The role of indigenous and local knowledge on climate adaptation for smallholder farmers in Chiredzi, Zimbabwe.

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Abstract

Increasing smallholder farmers' resilience to the impacts of climate change requires informed decision-making that utilises locally validated information sources, including Indigenous knowledge (IK) and local knowledge (LK). Smallholder farmers across multiple regions of the world rely on IK and LK forecasts for climate decision making. This knowledge provides a rich foundation for locally led adaptation by smallholder farmers because of its contextual embeddedness within microclimatic conditions. Recent peer-reviewed literature on IK and LK in Africa was analysed to assess the role of IK and LK in adaptation in the water sector, showing that adaptation responses with IK and LK had higher evidence of risk reduction, but only 10% of African governments included IK and LK in adaptation planning in their intended Nationally Determined Contributions. A cross-sectional survey was used to establish the role of IK and LK in adaptation for smallholder farmers in the Chiredzi District, Zimbabwe. Data were collected from 210 smallholder farmers between 2021–2022, through face-to-face interviews. The analysis of observed climate data for Chiredzi between 1972–2022 corroborated the survey data.

A framework was developed and applied to assess smallholder farmers' vulnerability in relation to their use of IK and LK. The results demonstrate that IK and LK are important in reducing the vulnerability of smallholder farmers by increasing the implementation of crop adaptation responses. These include the use of indigenous, drought-resistant seed crop varieties and using IK and LK weather and seasonal climate forecasts for informed decision making on appropriate crop varieties and timing of planting to reduce crop exposure to climate risk. Farmers using IK and LK forecasts implemented adaptation responses three times more than those relying on other sources of climate forecasts. Twenty-three decision types from the IK and LK forecasts that contributed to on-farm adaptation responses were identified, including crop variety selection (e.g., drought-resistant crops), cropping area management (e.g., water conservation measures), and agricultural calendar planning and management (e.g., zero tillage, dry planting, or irrigation).

A further framework was developed and applied to assess the effectiveness of IK- and LK-informed adaptation responses. IK and LK adaptation responses showed limited, positive, and promising signs of effectiveness. Eight (44%) of the 18 responses showed high and medium evidence of effectiveness in reducing climate risk by reducing exposure and vulnerability components of climate risk. The IK and LK seasonal forecasts were most reliable for near-

term forecasts. These findings led to the development of a conceptual framework that facilitates the inclusion of IK and LK in planned adaptation.

This study broadens the understanding of how IK and LK contribute to the adaptation cycle of the global goal on adaptation of the 2015 Paris Agreement, demonstrating the value of IK and LK to the global climate agenda. The findings of this study are important for interventions that target increasing effectiveness of adaptation responses, thereby reducing smallholder farmers' vulnerability and exposure to climate change. Greater recognition of and attention to IK and LK is needed across national climate adaptation planning in Nationally Determined Contributions and National Adaptation Plans for its potential to be realised.

Declaration for inclusion of Publications

I confirm that I have been granted permission by the University of Cape Town's Doctoral Degrees Board to include the following publication(s) in my PhD thesis, and where co-authorships are involved, my co-authors have agreed that I may include the publication(s):

1. **Zvobgo L**, Johnston P, Williams A. P, Trisos C. H and Simpson N. P, "The role of indigenous knowledge and local knowledge in water sector adaptation to climate change in Africa: a structured assessment", *Sustainability Science*. 2022. **17**(5), 2077–2092. doi: https://doi.org/10.1007/s11625-022-01118-x

2. **Zvobgo L**, Johnston P, Olagbeg O, Simpson N. P and Trisos C. H, "Role of Indigenous and local knowledge in seasonal forecasts and climate adaptation: A case study of smallholder farmers in Chiredzi, Zimbabwe", *Environmental Science & Policy*. 2023. **145**, 13–28. doi: https://doi.org/10.1016/j.envsci.2023.03.017

3. **Zvobgo L**, Johnston P, Simpson N. P and Trisos C. H, "Indigenous and local knowledge in the vulnerability of smallholder farmers to climate variability and change in Chiredzi, Zimbabwe. *Environmental Development* (in review).

4. **Zvobgo L**, Johnston P, Meyer Schwarz A, Trisos C. H and Simpson N. P, "Reliability and effectiveness of Indigenous and local knowledge in reducing climate risk: a case of smallholder farmers in Chiredzi, Zimbabwe", (to be submitted).

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Supervision, Funding and Declaration

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Declaration

I, **Luckson Zvobgo**, declare that this thesis is my own work and that all contributions from other people's work are properly referenced, cited, and acknowledged. I declare that neither the substance nor any part of the above thesis has been submitted in the past, or is being, or is to be submitted for a degree at this University or at any other university.

Chapter 2 of this thesis was published in Sustainability Science Volume 17. Chapter 3 is in review with the Journal of Environmental Management. Chapter 4 was published in Environmental Science and Policy Volume 145. Chapter 5 will be considered for submission to the journal (provisionally the climate Risk Management). I confirm that this declaration holds true for all the publications.

Signed by candidate

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Dedication

This thesis is dedicated to the memory of Cuthbert (the youngest brother in our family) and Dad, who passed on during my Ph.D. journey.

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To God, I give all the glory and praise. NDATENDA.

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"There are no completely safe places. There are only places of varying risks and vulnerabilities, and the people's capacity to prepare and adapt" ~ Jose Bernardo Gochoco, ICLEI, 2019

1 General Introduction

1.1. Smallholder farming, food security, and climate risk in sub-Saharan Africa

Economies in many developing countries depend on agriculture for their livelihood and economic growth. In the sub-Saharan Africa (SSA) region, most of the agricultural output is derived from smallholder farmers who practise rainfed agriculture (FAO, 2018; Giller et al., 2021; OECD/FAO, 2016; Ricciardi et al., 2018), estimated to be 90–95% of the total production in Africa (Adams, 2018). Smallholder farmers provide an estimated 80% of the food produced in SSA and Asia (Lowder, Skoet & Singh, 2014).

In SSA, approximately 123 million people are estimated to be acutely food insecure in 2022, have high malnutrition, and are unable to meet minimum food consumption needs (Baptista et al., 2022). Climate change is expected to further increase this number in the future (Baptista et al., 2022; Dickerson, Cannon & O'Neill, 2021; Trisos et al., 2022). This is despite the African region being among the lowest contributors to global greenhouse gas emissions causing climate change (Trisos et al., 2022). Evidence has already shown that growth in agricultural productivity has been slowed by anthropogenic climate change, with warmer regions, such as Africa experiencing greater reductions in productivity growth (Ortiz-Bobea et al., 2021; Ray et al., 2019; Sultan, Defrance & Iizumi, 2019; Trisos et al., 2022). Due to climate change, Africa has experienced a 34% reduction in agricultural productivity growth since 1961; more than in any other region (Ortiz-Bobea et al., 2021). Important food and cash crops in SSA are already being negatively affected by climate change. An estimated average yield reductions ranging from – 0.6 % to – 5.8 % for maize, rice, wheat, soybean, and sugarcane between 1974–2008 was observed (Ray et al., 2019). Climate change has also decreased consumable food calories from key crops by 1.4% on average per year from 1972–2008, with country-level variation approaching 10% reduction in Ghana, Zimbabwe, and South Africa (Ray et al., 2019).

In Africa and SSA, smallholder farmers are disproportionately affected by climate variability and change (IPCC, 2022c; Trisos et al., 2022), because of their high reliance on natural resources and subsistence farming for food security (Baptista et al., 2022; FAO, 2018; IPCC, 2023b). This is compounded by limited access to key resources and poor access to markets (Bekuma, Mamo & Regassa, 2023; Cohn et al., 2017; Meybeck et al., 2018; Odame Appiah et al., 2018). Additionally, smallholder farmers in these vulnerable regions often occupy land in areas highly exposed to climate hazards, which are projected to become drier with more intense and frequent occurrences of extreme weather events and increased rainfall variability due to anthropogenic climate change (Bryan et al., 2009; Dixon, Stringer & Challinor, 2014; Trisos et al., 2022).

If future global warming rises to more than 2 °C above pre-industrial levels, as current mitigation policies suggest, disruption to current food systems will be profound and catastrophic for millions of people in SSA (Bezner Kerr, R. et al., 2022; Pörtner et al., 2022; Trisos et al., 2022). Reduced food production from crops is identified as a key risk for Africa and is projected to increase to high risk by 2 °C global warming and transition to very high risk above 2 °C global warming levels, with overall yield reductions in staple crops compared to 2005 levels, even when accounting for adaptation actions (Pörtner et al., 2022; Trisos et al., 2022). Multiple Africa countries are projected to be at risk of simultaneous negative impacts on crops, fisheries and livestock systems (O'Neill et al., 2022; Trisos et al., 2022). Evidence from the latest generation of crop models suggests that the negative impacts of climate change on maize, soybean, and rice will occur earlier than previously estimated and will be especially negative in tropical regions (Jägermeyr et al., 2021). This is despite tropical regions being home to the majority of African smallholder farmers.

Increasing climate impacts and extreme events have exposed millions of smallholder farmers to flood and drought-related acute food insecurity and malnutrition in Africa (FAO & ECA, 2018; IPCC, 2022c; Trisos et al., 2022). For example, droughts induced by the 2015–2016 El Niño event attributed to anthropogenic climate change affected eastern and southern Africa (Bezner Kerr, R. et al., 2022). Yet the impacts of acute food insecurity on smallholder farming have far-reaching effects in SSA on key sectors, such as the economy, health, and livelihood. For example, the cascading impacts of extreme heat on worker productivity negatively affect the economic productivity. The heat impacts reduce economic output and productivity because people cannot work in industries and key economic sectors, such as agriculture, for smallholder farmers due to hunger and limited supply of food (Trisos et al., 2022). Food insecurity and nutritional deficiencies are projected to increase with increasing climate variability (Trisos et al., 2022). These have been shown to increase sexual risk-taking and migration, as well as increase susceptibility to other infections for smallholder farmers (Lieber et al., 2021).

Smallholder farmers in SSA are not only important for the region’s food security, but also fundamentally important for employment and economic development (African Development Bank, 2022; FAO, 2018; Nyambo et al., 2022). Approximately 55–62% of the SSA workforce is employed in agriculture (FAO, 2018; International Labour Office, 2018; World Bank, 2020). A reduction in future agricultural productivity due to projected climate impacts will negatively impact Africa's GDP (Baarsch et al., 2019). The decline in the productivity of food crops, commodity crops, and overall land productivity has contributed to lower macroeconomic performance, affecting Africa's GDP under rising temperatures (Adhikari, Nejadhashemi & Woznicki, 2015; Schlenker & Lobell, 2010). A meta-analysis of 56 studies indicated that, compared to 1995–2005, economic welfare in the agriculture sector in SSA is projected to decline by 5% for 2°C global warming and 10% for 3°C global warming (Moore et al., 2017).

As increased climate variability and change bring new uncertainties, add new risks, and change existing risks to smallholder farmers under rainfed conditions (Gitz & Meybeck, 2012), it is critical for smallholder farmers to adapt to increase their resilience to climate risks. Evidence shows that apart from changes in total or mean summer rainfall in southern Africa, the intra-seasonal characteristics of seasonal rainfall, including onset, duration, dry spell, and rainfall intensity, are highly variable (Tadross, M. et al., 2009; Thomas, David SG et al., 2007). The frequency of dry spells in southern Africa increased between 1961–2016 (Seneviratne et al., 2021; Yuan, Wang & Wood, 2018), affecting the quality of the rainy season. This affects planting dates of staple crops thus reducing yields of rainfed smallholder farmers. With a projected decrease by 10–20% of the mean annual summer rainfall under the highest baseline emissions scenario (RCP 8.5) in southern Africa, accompanied by a further increase in the number of consecutive dry days during the rainy season (Lazenby et al., 2018; Maúre et al., 2018; Spinoni et al., 2019), the climate risk to food production is projected to be very high especially for rainfed smallholder farmers (Trisos et al., 2022). In Zimbabwe, where the majority of the population relies on rainfed smallholder farming, climate variability affects the optimum conditions for key food crops (Mugiyo et al., 2021).

Taken together, the evidence demonstrates that climate impacts poses severe risks to food production and food security in Africa and why adaptation to climate variability and change is important in SSA, particularly for smallholder farmers (Bradshaw, Dolan & Smit, 2004; Davies et al., 2009). Given it is more likely than not global warming will reach 1.5°C during the 2030s and the often long times required for adaptation projects, the accelerated implementation of adaptation in this decade should be a key priority to ensure the food security and livelihoods of millions of Africans (IPCC, 2023b; Trisos et al., 2022). Thus, climate adaptation is important for rainfed smallholder farmers in SSA to reduce their vulnerability to climate change and improve their food security (Ajani, Mgbenka & Okeke, 2013; Ogundeji, 2022; Rahut, Aryal & Marenya, 2021).

1.2. Climate Adaptation and Vulnerability

The concepts of climate adaptation and vulnerability have been explored by many scholars from as far back as the early 1990s. With increased slow-onset and fast-onset climate impacts and events, climate adaptation has become critical, and many attempts have been made by scholars to define climate adaptation (Ng'ang'a et al., 2016; Vincent et al., 2013). In an attempt to differentiate adaptation from short-term coping mechanisms, Vincent et al. (2013) defined climate adaptation in simpler terms as longer-term shifts in behaviour and practices that will reduce underlying vulnerability and coping mechanisms as short-term mechanisms to ensure survival, which does not affect underlying vulnerability. In practice, these two concepts are difficult to distinguish and depend on the context in which they are observed (Vincent et al., 2013). Further work to define and understand adaptation has grown, and other nuanced definitions of adaptation have been developed. The UNFCCC developed a broader definition of climate adaptation that address the key themes of adaptation including the ecosystem and human (social and economic) elements that address both current and future climate impacts thus reduce vulnerability and climate risk. UNFCCC defines adaptation as adjustments in ecological, social or economic systems in response to actual or expected climatic stimuli and their effects[1]. With a greater understanding of climate adaptation, other concepts such as the effectiveness of adaptation (Ara Begum et al., 2022) and maladaptation (Schipper, E. Lisa F., 2020) have emerged. In this study, adaptation is understood and explored in the context of responses implemented by smallholder farmers to address both short-term climate variability and long-term climate change impacts informed by farmers' IK and LK. This consists of IK and LK adaptation responses that reduce the vulnerability of smallholder farmers to climate impacts. These responses were further explored to assess their contribution to effective adaptation, that is, their ability to reduce climate risk (Ara Begum et al., 2022).

Owing to an increased understanding of the concept, several forms of climate adaptation framing have been observed over the years. These include autonomous, reactive, community-based, local and community-driven, ecosystem-based (EBA), incremental and transformational adaptations (Donatti et al., 2020; Fankhauser, Smith & Tol, 1999; Forsyth & Evans, 2013; IPCC, 2022a; Reid & Huq, 2014; Vincent et al., 2013; Wilson et al., 2020). Most indigenous and local knowledge-related climate adaptation responses are autonomous (Berrang-Ford et al., 2021b; Malik, Qin & Smith, 2010; MoSTE, 2015; Naess, 2013), community-based, local, community-driven (McNamara & Buggy, 2017; Vincent, 2023), and

[1] https://unfccc.int/topics/adaptation-and-resilience/the-big-picture/introduction

are incremental in the context of these responses being able to maintain the essence and integrity of a system or process at a given scale (Vogt et al., 2016). Some scholars argue that these responses are not transformational adaptations because of their limited capacity to address all socio-ecological systems (Berrang-Ford et al., 2021b).

In the early 1990s, climate vulnerability emerged as a new concept (Bohle, Downing & Watts, 1994; Burton, 1997; Füssel & Klein, 2006; Kelly & Adger, 2000). Vulnerability and its causes play essential roles in determining impacts, and understanding the dynamics of vulnerability is as important as understanding the climate (Alvar-Beltrán et al., 2020). This concept has evolved over the past three decades, with many definitions and frameworks being developed to improve our scholarly understanding of climate vulnerability (Füssel & Klein, 2006; Kelly & Adger, 2000; Thornton et al., 2014). These definitions vary widely among the researchers. Kelly and Adger (2000) defines vulnerability in terms of the capacity of individuals and social groups to respond to, that is, to cope with, recover from or adapt to, any external stress placed on their livelihoods and well-being. Researchers in social geography and political ecology regard vulnerability as an a priori condition of a household or community that is determined by socio-economic and political factors (Blaikie et al., 2004; Bohle, Downing & Watts, 1994).

Scholars have conceptualised vulnerability as the dose-response relationship between an exogenous hazard to a system and its effects. From a natural hazard perspective, vulnerability can be defined as the characteristics of a person or group in terms of its capacity to anticipate, cope with, resist and recover from the impact of a natural hazard (Blaikie et al., 2004). In climate change scholarship, vulnerability is used as an integrative measure of threats to a system (IPCC, 2001; Kelly & Adger, 2000). Kelly and Adger (2000) defined vulnerability as the ability or inability of individuals or social groupings to respond to, in the sense of cope with, recover from, or adapt to, any external stress placed on their livelihoods and well-being. The most important element of reducing vulnerability is to enhance the adaptive capacity of people at various levels of decision-making, from the individual to national and regional levels (Thornton et al., 2014). Thus, the indigenous and local knowledge systems informed adaptation responses in this study were framed to understand how they contributed to reducing climate vulnerability.

1.3. History of Indigenous Knowledge and Local Knowledge.

The concepts of indigenous and local knowledge referred to in this study as Indigenous Knowledge and Local Knowledge (IK and LK, respectively) have been developed in the literature for decades. The use of IK and LK by communities to respond to societal challenges has a long history (Langill & Landon, 1998; Mafongoya, P. L. & Jiri, 2017; Mistry, 2009) and how communities have tap into IK and LK resources to respond to natural hazards (Dhungana et al., 2023). Thus, these concepts have been well understood; however, there is no agreed definition of these concepts in the literature (Yacoub, 1998). In most academic literature, the definitions and use of indigenous and local knowledge are not commonly referred to as IK and LK but are expressed in several terms and different forms. These terms commonly collapse into terms such as traditional knowledge, cultural knowledge, traditional ecological knowledge, native knowledge, and customary knowledge (Mafongoya, P. L. & Jiri, 2017; Yacoub, 1998). Most definitions attempt to include these specific terms in the definition of the concepts. IK and LK practices are rooted in cultural experiences (Bruchac, 2014; Yacoub, 1998). Berkes (2012) defines such traditional, ecological knowledge as “a cumulative body of knowledge, practice and belief, evolving by adaptation processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with their environment.” These knowledge systems are transmitted and renewed between generations through folk sharing and oral education to ensure the wellbeing of communities by providing food security, environmental conservation, and early warning systems for disaster risk management (Mafongoya, P. L. & Jiri, 2017; UNESCO, 2017; Yacoub, 1998). The working definitions of IK and LK adopted in this study are listed in Table 1-1. There is ample literature on IK and LK climate adaptation, including how their definitions have evolved in climate adaptation over time (Langill & Landon, 1998; Mafongoya, P. L. & Jiri, 2017).

