P., Ndou, N., 2017. Vulnerability assessment in African villages under conditions of land use and climate change: Case studies from Mkomazi and Keiskamma. Sustain. 9. https://doi.org/10.3390/su9060976

Guilpart, N., Grassini, P., Van Wart, J., Yang, H., Van Ittersum, M.K., Van Bussel, L.G.J., Wolf, J., Claessens, L., Leenaars, J.G.B., Cassman, K.G., 2017. Rooting for food security in Sub-Saharan Africa. Environ. Res. Lett. 12. https://doi.org/10.1088/1748-9326/aa9003

Gulacha, M.M., Mulungu, D.M.M., 2017. Generation of climate change scenarios for precipitation and temperature at local scales using SDSM in Wami-Ruvu River Basin Tanzania. Phys. Chem. Earth 100, 62–72. https://doi.org/10.1016/j.pce.2016.10.003

Guo, H., Zhang, X., Lian, F., Gao, Y., Lin, D., Wang, J., 2016. Drought risk assessment based on vulnerability surfaces: A case study of maize. Sustain. 8. https://doi.org/10.3390/su8080813

Haghtalab, N., Moore, N., Ngongondo, C., 2019. Spatio-temporal analysis of rainfall variability and seasonality in Malawi. Reg. Environ. Chang. 19, 2041–2054. https://doi.org/10.1007/s10113-019-01535-2

Haile, B., Signorelli, S., Azzarri, C., Johnson, T., 2018. Welfare effects of weather variability: Multi-country evidence from Africa south of the Sahara. PLoS One 13. https://doi.org/10.1371/journal.pone.0206415

Hasegawa, T., Fujimori, S., Havlík, P., Valin, H., Bodirsky, B.L., Doelman, J.C., Fellmann, T., Kyle, P., Koopman, J.F.L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Pérez Domínguez, I., Stehfest, E., Sulser, T.B., Tabeau, A., Takahashi, K., Takakura, J., van Meijl, H., van Zeist, W.-J., Wiebe, K., Witzke, P., 2018. Risk of increased food insecurity under stringent global climate change mitigation policy. Nat. Clim. Chang. 8, 699–703. https://doi.org/10.1038/s41558-018-0230-x

Haug, R., Wold, B.K.G., 2017. Social protection or humanitarian assistance: Contested input subsidies and climate adaptation in Malawi. IDS Bull. 48, 93–110. https://doi.org/10.19088/1968-2017.155

Hawinkel, P., Thiery, W., Lhermitte, S., Swinnen, E., Verbist, B., Van Orshoven, J., Muys, B., 2016. Vegetation response to precipitation variability in East Africa controlled by biogeographical factors. J. Geophys. Res. Biogeosciences 121, 2422–2444. https://doi.org/10.1002/2016JG003436

Hirvonen, K., 2016. Temperature Changes, Household Consumption, and Internal Migration: Evidence from Tanzania. Am. J. Agric. Econ. 98, 1230–1249. https://doi.org/10.1093/ajae/aaw042

Hlalele, B.M., 2019. Application of the force-field technique to drought vulnerability analysis: A phenomenological approach. Jamba J. Disaster Risk Stud. 11. https://doi.org/10.4102/jamba.v11i1.589

Hlalele, B.M., 2016. A probabilistic approach to drought frequency analysis in Mafube Local Municipality, South Africa. Res. J. Pharm. Biol. Chem. Sci. 7, 3008–3015.

# APPENDIX A: LITERATURE FROM SYSTEMATIC REVIEW

Holden, S.T., Quiggin, J., 2017. Climate risk and state-contingent technology adoption: shocks, drought tolerance and preferences. Eur. Rev. Agric. Econ. 44, 285–308. https://doi.org/10.1093/erae/jbw016

Jägermeyr, J., Gerten, D., Schaphoff, S., Heinke, J., Lucht, W., Rockström, J., 2016. Integrated crop water management might sustainably halve the global food gap. Environ. Res. Lett. 11. https://doi.org/10.1088/1748-9326/11/2/025002

Jaka, H., Shava, E., 2018. Resilient rural women's livelihoods for poverty alleviation and economic empowermen in semi-arid regions of Zimbabwe. Jamba J. Disaster Risk Stud. 10. https://doi.org/10.4102/jamba.v10i1.524

Jiri, O., Mafongoya, P.L., Chivenge, P., 2017. Contextual vulnerability of rainfed crop-based farming communities in semi-arid Zimbabwe: A case of Chiredzi District. Int. J. Clim. Chang. Strateg. Manag. 9, 777–789. https://doi.org/10.1108/IJCCSM-03-2017-0070

Joshua, M.K., Ngongondo, C., Chipungu, F., Monjerezi, M., Liwenga, E., Majule, A.E., Stathers, T., Lamboll, R., 2016. Climate change in semi-arid Malawi: Perceptions, adaptation strategies and water governance. Jamba J. Disaster Risk Stud. 8. https://doi.org/10.4102/jamba.v8i3.255

Kadigi, I.L., Richardson, J.W., Mutabazi, K.D., Philip, D., Bizimana, J.-C., Mourice, S.K., Waized, B., 2020. Forecasting yields, prices and net returns for main cereal crops in Tanzania as probability distributions: A multivariate empirical (MVE) approach. Agric. Syst. 180. https://doi.org/10.1016/j.agsy.2019.102693

Kahsay, G.A., Hansen, L.G., 2016. The effect of climate change and adaptation policy on agricultural production in Eastern Africa. Ecol. Econ. 121, 54–64. https://doi.org/10.1016/j.ecolecon.2015.11.016

Kamali, B., Abbaspour, K.C., Wehrli, B., Yang, H., 2019. A quantitative analysis of socio-economic determinants influencing crop drought vulnerability in Sub-Saharan Africa. Sustain. 11. https://doi.org/10.3390/su11216135

Kamali, B., Abbaspour, K.C., Wehrli, B., Yang, H., 2018. Drought vulnerability assessment of maize in Sub-Saharan Africa: Insights from physical and social perspectives. Glob. Planet. Change 162, 266–274. https://doi.org/10.1016/j.gloplacha.2018.01.011

Kamanga, T.F., Tantanee, S., Mwale, F.D., Buranajarukorn, P., 2020. A multi hazard perspective in flood and drought vulnerability: case study of Malawi. Geogr. Tech. 15, 132–142. https://doi.org/10.21163/GT_2020.151.12

Kangalawe, R.Y.M., 2017. Climate change impacts on water resource management and community livelihoods in the southern highlands of Tanzania. Clim. Dev. 9, 191–201. https://doi.org/10.1080/17565529.2016.1139487

Kangalawe, R.Y.M., Mung'ong'o, C.G., Mwakaje, A.G., Kalumanga, E., Yanda, P.Z., 2017. Climate change and variability impacts on agricultural production and livelihood systems in Western Tanzania. Clim. Dev. 9, 202–216. https://doi.org/10.1080/17565529.2016.1146119

Kassian, L.M., Tenywa, M., Liwenga, E.T., Dyer, K.W., Bamutaze, Y., 2017. Implication of climate change and variability on stream flow in Iringa region, Tanzania. J. Water Clim. Chang. 8, 336–347. https://doi.org/10.2166/wcc.2016.238

Katengeza, S.P., Holden, S.T., Fisher, M., 2019. Use of Integrated Soil Fertility Management Technologies in Malawi: Impact of Dry Spells Exposure. Ecol. Econ. 156, 134–152. https://doi.org/10.1016/j.ecolecon.2018.09.018