Beyond climate adaptation, the long history of the use of IK and LK in the Global South to increase livelihood resilience to the various challenges they face includes the application of IK and LK in managing environmental challenges (Horsthemke, 2008; Mafongoya, P. L. & Jiri, 2017), local community-based natural resource management and the mobilisation of resources to support livelihoods (DeWalt, 1994; Diawuo & Issifu, 2015; Langill & Landon, 1998; UNESCO, 2017). This also includes the use of IK and LK in biodiversity conservation (Gadgil, Berkes & Folke, 1993). There is also a long history of communities applying IK and LK for health solutions, including managing disease outbreaks (Saha et al., 2014; Smylie, Kaplan-Myrth & McShane, 2008; Tugume et al., 2016). This localised approach has also been utilised by smallholder farmers to implement locally led climate adaptation responses. Global South communities have a long history of relying on indigenous food to improve food security through the gathering of traditional foods to increase resilience to droughts and related natural hazards (Codjoe, Owusu & Burkett, 2014; Egeru, 2012; Ghosh-Jerath et al., 2015; Kamwendo & Kamwendo, 2014; Okoye & Oni, 2017). This history is well documented in unconventional sources among unofficial plays, dramas, and, more formally, in grey literature, such as reports (IPBES, 2016; UNESCO, 2017).

Despite the long history and background of how communities have used IK and LK to adapt to climate impacts (discussed in Section 1.4), few studies have investigated the concepts in a holistic approach from how IK and LK are used in weather and climate forecasting and the influence of these forecasts in decision making for climate adaptation to the role of these responses in reducing community vulnerability to climate impacts. Thus, in this study, the role of IK and LK in climate adaptation for smallholder farmers is examined by applying a holistic approach. This is important for understanding the contributions of IK and LK to climate adaptation beyond the study area, through the development of frameworks that support the integration of such knowledge and practices into more structured and policy-planned adaptation responses.

1.4. Smallholder farmers’ climate adaptation in Africa: Locating IK and LK

Despite the high levels of exposure and vulnerability in Africa, particularly among smallholder farmers (IPCC, 2022c; IPCC, 2023b; Trisos et al., 2022), evidence of climate adaptation has been widely observed with smallholder farmers as key stakeholders in the implementation of the adaptation responses (Berrang-Ford et al., 2021b; Magesa et al., 2023; Mukherji & Kumar, 2021; Trisos et al., 2022). Some of the adaptation options implemented by smallholder farmers show evidence of moderate feasibility and early signs of effectiveness under current conditions in addressing climate risk. These includes crop management responses, and sustainable agricultural practices (IPCC, 2022c; Mukherji & Kumar, 2021; Owen, 2020; Pörtner et al., 2022; Trisos et al., 2022; Williams et al., 2021). These responses farmers are significantly informed by IK and LK possessed by smallholder farmers (Leal Filho et al., 2022b; Nyadzi, Emmanuel , Ajayi & Ludwig, 2021; Trisos et al., 2022). Most of these adaptation responses are autonomous, incremental behavioural responses with less evidence for institutional and long-term planned adaptation (Berrang-Ford et al., 2021b; Schlingmann et al., 2021). This lack of transformative adaptation is not unique to Africa and is common across regions globally. Thus, it is imperative to establish how IK and LK climate adaptation can contribute to effective adaptation.

Climate adaptation in smallholder farming in Africa is mainly through crop management by adjusting crop choices, planting times, or the size, type, and location of planting areas and the use of drought-resistant crop varieties (Altieri et al., 2015; Berrang-Ford et al., 2021b; Magesa et al., 2023; Nyagumbo et al., 2017; Trisos et al., 2022). Central to the implementation of these measures is the important role of smallholder farmers' IK and LK. At the global level, IK and LK have been established to play a key role in climate adaptation (IPCC, 2014b; IPCC, 2019a; IPCC, 2019b; IPCC, 2022b; IPCC, 2023b; Schlingmann et al., 2021). IK and LK play an instrumental role in providing context-specific and socio-culturally relevant understanding for effective climate adaptation responses and policies (IPCC, 2019c; IPCC, 2022c). In Africa, the diversity of IK and LK provides a rich foundation for adaptation actions at the local scale (Leal Filho et al., 2022b; Leal Filho et al., 2023; Nyadzi, Emmanuel , Ajayi & Ludwig, 2021; Trisos et al., 2022). Also, IK and LK provide important understanding for acting effectively on climate risk and can help diversify knowledge that may enrich adaptation policies and practices (Ara Begum et al., 2022).

Despite Africa having rapid growth of evidence on IK and LK role in climate adaptation (Petzold et al., 2020; Schlingmann et al., 2021), a holistic understanding of this evidence through sectoral-based lenses sectors that are key for livelihoods of smallholder farmers – agriculture and water – is still lacking yet such an understanding is required to assess gaps in the current literature and to map the way forward for future research. Furthermore, the few existing regional IK and LK climate adaptation reviews (Leal Filho et al., 2022b; Leal Filho et al., 2023; Nyadzi, Emmanuel , Ajayi & Ludwig, 2021) have not comprehensively paid attention to the potential of IK and LK in reducing climate risk. To fully explore the gap in the current literature, a structured assessment of the IK and LK for climate adaptation literature was conducted as part of this thesis to better understand how adaptation responses informed by IK and LK are reducing climate risk.

Significant literature has emphasised how smallholder farmers use IK and LK for weather and seasonal climate forecasts as a climate adaptation strategy (Adanu, Abole & Gbedemah, 2022; Ankrah, Kwapong & Boateng, 2022; Ebhuoma, 2020; Jiri, O, Mafongoya & Chivenge, 2015; Jiri, Obert et al., 2016; Kagunyu, Wandibba & Wanjohi, 2016; Kijazi et al., 2013; Kolawole et al., 2016; Kom et al., 2022; Kyazze et al., 2019; Mafongoya, P. L. et al., 2017; Makwara, 2013; Mutula, Stilwell & Elia, 2014; Mwaniki & Stevenson, 2017; Nkomwa et al., 2014; Nkuba, M. R. et al., 2020; Nyadzi, Emmanuel et al., 2022; Okonya, Ajayi & Mafongoya, 2017; Tume, S. J. P. & Kimengsi, 2021; Zuma-Netshiukhwi, Stigter & Walker, 2013). However, little is known about how IK and LK seasonal weather and climate forecasts translate into the decisions taken and actions implemented by smallholder farmers to reduce climate risk and whether the actions are effective in addressing the current risk. A clear understanding of the reliability of these forecasts remains largely unknown, with very few studies attempting to establish their reliability in Africa (Chisadza, Bright et al., 2014; Chisadza, Bright et al., 2015; Guye, Legesse & Mohammed, 2022). This also applies to the effectiveness of IK- and LK-informed climate adaptation responses in reducing climate risk for smallholder farmers (Owen, 2020; Zvobgo et al., 2022).

Despite growing evidence on the wide use of IK and LK in climate adaptation in Africa, the inclusion of this knowledge in planned adaptation, mainly in key government adaptation planning and policy documents and commitments to the United Nations Framework Convention on Climate Change (UNFCCC) through Nationally Determined Contributions (NDCs), has not been assessed. A holistic understanding of how IK and LK are conceptualised and their influence on national adaptation and policy is key for its adoption in institutional and planned adaptation across the African and global south countries. With most of the IK and LK adaptation being characterised as incremental, it might not be enough for smallholder farmers to reduce future climate risks if IK and LK continue to be used in isolation and not integrated in planned and institutional adaptation. One way to achieve this is by conducting research that explicitly links IK and LK with decision-making, demonstrating how the actions contribute to overall adaptation and resilience, and establishing its effectiveness in reducing climate risk. Given this background, more research on IK and LK needs to explore ways to integrate IK and LK into institutional and planned adaptation. Assessing the role and extent to which IK and LK contribute to climate adaptation is essential for designing long-term transformative adaptation for smallholder farmers to the increasing climate risks. This also allows for the development of a policy framework that integrates planned adaptation strategies with autonomous IK and LK measures to increase smallholder farmers' resilience to climate risk.

1.5. Climate variability and change in Zimbabwe: Evidence, Gaps, & Opportunities

Similar to global, regional, and sub-regional trends, there is agreement in the literature on increased temperatures across Zimbabwe (Gwimbi, 2009; Jiri, Obert, Mafongoya & Chivenge, 2017; Manatsa et al., 2020; Mwadzingeni, Mugandani & Mafongoya, 2021; Rurinda et al., 2014a; World Bank Group, 2021a; World Bank Group, 2021b). The mean annual temperatures over Zimbabwe have increased by 1.6°C–1.8°C between 1961–2010 (Engelbrecht et al., 2015). The average increase per year in annual mean temperature was estimated as 0.03°C between 1970–2016 (World Bank Group, 2021b). Annual and seasonal precipitation changes have been recorded in Zimbabwe, with most evidence showing a reduction in the total precipitation in many parts of the country between 1950–2016 (Mamombe, Kim & Choi, 2017; Mazvimavi, 2010; Muchuru et al., 2016; Sibanda, Grab & Ahmed, 2020). The delayed rainy season onset, early cessation, reduced rainy season length, increased dry spells, and reduced rainy days are other critical rainfall indices observed during the same period in Zimbabwe (Brown et al., 2012; Muchuru et al., 2016; Mupangwa, Walker & Twomlow, 2011; Sibanda, Grab & Ahmed, 2020; Tadross, M. et al., 2009). These are manifests of increased rainfall variability and long term changes that increased climate risk. The risk is mostly from shifts to late rainy season onset, reduced rainy season length, increased frequency and intensity of heavy rainfall events, floods, increases in the proportion of low rainfall years, successive years of droughts, shortened rainy seasons, and increases in the frequency and intensity of mid-season dry spells (Brown et al., 2012; Government of Zimbabwe, 2016a; Mamombe, Kim & Choi, 2017; Manatsa et al., 2020; Mugiyo et al., 2021; Tadross, M. et al., 2009; Unganai, Leonard S. et al., 2013; World Bank Group, 2021b). Droughts have become more frequent in Zimbabwe, affecting the majority of the population (Belle, Sithabile & Ogundeji, 2017; Ndhlovu, M. P. & Mpofu, 2016; Nyakudya & Stroosnijder, 2011; UNDP, 2012; Unganai, Leonard S & Murwira, 2010; Unganai, Leonard S. et al., 2013; World Bank Group, 2021b; Zamasiya, Nyikahadzoi & Mukamuri, 2017).

Progress in assessing how climate variability and change affect the yields of staple crop production (primarily maize) in Zimbabwe has shown negative impacts, mostly overall yield reduction, as well as how increased climate variability and change affect the optimum growing conditions and planting dates that increase risk (Mamombe, Kim & Choi, 2017; Mugiyo et al., 2021; Nyakudya & Stroosnijder, 2011; Tadross, M. A., Hewitson & Usman, 2005). The increased climate risk due to increased rainfall variability in Zimbabwe results in several impacts such as crop failure, yield reduction, low fodder yields for livestock impacts, and the death of livestock (Gukurume, 2013; Unganai, Leonard S. et al., 2013; World Bank Group, 2021b). However, given the highly contextual and localised nature of precipitation in the country, temporal and spatial variability (Manatsa et al., 2020; Mugandani, R et al., 2012), knowledge gaps still exist across Zimbabwe, and the local level understanding of key relevant rainfall indices for rainfed farming, such as total seasonal rainfall patterns, rainy season onset, cessation, and length, and consecutive dry days are still a challenge in many local contexts, including the study area for this research – the Chiredzi Rural District. These rainfall characteristics are vital for decision-making by rainfed smallholder farmers (Tadross, M. et al., 2009; Tadross, M. A., Hewitson & Usman, 2005); thus, local-level vulnerability and exposure of smallholder farmers to climate variability and change are not fully understood, and further assessment is important to inform how smallholder farmers can locally respond to climate risks. With the increased understanding of the key climate risk in Zimbabwe above, it is important to distil the local-level livelihood impacts of climate change to smallholder farmers assessing how they are exposed while understanding the role of their IK and LK on adaptation, which improves farmers' resilience through informed and appropriate responses.

Responding to climate risk in Zimbabwe has been made more difficult by weak climate services and non-functional weather stations (Chisadza, B. et al., 2013; Grey, 2019; Gwenzi, Mashonjowa & Mafongoya, 2020; Jiri, O, Mafongoya & Chivenge, 2015; Mudombi & Nhamo, 2014; Trisos et al., 2022), with forecasts that are often not understood by smallholder farmers (Gwenzi et al., 2016; Unganai, Leonard S. et al., 2013). The lack of actionable climate services that smallholder farmers and communities can interpret and use to make informed decisions on key climate indices and conditions, such as the rainy season onset, cessation, and occurrence of dry spells, has left smallholder farmers to rely more on IK and LK-based weather and seasonal climate forecasting (Chisadza, B. et al., 2013; Grey, Masunungure & Manyani, 2020; Gwenzi et al., 2016; Jiri, O, Mafongoya & Chivenge, 2015; Mapfumo, P., Mtambanengwe & Chikowo, 2016; Soropa et al., 2015). However, the role of these forecasts in climate decision-making has not been fully explored and is often not clearly understood. It is essential to study the forecasts based on IK and LK in detail to learn their role in climate decision making and their contribution to the overall climate adaptation of smallholder farmers. This is important for the integration of IK and LK forecasts into national early warning systems and adaptation planning, and implementation agendas for Zimbabwe. IK and LK climate forecasts provide an enormous opportunity for smallholder farmers in Zimbabwe to understand seasons and respond to growing climate risk. Understanding the role of IK and LK climate forecasts is not only critical for their adoption in early warning systems, but knowing their reliability is key to offsetting the possibilities of maladaptation from the implementation of adaptation responses based on potentially inaccurate information.

1.5.1. IK and LK in Zimbabwe and Chiredzi: Policies, The Gaps, and Future

There have been efforts by the Government of Zimbabwe to include IK and LK in policy. This is evidenced by the inclusion of IK and LK in Zimbabwe's Intended Nationally Determined Contribution, National Adaptation Plan (NAP), and recognition of the role of IK and LK in the country's initial adaptation communication (AdComs) (Government of Zimbabwe, 2016b; Government of Zimbabwe, 2022). This progress to recognise the utility of IK and LK systems in complementing mainstream climate knowledge and practice in the national climate policy is encouraging (Government of Zimbabwe, 2016c). However, there are also policy inconsistencies regarding the inclusion of IK and LK in the national climate action agenda, as the first revised NDC excluded IK and LK (Government of Zimbabwe, 2021). It is therefore, important to develop approaches to ensure consistent consideration of IK and LK in national policies. One of the objectives of this study is to propose a framework that places IK and LK on the same level with other science knowledge sources. This also ensures equity in adaptation planning (Berrang-Ford et al., 2021b).

However, further research is required to explore and demonstrate how IK and LK can contribute to a country's climate adaptation planning and implementation of innovative and sustainable strategies. Therefore, this study explored this gap to establish how IK and LK integration in planned adaptation can be strengthened in Zimbabwe to inform national policy framing for the development of the second NCD. The need for research that prioritised IK and LK for climate adaptation was also expressed in national documents, such as the Zimbabwe National Climate Change Response Strategy (NCCRS) and the initial AdComs. The NCCRS and initial AdCom emphasises the importance of finding approaches that integrate IK and LK into evidence-based planning frameworks, informed by good science, to enhance informed decision-making by communities, local authorities, and national policymakers (Government of Zimbabwe, 2014; Government of Zimbabwe, 2022).

To ensure that IK and LK for climate adaptation go beyond business as usual in the current climate scholarship, it is vital that other critical elements of IK and LK use in climate and weather forecasting assess the reliability of IK and LK forecasts at local level and that the effectiveness of IK and LK adaptation responses in reducing climate risk are understood. This can potentially increase the consideration of IK and LK in the national climate discourse, such as climate services in Zimbabwe. Also, these studies at the local scale are important for building the evidence needed for the global synthesis of the effectiveness of IK- and LK-informed adaptation (Zvobgo et al., 2022).

1.6. Research question and objectives.

Building on the background provided in Sections 1.1–1.5, the research question and specific objectives were framed broadly to understand the role of IK and LK in climate adaptation beyond the current scholarship. The broader aim of this study was to critically explore and understand IK and LK in smallholder farmers' climate decision-making, including the overall influence on the adaptation responses and resilience of farmers. These include the reliability of IK and LK climate forecasts, and the effectiveness of IK and LK climate adaptation. Establishing the effectiveness of these adaptation responses was assumed to be important in accelerating the integration of IK and LK into national planned adaptation discourse.

To achieve this, the research questions and objectives of the study were anchored on five building blocks. First was to explore the current scholarship on IK and LK in climate adaptation focusing in one of Africa's key sectors – water (a key adaptation sector important for agriculture for smallholder farmers). This aimed to identify critical knowledge gaps. A case study approach was applied to understand the following: (a) role of IK and LK in reducing or increasing vulnerability of smallholder farmers to climate variability and change, (b) role of IK and LK weather and seasonal climate forecasts on climate decision making and the overall farmers' climate adaptation, (c) reliability of IK and LK seasonal forecasts, the effectiveness of IK and LK climate adaptation responses in reducing the risk of food insecurity. Finally, a framework is proposed in which IK and LK can be co-opted in mainstream national climate adaptation discourse to increase the diversity of adaptation options that improve smallholder farmers' resilience to climate variability. Thus, the research questions and objectives were framed to address the issues above.

1.6.1. Research question.

The study broadly asked the question on what role does IK and LK play in smallholder farmers' adaptation to climate impacts? The following are sub-questions to explore the main research question:

1. What are the current knowledge trends and gaps in Africa's IK and LK academic literature for water sector, and to what extent is IK and LK considered in national policy focusing on Nationally Determined Contributions (NDCs) submitted by African governments?
2. How vulnerable are smallholder farmers in the Chiredzi District to climate variability and change risks? Are smallholder farmers that use IK and LK more or less vulnerable than smallholder farmers relying on other forms of knowledge in the district?
3. What IK and LK are used by smallholder farmers for weather and seasonal climate forecasts and what is their influence on climate decision-making in Chiredzi?
4. What is the role of the IK and LK weather and climate forecasts in informing the climate adaptation responses implemented by smallholder farmers in Chiredzi?
5. How reliable are IK and LK seasonal climate forecasts, and what is the effectiveness of IK and LK adaptation responses in reducing the climate risk in Chiredzi?
6. How can IK and LK be integrated into planned and institutional adaptation to increase the resilience of smallholder farmers to manage climate risk?

1.6.2. Research Objectives

The six sub-questions above were addressed by five research objectives below.

1. Assess the trends and applications of IK and LK in the water sector adaptation in Africa, a key adaptation issue for agriculture, to identify knowledge gaps, including the adaptation commitments related to IK and LK by African governments in their NDCs (explore the research question 1 and it is addressed in Chapter 2).
2. Measure quantitatively and qualitatively the vulnerability and exposure of smallholder farmers in Chiredzi to climate variability and change (explore the research question 2 and it is addressed in Chapter 3).
3. Assess the role of IK and LK in weather and seasonal climate forecasts, climate decision-making, and the contribution of the decision actions to the overall smallholder farmers' adaptation to climate variability risks in Chiredzi (explore research question 3 and 4 and it is addressed in Chapter 4).
4. Evaluate the reliability of IK and LK seasonal climate forecasts and the effectiveness of IK and LK adaptation responses in reducing climate risk in Chiredzi (explores research question 5 and it is addressed in Chapter 5).
5. Propose a conceptual framework for integrating IK and LK into planned, institutional adaptation to support the transformation of current IK and LK for future climate risk reduction, which increase smallholder farmers' resilience to climate variability risks (explores research question 5 and it is addressed in Chapter 5).

1.7. Outline of the Methods

1.7.1. Study Area Description

The study was conducted in Chiredzi district in the southeast lowveld region of Zimbabwe. Chiredzi is found in semi-arid Natural Region V, which is the driest of Zimbabwe's Agro-Ecological Zones with highly variable rainfall patterns (Chikodzi & Mutowo, 2012; Mugandani, R et al., 2012). Five of the 32 wards in Chiredzi Rural District (wards 1, 3, 25, 27, and 32) were selected for data collection (Figure 1-1). The selection of wards to conduct interviews was based on strategic reasons, including accessibility, the characteristics of farmer settlement and geography, poverty levels (Zimbabwe Vulnerability Assessment Committee, 2017; ZimStat, 2015), prior knowledge of the vulnerability of the area to hazards (UNDP, 2016), and climate variability and change background (Manatsa et al., 2020). Based on the settlement type, wards were selected from communal and resettled farming areas. Communal wards consisted of farmers who have stayed in one area for several decades and longer than resettled wards who consisted of farmers that since 2000 were reallocated land under Zimbabwe's land reform programme in formerly commercially managed ranches that had not been previously tilled nor have settlements (Chaumba, Scoones & Wolmer, 2003; Ndhlovu, Emmanuel, 2018). It was anticipated that the IK and LK role in these two categories would differ with communal wards expected to have multigenerational and endemic IK and LK because farmers in communal areas have been staying in the same community and farming in the same area for several decades and build strong local knowledge base. The IK and LK in resettled areas were anticipated to be younger and syncretic of exogenous knowledge systems, including knowledge brought about by resettled farmers, and potentially adapt to local IK and LK over the past 15 – 20 years to the local context (see Chapters 3 and 4 Sections 3.3.2 and 4.2.2). Also, farmers from these two areas are expected to have different vulnerability levels owing to differences in socioeconomic status. There are three public meteorological weather stations in the Chiredzi district (Figure 1-1) and a private weather station at the Malilangwe Conservancy Trust where climate data used in this study was obtained (Figure 1-1). The characterisation of the study area is presented in each empirical chapter (3 – 5) to address the specific needs of the research objectives.

Lessons and key findings from the Chiredzi district can feed into the national climate discourse and action. Prior evidence exists for Chiredzi regarding the use of IK and LK for weather and seasonal climate forecasting (Jiri, O, Mafongoya & Chivenge, 2015; Soropa et al., 2015). However, the extent and influence of the forecasts in climate decision making by smallholder farmers has not been fully studied, and how the decisions translate into actions that determine the overall farmer adaptation is still lacking. The relevance of such decisions has yet to be assessed as well

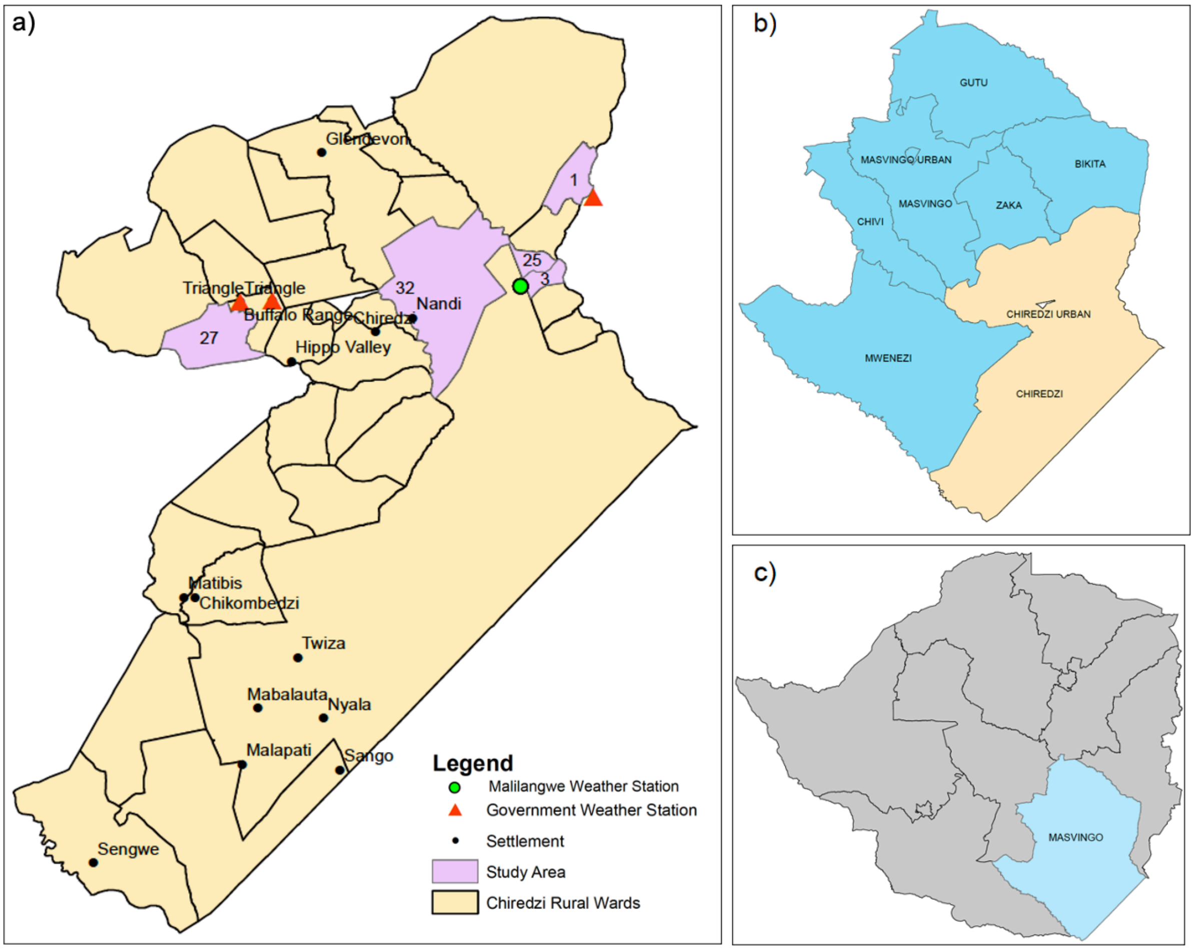

Figure 1-1: Map showing the study area: **a**) Chiredzi district map showing the five wards in Chiredzi considered in this assessment and the weather stations including the Malilangwe Weather Station with climate data used for this study, **b**) Masvingo provincial map showing the location of Chiredzi district in relation to other districts in the province, and c) is the map for Zimbabwe showing the location of Masvingo province in relation to other provinces.

1.7.2. Summary of the Methods

To answer the research questions and achieve the research objectives, a mixed-methods approach was used (Ashley & Boyd, 2006; Hesse-Biber & Johnson, 2015; Molina-Azorín & López-Gamero, 2016), in which qualitative and quantitative techniques were integrated to perform various sub-component analyses of each objective (Figure 1-2). A total of 210 smallholder farmers were engaged between 2021–2022. Data were collected twice: the first set of data was collected in September and October 2021. This informed analysis and conclusions in Chapters 3 and 4 on IK and LK weather and climate forecasting, decision making and implementation of adaptation responses as well as if the responses are reducing farmers' livelihood vulnerability to climate impacts. The second set of data was collected in May and June 2022. This data analysis supports the conclusion in Chapter 4 of the thesis, assessing the reliability of IK and LK climate forecasts and the effectiveness of IK and LK adaptation responses implemented by farmers.

A multistage sampling technique was applied to select villages to conduct interviews. Four villages were selected from each ward to ensure uniform sampling across the ward. In each village, five farmers were randomly selected for interviews. Specific data collection procedures are provided in each empirical chapter, including the types of data collected and the analysis performed. Ethical clearance was obtained from the Faculty of Science Research Ethics Committee of the University of Cape Town (FSREC 002 – 2021). The specific methods for assessing each objective are presented in Chapters 2–5 of this thesis.

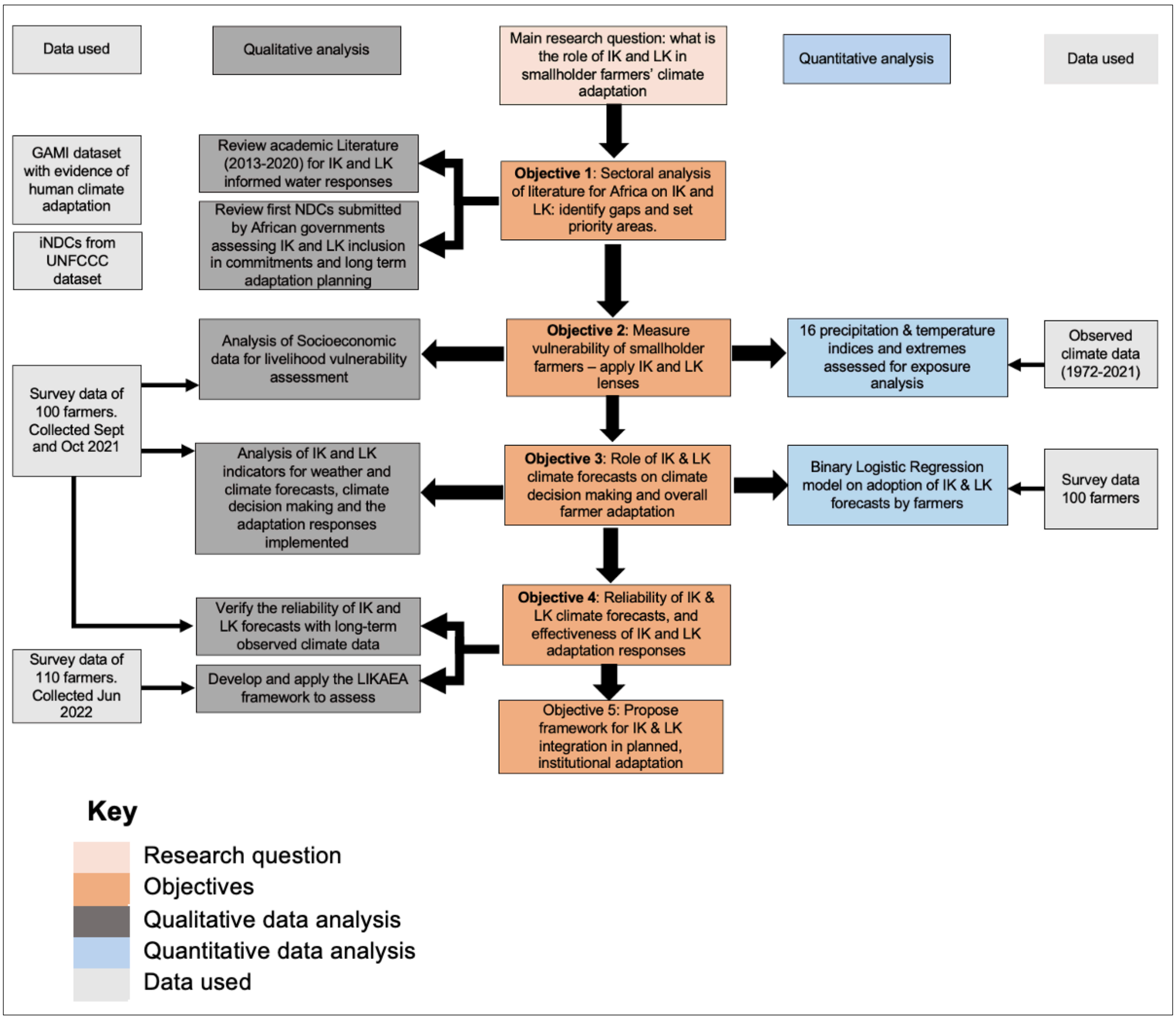

Figure 1-2: Summary outline of the methodology and tools used for data collection and analysis in Chiredzi. The bold black arrows show the connections between different phases and the process flow of the methodology.

1.8. Definition of Key Terms

Table 1-1 below presents the definitions of the key terms frequently used in this study.

Table 1-1: Definitions of key terms for this study.

Term	Definition	Reference
Climate variability	Deviations of a climate variable from a given mean state (including the occurrence of extremes, etc.) at all spatial and temporal scales beyond that of individual weather events.	(IPCC, 2022a)
Climate change (*anthropogenic*)	A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods	(IPCC, 2022a)
Climate adaptation (*in human system*)	The process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities.	(Ara Begum et al., 2022; IPCC, 2022a)
Climate vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.	(IPCC, 2022a)
Adaptation options	The array of strategies, responses, and measures that are available and appropriate for addressing adaptation. They include a wide range of actions that can be categorised as structural, institutional, ecological, or behavioural.	(IPCC, 2022a)
Climate risk	The potential for adverse consequences for human or ecological systems from climatic events, recognising the diversity of values and objectives associated with such systems. In the context of climate change impacts, risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards. Hazards, exposure, and vulnerability may each be subject to uncertainty in terms of magnitude and likelihood of occurrence, and each may change over time and space due to socio-economic changes and human decision-making	(IPCC, 2022a)
Indigenous knowledge	The understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings. For many Indigenous Peoples, IK informs decision-making about fundamental aspects of life, from day-to-day activities to longer-term actions. This knowledge is integral to cultural complexes, which also encompass language, systems of classification, resource use practices, social interactions, values, ritual, and spirituality. These distinctive ways of knowing are important facets of the world's cultural diversity.	(IPCC, 2022a; UNESCO, 2018)
Local knowledge	The understandings and skills developed by individuals and populations, specific to the places where they live. Local knowledge informs decision-making about fundamental aspects of life, from day-to-day activities to longer-term actions. This knowledge is a key element of the social and cultural systems which influence observations of and responses to climate change; it also informs governance decisions.	(IPCC, 2022a; UNESCO, 2018)
Effectiveness of adaptation	The extent to which an action reduces vulnerability and climate-related risk, increases resilience, and avoids maladaptation	(Ara Begum et al., 2022; IPCC, 2022c)

Vulnerability	The propensity or predisposition to be adversely affected by an event or hazard. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.	(Ara Begum et al., 2022; IPCC, 2022a)

1.9. Structure of this Thesis

This thesis is comprised of six chapters, including the current chapter (general introduction with research questions and objectives). Four of the chapters (two to five) are empirically based and present the main research work of the study. The last chapter (six) presents the synthesis of key findings and concludes the study. The remainder of this thesis is organised as follows.

Chapter Two: An in-depth systematic literature analysis of the existing scholarship on IK and LK for climate adaptation in Africa. This Chapter assesses the role of IK and LK in the implementation of various climate adaptation responses for the water sector in Africa and reviews the extent to which IK and LK were covered in the first NDCs submitted by African governments (published as Zvobgo et al., 2022). This chapter identifies knowledge and research gaps in the current IK and LK literature across Africa. This is the first empirical chapter that addresses objective 1 of this thesis.

Chapter Three: The Chapter assesses how the livelihoods of smallholder farmers in the Chiredzi District are vulnerable to climate variability and change (in review with Environmental Development). This chapter develops the livelihood vulnerability index for Chiredzi applying the IK and LK lenses, and it corroborates the assessment with a quantitative analysis of long-term observed data for Chiredzi to determine farmers' exposure to climate variability and change. This is the second empirical chapter that addresses objective 2 of this thesis.

Chapter Four: This chapter explores what IK and LK smallholder farmers use for weather and seasonal climate forecasting in Chiredzi. It comprehensively assesses the role of IK and LK forecasts in climate decision-making and their contribution to the overall climate adaptation of smallholder farmers in Chiredzi (published as, Zvobgo, Luckson et al., 2023). This is the third empirical chapter, addressing objective 3 of this thesis.

Chapter Five: This chapter evaluates the reliability of the IK and LK seasonal climate forecasts (identified in Chapter Four) using the observed climate data and assessing the effectiveness of IK and LK climate adaptation responses in reducing food insecurity from climate risk in Chiredzi (to be submitted to the One Earth journal). This is the fourth empirical chapter, addressing objective 4 of this thesis.

Chapter Six: The chapter synthesis the key findings from the four empirical chapters in coherent and broad terms as well as setting the agenda for future research. The discussion also locates the study findings in broader academic scholarship and how they relate to other studies. The Chapter further probes the conceptual framework for the inclusion of IK and LK in planned climate adaptation for smallholder farmers at all levels, addressing the objective 5 of the thesis.