Kgosikoma, K.R., Lekota, P.C., Kgosikoma, O.E., 2018. Agro-pastoralists' determinants of adaptation to climate change. Int. J. Clim. Chang. Strateg. Manag. 10, 488–500. https://doi.org/10.1108/IJCCSM-02-2017-0039

Kimambo, O.N., Chikoore, H., Gumbo, J.R., 2019. Understanding the Effects of Changing Weather: A Case of Flash Flood in Morogoro on January 11, 2018. Adv. Meteorol. 2019. https://doi.org/10.1155/2019/8505903

Kimaro, A.A., Mpanda, M., Rioux, J., Aynekulu, E., Shaba, S., Thiong'o, M., Mutuo, P., Abwanda, S., Shepherd, K., Neufeldt, H., Rosenstock, T.S., 2016. Is conservation agriculture 'climate-smart' for maize farmers in the highlands of Tanzania? Nutr. Cycl. Agroecosystems 105, 217–228. https://doi.org/10.1007/s10705-015-9711-8

Kogan, F., Guo, W., 2017. Strong 2015–2016 El Niño and implication to global ecosystems from space data. Int. J. Remote Sens. 38, 161–178. https://doi.org/10.1080/01431161.2016.1259679

Kolawole, O.D., Motsholapheko, M.R., Ngwenya, B.N., Thakadu, O., Mmopelwa, G., Kgathi, D.L., 2016. Climate variability and rural livelihoods: How households perceive and adapt to climatic shocks in the Okavango Delta, Botswana. Weather. Clim. Soc. 8, 131–145. https://doi.org/10.1175/WCAS-D-15-0019.1

Kruger, L., 2016. The timing of agricultural production in hazard-prone areas to prevent losses at peak-risk periods: A case of Malawi, Madagascar and Mozambique. Jamba J. Disaster Risk Stud. 8, 1–9. https://doi.org/10.4102/jamba.v8i2.179

Kubik, Z., Maurel, M., 2016. Weather Shocks, Agricultural Production and Migration: Evidence from Tanzania. J. Dev. Stud. 52, 665–680. https://doi.org/10.1080/00220388.2015.1107049

Lana, M.A., Vasconcelos, A.C.F., Gornott, C., Schaffert, A., Bonatti, M., Volk, J., Graef, F., Kersebaum, K.C., Sieber, S., 2018. Is dry soil planting an adaptation strategy for maize cultivation in semi-arid Tanzania? Food Secur. 10, 897–910. https://doi.org/10.1007/s12571-017-0742-7

Lawlor, K., Handa, S., Seidenfeld, D., Evaluat, Z.C.T., 2019. Cash Transfers Enable Households to Cope with Agricultural Production and Price Shocks: Evidence from Zambia. J. Dev. Stud. 55, 209–226. https://doi.org/10.1080/00220388.2017.1393519

Lebek, K., Senf, C., Frantz, D., Monteiro, J.A.F., Krueger, T., 2019. Interdependent effects of climate variability and forest cover change on streamflow dynamics: a case study in the Upper Umvoti River Basin, South Africa. Reg. Environ. Chang. 19, 1963–1971. https://doi.org/10.1007/s10113-019-01521-8

Letta, M., Montalbano, P., Tol, R.S.J., 2018. Temperature shocks, short-term growth and poverty thresholds: Evidence from rural Tanzania. World Dev. 112, 13–32. https://doi.org/10.1016/j.worlddev.2018.07.013

Limuwa, Moses Majid, Singin, W., Storebakken, T., 2018. Is Fish Farming an Illusion for Lake Malawi Riparian Communities under Environmental Changes? Sustainability 10. https://doi.org/10.3390/su10051453

Limuwa, M M, Sitaula, B.K., Njaya, F., Storebakken, T., 2018. Evaluation of small-scale fishers' perceptions on climate change and their coping strategies: Insights from lake Malawi. Climate 6. https://doi.org/10.3390/cli6020034

Litskas, V.D., Migeon, A., Navajas, M., Tixier, M.-S., Stavrinides, M.C., 2019. Impacts of climate change on tomato, a notorious pest and its natural enemy: Small scale agriculture at higher risk. Environ. Res. Lett. 14. https://doi.org/10.1088/1748-9326/ab3313

Luan, Y., Zhu, W., Cui, X., Fischer, G., Dawson, T.P., Shi, P., Zhang, Z., 2019. Cropland yield divergence over Africa and its implication for mitigating food insecurity. Mitig. Adapt. Strateg. Glob. Chang. 24, 707–734. https://doi.org/10.1007/s11027-018-9827-7

Luetkemeier, R., Stein, L., Drees, L., Liehr, S., 2017. Blended drought index: Integrated drought hazard assessment in the Cuvelai-Basin. Climate 5. https://doi.org/10.3390/cli5030051

# APPENDIX A: LITERATURE FROM SYSTEMATIC REVIEW


Luhunga, P., Chang'a, L., Djolov, G., 2017. Assessment of the impacts of climate change on maize production in the wami ruvu Basin of Tanzania. J. Water Clim. Chang. 8, 142–164. https://doi.org/10.2166/wcc.2016.055

Luhunga, P.M., 2017. Assessment of the impacts of climate change on maize production in the southern and western highlands sub-agro ecological Zones of Tanzania. Front. Environ. Sci. 5. https://doi.org/10.3389/fenvs.2017.00051

Mabhaudhi, T., Chibarabada, T.P., Chimonyo, V.G.P., Modi, A.T., 2018. Modelling climate change impact: A case of bambara groundnut (Vigna subterranea). Phys. Chem. Earth 105, 25–31. https://doi.org/10.1016/j.pce.2018.01.003

Mabuku, M.P., Senzanje, A., Mudhara, M., Jewitt, G.P.W., Mulwafu, W.O., 2019. Strategies for coping and adapting to flooding and their determinants: A comparative study of cases from Namibia and Zambia. Phys. Chem. Earth 111, 20–34. https://doi.org/10.1016/j.pce.2018.12.009

Mabuza, M.L., Ortmann, G.F., Wale, E., 2016. Frequency and extent of employing food insecurity coping strategies among rural households: determinants and implications for policy using evidence from Swaziland. Food Secur. 8, 255–269. https://doi.org/10.1007/s12571-015-0527-9

MacAlister, D, Muasya, A.M., Crespo, O., Ogola, J.B.O., Maseko, S., Valentine, A.J., Ottosen, C.-O., Rosenqvist, E., Chimphango, S.B.M., 2020. Stress tolerant traits and root proliferation of Aspalathus linearis (Burm.f.) R. Dahlgren grown under differing moisture regimes and exposed to drought. South African J. Bot. 131, 342–350. https://doi.org/10.1016/j.sajb.2020.03.003

MacAlister, Dunja, Muasya, A.M., Crespo, O., Ogola, J.B.O., Maseko, S.T., Valentine, A.J., Ottosen, C.-O., Rosenqvist, E., Chimphango, S.B.M., 2020. Effect of temperature on plant growth and stress tolerant traits in rooibos in the Western Cape, South Africa. Sci. Hortic. (Amsterdam). 263. https://doi.org/10.1016/j.scienta.2019.109137

Macedo, R., Sales, L.P., Yoshida, F., Silva-Abud, L.L., Lobo, M., 2017. Potential worldwide distribution of Fusarium dry root rot in common beans based on the optimal environment for disease occurrence. PLoS One 12. https://doi.org/10.1371/journal.pone.0187770

Maggio, G., Sitko, N., 2019. Knowing is half the battle: Seasonal forecasts, adaptive cropping systems, and the mediating role of private markets in Zambia. Food Policy 89. https://doi.org/10.1016/j.foodpol.2019.101781