2. Literature Analysis

The role of indigenous knowledge and local knowledge in water sector adaptation to climate change in Africa: a structured assessment*

Abstract

Evidence is increasing of human responses to the impacts of climate change in Africa. However, understanding of the effectiveness of these responses for adaptation to climate change across the diversity of African contexts is still limited. Despite high reliance on indigenous knowledge (IK) and local knowledge (LK) for climate adaptation by African communities, potential of IK and LK to contribute to adaptation through reducing climate risk or supporting transformative adaptation responses is yet to be established. The influence of IK and LK for the implementation of water sector adaptation responses in Africa to better understand the relationship between responses to climate change and indigenous and local knowledge systems is assessed. Eighteen (18) water adaptation response types were identified from the academic literature through the Global Adaptation Mapping Initiative (GAMI) and intended nationally determined contributions (iNDCs) for selected African countries. Southern, West, and East Africa show relatively high evidence of the influence of IK and LK on the implementation of water adaptation responses while North, and Central Africa show lower evidence. At country level, Zimbabwe displays the highest evidence (77.8%) followed by Ghana (53.6%), Kenya (46.2%), and South Africa (31.3%). Irrigation, rainwater harvesting, water conservation, and ecosystem-based measures, mainly agroforestry, were the most implemented measures across Africa. These were mainly household and individual measures influenced by local and indigenous knowledge. Adaptation responses with IK and LK influence recorded higher evidence of risk reduction compared to responses without IK and LK. Analysis of iNDCs shows the most implemented water adaptation actions in academic literature are consistent with water sector adaptation targets set by most African governments. Yet only 10.4% of the African governments included IK and LK in adaptation planning in the iNDCs. This study recommends a coordinated approach to adaptation that integrates multiple knowledge sources, including IK and LK, to ensure sustainability of both current and potential water adaptation measures in Africa.

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*This chapter was published as:

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2.1. Introduction

Climate hazards are projected to intensify in the 21st century with severe risks projected for both humans and ecosystems (Global Risk Report, 2021; IPCC, 2018b). African countries have contributed relatively little to the greenhouse gas emissions causing climate change, but face many of the most severe risks in key sectors, including water, food systems, economies, health, and biodiversity (Niang et al., 2014). Anthropogenic climate change has already increased the likelihood of extreme climate change and variability in Africa, such as the 2015-2017 Cape Town drought (Otto et al., 2018; Pascale et al., 2020). Climate change adaptation is thus essential in order to manage current impacts and reduce future risks.

Understanding which adaptation actions are being implemented, how, and the effectiveness of specific responses for reducing risk is crucial for adaptation planning (Berrang-Ford et al., 2021b; Owen, 2020; Williams et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) defines climate adaptation in human systems as “the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities” (IPCC, 2018a:542). Since the publication of the IPCC 5th Assessment Report (AR5) in 2014, there has been a substantial increase in peer-reviewed publications documenting evidence of the impacts of climate change and climate change adaptation responses, with the greatest increase evident in the literature on Africa (Berrang-Ford et al., 2021b; Callaghan et al., 2021; Sietsma et al., 2021). This growing literature record has improved information on where and how adaptation is taking place, including possible maladaptation threats. It has shown that for Africa most human responses to climate change are taken incrementally by individuals, while planned adaptation is considered to be limited, fragmented, and poorly governed (Berrang-Ford et al., 2021b; Sietsma et al., 2021).

However, little is known in Africa about what effect indigenous knowledge (IK) and local knowledge (LK) are having on climate change adaptation actions. Indigenous knowledge refers to the understanding, skills, and philosophies developed by societies with long histories of interaction with their natural surroundings (IPCC, 2018b). Local knowledge refers to the understanding and skills developed by individuals and populations, specific to the place where they live (IPCC, 2018b). IK and LK systems in Africa are central to managing resources, particularly during periods of resource scarcity (Leal Filho et al., 2021), and thus important to broader and more effective implementation of climate change adaptation options. For example, despite being climate change literate and having access to radios, it is common for communities across Africa to use IK to make important livelihood decisions such as deciding on planting dates (Kaganzi et al., 2021). Further, the highly context-specific nature of adaptation has led scholars to highlight the need for inclusion of IK and LK for enhanced efficacy of adaptation projects due to their social acceptability and rich understanding of local environmental parameters (Leal Filho et al., 2021; Makondo & Thomas, 2018; Nyong, Adesina & Elasha, 2007). Consequently, a range of localised case studies have highlighted the importance of IK and LK for coping responses and adaptation scalability (Kanda, Murongazvombo & Ncube, 2017; Mwaniki & Stevenson, 2017; Nkomwa et al., 2014; Opare, 2018; Williams, Sikutshwa & Shackleton, 2020). Recent IPCC Special Reports for AR6 highlight the potential role IK and LK can play to reduce climate risks to natural and managed ecosystems (IPCC, 2018b; IPCC, 2019b; IPCC, 2019c). This role of indigenous and local people has been recognised by the Green Climate Fund, Global Environment Facility, and International Climate Initiative as key to facilitating adaptation with important stakeholders and framing adaptation and financing of projects in Africa (UNEP, 2021). Further, the necessity to consider the role of IK and LK systems in climate adaptation was established in the IPCC-AR5 (IPCC, 2014a) citing the lack thereof in previous IPCC Assessments (Ford, James D. et al., 2016). The IPCC AR6 Special Reports have also highlighted how crucial IK and LK is to climate adaptation especially for regions, like Africa, and the importance of IK and LK in knowledge co-production for effective climate adaptation across sectors and regions (Abram et al., 2019). A synthesis of the inclusion of IK and LK in climate change adaptation across Africa is crucial to policymakers for several reasons, including (1) assessing which adaptation actions include IK and LK and where these are being implemented, (2) assessing the effectiveness of adaptation options that include IK and LK for reducing risk, (3) assessing the adaptation gap in Africa, and (4) prioritising the distribution of limited financial resources to adaptation options and guiding decisions on adaptation funding from multilateral funders.

Here, the study begin to fill these knowledge gaps by reviewing evidence of the use of IK and LK in the implementation of water adaptation responses across Africa and provide the first regional assessment on the role of IK and LK in adaptation responses related to water in Africa. Water is a key resource linking multiple different sectors (e.g. food, energy, health) in climate adaptation (Global Water Partnership, 2018; UN Water, 2013; United Nations Economic Commission for Europe, 2009). The study identify several IK and LK-informed adaptation measures and unpack how IK and LK possessed by communities is used in the implementation of water adaptation responses across Africa. Mapping where this adaptation is taking place is vital for planning and feasibility assessment of the water adaptation measures, including the different types of knowledge being used for decision making during adaptation. The study therefore relate these observations of local and incremental responses to climate change to planned adaptation at the National level through analysis of intended nationally determined contributions (iNDCs) and discuss the role that IK and LK currently plays in key policy tools used to shape climate adaptation.

2.2. Methods

A structured assessment (Kofod-Petersen, 2012) of the academic literature published between 2013 and 2019 was conducted, aligned with the timeframe of the IPCC 6th Assessment. The data used was obtained from the Global Adaptation Mapping Initiative (GAMI), a global dataset with 1 682 coded articles on human adaptation to climate change. GAMI articles were retrieved from three online libraries: Web of Sciences, Medline, and Scopus. Over 48 000 articles were screened through supervised machine learning tools aided by physical human screening. A total of 2 032 articles were retrieved from the screening stage and deemed potentially eligible for data extraction. The final coding resulted in the processing of 1 682 articles which had evidence of human climate adaptation responses implemented globally. Further details on how the articles were retrieved, the screening process (machine learning plus human screening), and coding are provided in Berrang-Ford et al. (2021b) with accompanying protocols by Berrang-Ford et al. (2021a), Fischer et al. (2021), and Lesnikowski et al. (2021). The inclusion and exclusion criteria for the articles used in the GAMI are explained in Fischer et al. (2021), particularly, documents that reported responses that constituted adaptation based on a strict definition of the term as behaviours that directly aimed to reduce risk or vulnerability. Articles that were theoretical, or assessments of potential or future adaptation, were excluded to maintain the empirical foundation of observed responses to climate change.

The GAMI dataset has been used to provide global, regional, and sectoral reviews of adaptation feasibility (Williams et al., 2021), policy tools to support climate adaptation (Ulibarri et al., 2021), responses to climate-related water scarcity (Leal Filho et al., 2022a), equity in adaptation (Araos et al., 2021), health effects of adaptation (Scheelbeek et al., 2021), constraints and limits to adaptation (Thomas, Adelle et al., 2021), adaptation to extreme heat (Turek-Hankins et al., 2021), adaptation in conflict affected areas (Sitati et al., 2021), and a systematic global stocktake of evidence of human adaptation to climate change (Berrang-Ford et al., 2021b). The assessment here focuses on water sector responses within the five hundred and seventy (570) articles on the region of Africa. These articles are drawn from the global GAMI data-set of 1 682 articles with evidence of human adaptation responses to climate change. The study assessed the evidence and role of IK and LK on the implementation of the adaptation responses. Articles that were included in the IK and LK assessment were selected based on these criteria: articles that include specific words – “indigenous knowledge”, “local knowledge”, “traditional knowledge”, “traditional ecological knowledge”, and “local or traditional institutions” in the article text linked to adaptation responses implemented or in specific adaptation responses (Figure 2-1). This was based on IPCC framing of the IK and LK systems and practices for climate change adaptation in AR6 (Abram et al., 2019). Although useful for clarity in discussion, the IPCC definitions of IK and LK are not commonly used in the African literature on climate change adaptation. In the latter case, IK and LK is commonly collapsed into terms, like “traditional knowledge”, “indigenous knowledge systems”, or “local and indigenous knowledge” where the IPCC distinction is lost or considered by a particular study as too strict for the African context where constructions of “local” or “indigenous” can be problematic. The IPCC’s four evidence levels - strong, high, medium, and low - are used throughout the study to describe the evidence levels for both water adaptation responses and IK and LK in the articles across Africa sub-regions (Mastrandrea et al., 2011) (Supplementary Material 1).

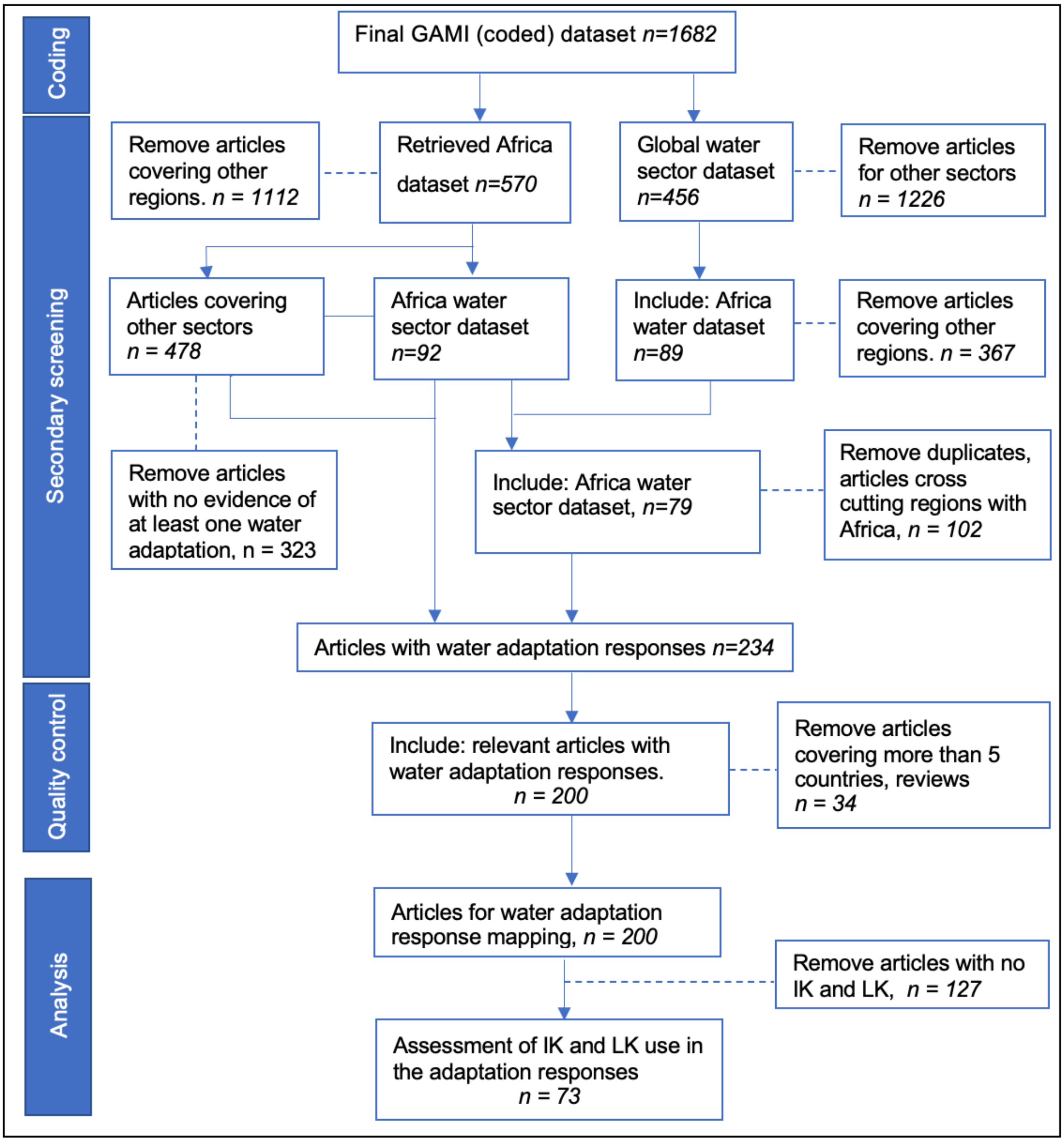

Figure 2-1: Flowchart of the procedure used in this study. Developed after Haddaway Haddaway et al. (2018) ROSES (RepOrting standards for Systematic Evidence Syntheses) for conducting environmental systematic reviews and systematic maps procedure.
Key: - - - - - - Means articles removed from the assessment.

2.2. Framing water adaptation responses

To extract relevant water adaptation responses from the GAMI data-set, a criteria was developed based on a broad definition of water adaptation responses using the United Nations Economic Commission for Europe (2009) framing of water adaptation responses, the IPCC (2018a) framing of adaptation options, and also the face value reporting of adaptation responses in the articles. The study included water adaptation responses as responses or actions that were undertaken to reduce the risk that is water related, for example, the risk that emanates from hazard and exposure caused by floods, droughts, groundwater depletion, and soil moisture reduction (e.g., groundwater abstraction or mulching). Then also included water adaptation responses in terms of actual adaptation interventions that were water related in their implementation, for example, practices, such as irrigation, soil moisture conservation, rainwater harvesting, and wastewater reuse.

2.3. Data extraction

Data extraction in GAMI was guided by an adaptation typology designed to characterise who is responding, what responses are being observed, what the extent of the adaptation-related response is and whether adaptation-related responses are reducing vulnerability and/or risk. A detailed codebook for data extraction is available in the Supplemental Material of Berrang-Ford et al. (2021b). The screening of adaptation responses for this review used the filter selection in excel and content analysis in Nvivo 12 following the criteria for systematic reviews in Vaismoradi, Turunen and Bondas (2013). Key word analysis focused on water in the sector analysis and specific water adaptation responses (e.g. irrigation, water harvesting, water conservation, and water management). For assessing the role of IK and LK, the study further developed extension codes to the existing GAMI codes (Supplementary Material 1 - Table 1-10) attributing the nature and form of IK and LK based on the systematic mapping approach set by Petzold et al. (2020).

2.4. Analysis of water adaptation responses and role of IK and LK

A qualitative assessment through content analysis of adaptation responses text following the procedure in Vaismoradi, Turunen and Bondas (2013) in Nvivo 12 was performed. Based on the framing of water adaptation responses presented in section 2.1, the developed five categories of water adaptation responses: water adaptation responses in agriculture, domestic and potable water management responses, ecosystem-based responses, grey infrastructure development responses and policy, and strategy and enabling conditions responses.

The attributes of IK and LK were adapted from Petzold et al. (2020) (see Supplementary Material 1 – Table 10 on the definition of attributes of IK and LK in the articles). The interactions of local and indigenous people with other adaptation actors (local government, national government, civil society, multilateral organisations) were assessed to ascertain the level of inclusion and influence of local people in both planning and implementation of adaptation responses. The assessment further explored instances where climate risk reduction was associated with evidence of indigenous and local knowledge to elicit efficacy of the IK and LK for adaptation.

2.5. IK and LK and African governments iNDCs

Finally, to assess the role of African governments on framing the water sector adaptation to climate risks and the inclusion of IK and LK in adaptation planning by governments, thematic content analysis of the first NDCs pledges submitted by African governments (2015 - 2019) to UNFCCC was done using the approach sets in Vaismoradi et al. (2013; 2016). Analysis of NDCs is important as they embody efforts by each country to reduce national emissions and adapt to the impacts of climate change (Biesbroek et al., 2022), [2]. The assessment focused on water sector adaptation targets under the adaptation theme per country and whether IK and LK was integrated in long-term adaptation plans. Fifty-two iNDCs were retrieved, but only 36 were considered (those submitted in English). NDCs submitted in Spanish and French languages were excluded due to lack of French and Spanish speakers among the author team; also NDCs submitted by small island Africa states were removed because the study followed the AR6 five African regions (Section 2.1.2.1).

2.6. Limitations

The GAMI dataset used does not consider grey literature, such as government reports, policies, patents including the National Adaptation Plans of Action (NAPA), and country's climate change adaptation strategies as well as relevant multilateral organisation reports – the UN, United Nations Environment Programme (adaptation gap reports), World Bank, Global Environment Facility, or Green Climate Fund. While GAMI provides an unmatched quantity of literature on adaptation, the study acknowledge that considering other reports from grey sources could provide further information, particularly concerning adaptation feasibility at future global warming levels. These reports contain important information on country level adaptation and specific measures that will complement the assessment of scientific literature

[2] https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs

here. Future studies should consider other sources of data such as grey literature to complement assessment of the scientific literature.

2.3. Results

Analysis of 570 articles on climate change adaptation in Africa identified the range of sectors within which human responses to climate change have been recorded in the peer-reviewed literature including agriculture, domestic use, ecosystem-based responses, grey water infrastructure development, and policy enabling conditions. The analysis identified 200 articles with evidence of water adaptation responses to climate change in Africa. Of the 200 articles, 73 articles (36.5%) had evidence of the use of IK and LK in the implementation of the responses. Of these 73 articles with IK and LK use, 67.1% indicate evidence of risk reduction associated with the adaptation responses. Key actors and attributes of IK and LK are identified, together with gaps in both. Finally, given the role of IK and LK in water adaptation responses, analysis of the iNDCs highlights the lack of consideration of IK and LK by African governments in national adaptation planning.