Makame, M.O., Shackleton, S., 2019. Perceptions of climate variability and change in relation to observed data among two east coast communities in Zanzibar, East Africa. Clim. Dev. https://doi.org/10.1080/17565529.2019.1697633

Makate, C., Makate, M., 2019. Interceding role of institutional extension services on the livelihood impacts of drought tolerant maize technology adoption in Zimbabwe. Technol. Soc. 56, 126–133. https://doi.org/10.1016/j.techsoc.2018.09.011

Makate, C., Makate, M., Mango, N., 2019a. Wealth-related inequalities in adoption of drought-tolerant maize and conservation agriculture in Zimbabwe. Food Secur. 11, 881–896. https://doi.org/10.1007/s12571-019-00946-7

Makate, C., Makate, M., Mango, N., Siziba, S., 2019b. Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa. J. Environ. Manage. 231, 858–868. https://doi.org/10.1016/j.jenvman.2018.10.069

Makate, C., Wang, R., Makate, M., Mango, N., 2017. Impact of drought tolerant maize adoption on maize productivity, sales and consumption in rural Zimbabwe. Agrekon 56, 67–81. https://doi.org/10.1080/03031853.2017.1283241

Maliro, M.F.A., Guwela, V.F., Nyaika, J., Murphy, K.M., 2017. Preliminary studies of the performance of quinoa (Chenopodium quinoa Willd.) genotypes under irrigated and rainfed conditions of central Malawi. Front. Plant Sci. 8. https://doi.org/10.3389/fpls.2017.00227

Maltou, R., Bahta, Y.T., 2019. Factors influencing the resilience of smallholder livestock farmers to agricultural drought in South Africa: Implication for adaptive capabilities. Jamba J. Disaster Risk Stud. 11. https://doi.org/10.4102/jamba.v11i1.805

Mango, N., Makate, C., Mapemba, L., Sopo, M., 2018a. The role of crop diversification in improving household food security in central Malawi. Agric. Food Secur. 7. https://doi.org/10.1186/s40066-018-0160-x

Mango, N., Makate, C., Tamene, L., Mponela, P., Ndengu, G., 2018b. Adoption of small-scale irrigation farming as a climate-smart agriculture practice and its influence on household income in the Chinyanja Triangle, Southern Africa. Land 7. https://doi.org/10.3390/land7020049

Mapfumo, P., Mtambanengwe, F., Chikowo, R., 2016. Building on indigenous knowledge to strengthen the capacity of smallholder farming communities to adapt to climate change and variability in southern Africa. Clim. Dev. 8, 72–82. https://doi.org/10.1080/17565529.2014.998604

Marcantonio, R.A., 2020. Water, anxiety, and the human niche: a study in Southern Province, Zambia. Clim. Dev. 12, 310–322. https://doi.org/10.1080/17565529.2019.1617664

Martinsen, V., Munera-Echeverri, J.L., Obia, A., Cornelissen, G., Mulder, J., 2019. Significant build-up of soil organic carbon under climate-smart conservation farming in Sub-Saharan Acrisols. Sci. Total Environ. 660, 97–104. https://doi.org/10.1016/j.scitotenv.2018.12.452

Mashizha, T.M., 2019. Adapting to climate change: Reflections of peasant farmers in Mashonaland West Province of Zimbabwe. Jamba J. Disaster Risk Stud. 11. https://doi.org/10.4102/jamba.v11i1.571

Masoni, A., Calamai, A., Marini, L., Benedettelli, S., Palchetti, E., 2020. Constitution of Composite Cross Maize (Zea mays L.) Populations Selected for the Semi-Arid Environment of South Madagascar. AGRONOMY-BASEL 10. https://doi.org/10.3390/agronomy10010054

Masupha, T.E., Moeletsi, M.E., 2018. Analysis of potential future droughts limiting maize production, in the Luvuvhu River catchment area, South Africa. Phys. Chem. Earth 105, 44–51. https://doi.org/10.1016/j.pce.2018.03.009

Masupha, T.E., Moeletsi, M.E., 2017. Use of standardized precipitation evapotranspiration index to investigate drought relative to maize, in the Luvuvhu River catchment area, South Africa. Phys. Chem. Earth 102, 1–9. https://doi.org/10.1016/j.pce.2017.08.002

Masupha, T.E., Moeletsi, M.E., Tsubo, M., 2016. Dry spells assessment with reference to the maize crop in the Luvuvhu River catchment of South Africa. Phys. Chem. Earth 92, 99–111. https://doi.org/10.1016/j.pce.2015.10.014

Masvaya, E.N., Nyamangara, J., Descheemaeker, K., Giller, K.E., 2017. Tillage, mulch and fertiliser impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe. Soil Tillage Res. 168, 125–132. https://doi.org/10.1016/j.still.2016.12.007

Maure, G., Pinto, I., Ndebele-Murisa, M., Muthige, M., Lennard, C., Nikulin, G., Dosio, A., Meque, A., 2018. The southern African climate under 1.5 °c and 2 °c of global warming as simulated by CORDEX regional climate models. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aab190

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Maurice, L., Taylor, R.G., Tindimugaya, C., MacDonald, A.M., Johnson, P., Kaponda, A., Owor, M., Sanga, H., Bonsor, H.C., Darling, W.G., Gooddy, D., 2019. Characteristics of high-intensity groundwater abstractions from weathered crystalline bedrock aquifers in East Africa. Hydrogeol. J. 27, 459–474. https://doi.org/10.1007/s10040-018-1836-9

Mavhura, E., 2019. Systems Analysis of Vulnerability to Hydrometeorological Threats: An Exploratory Study of Vulnerability Drivers in Northern Zimbabwe. Int. J. Disaster Risk Sci. 10, 204–219. https://doi.org/10.1007/s13753-019-0217-x

Mberego, S., 2017. Temporal patterns of precipitation and vegetation variability over Botswana during extreme dry and wet rainfall seasons. Int. J. Climatol. 37, 2947–2960. https://doi.org/10.1002/joc.4891

McNally, A., Arsenault, K., Kumar, S., Shukla, S., Peterson, P., Wang, S., Funk, C., Peters-Lidard, C.D., Verdin, J.P., 2017. A land data assimilation system for sub-Saharan Africa food and water security applications. Sci. Data 4. https://doi.org/10.1038/sdata.2017.12

Meza, I., Siebert, S., Doell, P., Kusche, J., Herbert, C., Rezaei, E.E., Nouri, H., Gerdener, H., Popat, E., Frischen, J., Naumann, G., Vogt, J. V, Walz, Y., Sebesvari, Z., Hagenlocher, M., 2020. Global-scale drought risk assessment for agricultural systems. Nat. Hazards Earth Syst. Sci. 20, 695–712. https://doi.org/10.5194/nhess-20-695-2020

Mhlanga-Ndlovu, B.F.N., Nhamo, G., 2016. Farmer perceptions of climate change impacts on Swaziland's sugar industry. African J. Sci. Technol. Innov. Dev. 8, 429–438. https://doi.org/10.1080/20421338.2016.1219503

Mhlanga, I., Ndaimani, H., Mpakairi, K., Mujere, N., 2018. Climate change: An uncertain future for dairy farming in Zimbabwe. Trans. R. Soc. South Africa 73, 237–242. https://doi.org/10.1080/0035919X.2018.1503203

Michler, J.D., Baylis, K., Arends-Kuenning, M., Mazvimavi, K., 2019. Conservation agriculture and climate resilience. J. Environ. Econ. Manage. 93, 148–169. https://doi.org/10.1016/j.jeem.2018.11.008