2.3.1. The geographical distribution of the evidence of water adaptation responses and IK and LK

The majority of adaptation measures (76.5%) were in response to droughts and precipitation variability (63.5%) (Figure 2-2). The articles with water adaptation responses were distributed among 31 African countries (Figure 2-2). Southern, East, and West Africa have high evidence for both water adaptation responses and water adaptation measures where IK and LK was used. There is low evidence in Central and North African regions. Ethiopia had the highest evidence of water adaptation responses followed by Ghana and Kenya, respectively. South Africa, Nigeria, Tanzania, Zimbabwe, and Uganda had medium evidence with article range between 9 and 19 articles. There is high evidence of the use of IK and LK in water adaptation in Ghana, Kenya, and Zimbabwe (Figure 2-2). Zimbabwe indicates the highest number of articles with IK and LK (77.8%), followed by Ghana (53.6%), Kenya (46.2%) and South Africa with 31.3%. According to response types, many of the adaptation responses were behavioural/cultural and technological/infrastructural (Table 2-1). Linking the adaptation response types with IK and LK, results show that 92% of the IK and LK influenced adaptation responses were associated with behavioural/cultural responses followed by technological/infrastructural (76%) and then ecosystem-based responses (68%). Technological responses were more linked to how communities use IK and LK to implement local irrigation practices during periods of water stress and in the off-season. Institutional responses were the least with 33.3% of the responses linked to institutionally implemented adaptation.

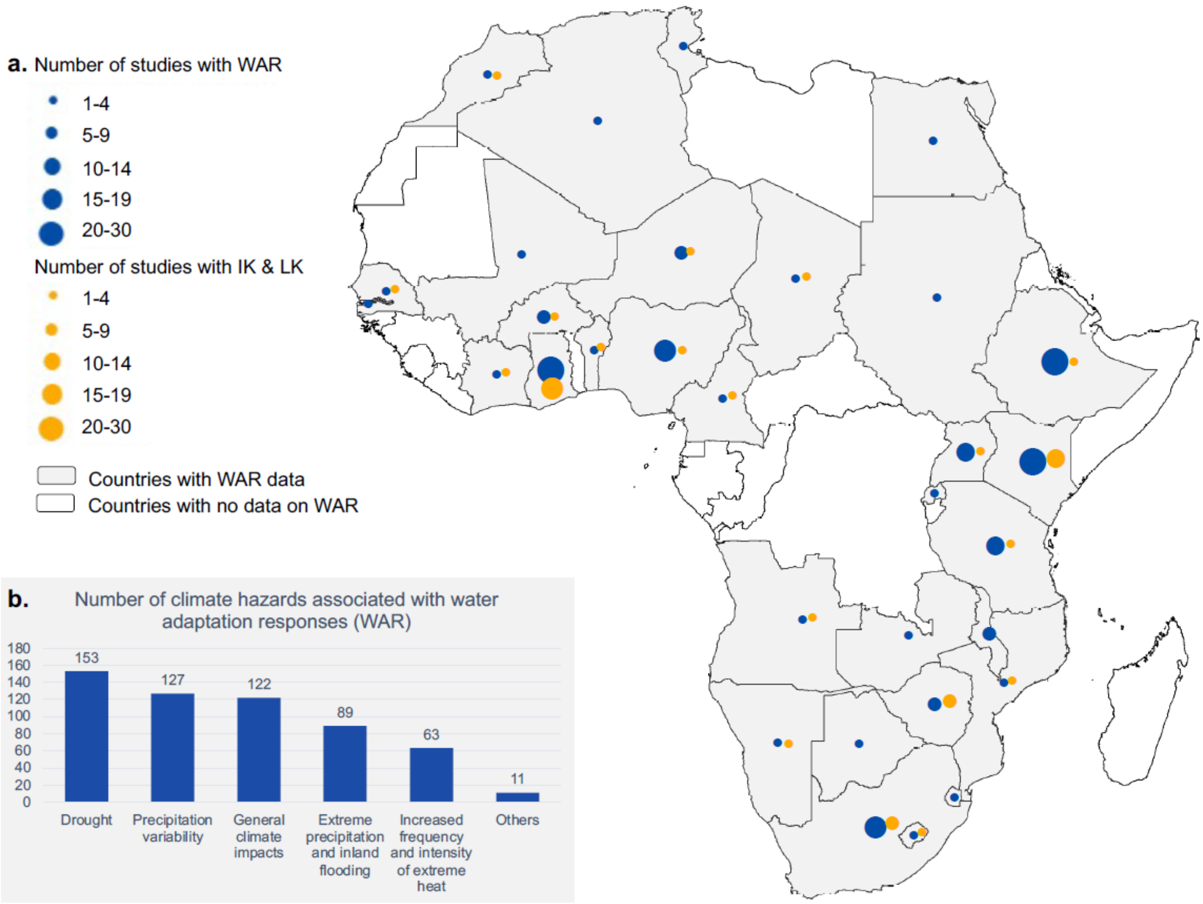

Figure 2-2: Evidence of water adaptation measures implemented in Africa and the role of IK and LK. **a**) Geographic distribution of evidence of water adaptation responses (WAR) (blue dots) and the water adaptation responses influenced by IK and LK (orange dots) in Africa between 2013 and 2019, and **b**) Climate hazards that are responded to in the articles.

Table 2-1: Types of adaptation responses recorded in the literature.

Adaptation responses	**Count**	**Proportion**	**IK and LK associated**	**Proportion**
Behavioural/cultural	169	81%	69	92%
Ecosystem-based	141	70.1%	51	68%
Institutional	60	29.9%	25	33.3%
Technological/infrastructure	160	79.6	57	76%

2.3.2. The distribution of water adaptation response types

The study identified 18 types of water adaptation responses implemented in Africa across sectors (Table 2-2). The geographic distribution of these water adaptation responses shows that literature on water sector adaptation in Africa is not evenly distributed across the continent and not evenly distributed across different types of adaptation. The majority of the articles were drawn from literatures covering food, fibre, and other ecosystems (73%) and poverty, livelihoods, and sustainable development sectors (64.5%) (SM 2.1 Table 9). Irrigation is the most implemented response recorded in 47% of the articles. This includes the increased use of water saving irrigation methods, such as drip irrigation which is widely implemented across Africa, including in some parts of North Africa. Rainwater harvesting was the second most implemented response (36.3%). Rainwater harvesting was implemented through a diversity of technologies, which include in situ measures, rooftop water collection, valley tanks, pitting, contour bunds, rooftop harvesting for potable water, diversion weirs for irrigation, check-dam ponds, dugouts, and shallow wells. Water conservation techniques in the agriculture sector were the third highest response recorded (31.8%). Other measures with medium evidence of implementation include agroforestry measures to increase infiltration and groundwater recharge through forestry and catchment management. Details of the geographic distribution of specific water adaptation responses per country are presented in Figure 1 of the Supplementary Material 1.

Table 2-2. Assessment of the water adaptation responses across sub-regions of Africa and the evidence of IK and LK per adaptation response.

Category	Specific water adaptation responses	Africa regions					IK and LK				
		SA	EA	WA	NA	CA	SA	EA	WA	NA	CA
Water adaptation responses in agriculture	Irrigation including responses to reduce water use through technological interventions e.g., change from surface to drip irrigation.	16	37	33	6	2	9	8	8	1	2
	Rainwater/water harvesting (field in-situ responses – contours, semi-circular bunds, strip catchment, pitting -zai pits etc)	17	26	7	0	0	4	12	5	0	0
	Soil and water conservation (e.g., ditches, terracing, soil -water moisture retention strategies, moisture conservation farming).	9	24	28	3	1	1	10	10	0	1
	Increased groundwater abstraction for irrigation, livestock - wells	4	5	1	2	0	2	2	0	1	0
	Flood water control (flood water harvesting, diverting, drainage)	3	2	2	0	1	1	0	0	0	0
Domestic & potable water management adaptation responses	Rainwater harvesting include increased household bulk water storage	8	11	4	0	0	4	2	0	0	0
	Household level water management and resilience (water saving responses, reduce water usage, improve usage, improve storage during droughts and floods)	7	5	2	2	0	3	2	1	1	0
	Water markets - vending (community level water transfers), recycling, re-use.	1	2	4	1	0	1	1	1	0	0
	Increased groundwater abstraction for domestic purposes – mainly borehole drilling and deepening of wells.	6	1	0	0	0	2	2	0	0	0
	Improve drainage systems for flood water removal	4	2	3	0	0	1	1	1	0	0
	Municipal level water supply rationing	3	1	0	0	0	0	0	0	0	0
	Flood relief responses e.g., construction of raised ground platforms for houses located in flood plains, sandbags, permanent or temporary to less flood vulnerable areas.	6	4	4	0	0	1	1	1	0	0
Ecosystem based responses	Agroforestry to improve infiltration for groundwater recharge	6	11	20	1	2	1	6	7	0	2
	Protection of watersheds, catchment management, wetland restoration, mulching to increase, infiltration, soil moisture and groundwater recharge	7	8	4	0	0	3	5	4	0	0
Grey infrastructure development	Increase reservoir storage through dam construction of small, medium & large-scale (for water supply – agriculture & potable) and flood control dams, weir construction.	10	9	2	0	1	0	2	1	0	1
Policy, strategy and enabling conditions responses	Introduction of a policy, improving enabling environment for water management under climate stressed shortages, flood management plans, strategies, and other governance mechanisms.	2	1	1	2	0	0	0	0	0	0
	Implementation of IWRM plans	1	0	0	0	0	0	0	0	0	0
	Effective water tariffing.	1	0	0	0	0	0	0	0	0	0

*SA = southern Africa, EA = east Africa, CA = central Africa, WA = west Africa, NA = north Africa.

Evidence of water adaptation responses	Evidence of IK and LK per adaptation responses
Strong evidence	Strong evidence
High evidence	High evidence
Medium evidence	Medium evidence
Low evidence	Low evidence
No data	No data

* The figures are indicating the number of articles per adaptation responses per region.

2.3.3. IK and LK role in water adaptation responses

Out of the 200 articles with water adaptation responses, 36.5 % (73) of the articles had evidence of the use of IK and LK in the implementation of the adaptation responses. Attribution of the IK and LK used by communities in response to the impacts of climate change shows that 45.3% of this knowledge was factual knowledge about the use of the environment, and 30.1% of the knowledge was factual knowledge about environmental changes (Table 2-3). Both types of factual knowledge triggered behavioural changes, a shift in practices and technological interventions using indigenous knowledge by farmers and communities. Of the articles with evidence of IK and LK use, 67.1% recorded risk reduction compared to 60.6% for the articles without IK and LK (Table 2-4).

Table 2-3. Attributes of IK and LK used in the adaptation responses implemented in Africa.

Attributes of IK and LK	Number of Publications	Example	Representative study
Factual knowledge about the environment and environmental changes	22	Early warnings based on observation of the environment and natural phenomena (water wells) in Ramarumo, Kubake, and Malumeng communities in Lesotho	(Kamara, Agho & Renzaho, 2019)
		Pollution of open water sources from strong winds gust and drying of water wells for disaster (droughts) early warning in Swaziland and Lesotho	(Kamara, Agho & Renzaho, 2019)
Factual knowledge about the use of the environment	34	Indigenous soil and water conservation responses in Atankwidi basin, Ghana – communities use indigenous organic matter (*Nandeene, Tampugere, Na'ambea*) to improve soil fertility, thus increases the water retention capacity of their soils.	(Derbile, 2013)
		Use traditional knowledge for water conservation in Ghana.	(Ahmed et al., 2016)
		Traditional and indigenous irrigation methods.	(Ologeh, Akarakiri & Adesina, 2018)
Cultural values	6	The *Zunde raMambo* (the chief's granary) – a traditional social security arrangement designed to protect	(Mavhura, E., 2017; Mavhura, Emmanuel, 2017)

		vulnerable groups and those affected by disasters such as floods and drought practised by local and indigenous people in Muzarabani, Zimbabwe.	
Governance and social capital	15	Communities use social networking to build safety nets for adaptation in Ghana.	(Ahmed et al., 2016)
		Use of societal customs, traditions, rules, laws to increase societal resilience to water stress caused by droughts in Swaziland and Lesotho.	(Kamara, Agho & Renzaho, 2019)
		Traditional authorities assign higher ground areas that people gather during floods in Kenya.	(Thorn, Thornton & Helfgott, 2015)
Others	4	Rain seeking ceremonies in Zimbabwe.	(Bhatasara, 2017)

Table 2-4. Risk reduction for adaptation responses with evidence of IK and LK vs adaptation responses without evidence of IK and LK

Category	**Evidence of risk reduction**		**Number of publications**
	Yes	No	
Evidence of indigenous and local knowledge	49 (*67.1%*)	24 (*32.9%*)	n = 73
No evidence of indigenous and local knowledge	77 (*60.6%*)	49 (*39.4%)*	n = 127

2.3.4. The role of governments on framing water sector adaptation

More than 90% of the African governments have clear water sector adaptation targets. Table 2-5 shows a breakdown of the water sector targets in iNDCs submitted by African governments and the acknowledgement of IK and LK in planned adaptation. Only 5 (10.4%) African governments (Benin, Burkina Faso, Somalia, South Africa, and Zimbabwe) acknowledged and included IK and LK in their long-term adaptation planning (Table 2-5). About 33.3% of the African governments are planning to expand irrigation capacity through increasing irrigation infrastructure and improved efficiency of irrigation systems; 72% of the governments are prioritising investments in grey infrastructure development to increase reservoir capacity and storage of rainfall through rainwater harvesting, large-scale multipurpose dams, reservoir improvement and monitoring; and 53% of the countries target improved water sector governance systems through policy, integrated management plans, strategies, sustainable water resources development that promotes ecosystem-based management responses, and other soft path adaptation responses.

Table 2-5. iNDCs water adaptation goals for African governments and the acknowledgment of IK and LK in adaptation planning.

Country	Country water sector adaptation priorities and evidence of IK and LK inclusion		
	Water governance priorities	Grey water infrastructure development priorities	Acknowledged IK and LK in adaptation planning
Algeria	•		
Angola	•	•	
Benin	•	•	•
Botswana		•	
Burkina Faso	•	•	•
Burundi		•	
Central A. Republic	•	•	
Chad	•	•	
Djibouti		•	
Egypt		•	
Eritrea		•	
Ethiopia		•	
Gambia	•	•	
Ghana	•	•	
Guinea		•	
Guinea-Bissau		•	
Kenya	•		
Lesotho	•	•	
Liberia	•	•	
Malawi	•	•	
Morocco		•	
Mozambique	•	•	
Namibia		•	
Nigeria		•	
Rwanda	•	•	
Somalia	•	•	•
South Africa	•	•	•
Sudan	•	•	
Swaziland	•	•	
Tanzania	•	•	
Togo	•	•	

Tunisia		•	
Uganda	•	•	
Zambia	•	•	
Zimbabwe	•	•	•

2.4. Discussion

The assessment identified and mapped the influence of IK and LK in the implementation of the water sector adaptation responses across human responses to climate change implemented in Africa, and recorded in peer-reviewed literature between 2013 and 2019. Consistent with previous studies (Berrang-Ford et al., 2021b; Leal Filho et al., 2022a), droughts and precipitation variability (153 and 127, papers respectively) were the most frequently responded to climate hazards in Africa (Figure 2-2). Overall, there is high evidence of water adaptation responses implemented in the East, West, and Southern African regions and little evidence in North and Central Africa. These results are consistent with reviews of responses to climate-related water scarcity in Africa (Leal Filho et al., 2022a), as well as reviews of climate change research funding for Africa (Overland et al., 2021).

Communities across Africa are using IK and LK to inform decisions influencing the implementation of the adaptation responses. Knowledge on scalability of these responses to regional scale is not yet established. This is partly due to lack of coordinated implementation or early stage of implementation of most water sector adaptation actions in Africa (Berrang-Ford et al., 2021b; Leal Filho et al., 2022a). Given the proposed increase of multilateral funding for adaptation 2020 - 2030 from the four major climate and development funders, including Green Climate Fund, Adaptation Fund, Global Environment Facility, and the International Climate Initiative, there is a window of opportunity for these measures to be scaled up through better integration of IK and LK (UNEP, 2021).

Most of the water adaptation responses are water management actions in agriculture with 229 adaptation responses recorded in the articles (Table 2-2) that were linked to farmers' and communities' agronomic practices. There is consistency between the results on IK and LK linked adaptation response type (Table 2-1) and IK and LK attribution (Table 2-3), where factual knowledge about the use of the environment records the highest. We find that where African communities are applying IK and LK, that this leads to behavioural and cultural changes in water use, management, and conservation, which is vital for climate risk adaptation particularly during drought and floods. A third of the water adaptation response articles had evidence of IK and LK use in the implementation of the adaptation responses. The results on the distribution of literature on IK and LK use in climate adaptation extend the findings of the systematic review of Petzold et al. (2020) that observed high evidence of IK and LK in climate change adaptation in Zimbabwe and Kenya. IK and LK exists in various forms with the majority being factual knowledge about the use of the environment, followed by factual knowledge on the environment and environmental change, cultural values, and governance and social capital. Local institutions (local governance system) are recorded as informal institutions in literature despite these channels being responsible for stricter measures or by-laws, which they put in place to check both social and environmental controls at the local level in communities (Abass, Mensah & Fosu-Mensah, 2018).

Adaptation responses with IK and LK over this reference period of 2013 - 2019 record higher evidence of risk reduction compared to responses without IK and LK (Table 2-4). This is an important preliminary finding as understanding the extent to which IK and LK adaptation response contributes to climate risk reduction is critical to evaluate effectiveness of the responses to reduce climate risks, which is the aim of climate adaptation (Berrang-Ford et al., 2021b). Risk reduction in this study was not thoroughly assessed, both qualitatively and quantitatively. However, the results form the basis for future research to concentrate more comprehensively on risk reduction for IK and LK adaptation response types.

In the Atankwidi basin, in north-east Ghana, indigenous knowledge systems (indigenous water conservation measures) for climate adaptation record dual moderating effects on reducing the vulnerability to droughts (Derbile, 2013). Traditional adaptation measures practised by local communities provide both temporary and long-term solutions; for example, stone terraces to harvest water for irrigation have been used for 19 years, on average, by households to adapt to changing micro-environments in the Semien Mountains of Ethiopia (Yohannes, Teshome & Belay, 2019). This illustrates how communities have developed trust in such measures; however, it is important to establish whether these long practised measures are reducing the climate risks, or whether they are creating cultural lock-ins that are increasing their vulnerability. Most of the adaptation responses in literature are highly localised and implemented to address specific situations. Scaling up of some of the knowledge and creating platforms to advance the sharing of the knowledge is key to ensure a regional transformative adaptation process. Passing on of this knowledge to future generations would also ensure sustainability of these responses; for example, communities in Kenya have passed on traditional methods of responding to floods through many generations and these strategies are integrated into daily praxis (Thorn, Thornton & Helfgott, 2015).