Midega, C.A.O., Pittchar, J.O., Pickett, J.A., Hailu, G.W., Khan, Z.R., 2018. A climate-adapted push-pull system effectively controls fall armyworm, Spodoptera frugiperda (J E Smith), in maize in East Africa. Crop Prot. 105, 10–15. https://doi.org/10.1016/j.cropro.2017.11.003

Mkonda, M.Y., He, X., 2018. Vulnerability assessment of the livelihoods in Tanzania's semi-arid agro-ecological zone under climate change scenarios. Climate 6. https://doi.org/10.3390/cli6020027

Mkonda, M.Y., He, X., 2017a. Yields of the major food crops: Implications to food security and policy in Tanzania's semi-arid agro-ecological zone. Sustain. 9. https://doi.org/10.3390/su9081490

Mkonda, M.Y., He, X., 2017b. Are rainfall and temperature really changing? Farmer's perceptions, meteorological data, and policy implications in the Tanzanian semi-arid zone. Sustain. 9. https://doi.org/10.3390/su9081412

Mlenga, D.H., Jordaan, A.J., 2019. Monitoring droughts in Eswatini: A spatiotemporal variability analysis using the Standard Precipitation Index. Jamba J. Disaster Risk Stud. 11. https://doi.org/10.4102/jamba.v11i1.712

Mogomotsi, P.K., Sekelemani, A., Mogomotsi, G.E.J., 2020. Climate change adaptation strategies of small-scale farmers in Ngamiland East, Botswana. Clim. Change 159, 441–460. https://doi.org/10.1007/s10584-019-02645-w

Möllmann, J., Buchholz, M., Kölle, W., Musshoff, O., 2020. Do remotely-sensed vegetation health indices explain credit risk in agricultural microfinance? World Dev. 127. https://doi.org/10.1016/j.worlddev.2019.104771

Mourice, S.K., 2020. Climate Change Will Intensify Drought Risk at the Newly Established Mkulazi II Sugar Estate, Mvomero District, Tanzania. Sugar Tech 22, 157–170. https://doi.org/10.1007/s12355-019-00748-3

Mpandeli, S., Nhamo, L., Moeletsi, M., Masupha, T., Magidi, J., Tshikolomo, K., Liphadzi, S., Naidoo, D., Mabhaudhi, T., 2019. Assessing climate change and adaptive capacity at local scale using observed and remotely sensed data. Weather Clim. Extrem. 26. https://doi.org/10.1016/j.wace.2019.100240

Msowoya, K., Madani, K., Davtalab, R., Mirchi, A., Lund, J.R., 2016. Climate Change Impacts on Maize Production in the Warm Heart of Africa. Water Resour. Manag. 30, 5299–5312. https://doi.org/10.1007/s11269-016-1487-3

Mthembu, N.N., Zwane, E.M., 2017. The adaptive capacity of smallholder mixed-farming systems to the impact of climate change: The case of KwaZulu-Natal in South Africa. Jamba J. Disaster Risk Stud. 9. https://doi.org/10.4102/jamba.v9i1.469

Mtongori, H.I., Stordal, F., Benestad, R.E., 2016. Evaluation of empirical statistical downscaling models' skill in predicting Tanzanian rainfall and their application in providing future downscaled scenarios. J. Clim. 29, 3231–3252. https://doi.org/10.1175/JCLI-D-15-0061.1

Mubanga, K.H., Ferguson, W., 2017. Threats to food sufficiency among smallholder farmers in Choma, Zambia. Food Secur. 9, 745–758. https://doi.org/10.1007/s12571-017-0700-4

Mubaya, C.P., Mafongoya, P., 2017. Local-level climate change adaptation decision-making and livelihoods in semi-arid areas in Zimbabwe. Environ. Dev. Sustain. 19, 2377–2403. https://doi.org/10.1007/s10668-016-9861-0

Mulenga, B.P., Wineman, A., Sitko, N.J., 2017. Climate Trends and Farmers' Perceptions of Climate Change in Zambia. Environ. Manage. 59, 291–306. https://doi.org/10.1007/s00267-016-0780-5

Müller, F.L., Raitt, L.M., Chimphango, S.B.M., Samuels, M.I., Cupido, C.F., Boatwright, J.S., Knight, R., Trytsman, M., 2017. Prioritisation of native legume species for further evaluation as potential forage crops in water-limited agricultural systems in South Africa. Environ. Monit. Assess. 189. https://doi.org/10.1007/s10661-017-6230-x

Mupakati, T., Tanyanyiwa, V.I., 2017. Cassava production as a climate change adaptation strategy in Chilonga Ward, Chiredzi District, Zimbabwe. Jamba J. Disaster Risk Stud. 9. https://doi.org/10.4102/jamba.v9i1.348

Mupangwa, W., Walker, S., Masvaya, E., Magombeyi, M., Munguambe, P., 2016. Rainfall risk and the potential of reduced tillage systems to conserve soil water in semi-arid cropping systems of southern Africa. AIMS Agric. Food 1, 85–101. https://doi.org/10.3934/agrfood.2016.1.85

Murray, U., Gebremedhin, Z., Brychkova, G., Spillane, C., 2016. Smallholder Farmers and Climate Smart Agriculture: Technology and Labor-productivity Constraints amongst Women Smallholders in Malawi. Gend. Technol. Dev. 20, 117–148. https://doi.org/10.1177/0971852416640639

Murungweni, C., Van Wijk, M.T., Smaling, E.M.A., Giller, K.E., 2016. Climate-smart crop production in semi-arid areas through increased knowledge of varieties, environment and management factors. Nutr. Cycl. Agroecosystems 105, 183–197. https://doi.org/10.1007/s10705-015-9695-4

Mushore, T., Manatsa, D., Pedzisai, E., Muzenda-Mudavanhu, C., Mushore, W., Kudzotsa, I., 2017. Investigating the implications of meteorological indicators of seasonal rainfall performance on maize yield in a rain-fed agricultural system: case study of Mt. Darwin District in Zimbabwe. Theor. Appl. Climatol. 129, 1167–1173. https://doi.org/10.1007/s00704-016-1838-2

Musiyiwa, K., Harris, D., Filho, W.L., Gwenzi, W., Nyamangara, J., 2017. An assessment of smallholder soil and water conservation practices and perceptions in contrasting agro-ecological regions in Zimbabwe. Water Resour. Rural Dev. 9, 1–11. https://doi.org/10.1016/j.wrr.2016.09.001

# APPENDIX A: LITERATURE FROM SYSTEMATIC REVIEW


Mutenje, M.J., Farnworth, C.R., Stirling, C., Thierfelder, C., Mupangwa, W., Nyagumbo, I., 2019. A cost-benefit analysis of climate-smart agriculture options in Southern Africa: Balancing gender and technology. Ecol. Econ. 163, 126–137. https://doi.org/10.1016/j.ecolecon.2019.05.013

Muthoni, F.K., Odongo, V.O., Ochieng, J., Mugalavai, E.M., Mourice, S.K., Hoesche-Zeledon, I., Mwila, M., Bekunda, M., 2019. Long-term spatial-temporal trends and variability of rainfall over Eastern and Southern Africa. Theor. Appl. Climatol. 137, 1869–1882. https://doi.org/10.1007/s00704-018-2712-1

Mwenge Kahinda, J., Meissner, R., Engelbrecht, F.A., 2016. Implementing Integrated Catchment Management in the upper Limpopo River basin: A situational assessment. Phys. Chem. Earth 93, 104–118. https://doi.org/10.1016/j.pce.2015.10.003