2.4.1. Water adaptation responses and IK and LK

Irrigation methods is the most commonly reported adaptation response and implemented by most communities and farmers across African countries. This includes expanding the irrigation capacity in Kenya, Zimbabwe, Zambia, and Ethiopia and improving irrigation water use efficiency through adoption of efficient irrigation systems and local irrigation water saving techniques such as drip irrigation, using local initiatives in countries, such as Morocco (Aziz & Sadok, 2015), South Africa (Elum, Modise & Marr, 2017), and Uganda (Nakabugo, Mukwaya & Geoffrey, 2019). If scaled, improvements in irrigation efficiency in Africa's agriculture system has the potential to reduce water used by the agriculture sector especially in water-stressed regions. This can address some maladaptation concerns linked to the increased use of irrigation, such as the excessive abstraction of limited water resources. As many African governments pledged in their iNDCs to expand irrigation, the shift from high water demand irrigation systems to efficient, water saving irrigation systems that can adjust to future water stress is key. Government's role in promoting adoption of such technology is important; this can be through implementation of irrigation policies that enable the adoption of water saving irrigation technology and farmer support.

In many cases, farmers and communities are using indigenous knowledge to apply traditional irrigation methods during the dry season or when there is limited supply of water e.g. use of post-inundation residual moisture as natural irrigation in Zimbabwe (Mavhura, Emmanuel, 2017), cultivating on stream banks to increase access to irrigation water e.g. indigenous swamp farming in Nigeria (Ologeh, Akarakiri & Adesina, 2018), floodplain cultivation in Zimbabwe (Mavhura, Emmanuel, 2017), and indigenous cultivation in wetlands to increase moisture availability in Nigeria (Ajayi, 2014). However, some of these water adaptation options that are working today present maladaptation threats over the long-term, e.g. continuous water harvesting in a catchment may reduce water supply risk to the communities upstream but may have negative outcomes to the downstream communities (Eriksen et al., 2021; Singh, 2018). Also, stream bank cultivation will increase the vulnerability of crops to future river flooding; wetlands often act as natural barriers to flooding and therefore, cultivation in such areas increases flooding chances to downstream areas.

As many regions in Africa are experiencing water scarcity and insecurity linked to climate change, regions and countries are exploring alternative water sources informed by IK and LK. For example, during siting and accessing groundwater to increase their access to water resources, e.g., in Tanzania communities are using indigenous knowledge for groundwater exploring and management for drinking water that allows them to access deep aquifers (Shemsanga et al., 2018). The accessed water is also used to supplement agricultural activities through indigenous means of irrigating crop fields as practised in Ghana (Abass, Mensah & Fosu-Mensah, 2018). In Dupong communities in Ghana, this extended to community members who, through their indigenous and local weather predictions, use less water, which enabled them to save enough water for other equally relevant uses during droughts and limited supply (Opare, 2018). In Tanzania, pastoralists are digging watering points during periods of reduced water supply (Sangeda, Maleko & Mtengeti, 2013) and increasing protected well water use to improve domestic water supply especially in Zimbabwean urban areas practicing strict water rationing (Chanza, 2017) as well as in rural areas (Kanda, Murongazvombo & Ncube, 2017).

Local communities and indigenous people are using local and indigenous knowledge on water management, i.e. collection and storage during wet seasons. This involved rainy season water harvesting through indigenous means for both agricultural purposes (Mugi-Ngenga et al., 2016; Nakabugo, Mukwaya & Geoffrey, 2019), such as irrigation (Abass, Mensah & Fosu-Mensah, 2018), and water for livestock by pastoralists (Filho et al., 2017; Mashizha, 2019), and to increase domestic water supply by diversifying sources of potable water (Nakabugo, Mukwaya & Geoffrey, 2019). Various initiatives implemented to harvest rainwater that are influenced by IK and LK include the use of valley tanks in Uganda (Nakabugo, Mukwaya & Geoffrey, 2019), the use of water pans in Kenya (Mugi-Ngenga et al., 2016), zai pits, semi-circular bunds, and small dams in Kenya (Recha, Mukopi & Otieno, 2014), contour bunds in Nigeria (Ajayi, 2015), and digging dead end contours in Zimbabwe (Mupakati & Tanyanyiwa, 2017). All these measures were linked to the locals' and indigenous people's factual knowledge about the environment and environmental changes and factual knowledge about the use of the environment. Water harvesting has increased communities' resilience to water stress conditions by supplementing water for irrigation during rainy and dry seasons, thus improving food security. However, these were mostly seasonal storage options that can be badly affected during successive years of droughts as demonstrated in Ghana where ponds used by farmers to harvest water to support agricultural activities dry up easily after rainy seasons (Abass, Mensah & Fosu-Mensah, 2018). Further, the scalability of some of the water harvesting technologies and practices is yet to be established. For potable water harvesting, communities used various technologies and initiatives among them the digging of pits that provide additional water to households in Ghana (Opare, 2018) and hand-dug wells in Ethiopia (Yohannes, Teshome & Belay, 2019). Potable rainwater harvesting improves household water security by supplementing existing water sources to address the water scarcity linked to climate stress (Ofoegbu et al., 2016).

Many communities in East and Southern Africa are implementing water conservation practices. These include both communities' behavioural and cultural changes and technological and infrastructure interventions related to farmers' and household agronomic practices that save water, mostly green water. Most of the water conservation technology and practices, include terracing technology in Ethiopia (Cholo et al., 2018), and communities' construction of trenches for water management in Ghana and Uganda (Jost et al., 2015). Local and indigenous groups extend these practices to broader catchment management practices applying a spectrum of knowledge and initiatives. These responses improve catchment storage; the review shows that several communities in Africa are implementing ecosystem-based management responses, such as agroforestry using indigenous species, to reduce erosion, which improved water infiltration and groundwater recharge (Aimé et al., 2016; Awazi, Tchamba & Avana, 2019; Sanogo et al., 2016; Tambo & Wünscher, 2017). Also, communities use traditional knowledge to manage and conserve water during water-stressed seasons (Ahmed et al., 2016).

Several regions across Africa are implementing local level water management initiatives using their traditional knowledge to manage scarce resources during periods of crisis. Some of the water management strategies implemented during droughts and water scarcity include reducing water usage, improving storage, and water re-use. Under conditions of limited access to potable water caused by droughts, communities in Benin use indigenous knowledge to treat water to increase drinking water supply (Oyerinde, Lawin & Odofin, 2017). Communities across Africa use IK and LK to implement watershed management responses to water supply shortages caused by climate seasonal variability. For example, local farmers implement catchment water conservation using local plant varieties in Mutoko, Zimbabwe (Bhatasara, 2017), while in Ghana communities minimise deforestation to improve groundwater storage through increased infiltration (Abass, Mensah & Fosu-Mensah, 2018).

2.4.2. Limits to adaptation of IK and LK use in the water responses

To determine the sustainability and opportunities of IK and LK use in climate adaptation in Africa, it is important to discuss limits to adaptation associated with IK and LK observed in literature across Africa. 78.1% of the articles with IK and LK record limits to adaptation. A majority of these limits were linked to lack of financial resources needed for effective adaptation, lack of access to climate information to complement the indigenous, and traditional indicators used for early warning systems used by communities. Since most of the IK and LK responses were technological and behavioural/cultural responses (Table 2-1), lack of human capacity was one of the main limiting factors in the implementation of labour-intensive irrigation and agriculture water conservation techniques (Yohannes, Teshome & Belay, 2019). This is because the responses were implemented at household level relying mostly on family labour. Although these communities have relevant knowledge and practices crucial for climate adaptation, the success of labour-intensive responses depends on the family availability of the labour force. Due to factors, such as the limited financial resources and poverty, they cannot outsource the labour. In some cases, indigenous practices, such as *Zunde raMambo* (the chief's granary) in Zimbabwe help address labour shortages as communities gather to share labour (Mavhura, E., 2017) in addressing drought effects.

The lack of access to climate information, which is critical for adaptation planning, constrained local and indigenous people (Sadiq et al., 2019; Spear & Chappel, 2018; Williams, Crespo & Abu, 2019). Language barriers also hinder the access to climate information for local and indigenous people. A lack of finance was among the important constraints to the implementation of IK and LK practices cited in the publications (Abass, Mensah & Fosu-Mensah, 2018; Sadiq et al., 2019); this is due to the high cost associated with procurement of equipment that aids the success of the technology (Filho et al., 2017). Gender and cultural norms and traditional practices also hindered the implementation of some water adaptation responses. For example, the capability to collect water from outlying water sources in Ghana encountered social and cultural limitations in communities where women are not allowed to use bicycles to collect water (Opare, 2018).

2.4.3. Integrating IK and LK in water sector adaptation

Water is the most prioritised sector by African governments for adaptation to climate change. Over 90% of African countries have water sector targets in their iNDCs. More broadly, this aligns with trends identified in analysis of UNFCCC National Communications over the period 1994–2019 which has shown water for agriculture has become an important theme in NDCs, particularly since 2008 for Africa and Asia (Biesbroek et al., 2022). A comparison between water sector adaptation goals in the iNDCs and the evidence of water sector adaptation responses recorded in various African countries shows a link between government policies and how various stakeholders are adapting. For example, many grey infrastructure goals expressed in the iNDCs (increase water supply, increase irrigation capacity, rainwater harvesting infrastructure) were also the highest recorded water adaptation responses recorded in literature as evidence of how the water sector in Africa is adapting to climate change. This potentially characterises how countries will drive water sector adaptation and the influence of policy on adaptation in Africa. Yet we found IK and LK is barely included in planned adaptation, only 10.4% of the African governments acknowledge and include IK and LK in planned adaptation. Given the evidence of the high reliance of African communities on IK and LK for water sector adaptation, this is a concerning lack of consideration of IK and LK to give effect to planned responses.

The above highlights a gap in academic literature on the role of IK and LK in implementation of adaptation responses and the acknowledgment of this knowledge at a policy level by African governments through formal adaptation channels. These shortcomings, notwithstanding, evidence of the role IK and LK play in water sector adaptation, cautions that planned adaptation in Africa is likely to be more broadly adopted, accepted by communities, and aligned with cultural norms if IK and LK is included. There is a window for African governments to incorporate IK and LK into national adaptation planning to increase their realisation of the adaptation goals set in the NDCs. The use of multiple sources of knowledge (scientific, and indigenous and local knowledge) is crucial and will enhance transformational adaptation in Africa. This is also key in developing disruptive adaptation responses that effectively address the climate risk in the water sector.

2.5. Conclusion

The evidence of implementation of water adaptation responses to climate risk is growing in Africa. The study identified and mapped water adaptation responses implemented across Africa and the role of IK and LK in the implementation of these adaptation responses. Irrigation, water conservation (green water), rainwater harvesting, and catchment management responses such as the use of ecosystem-based approaches, are among the most implemented responses. The evidence of water adaptation responses and IK and LK influence is high in East Africa – Ethiopia, Kenya, Uganda, West Africa – Ghana and Nigeria and in Southern Africa – Zimbabwe, South Africa. There is low evidence of water adaptation responses in north and central Africa. Knowledge on the efficacy of these responses and potential maladaptation threats from some of the adaptation practices is not yet established. This is likely because the adaptation in Africa is at the early stage of implementation (Berrang-Ford et al., 2021b).

There is a need for a comprehensive approach that assesses risk reduction of IK and LK climate change adaptation response type in Africa. The assessment shows that most of the water adaptation responses are highly localised; therefore, the aspect of scalability of the responses at regional level should be considered carefully. IK and LK in communities is important for water management and initiatives implemented by communities in Africa. However, in the current academic literature, it is evidently viewed as informal knowledge with less value. There is also a lack of coverage and respect of this knowledge in formal climate adaptation channels in Africa. Analysis of Africa iNDCs showed that IK and LK was barely included in adaptation planning, despite Africa being one of the regions with rich IK and LK practices used for climate change adaptation. The study recommends a coordinated approach that integrates multiple knowledge systems in adaptation including local and indigenous knowledge, to ensure sustainability of both the current and proposed water adaptation responses in Africa.

3. Climate Change Vulnerability and Exposure in Chiredzi

Indigenous and local knowledge in the vulnerability of smallholder farmers to climate variability and change in Chiredzi, Zimbabwe*

Abstract

Africa is highly vulnerable to climate change, with Indigenous peoples and smallholder farmers being among the most vulnerable. However, there is limited understanding of how Indigenous knowledge (IK) and local knowledge (LK) can reduce or contribute to smallholder farmers' vulnerability and the conditions under which they can effectively reduce overall climate risk. This is partly because IK and LK are often excluded from vulnerability assessments. Therefore, we developed a locally calibrated Livelihood Vulnerability Index (LVI) that integrates IK and LK as one of the pathways to assess the vulnerability of smallholder farmers to climate variability and change in Chiredzi, Zimbabwe. A cross-sectional survey of 100 smallholder farmers was conducted to understand their perceptions, household-level sensitivity, exposure, and adaptative capacity. Analysis of local climate data (1972–2021) showed a delayed onset of the rainy season for sorghum and maize and increased mean maximum annual temperatures—important changes in local climate that align with changes perceived by smallholder farmers and affect their exposure and livelihoods. Farmers with IK and LK had a higher adaptive capacity and lower vulnerability than farmers with no IK and LK. Farmers with IK and LK reduced their vulnerability (LVI = 0.379) by using IK and LK weather and seasonal forecasts to make climate-informed decisions that improved food and livelihood strategies compared to farmers with no IK and LK (LVI = 0.412). Farmers with IK and LK diversify the number of crops they plant and implement more crop adaptation responses, thereby diversifying the risk of crop failure and reducing food shortage. Although Indigenous peoples and local communities including smallholder farmers are generally highly vulnerable, this study shows that IK and LK can reduce absolute and relative vulnerability, thus highlighting the important role of IK and LK in reducing smallholder farmers' livelihood vulnerability by improving their adaptive capacity.

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3.1. Introduction

Globally, Indigenous peoples and rainfed smallholder farmers are among the most vulnerable groups to climate change risks (IPCC, 2022c; IPCC, 2023b; Mbow et al., 2019). In addition, Africa is among the most vulnerable regions to climate variability and change, with the vulnerability of smallholder farmers particularly high (Birkmann, J. et al., 2022; IPCC, 2023b; Trisos et al., 2022). With current greenhouse gas mitigation policies projected to result in global warming above 2^{o}C above preindustrial levels by 2100 (IPCC, 2023b), additional warming is expected to disproportionately affect smallholder farming, putting over half a billion families at risk globally (FAO, 2014). In Africa, this risk is exacerbated by the fact that 90–95% of cropland is rainfed agricultural systems and 55–62% of the Sub-Saharan Africa workforce is employed in agriculture (FAO, 2018; International Labour Office, 2018; World Bank, 2020).

Therefore, it is vital to improve our understanding of the drivers of vulnerability and exposure of smallholder farmers' livelihoods to climate variability and change; and how to reduce their exposure and vulnerability. In particular, Indigenous knowledge (IK) and local knowledge (LK) have been recognised for their role in shaping how vulnerable communities across the global south, small island nations, and polar regions understand climate risk and implement measures to adapt (IPCC, 2019b; IPCC, 2022c; IPCC, 2023b). There is increasing evidence of the role that IK and LK can play in adapting to climate impacts, including in agriculture (Berrang-Ford et al., 2021b; Leal Filho et al., 2022b; Mukherji & Kumar, 2021; Petzold et al., 2020; Schlingmann et al., 2021; Zvobgo et al., 2022). IK and LK are recognised as important for climate disaster risk reduction, thus potentially reducing the vulnerability of communities, including those reliant on smallholder farming for their livelihoods (Baumwoll, 2008; Castellanos et al., 2022; Mikulecký et al., 2023; Trisos et al., 2022; Zvobgo et al., 2022).

However, there remains a lack of incorporation and understanding of IK and LK in vulnerability assessments for smallholder farmers, particularly in the literature on the Livelihood Vulnerability Index (LVI) (Monirul Alam et al., 2017), the most widely applied index for assessing vulnerability to climate change in smallholder farming (Adu et al., 2018; Ho et al., 2021; Monirul Alam et al., 2017; Mwadzingeni, Mugandani & Mafongoya, 2021; Panthi et al., 2016; Tessema & Simane, 2019; Williams, Crespo & Abu, 2020). Vulnerability to climate variability and change varies widely across people, sectors, and regions (Ayanlade et al., 2023; Birkmann, Joern et al., 2022; Jurgilevich et al., 2017; O'Neill et al., 2022; Panthi et al., 2016), and livelihood vulnerability assessments have focused on other important dimensions of vulnerability, such as gender (Shah et al., 2013) and the intersection of gender and age (Ayanlade et al., 2023). For smallholder farmers, including consideration of IK and LK in climate change vulnerability assessments can inform the use of IK and LK in adaptation planning and the implementation of feasible adaptation options that are effective at addressing risks (Rurinda et al., 2014a; Williams et al., 2021; Zvobgo et al., 2022).

Another knowledge gap is understanding vulnerability at local levels and how different factors intersect to affect vulnerability locally. Although we have a coarse-grained understanding of general patterns of vulnerability at continental and national levels in Africa, our knowledge is less at local levels, especially in systemically under-researched contexts such as Zimbabwe (Ayanlade et al., 2023; Birkmann, J. et al., 2022; Overland et al., 2021). In addition, sources and levels of vulnerability vary locally, despite exposure to the same climate hazards (Asfaw et al., 2021; Kuran et al., 2020; Rurinda et al., 2014a). For example, IK and LK are one dimension of many factors influencing vulnerability to climate change, with smallholder farmer vulnerability differing owing to socioeconomic factors, land resource allocation, and geographic location (among others) (Asfaw et al., 2017; Bryceson, 2019; Clay & Zimmerer, 2020; Hufe & Heuermann, 2017; Jayne et al., 2019a; Jayne et al., 2019b). We have insufficient knowledge on how multiple existing stressors combine with climate change at the local level to affect the vulnerability of smallholder farmers (Ayanlade et al., 2023; O'Brien, Quinlan & Ziervogel, 2009). Therefore, to better understand the differences in vulnerability in Africa across gender, age, migrant status, ethnicity, and other social and cultural factors, including Indigenous peoples and their knowledge systems and lifeways, it is crucially important for vulnerability analysis to start at local levels (Ayanlade et al., 2023). For smallholder farmers, information about local-level vulnerability is important for designing feasible adaptation strategies that are effective in addressing risks, including the consideration of IK and LK in adaptation planning and implementation (Rurinda et al., 2014a; Williams et al., 2021; Zvobgo et al., 2022). This local approach can also help advance the understanding of the distributional consequences of climate change impacts and aid in the development of targeted response strategies for those who are more vulnerable, such as women in patrilineal kinship systems, people living with disabilities, youth, girls, and the elderly (Azong & Kelso, 2021; Trisos et al., 2022).