Näschen, K., Diekkrüger, B., Leemhuis, C., Seregina, L.S., van der Linden, R., 2019. Impact of climate change on water resources in the Kilombero Catchment in Tanzania. Water (Switzerland) 11. https://doi.org/10.3390/w11040859

Ndhleve, S., Nakin, M.D. V, Longo-Mbenza, B., 2017. Impacts of supplemental irrigation as a climate change adaptation strategy for maize production: A case of the Eastern Cape Province of South Africa. Water SA 43, 222–228. https://doi.org/10.4314/wsa.v43i2.06

Negrini, M., Fidelis, E.G., Picanço, M.C., Ramos, R.S., 2020. Mapping of the Steneotarsonemus spinki invasion risk in suitable areas for rice (Oryza sativa) cultivation using MaxEnt. Exp. Appl. Acarol. 80, 445–461. https://doi.org/10.1007/s10493-020-00474-6

Nezomba, H., Mtambanengwe, F., Rurinda, J., Mapfumo, P., 2018. Integrated soil fertility management sequences for reducing climate risk in smallholder crop production systems in southern Africa. F. Crop. Res. 224, 102–114. https://doi.org/10.1016/j.fcr.2018.05.003

Ng'ombe, J.N., Tembo, M.C., Masasi, B., 2020. Are They Aware, and Why? Bayesian Analysis of Predictors of Smallholder Farmers' Awareness of Climate Change and Its Risks to Agriculture. Agronomy-Basel 10. https://doi.org/10.3390/agronomy10030376

Ngoma, H., 2018. Does minimum tillage improve the livelihood outcomes of smallholder farmers in Zambia? Food Secur. 10, 381–396. https://doi.org/10.1007/s12571-018-0777-4

Ngwenya, B.N., Thakadu, O.T., Magole, L., Chimbari, M.J., 2017. Memories of environmental change and local adaptations among molapo farming communities in the Okavango Delta, Botswana—A gender perspective. Acta Trop. 175, 31–41. https://doi.org/10.1016/j.actatropica.2016.11.029

Nhamo, L., Ebrahim, G.Y., Mabhaudhi, T., Mpandeli, S., Magombeyi, M., Chitakira, M., Magidi, J., Sibanda, M., 2020. An assessment of groundwater use in irrigated agriculture using multi-spectral remote sensing. Phys. Chem. EARTH 115. https://doi.org/10.1016/j.pce.2019.102810

Nhamo, L., Mabhaudhi, T., Modi, A.T., 2019. Preparedness or repeated short-term relief aid? Building drought resilience through early warning in southern africa. Water SA 45, 75–85. https://doi.org/10.4314/wsa.v45i1.09

Nhamo, L., Matchaya, G., Nhemachena, C., van Koppen, B., 2016. The impact of investment in smallholder irrigation schemes on irrigation expansion and crop productivity in Malawi. African J. Agric. Resour. Econ. 11, 141–153.

Notenbaert, A., Pfeifer, C., Silvestri, S., Herrero, M., 2017. Targeting, out-scaling and prioritising climate-smart interventions in agricultural systems: Lessons from applying a generic framework to the livestock sector in sub-Saharan Africa. Agric. Syst. 151, 153–162. https://doi.org/10.1016/j.agsy.2016.05.017

Nyagumbo, I., Mkuhlani, S., Mupangwa, W., Rodriguez, D., 2017. Planting date and yield benefits from conservation agriculture practices across Southern Africa. Agric. Syst. 150, 21–33. https://doi.org/10.1016/j.agsy.2016.09.016

Nyagumbo, I., Nyamadzawo, G., Madembo, C., 2019. Effects of three in-field water harvesting technologies on soil water content and maize yields in a semi-arid region of Zimbabwe. Agric. Water Manag. 216, 206–213. https://doi.org/10.1016/j.agwat.2019.02.023

Nyahunda, L., Tirivangasi, H.M., 2019. Challenges faced by rural people in mitigating the effects of climate change in the Mazungunye communa lands, Zimbabwe. Jamba J. Disaster Risk Stud. 11. https://doi.org/10.4102/jamba.v11i1.596

Nyamwanza, A.M., New, M.G., Fujisawa, M., Johnston, P., Hajat, A., 2017. Contributions of decadal climate information in agriculture and food systems in east and southern Africa. Clim. Change 143, 115–128. https://doi.org/10.1007/s10584-017-1990-4

Nyikahadzoi, K., Adekunle, A., Fatunbi, Zamasiya, B., 2017a. Promoting production and marketing of root crops in Southern Africa in a changing climate using integrated agricultural research for development (IAR4D) pathway. African J. Food, Agric. Nutr. Dev. 17, 11787–11802. https://doi.org/10.18697/ajfand.77.13765

Nyikahadzoi, K., Mombo, O., Zamasiya, B., Warinda, P., 2017b. Enhancing Household Food Security Under Changing Climatic Conditions: A Case Study of Gokwe North and Hurungwe Districts in Zimbabwe. J. Agric. Food Inf. 18, 96–109. https://doi.org/10.1080/10496505.2017.1297239

Obia, A., Cornelissen, G., Martinsen, V., Smebye, A.B., Mulder, J., 2020. Conservation tillage and biochar improve soil water content and moderate soil temperature in a tropical Acrisol. SOIL TILLAGE Res. 197. https://doi.org/10.1016/j.still.2019.104521

Oduniyi, O.S., Antwi, M.A., Tekana, S.S., 2020. Farmers' Willingness to Pay for Index-Based Livestock Insurance in the North West of South Africa. Climate 8. https://doi.org/10.3390/cli8030047

Orimoloye, I.R., Ololade, O.O., Mazinyo, S.P., Kalumba, A.M., Ekundayo, O.Y., Busayo, E.T., Akinsanola, A.A., Nel, W., 2019. Spatial assessment of drought severity in Cape Town area, South Africa. Heliyon 5. https://doi.org/10.1016/j.heliyon.2019.e02148

Osewe, M., Liu, A., Njagi, T., 2020. Farmer-Led Irrigation and Its Impacts on Smallholder Farmers' Crop Income: Evidence from Southern Tanzania. Int. J. Environ. Res. Public Health 17. https://doi.org/10.3390/ijerph17051512

Osima, S., Indasi, V.S., Zaroug, M., Endris, H.S., Gudoshava, M., Misiani, H.O., Nimusiima, A., Anyah, R.O., Otieno, G., Ogwang, B.A., Jain, S., Kondowe, A.L., Mwangi, E., Lennard, C., Nikulin, G., Dosio, A., 2018. Projected climate over the Greater Horn of Africa under 1.5 °c and 2 °c global warming. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aaba1b

Papaioannou, K.J., de Haas, M., 2017. Weather Shocks and Agricultural Commercialization in Colonial Tropical Africa: Did Cash Crops Alleviate Social Distress? World Dev. 94, 346–365. https://doi.org/10.1016/j.worlddev.2017.01.019

Pauline, N.M., Grab, S., 2018. Whose knowledge matters in climate change adaptation? Perceived and measured rainfall trends during the last half century in south-western Tanzania. Singap. J. Trop. Geogr. 39, 266–280. https://doi.org/10.1111/sjtg.12232

# APPENDIX A: LITERATURE FROM SYSTEMATIC REVIEW


Payet-Burin, R., Kromann, M., Pereira-Cardenal, S., Marc Strzepek, K., Bauer-Gottwein, P., 2019. WHAT-IF: An open-source decision support tool for water infrastructure investment planning within the water-energy-food-climate nexus. Hydrol. Earth Syst. Sci. 23, 4129–4152. https://doi.org/10.5194/hess-23-4129-2019

Penot, E., Fevre, V., Flodrops, P., Razafimahatratra, H.M., 2018. Conservation Agriculture to buffer and alleviate the impact of climatic variations in Madagascar: Farmers' perception. Cah. Agric. 27. https://doi.org/10.1051/cagri/2018009

Peter, B.G., Mungai, L.M., Messina, J.P., Snapp, S.S., 2017. Nature-based agricultural solutions: Scaling perennial grains across Africa. Environ. Res. 159, 283–290. https://doi.org/10.1016/j.envres.2017.08.011

Popoola, O.O., Monde, N., Yusuf, S.F.G., 2018. Perceptions of climate change impacts and adaptation measures used by crop smallholder farmers in Amathole district municipality, Eastern Cape province, South Africa. GeoJournal 83, 1205–1221. https://doi.org/10.1007/s10708-017-9829-0

Raaijmakers, S., Swanepoel, P.A., 2020. Vulnerability, institutional arrangements and the adaptation choices made by farmers in the Western Cape province of South Africa. South African J. Plant Soil 37, 51–59. https://doi.org/10.1080/02571862.2019.1645219

Rahn, E., Vaast, P., Läderach, P., van Asten, P., Jassogne, L., Ghazoul, J., 2018. Exploring adaptation strategies of coffee production to climate change using a process-based model. Ecol. Modell. 371, 76–89. https://doi.org/10.1016/j.ecolmodel.2018.01.009

Ramirez-Cabral, N.Y.Z., Kumar, L., Shabani, F., 2017. Global alterations in areas of suitability for maize production from climate change and using a mechanistic species distribution model (CLIMEX). Sci. Rep. 7. https://doi.org/10.1038/s41598-017-05804-0

Randrianjafizanaka, M.T., Autfray, P., Andrianaivo, A.P., Ramonta, I.R., Rodenburg, J., 2018. Combined effects of cover crops, mulch, zero-tillage and resistant varieties on Striga asiatica (L.) Kuntze in rice-maize rotation systems. Agric. Ecosyst. Environ. 256, 23–33. https://doi.org/10.1016/j.agee.2017.12.005

Rankoana, S.A., 2016. Perceptions of climate change and the potential for adaptation in a rural community in Limpopo Province, South Africa. Sustain. 8. https://doi.org/10.3390/su8080672

Rao Kolusu, S., Shamsudduha, M., Todd, M.C., Taylor, R.G., Seddon, D., Kashaigili, J.J., Ebrahim, G.Y., Cuthbert, M.O., Sorensen, J.P.R., Villholth, K.G., Macdonald, A.M., Macleod, D.A., 2019. The El Niño event of 2015-2016: Climate anomalies and their impact on groundwater resources in East and Southern Africa. Hydrol. Earth Syst. Sci. 23, 1751–1762. https://doi.org/10.5194/hess-23-1751-2019

Rippke, U., Ramirez-Villegas, J., Jarvis, A., Vermeulen, S.J., Parker, L., Mer, F., Diekkrüger, B., Challinor, A.J., Howden, M., 2016. Timescales of transformational climate change adaptation in sub-Saharan African agriculture. Nat. Clim. Chang. 6, 605–609. https://doi.org/10.1038/nclimate2947

Rotich, S.C., Mulungu, D.M.M., 2017. Adaptation to climate change impacts on crop water requirements in kikafu catchment, Tanzania. J. Water Clim. Chang. 8, 274–292. https://doi.org/10.2166/wcc.2017.058

Roxburgh, C.W., Rodriguez, D., 2016. Ex-ante analysis of opportunities for the sustainable intensification of maize production in Mozambique. Agric. Syst. 142, 9–22. https://doi.org/10.1016/j.agsy.2015.10.010

Roy, T., Valdés, J.B., Lyon, B., Demaria, E.M.C., Serrat-Capdevila, A., Gupta, H. V, Valdés-Pineda, R., Durcik, M., 2018. Assessing hydrological impacts of short-term climate change in the Mara River basin of East Africa. J. Hydrol. 566, 818–829. https://doi.org/10.1016/j.jhydrol.2018.08.051

Rybak, C., Mbwana, H.A., Bonatti, M., Sieber, S., Müller, K., 2018. Status and scope of kitchen gardening of green leafy vegetables in rural Tanzania: implications for nutrition interventions. Food Secur. 10, 1437–1447. https://doi.org/10.1007/s12571-018-0869-1

Salazar, C., Ayalew, H., Fisker, P., 2019. Weather Shocks and Spatial Market Efficiency: Evidence from Mozambique. J. Dev. Stud. 55, 1967–1982. https://doi.org/10.1080/00220388.2018.1528352

Salite, D., 2019. Traditional prediction of drought under weather and climate uncertainty: analyzing the challenges and opportunities for small-scale farmers in Gaza province, southern region of Mozambique. Nat. Hazards 96, 1289–1309. https://doi.org/10.1007/s11069-019-03613-4

Salite, D., Poskitt, S., 2019. Managing the impacts of drought: The role of cultural beliefs in small-scale farmers' responses to drought in Gaza Province, southern Mozambique. Int. J. Disaster Risk Reduct. 41. https://doi.org/10.1016/j.ijdrr.2019.101298

Samuel, O.O., Sylvia, T.S., 2019. Analysis of rural livelihood diversification strategies among maize farmers in north west province of South Africa. Int. J. Entrep. 23.

Santana, P.A., Kumar, L., Da Silva, R.S., Picanço, M.C., 2019. Global geographic distribution of Tuta absoluta as affected by climate change. J. Pest Sci. (2004). 92, 1373–1385. https://doi.org/10.1007/s10340-018-1057-y

Santillán, D., Iglesias, A., La Jeunesse, I., Garrote, L., Sotes, V., 2019. Vineyards in transition: A global assessment of the adaptation needs of grape producing regions under climate change. Sci. Total Environ. 657, 839–852. https://doi.org/10.1016/j.scitotenv.2018.12.079

Saronga, N.J., Mosha, I.H., Kessy, A.T., Ezekiel, M.J., Zizinga, A., Kweka, O., Onyango, P., Kovats, S., 2016. I eat two meals per day impact of climate variability on eating habits among households in rufiji district, tanzania: A qualitative study. Agric. Food Secur. 5. https://doi.org/10.1186/s40066-016-0064-6

Schaafsma, M., Ferrini, S., Turner, R.K., 2019. Assessing smallholder preferences for incentivised climate-smart agriculture using a discrete choice experiment. Land use policy 88. https://doi.org/10.1016/j.landusepol.2019.104153

Schleussner, C.-F., Lissner, T.K., Fischer, E.M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., Schewe, J., Frieler, K., Mengel, M., Hare, W., Schaeffer, M., 2016. Differential climate impacts for policy-relevant limits to global warming: The case of 1.5 °c and 2 °c. Earth Syst. Dyn. 7, 327–351. https://doi.org/10.5194/esd-7-327-2016

Schwarz, M., Landmann, T., Cornish, N., Wetzel, K.-F., Siebert, S., Franke, J., 2020. A Spatially Transferable Drought Hazard and Drought Risk Modeling Approach Based on Remote Sensing Data. Remote Sens. 12. https://doi.org/10.3390/rs12020237

Senyolo, M.P., Long, T.B., Blok, V., Omta, O., 2018. How the characteristics of innovations impact their adoption: An exploration of climate-smart agricultural innovations in South Africa. J. Clean. Prod. 172, 3825–3840. https://doi.org/10.1016/j.jclepro.2017.06.019

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M., Reinhardt, J., 2017. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. Reg. Environ. Chang. 17, 1585–1600. https://doi.org/10.1007/s10113-015-0910-2