To address these knowledge gaps, we used IK and LK lenses to unpack livelihood vulnerability for smallholder farmers at the local level by integrating IK and LK components into the LVI approach. We explored the local vulnerability of smallholder farmers reliant on rain-fed agriculture in Chiredzi district in Zimbabwe, a district with high rainfall variability and where food shortages among smallholder farmers are common. We focused on how different dimensions of farmer experience and localities intersect to contribute to vulnerability to climate risks.

3.2. Conceptualising Livelihood vulnerability of farmers in Chiredzi

A thematic sector approach was employed that focused on the key sectors that sustain the livelihoods of rainfed smallholder farmers in the Chiredzi District to assess their vulnerability to climate change. The thematic sectors we considered were food (food production and food security), water resources, natural resources (especially firewood for fuel), and health because these sectors are key to the livelihoods of smallholder farmers in Chiredzi (UNDP, 2012) (and in Africa more widely), and yet are at risk from climate change (IPCC, 2022c; Pörtner et al., 2022; Talukder et al., 2021; Trisos et al., 2022). These sectors were used to inform the components of the LVI analysis.

To understand how smallholder farmers in Chiredzi are vulnerable to climate variability and change, the LVI approach was applied with an additional strong focus on understanding the role of IK and LK in determining farmers' vulnerability. Particular attention was paid to IK and LK in the development of indicators, as local perceptions and experiences of climate extremes help identify factors that enable or constrain smallholder farmers ability to respond to climate variability and change (Shah et al., 2013). We used the LVI approach because it incorporates multiple components of sensitivity and adaptive capacity in more depth when assessing local-level vulnerability than other climate change vulnerability assessment methods, such as the social vulnerability index, sustainable livelihood approach, climate vulnerability index, and vulnerability as expected poverty tool (Arias et al., 2016; Bouroncle et al., 2017; Chambers & Conway, 1992; Dumenu & Takam Tiamgne, 2020; Monirul Alam et al., 2017). The LVI also integrates exposure to climate hazards and accounts for farmers' adaptation responses, which are key to the comprehensive evaluation of livelihood risks resulting from climate variability and change (Hahn, Riederer & Foster, 2009). This makes the LVI more relevant to emerging thinking on complex climate risk and the updated definition of risk in the IPCC's 6th Assessment Report (AR6), which now emphasises the importance of responses to climate change as a determinant of risk (Ara Begum et al., 2022; Simpson, Nicholas P. et al., 2023; Simpson, Nicholas P. et al., 2021b).

Previous case studies have applied LVI using seven components identified by Hahn, Riederer and Foster (2009) to better understand the local complexities of smallholder farmers' livelihood vulnerability to climate variability and change (Adu et al., 2018; Asfaw et al., 2021; Ho et al., 2021; Mugandani, Raymond et al., 2022; Mwadzingeni, Mugandani & Mafongoya, 2021; Panthi et al., 2016; Sarker et al., 2019; Tessema & Simane, 2019; Williams, Crespo & Abu, 2020). In all these case studies, the LVI was modified by adding more components to the estimation of vulnerability to address the research and study area context. In this study, we adapted the LVI to have 11 main components by adding four components focused on: Indigenous Knowledge and Local Knowledge, education and training, land, and natural resources (Figure 3-1). The 11 components were further specified and estimated using 44 sub-components identified as important for understanding vulnerability levels in Chiredzi (Table 3-1 and Methods).

The IK and LK component considers the use of IK and LK for weather and seasonal forecasting, the use of IK and LK weather and seasonal forecasts for implementing adaptation measures, the number of crop adaptation responses, and access to scientific weather forecasting. These subcomponents were developed to encompass important pathways through which IK and LK could shape vulnerability, considering: (1) the demonstrated importance of IK and LK for weather and seasonal climate forecasts for smallholder farmers across Africa (Adanu, Abole & Gbedemah, 2022; Balehegn et al., 2019; Nkuba, M. R. et al., 2020; Salite, 2019; Ubisi, Kolanisi & Jiri, 2020); (2) evidence that the use of IK and LK seasonal forecasts by farmers in Chiredzi is associated with an increased number of adaptation options being implemented (Jiri, O, Mafongoya & Chivenge, 2015; Zvobgo, Luckson et al., 2023); (3) that IK and LK forecasts are blended with scientific forecasts to inform adaptation measures (Nyadzi, Emmanuel et al., 2022; Streefkerk et al., 2022); and (4) the number of crop adaptation responses informed by IK and LK. The aim was to establish the role of IK and LK in reducing or increasing smallholder farmers' vulnerability to climate variability.

The education and training component was also added – the levels of farmer education and other climate-related training received by farmers from government extension officials or relevant NGOs operating in the district. This is because in Africa and globally, climate change literacy increases with education and can be important in the implementation of adaptation responses and determining the urgency of responding to climate change thereby potentially reducing vulnerability (Saleh Safi, James Smith Jr & Liu, 2012; Simpson, Nicholas P. et al., 2021a; Trisos et al., 2022). The land components considered were access to farmland and evidence of land degradation. Limited access to land resources affects smallholder farmers' agricultural productivity in Africa, thus increasing their vulnerability, as they mostly rely on agriculture for their livelihoods (Bryceson, 2019; Hufe & Heuermann, 2017; Jayne et al., 2019b). Also, climate change hazards have degraded farmlands and reduced the productivity of land, negatively affecting food security and thus increasing the vulnerability of farmers (Olsson et al., 2019; UN, 2018; Webb et al., 2017). The natural resources component considers the availability of other natural resources that can diversify farming livelihoods, which affects the vulnerability of farmers to climate change impacts (Nigussie et al., 2018). The natural resources component also includes household energy sources, as most rural communities in Zimbabwe rely on firewood (International Renewable Energy Agency, 2022; Republic of Zimbabwe, 2021). This has a potential long-term impact on climate mitigation, affecting the occurrence of climate hazards and increasing future vulnerability.

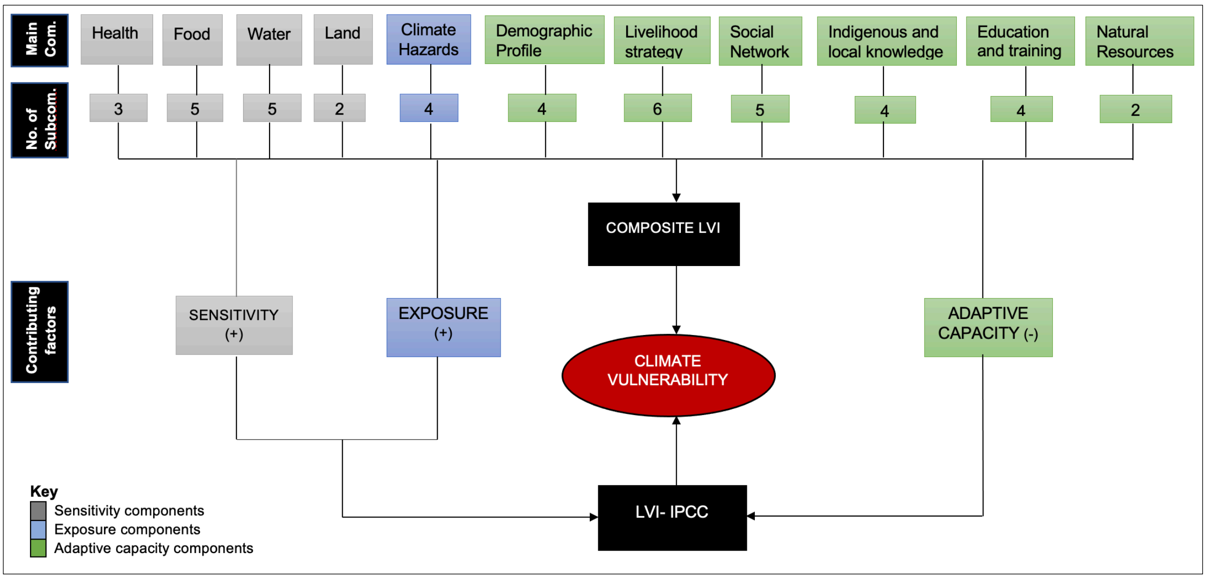

Figure 3-1: Illustration of 11 main components and 44 subcomponents that were used to calculate the composite LVI in this study and further grouped into three LVI–IPCC contributing factors (sensitivity, exposure and adaptive capacity) for calculating the LVI–IPCC. It also locates the Indigenous knowledge and local knowledge and its role in addressing the adaptive capacity of smallholder farmers, which is new for LVI assessment. As sensitivity and exposure increase, they contribute to an increase in the LVI–IPCC index of vulnerability whereas an increase in adaptive capacity leads to a decrease in LVI–IPCC.

In addition to the LVI, we also calculated the LVI–IPCC which separates out the individual contributions of the components of sensitivity, exposure, and adaptive capacity to vulnerability (Hahn, Riederer & Foster, 2009). For LVI–IPCC vulnerability is defined as follows:

$$\text{Vulnerability} = f(S + E) - A) \qquad (1)$$

where S is the sensitivity or susceptibility of the system/human to harm

E is the exposure to climate hazard and A is the capacity to adapt or cope

Increases in sensitivity and exposure contribute to an increase in the LVI–IPCC index of vulnerability, whereas an increase in the adaptive capacity decreases vulnerability. Sensitivity to climate hazards was measured based on how important livelihood systems (food security, water security, land, and health) were adversely affected by climate variability and change. For example, the distance to reliable potable water, sufficient food for farmers and access to health infrastructure can be affected by occurrences of climate hazards such as floods and drought. Exposure of the farmers was measured by the number of climate hazards experienced by farmers, the number of farmers receiving early warnings for climate hazards, and the related human and physical property losses and damages. Finally, adaptive capacity was quantified by farmers' use of IK and LK for climate adaptation to reduce or increase their vulnerability; demographic profiles, such as age and gender, which affect the implementation of adaptation responses by farmers; education and training received by farmers as climate literacy influences adaptation response implementation; and the strength of social networks for social safety nets and information sharing required for climate adaptation.

To conceptualise livelihood vulnerability to climate variability and change in Chiredzi, the climate perceptions of smallholder farmers were also assessed. Perceptions of change can positively or negatively affect farmers' risk perceptions and urgency, which influence their actions (Simpson, Nicholas P. et al., 2021a; Trisos et al., 2022). These actions are important for understanding the adaptive capacity of the farmers in this study. These actions can reduce or increase the vulnerability of farmers depending on the adaptation responses implemented (Arbuckle, Morton & Hobbs, 2015; Owusu et al., 2021). Thus, understanding farmers' perceptions of change is an important aspect of understanding smallholder farmers' vulnerability to climate variability and change.

3.3. **Methods**

3.3.1. **Study area**

Chiredzi district is located in Natural Region V of the Zimbabwe Agro-Ecological Zones, which is the driest region in Zimbabwe. It is a semi-arid region that receives average total annual rainfall of 500 mm per annum (Chikodzi & Mutowo, 2012; Mugandani, R et al., 2012). Rainfall patterns in Chiredzi are highly variable (Jiri, Obert, Mafongoya & Chivenge, 2017; Manatsa et al., 2020), making it one of the most vulnerable to increased climate variability (Unganai, Leonard S & Murwira, 2010). The high reliance on rain-fed smallholder agriculture as the main source of livelihood in the district exacerbates vulnerability (Jiri, O, Mafongoya & Chivenge, 2015). Chiredzi has been assessed as a hotspot for climate hazards in Zimbabwe, with drought being a major climate hazard (UNDP, 2016). Maize and sorghum are cereal staple crops grown by rainfed smallholder farmers and provide food to the majority of the Chiredzi population (Mupakati & Tanyanyiwa, 2017; Unganai, Leonard S & Murwira, 2010; Zvobgo, Luckson et al., 2023). Smallholder farmers in Chiredzi have one growing season per year, and the produce obtained should last 12 months until the next harvest. Food shortages in Chiredzi are common among smallholder farmers and have been linked to adverse climate conditions, mostly droughts, rainfall uncertainties, and high temperatures (Chafa, Jaka & Chazireni, 2021; Defe & Matsa, 2021; UNDP, 2012; Unganai, Leonard S & Murwira, 2010). Chiredzi is among the poorest districts in Zimbabwe (Zimbabwe Vulnerability Assessment Committee, 2017; ZimStat, 2015).

Vulnerability assessment in this study used a ward-level scale for two main reasons. First, the Zimbabwe National Adaptation Planning (NAP) roadmap recommends a ward as the smallest unit for adaptation planning in Zimbabwe (Government of Zimbabwe, 2019). Second, the United Nations Development Programme mapped climate hazards affecting Zimbabwe at the ward level (UNDP, 2016).

3.3.2. **Sampling and socioeconomic data collection**

A participatory vulnerability assessment approach (Rurinda et al., 2014a) was used to collect socioeconomic data from smallholder farmers in Chiredzi. Data collection was conducted in five wards of the Chiredzi rural district: 1, 3, 25, 27, and 32 (Figure 1-1). The five wards considered in this study constitute 15% of the 32 wards of the Chiredzi rural district. We considered only five wards because of limited resources and time allocated for data collection. The five wards were strategically selected from two clusters: three from communal areas; and two from resettled farmlands. Communal wards consisted of farmers who had stayed in one area for several decades or longer. Resettled wards consisting of farmers that since 2000 were reallocated land under Zimbabwe’s land reform programme to formerly commercially managed ranches that had not been previously occupied by settlement (Chaumba, Scoones & Wolmer, 2003; Ndhlovu, Emmanuel, 2018). These two categories of settlement were considered because farming types are different and other key structural infrastructure and sectors that support livelihoods, such as clinics, clean water access (water and sanitation), IK and LK, access to land, social networks, government support and programs were different, which are key in assessing livelihood vulnerability in this study. The exact wards to sample in each cluster were further selected based on whether the ward was located in or near the main river valleys (Save and Mtirikwi), or whether the ward was from dryland conditions. This was essential for establishing the impact of the Save and Mtirikwi Valleys (via the availability of continuous water supply and traditional irrigation techniques) on the livelihoods of smallholder farmers and the effect of different farming types on the vulnerability to climate risks of the smallholder farmers in Chiredzi. For resettled areas, one ward along the Mtirikwi Valley was selected (ward 27) and one ward from dryland conditions was selected (ward 32). For communal areas, two wards along the Save Valley were selected (wards 1 and 25) and one ward from dryland conditions (ward 3).

A cross-sectional household survey of 100 smallholder farmers was conducted to investigate the extent of their vulnerability to risks from climate variability and change and to understand the factors contributing to vulnerability (see Supplementary Material 2 with the questionnaire). Multi-stage sampling (Etikan & Bala, 2017; Kuno, 1976) was used to select wards and villages. Four villages were selected from each ward to ensure uniform sampling across the ward. In each village, five households were randomly selected for interviews. The survey was conducted in the local language to ensure participation and engagement with farmers. Data were collected from October to November 2021, toward the beginning of the new growing season. During this period, smallholder farmers faced off-season food shortages and limited access to potable water. The timing of the survey was important for establishing whether farmers were producing sufficient food to last until the following season. Ethical clearance was obtained from the University of Cape Town (FSREC 002–2021). Permission from the headman was obtained before conducting the surveys in each village. Free and informed consent was obtained before each interview with each respondent. The farmers' participation was free and anonymous.

3.3.3 **Vulnerability assessment in Chiredzi**

A three-tier approach was used to assess the vulnerability of farmers and their exposure to climate variability and change. First was the analysis of socioeconomic data from the household survey to estimate farmers' livelihood vulnerability to climate risks using composite LVI to estimate overall vulnerability, and LVI–IPCC to differentiate and distinguish differences in vulnerability due to sensitivity, exposure, and adaptive capacity, including the role of IK and LK in improving adaptive capacity. Second, the exposure of smallholder farmers to climate variability and climate change hazards was further quantified using statistical analysis of trends in weather station climate data from Chiredzi. Third, we collected data on farmers' perceptions of climate variability and change to better understand their perspectives on exposure and to assess the alignment of their perceptions with statistical analysis of climate trends, as well as the role of perceptions on risk and urgency that influence actions taken by farmers that reduce or increase their vulnerability.

3.3.4 **Data analysis for LVI and LVI-IPCC**

Two sets of analyses were performed to analyse farmers' livelihood vulnerability: (i) calculation of a balanced weighted average LVI ("composite LVI" illustrated in Figure 3-1) and (ii) calculation of exposure, sensitivity, and adaptive capacity as the three contributing factors for the LVI-IPCC (Section 3.3.4.2; Figure 3-1). LVI and LVI–IPCC were calculated for each of four categories: farmers using IK and LK, farmers with no IK and LK, farmers in communal areas, and farmers in resettled areas.

3.3.4.1 **LVI analysis**

The LVI assessment used 11 main components, comprising 44 sub-components, to calculate livelihood vulnerability (Figure 3-1; Table 3-1; Supplementary Material 2 Table 2). We used the guidelines outlined by Winograd (2007) on how to define and use indicators that reduce environmental, social, and economic vulnerability and increase sustainability when developing sub-components for Chiredzi. See Supplementary Material 2 Table 2-2 for a description of each sub-component and the related household survey questions used to estimate the sub-component.

The LVI balanced weighting concept (Sullivan, Meigh & Fediw, 2002) was applied in which every subcomponent contributed equally to the overall index, although each main component was composed of a different number of subcomponents. The sub-components were standardised because they were measured using different scales. This was performed to combine all the measures into a single LVI index. The subcomponents are standardised using the following expression:

$$index_{s_w} = \frac{s_w - s_{min}}{s_{max} - s_{min}} \qquad (2)$$

where s_w is the original sub-component for Ward w,

S_{min} and S_{max} are the minimum and maximum values, respectively, for each subcomponent determined using data from both wards.

To calculate the value of each main component after subcomponent standardisation, subcomponents were averaged using the following expression:

$$M_w = \frac{\sum_{i=1}^{n} index_{s_{wi}}}{n} \qquad (3)$$

where M_w is one of the 11 main components in Ward w

$index_{S_w i}$ represents the subcomponents, indexed by i, that make up each main component,

n is the number of sub-components in each main component.

The calculated values for each of the 11 main components for a ward were obtained using the following expression to establish the ward-level LVI:

$$LVI_w = \frac{\sum_{i=1}^{10} w_{M_i} M_i}{\sum_{i=1}^{10} w_{M_i}} \quad (4)$$

where LVI_w is the Livelihood Vulnerability Index for Ward w, equals the weighted average of the 11 main components.

The weights of each main component, w_{M_i}, were determined by the number of sub-components that make up each main component (Sullivan, Meigh & Fediw, 2002). They were averaged to ensure that all main components contribute equally to the overall LVI of the ward. The overall LVI was scaled from 0 as the least vulnerable to 0.5 as most vulnerable (Hahn, Riederer & Foster, 2009).