# APPENDIX A: LITERATURE FROM SYSTEMATIC REVIEW


Setimela, P., Gasura, E., Thierfelder, C., Zaman-Allah, M., Cairns, J.E., Boddupalli, P.M., 2018. When the going gets tough: Performance of stress tolerant maize during the 2015/16 (El Niño) and 2016/17 (La Niña) season in southern Africa. Agric. Ecosyst. Environ. 268, 79–89. https://doi.org/10.1016/j.agee.2018.09.006

Shava, E., Gunhidzirai, C., 2017. Fish farming as an innovative strategy for promoting food security in drought risk regions of Zimbabwe. Jamba J. Disaster Risk Stud. 9. https://doi.org/10.4102/jamba.v9i1.491

Shinn, J.E., 2018. Toward anticipatory adaptation: Transforming social-ecological vulnerabilities in the Okavango Delta, Botswana. Geogr. J. 184, 179–191. https://doi.org/10.1111/geoj.12244

Shinn, J.E., 2016. Adaptive environmental governance of changing social-ecological systems: Empirical insights from the Okavango Delta, Botswana. Glob. Environ. Chang. 40, 50–59. https://doi.org/10.1016/j.gloenvcha.2016.06.011

Shisanya, S., Mafongoya, P., 2016. Adaptation to climate change and the impacts on household food security among rural farmers in uMzinyathi District of Kwazulu-Natal, South Africa. Food Secur. 8, 597–608. https://doi.org/10.1007/s12571-016-0569-7

Sifundza, L.S., van der Zaag, P., Masih, I., 2019. Evaluation of the responses of institutions and actors to the 2015/2016 el niño drought in the komati catchment in Southern Africa: Lessons to support future drought management. Water SA 45, 547–559. https://doi.org/10.17159/wsa/2019.v45.i4.7535

Silungwe, F.R., Graef, F., Bellingrath-Kimura, S.D., Chilagane, E.A., Tumbo, S.D., Kahimba, F.C., Lana, M.A., 2019a. Modelling rainfed pearl millet yield sensitivity to abiotic stresses in semi-arid central Tanzania, Eastern Africa. Sustain. 11. https://doi.org/10.3390/su11164330

Silungwe, F.R., Graef, F., Bellingrath-Kimura, S.D., Tumbo, S.D., Kahimba, F.C., Lana, M.A., 2019b. Analysis of intra and interseasonal rainfall variability and its effects on pearl millet yield in a semiarid agroclimate: Significance of scattered fields and tied ridges. Water (Switzerland) 11. https://doi.org/10.3390/w11030578

Smith, A., Snapp, S., Dimes, J., Gwenambira, C., Chikowo, R., 2016. Doubled-up legume rotations improve soil fertility and maintain productivity under variable conditions in maize-based cropping systems in Malawi. Agric. Syst. 145, 139–149. https://doi.org/10.1016/j.agsy.2016.03.008

Sonkoué, D., Monkam, D., Fotso-Nguemo, T.C., Yepdo, Z.D., Vondou, D.A., 2019. Evaluation and projected changes in daily rainfall characteristics over Central Africa based on a multi-model ensemble mean of CMIP5 simulations. Theor. Appl. Climatol. 137, 2167–2186. https://doi.org/10.1007/s00704-018-2729-5

Sonwa, D.J., Dieye, A., El Mzouri, E.-H., Majule, A., Mugabe, F.T., Omolo, N., Wouapi, H., Obando, J., Brooks, N., 2017. Drivers of climate risk in African agriculture. Clim. Dev. 9, 383–398. https://doi.org/10.1080/17565529.2016.1167659

Spalding-Fecher, R., Chapman, A., Yamba, F., Walimwipi, H., Kling, H., Tembo, B., Nyambe, I., Cuamba, B., 2016. The vulnerability of hydropower production in the Zambezi River Basin to the impacts of climate change and irrigation development. Mitig. Adapt. Strateg. Glob. Chang. 21, 721–742. https://doi.org/10.1007/s11027-014-9619-7

Spear, D., Chappel, A., 2018. Livelihoods on the edge without a safety net: The case of smallholder crop farming in north-central Namibia. Land 7. https://doi.org/10.3390/land7030079

Stalenberg, E., Hutchinson, M.F., Foley, W.J., 2018. Using historical normals to improve modern monthly climate normal surfaces for Madagascar. Int. J. Climatol. 38, 5746–5765. https://doi.org/10.1002/joc.5776

Stevens, T., Madani, K., 2016. Future climate impacts on maize farming and food security in Malawi. Sci. Rep. 6. https://doi.org/10.1038/srep36241

Steward, P.R., Dougill, A.J., Thierfelder, C., Pittelkow, C.M., Stringer, L.C., Kudzala, M., Shackelford, G.E., 2018. The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: A meta-regression of yields. Agric. Ecosyst. Environ. 251, 194–202. https://doi.org/10.1016/j.agee.2017.09.019

Steward, P.R., Thierfelder, C., Dougill, A.J., Ligowe, I., 2019. Conservation agriculture enhances resistance of maize to climate stress in a Malawian medium-term trial. Agric. Ecosyst. Environ. 277, 95–104. https://doi.org/10.1016/j.agee.2018.07.009

Strydom, S., Savage, M.J., Clulow, A.D., 2019. Long-term trends and variability in the dryland microclimate of the Northern Cape Province, South Africa. Theor. Appl. Climatol. 137, 963–975. https://doi.org/10.1007/s00704-018-2642-y

Sutcliffe, C., Dougill, A.J., Quinn, C.H., 2016. Evidence and perceptions of rainfall change in Malawi: Do maize cultivar choices enhance climate change adaptation in sub-Saharan Africa? Reg. Environ. Chang. 16, 1215–1224. https://doi.org/10.1007/s10113-015-0842-x

Swanepoel, C.M., Rötter, R.P., van der Laan, M., Annandale, J.G., Beukes, D.J., du Preez, C.C., Swanepoel, L.H., van der Merwe, A., Hoffmann, M.P., 2018. The benefits of conservation agriculture on soil organic carbon and yield in southern Africa are site-specific. Soil Tillage Res. 183, 72–82. https://doi.org/10.1016/j.still.2018.05.016

Tamoffo, A.T., Moufouma-Okia, W., Dosio, A., James, R., Pokam, W.M., Vondou, D.A., Fotso-Nguemo, T.C., Guenang, G.M., Kamsu-Tamo, P.H., Nikulin, G., Longandjo, G.-N., Lennard, C.J., Bell, J.-P., Takong, R.R., Haensler, A., Tchotchou, L.A.D., Nouayou, R., 2019. Process-oriented assessment of RCA4 regional climate model projections over the Congo Basin under 1.5. C and 2. C global warming levels: influence of regional moisture fluxes. Clim. Dyn. 53, 1911–1935. https://doi.org/10.1007/s00382-019-04751-y

Terry, A.K., 2020. The impact of the 2015-16 El Nino drought on the irrigated home gardens of the Komati downstream development project, Swaziland. South African Geogr. J. 102, 41–58. https://doi.org/10.1080/03736245.2019.1614477

Tesfaye, K., Kruseman, G., Cairns, J.E., Zaman-Allah, M., Wegary, D., Zaidi, P.H., Boote, K.J., Rahut, D., Erenstein, O., 2018. Potential benefits of drought and heat tolerance for adapting maize to climate change in tropical environments. Clim. Risk Manag. 19, 106–119. https://doi.org/10.1016/j.crm.2017.10.001

Thierfelder, C., Matemba-Mutasa, R., Bunderson, W.T., Mutenje, M., Nyagumbo, I., Mupangwa, W., 2016a. Evaluating manual conservation agriculture systems in southern Africa. Agric. Ecosyst. Environ. 222, 112–124. https://doi.org/10.1016/j.agee.2016.02.009

Thierfelder, C., Rusinamhodzi, L., Setimela, P., Walker, F., Eash, N.S., 2016b. Conservation agriculture and drought-tolerant germplasm: Reaping the benefits of climate-smart agriculture technologies in central Mozambique. Renew. Agric. Food Syst. 31, 414–428. https://doi.org/10.1017/S1742170515000332

Tibesigwa, B., Visser, M., Turpie, J., 2017. Climate change and South Africa's commercial farms: an assessment of impacts on specialised horticulture, crop, livestock and mixed farming systems. Environ. Dev. Sustain. 19, 607–636. https://doi.org/10.1007/s10668-015-9755-6

Torresan, S., Critto, A., Rizzi, J., Zabeo, A., Furlan, E., Marcomini, A., 2016. DESYCO: A decision support system for the regional risk assessment of climate change impacts in coastal zones. Ocean Coast. Manag. 120, 49–63. https://doi.org/10.1016/j.ocecoaman.2015.11.003

# APPENDIX A: LITERATURE FROM SYSTEMATIC REVIEW


Trnka, M., Feng, S., Semenov, M.A., Olesen, J.E., Kersebaum, K.C., Rötter, R.P., Semerádová, D., Klem, K., Huang, W., Ruiz-Ramos, M., Hlavinka, P., Meitner, J., Balek, J., Havl\'\ik, P., Büntgen, U., 2019. Mitigation efforts will not fully alleviate the increase in water scarcity occurrence probability in wheat-producing areas. Sci. Adv. 5. https://doi.org/10.1126/sciadv.aau2406

Vahrmeijer, J.T., Annandale, J.G., Steyn, J.M., Bristow, K.L., 2018. Model parameters of four important vegetable crops for improved water use and yield estimation. Water SA 44, 528–538. https://doi.org/10.4314/wsa.v44i4.02

Van Aelst, K., Holvoet, N., 2018. Climate change adaptation in the Morogoro Region of Tanzania: women's decision-making participation in small-scale farm households. Clim. Dev. 10, 495–508. https://doi.org/10.1080/17565529.2017.1318745

Van Hoolst, R., Eerens, H., Haesen, D., Royer, A., Bydekerke, L., Rojas, O., Li, Y., Racionzer, P., 2016. FAO's AVHRR-based Agricultural Stress Index System (ASIS) for global drought monitoring. Int. J. Remote Sens. 37, 418–439. https://doi.org/10.1080/01431161.2015.1126378

van Oort, A.J., Saito, K., Dieng, I., Grassini, P., Cassman, K.G., van Ittersum, M.K., 2017. Can yield gap analysis be used to inform R & D prioritisation? Glob. Food Secuirty- Agric. Policy Econ. Environ. 12, 109–118. https://doi.org/10.1016/j.gfs.2016.09.005

van Oort, P.A.J., Zwart, S.J., 2018. Impacts of climate change on rice production in Africa and causes of simulated yield changes. Glob. Chang. Biol. 24, 1029–1045. https://doi.org/10.1111/gcb.13967

Von Uexkull, N., Croicu, M., Fjelde, H., Buhaug, H., 2016. Civil conflict sensitivity to growing-season drought. Proc. Natl. Acad. Sci. U. S. A. 113, 12391–12396. https://doi.org/10.1073/pnas.1607542113

Waha, K., van Wijk, M.T., Fritz, S., See, L., Thornton, P.K., Wichern, J., Herrero, M., 2018. Agricultural diversification as an important strategy for achieving food security in Africa. Glob. Chang. Biol. 24, 3390–3400. https://doi.org/10.1111/gcb.14158

Warnatzsch, E.A., Reay, D.S., 2020. Assessing climate change projections and impacts on Central Malawi's maize yield: The risk of maladaptation. Sci. Total Environ. 711. https://doi.org/10.1016/j.scitotenv.2019.134845

Warnatzsch, E.A., Reay, D.S., 2019. Temperature and precipitation change in Malawi: Evaluation of CORDEX-Africa climate simulations for climate change impact assessments and adaptation planning. Sci. Total Environ. 654, 378–392. https://doi.org/10.1016/j.scitotenv.2018.11.098

Weinzierl, T., Wehberg, J., Böhner, J., Conrad, O., 2016. Spatial Assessment of Land Degradation Risk for the Okavango River Catchment, Southern Africa. L. Degrad. Dev. 27, 281–294. https://doi.org/10.1002/ldr.2426

Weldon, C.W., Nyamukondiwa, C., Karsten, M., Chown, S.L., Terblanche, J.S., 2018. Geographic variation and plasticity in climate stress resistance among southern African populations of Ceratitis capitata (Wiedemann) (Diptera: Tephritidae). Sci. Rep. 8. https://doi.org/10.1038/s41598-018-28259-3

Wineman, A., Crawford, E.W., 2017. Climate change and crop choice in Zambia: A mathematical programming approach. NJAS - Wageningen J. Life Sci. 81, 19–31. https://doi.org/10.1016/j.njas.2017.02.002

Xulu, S., Peerbhay, K., Gebreslasie, M., Ismail, R., 2018. Drought influence on forest plantations in Zululand, South Africa, using MODIS time series and climate data. Forests 9. https://doi.org/10.3390/f9090528

Yanda, P.Z., Mabhuye, E., Johnson, N., Mwajombe, A., 2019. Nexus between coastal resources and community livelihoods in a changing climate. J. Coast. Conserv. 23, 173–183. https://doi.org/10.1007/s11852-018-0650-9

Yue, Y., Zhang, P., Shang, Y., 2019. The potential global distribution and dynamics of wheat under multiple climate change scenarios. Sci. Total Environ. 688, 1308–1318. https://doi.org/10.1016/j.scitotenv.2019.06.153

Zamasiya, B., Nyikahadzoi, K., Mukamuri, B.B., 2017. Factors influencing smallholder farmers' behavioural intention towards adaptation to climate change in transitional climatic zones: A case study of Hwedza District in Zimbabwe. J. Environ. Manage. 198, 233–239. https://doi.org/10.1016/j.jenvman.2017.04.073

Zeng, B., Zhu, W., Fu, Y., Zhou, S., 2019. Response Mechanism of Oviposition and Relevant Protein Expression of Bactrocera cucurbitae (Coquillet) to Short-Term High-Temperature Conditions. Neotrop. Entomol. 48, 197–206. https://doi.org/10.1007/s13744-018-0638-z

Zeng, H., Wu, B., Zhang, N., Tian, F., Phiri, E., Musakwa, W., Zhang, M., Zhu, L., Mashonjowa, E., 2019. Spatiotemporal analysis of precipitation in the sparsely gauged Zambezi River Basin using remote sensing and google Earth engine. Remote Sens. 11. https://doi.org/10.3390/rs11242977

Zhang, W., Zhou, T., Zhang, L., Zou, L., 2019. Future intensification of the water cycle with an enhanced annual cycle over global land monsoon regions. J. Clim. 32, 5437–5452. https://doi.org/10.1175/JCLI-D-18-0628.1

Zhao, Y., Vergopolan, N., Baylis, K., Blekking, J., Caylor, K., Evans, T., Giroux, S., Sheffield, J., Estes, L., 2018. Comparing empirical and survey-based yield forecasts in a dryland agro-ecosystem. Agric. For. Meteorol. 262, 147–156. https://doi.org/10.1016/j.agrformet.2018.06.024

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