Table 3-1: Main and subcomponents comprising the LVI developed for the assessment (with IK and LK added as main component) of smallholder farmers' livelihood vulnerability to climate variability in Chiredzi. See the Supplementary Material 2 Table 2-2 for a detailed explanation of the components and how they contributed to the vulnerability assessment in Chiredzi.

Capitals	Main	Subcomponents	Unit	Source
Human	Food	1. Percent of households dependent on family farm for food	Percent	(Hahn, Riederer & Foster, 2009)
		2. Average number of months households struggle to get food (range: 0–12)	Months	(Hahn, Riederer & Foster, 2009)
		3. Percent of households who do not save crops	Percent	(Huong, Yao & Fahad, 2019)
		4. Average Crop Diversity Index (range: >0–1)	1/no. crops	(Hahn, Riederer & Foster, 2009), Modified
		5. Percent of households that do not sell/ barter trade crops for other food supplies	Percent	(Shah et al., 2013)
	Livelihood strategy	6. Percent of households without family member working in a different community in Zimbabwe	Percent	(Hahn, Riederer & Foster, 2009), Modified
		7. Percent of households without family member working in diaspora	Percent	Developed for this study
		8. Percent of households dependent solely on crop production as source of income	Percent	(Hahn, Riederer & Foster, 2009), Modified
		9. Percent of households do not practice mixed farming	Percent	Developed for this study
		10. Percent of households without non-agricultural livelihood income contribution	Percent	(Shah et al., 2013)
		11. Average Agricultural Livelihood Diversification Index (range: 0.2 –1)	1/no. livelihoods	(Hahn, Riederer & Foster, 2009)
	Health	12. Average distance to a health facility	Meters	(Hahn, Riederer & Foster, 2009), Modified
		13. 13. Percent of households with family member with chronic illness	Percent	(Hahn, Riederer & Foster, 2009)
		14. Percent of households where a family member had to miss work or school in the last 2 weeks due to illness	Percent	(Hahn, Riederer & Foster, 2009)

	Education and climate change training (modified)	15. Percent of households where household head has not attended school	Percent	(Hahn, Riederer & Foster, 2009)
		16. Percent of households where household head just passed primary school	Percent	(Huong, Yao & Fahad, 2019)
		17. Percent of households where household head did not attend tertiary learning.	Percent	Developed for this study
		18. Percent of households where a family member did not receive any training or information shared to them on climate change impacts and its causes.	Percent	Developed for this study
	Indigenous knowledge and local knowledge (new)	19. Percent of households do not use indigenous and local knowledge for weather and seasonal climate forecasting	Percent	Developed for this study
		20. Percent of farmers that do not make climate decisions and implement adaptation measures from indigenous and local knowledge forecasts	Percent	Developed for this study
		21. Average Crop Adaptation Response (CAR) Index (range: 0 –1)	1/no. of CAR	Developed for this study
		22. Percent of households that do not have access to scientific weather and climate forecasting	Percent	Developed for this study
Social	Socio-demographic profile	23. Dependency ratio	Ratio	(Hahn, Riederer & Foster, 2009), Modified
		24. Percent of female-headed households	Percent	(Hahn, Riederer & Foster, 2009)
		25. Average number of family members in a household	Persons	(Huong, Yao & Fahad, 2019)
		26. Percent of households with members needing dependent care	Percent	(Shah et al., 2013)
	Social network	27. Average Receive: Give ratio (range: 0–15)	Ratio	(Hahn, Riederer & Foster, 2009)
		28. Percent of households do not have access to government subsidies and support on agricultural production inputs in the past 12 months and other social welfare and safety net programmes including NGO support.	Percent	(Williams, Crespo & Abu, 2020), Modified
		29. Percent of households not associated with any farmer-based organization (FBO)	Percent	(Williams, Crespo & Abu, 2020)
		30. Percent of households not having communication devices	Percent	(Williams, Crespo & Abu, 2020)
		31. Percent of households not associated with any community social group	Percent	(Williams, Crespo & Abu, 2020)
Natural	Natural resources	32. Percent of households that depend on (exploit) natural resources	Percent	(Huong, Yao & Fahad, 2019)
		33. Percent of households using only forest-based energy for cooking purpose	Percent	(Huong, Yao & Fahad, 2019)
	Land	34. Percent of households with small farmland (0.1–0.5 ha)	Percent	(Huong, Yao & Fahad, 2019)
		35. Percentage of households reporting land degradation by climate-related extremes during past 20 years	Percent	(Huong, Yao & Fahad, 2019)
	Water	36. Percent of household that collect water directly from natural water system	Percent	(Shah et al., 2013)
		37. Inverse of the average number of litres of water stored per household (range: > 0–1)	Percent	(Hahn, Riederer & Foster, 2009)
		38. Percent of household that do not collect water from a reliable source	Percent	Developed for this study
		39. Number of boreholes in a ward	Count	Developed for this study
		40. Average distance to water source	Meters	(Williams, Crespo & Abu, 2020)
	Climate hazards	41. Average number of floods, drought, and cyclone events in the past 20 years as accounted by the farmers (range: 0 – 10)	Count	(Hahn, Riederer & Foster, 2009)
		42. Percent of households that did not receive a warning about the about expected natural disasters/event	Percent	(Hahn, Riederer & Foster, 2009)
		43. Percent of households with an injury or death as a result of the most severe natural disaster in the past 20 years	Percent	(Hahn, Riederer & Foster, 2009)
		44. Percent of households with losses to physical assets (house/ machinery) due to flooding	Percent	(Shah et al., 2013)

3.3.4.2. **LVI–IPCC analysis**

The 11 main components of the LVI for Chiredzi were grouped into three LVI–IPCC contributing factors: exposure, sensitivity, and adaptive capacity (Figure 3-1). The main purpose of applying the LVI–IPCC was to understand and explore the adaptive capacity potential of the four categories: farmers using IK and LK, farmers with no IK and LK, farmers in communal areas, and farmers in resettled areas. The LVI–IPCC elaborates the differences in adaptive capacity in vulnerability analysis better as the three contributing factors of the vulnerability framework are studied compared to the balanced weighting of the composite LVI above. Vulnerability was calculated using the following equation.

$$\mathrm{CF}_d = \frac{\sum_{i=1}^{n} w_{Mi} M_{di}}{\sum_{i=1}^{n} w_{Mi}} \quad (5)$$

where CF_d is an IPCC defined contributing factor (exposure, sensitivity, and adaptive capacity) for community d,
M_{di} are main components for community d indexed by i,
w_{Mi} is the weight of each main component, and
n is the number of main components in each contributing factor.

Once the exposure, sensitivity, and adaptive capacity were calculated, the three contributing factors were combined (Hahn, Riederer & Foster, 2009; IPCC, 2014a) using the following formula:

$$\mathrm{LVI\ IPCC}_w = (e_w - a_w) \times s_w \quad (6)$$

where $\mathrm{LVI\ IPCC}_w$ is the LVI for the Ward w expressed using the IPCC vulnerability framework
e is the calculated exposure index for the Ward w,
a is the calculated adaptive capacity index (taking the inverse of the adaptive capacity sub-component indicators) for the Ward w and
s is the calculated sensitivity index for the Ward district w.

The LVI–IPCC was scaled from -1 as the least vulnerable to 1 as the most vulnerable.

3.3.4.3. **Observed climate data analysis**

Observed daily precipitation (1972–2021) and temperature (2001–2021) data were used for long-term trend analysis. The timeframe for the observed data analysis was selected on the basis of data availability. Data were obtained from a local weather station at the Malilangwe Conservancy Trust (Figure 1-1). To assess how smallholder farmers have been exposed to climate variability and change, we quantified variability and multidecadal trends in temperature and rainfall in Chiredzi district. The focus was mainly on climate indices that were shown to be important for maize and sorghum crops, which are staple crops in Chiredzi. The selection of the indices was further based on farmers' perceptions of the climate and relevance of the indices for the two most critical decisions faced by rainfed smallholder farmers: (i) when to plant and (ii) which seed or cultivar to plant (Tadross, M. et al., 2009). Sixteen rainfall, temperature, and extreme event indices were considered (Table 3-2).

Table 3-2: Climate indices and trends measured for Chiredzi. The details of the metrics used for the rainy season onset, cessation, length of the rainy season, and thresholds for hot days are described here for maize. Those for sorghum are provided in the Supplementary Material 2. Dekad: 10 d period.

Parameter	Indices	Description	Reference crop	Sources
Temperature	Temperature change	Trends in the minimum and maximum temperature at annual and seasonal scales (rainy season; Nov–April).	All crops	(Tartakovsky, Cheredko & Maksimov, 2021)
	Hot days	The number of days with maximum temperature above 30 °C in December, January, February (DJF) months of the growing season.	Maize	(Lobell et al., 2011; Rurinda et al., 2014a)
Rainfall	Total seasonal rainfall	Trends in the total rainfall received per rainy season (Nov–April).	All crops	(Raes et al., 2004)
	Rainy season onset/ start	25 mm of accumulated rainfall in 10 d (after 1 August), without 10 consecutive dry days (rainfall <2 mm) occurring in the next 20 d.	Maize	(Tadross, M. et al., 2009)
	Rainy season cessation	3 consecutive dekads, each <20 mm (d after 1 Feb).	Maize	(Tadross, M. et al., 2009)
	Rainy season length	The number of days between start and cessation of the rainy season.	All crops	(Mupangwa, Walker & Twomlow, 2011; Tadross, M. et al., 2009)
	Wet (agricultural rain) days	Number of days in a rainy season receiving 5mm or more of rainfall (Nov–April).	Maize	(Mugiyo et al., 2021)
	Consecutive Dry days (CDD)	The longest period of consecutive days during the rainy season in which <1mm of precipitation has fallen (Nov–April).	All crops	(Nnoli et al., 2020)
	CDD5 and CDD10	The number of occurrences of 5 consecutive dry days (CDD5) or 10 days (CDD10) during the rainy season.	All crops	(Winsemius et al., 2014)
Extreme events	Drought	Used the Standardised Precipitation Index: A drought measure specified as a	All crops	(McKee, Doesken & Kleist, 1993; Tirivarombo, Osupile & Eliasson, 2018)

	precipitation deficit calculated over 3 months - SPI-3 (Dec–Feb) and 6 months SPI-6 (Nov–April). Values from 0 to -0.9 show mild drought, -1 to -1.49 is moderate drought, -1.5 to -1.99 is severe drought and < -2 .00 is extreme drought.		
Storm days	The number of events with at least 100 mm of rain within five consecutive days during the rainy season (Nov–April).	All crops	(Mugiyo et al., 2021)
Hottest day	Warmest daily maximum temperature.	All crops	(Peterson et al., 2001)
Hottest night	Warmest daily minimum temperature.	All crops	(Peterson et al., 2001)
Coldest day	Coldest daily maximum temperature.	All crops	(Peterson et al., 2001)
Coldest night	Coldest daily minimum temperature.	All crops	(Peterson et al., 2001)

Precipitation and minimum and maximum temperature data were analysed at seasonal and annual timescales. We applied the non-parametric Mann–Kendall tau test (Kendall, 1975; Mann, 1945) to assess the statistical significance of trends in time series of the climate indices, and then used the Sen slope estimator (Sen, 1968) to determine the magnitude of the trends. All analyses were performed in *R* statistical package. We used the Mann–Kendall test because of its tolerance of outliers (Hamed & Ramachandra Rao, 1998), and ability to detect monotonic trends in climate data time series (Aditya, Gusmayanti & Sudrajat, 2021; Pohlert, 2017).

3.3.4.4 **IK and LK and climate perceptions of the farmers**

Data on farmers' climate perceptions were collected from 100 smallholder farmers (see Section 3.2. with details of the sampling process). Farmers were asked to state their opinions about changes in rainfall and temperature over the past seven years and the signs they observed for climate change over the past two decades (see Supplementary Material). The proportion of farmers perceiving a specific change in climate in Chiredzi was compared with the observed climate data analysis to assess the extent of alignment or misalignment of farmers' perceptions with climate trends. The role of IK and LK in shaping farmers' climate perceptions was statistically tested using the Pearson Chi-Square (χ^2) test (Pearson, 1900). A χ^2 test of independence was performed for farmers with IK and LK and with no IK and LK. The null hypothesis (H_0) was: the proportion of farmers who perceived a particular climate condition are the same for farmers with IK and LK and those with no IK and LK.

3.4 Results

3.4.1 Smallholder farmer vulnerability in Chiredzi

Farmers with IK and LK had a lower overall livelihood vulnerability (LVI = 0.379) than farmers with no IK and LK (LVI = 0.412) (Figure 3-2 and Table 3-3). Farmers with IK and LK had lower vulnerability in the food component of LVI (Figure 3-2). The difference in vulnerability in the food component was driven by farmers with IK and LK planting a greater diversity of crop types (Food subcomponent 4 in Table 3-3) and a higher percentage of farmers with IK and LK saving crop yields (Food subcomponent 3), leading to farmers with IK and LK having fewer months of struggle with food shortages (Food subcomponent 2) compared to farmers with no IK and LK (Table 3-3). In addition, farmers with IK and LK implemented more crop adaptation responses, including changing the timing of planting and use of indigenous drought-resistant seeds (Indigenous and local knowledge subcomponent 21) compared with farmers with no IK and LK (Table 3-3).

Farmers in resettled wards were more vulnerable (LVI = 0.408) than those in communal wards (LVI = 0.376) (Figure 3-2). This difference in vulnerability was driven by farmers in resettled areas being more vulnerable in the health and social network components, which are key for increasing the adaptive capacity of farmers (Table 3-3). The main difference between resettled and communal farmers in the health component was the longer distance to the nearest healthcare facility for farmers in resettled areas (Health subcomponent 12 in Table 3-3). The difference in the social network component of vulnerability was due to a lower percentage of farmers in resettled wards receiving government subsidies and support with agricultural inputs, social welfare and safety net programmes, and NGO support (Social network subcomponent 28), a higher percentage of farmers in resettled wards not associated with any farmer-based organization (Social network subcomponent 29), and a higher percent of households not having communication devices (Social network subcomponent 30) that they can use to receive weather and seasonal forecasts and other important farming advice required to increase their adaptive capacity which reduces vulnerability (Table 3-3).

Table 3-3: Livelihood Vulnerability Index (LVI) main components, sub-components, and overall LVI of the four categories of farmers assessed: farmers with IK and LK, farmers with no IK and LK, farmers in communal wards, and farmers in resettled wards. Values range from 0 to 1 and lower values indicate lower vulnerability for a particular component or subcomponent. Values have been rounded to three decimal places.

Main components	Farmers with IK and LK	Farmers with no IK and LK	Communal wards	Resettled wards	Sub-components	Farmers with IK and LK	Farmers with no IK and LK	Communal wards	Resettled wards
Food	0.432	0.528	0.472	0.453	1. Percent of households dependent on family farm for food	0.98	0.926	0.97	1
					2. Average number of months households struggle to get food (range: 0–12)	0.420	0.59	0.448	0.479
					3. Percent of households who do not save crops	0.055	0.217	0.05	0.15
					4. Average Crop Diversity Index (range: >0–1)	0.087	0.129	0.126	0.058
					5. Percent of households that do not sell/ barter trade crops for other food supplies	0.616	0.778	0.767	0.577
Livelihood strategy	0.295	0.339	0.307	0.3	6. Percent of households without family member working in a different community in Zimbabwe	0.699	0.963	0.8	0.725
					7. Percent of households without family member working in diaspora	0.466	0.407	0.367	0.575
					8. Percent of households dependent solely on crops production as source of income	0.137	0.185	0.133	0.175
					9. Percent of households do not practice mixed farming	0.315	0.259	0.35	0.225
					10. Percent of households without non-agricultural livelihood income contribution	0.014	0.074	0.03	0
					11. Average Agricultural Livelihood Diversification Index (range: 0.2 –1)	0.139	0.144	0.165	0.103
Health	0.396	0.368	0.215	0.433	12. Average distance to a health facility	0.365	0.364	0.111	0.689
					13. Percent of households with family member with chronic illness	0.411	0.407	0.2	0.21
					14. Percent of households where a family member had to miss work or school in the last 2 weeks due to illness	0.411	0.333	0.333	0.4
Education and climate change training	0.51	0.546	0.475	0.563	15. Percent of households where household head has not attended school	0.164	0,222	0.15	0.225
					16. Percent of households where household head just passed primary school	0.6712	0.63	0.633	0.6
					17. Percent of households where household head did not attend tertiary learning.	0.973	1.000	0.967	1
					18. Percent of households where a family member did not receive any training or	0.233	0.333	0.15	0.425

Main components	Farmers with IK and LK	Farmers with no IK and LK	Communal wards	Resettled wards	Sub-components	Farmers with IK and LK	Farmers with no IK and LK	Communal wards	Resettled wards
					information shared to them on climate change impacts and its causes.				
Indigenous and local knowledge	0.069	0.42	0.178	0.201	19. Percent of households do not use indigenous and local knowledge for weather forecasting	0.002	1.00	0.267	0.275
					20. Percent of farmers that do not implement planning and adaptation measures from indigenous knowledge	0.069	1.00	0.3	0.35
					21. Average Crop Adaptation Response (CAR) Index (range: 0 –1)	0.042	0.076	0.045	0.054
					22. Percent of households that do not have access to scientific weather forecasting	0.096	0.185	0.1	0.125
Socio-demographic profile	0.375	0.368	0.414	0.333	23. Dependency ratio	0.049	0.048	0.051	0.055
					24. Percent of female-headed households	0.589	0.593	0.683	0.45
					25. Average number of family member in a household	0.45	0.423	0.461	0.415
					26. Percent of households with members needing dependent care	0.411	0.407	0.333	0.525
Social network	0.567	0.584	0.485	0.643	27. Average Receive: Give ratio (range: 0–15)	0.466	0.440	0.466	0.44
					28. Percent of households do not have access to government subsidies and support on agricultural production inputs in the past 12 months and other social welfare and safety net programmes from both government and NGO.	0.644	0.704	0.583	0.775
					29. Percent of households not associated with any farmer-based organization (FBO)	0.452	0.592	0.243	0.575
					30. Percent of households not having communication devices	0.48	0.40	0.4	0.55
					31. Percent of households not associated with any community social group	0.795	0.778	0.733	0.875
Natural resources	0.519	0.519	0.525	0.513	32. Percent of households that depend on (exploit) natural resources	0.039	0.037	0.05	0.025
					33. Percent of households using only Forest-based energy for cooking purpose	1.00	1.000	1.00	1.00
Land	0.48	0.426	0.450	0.438	34. Percent of households with small farmland (0.1–0.5 ha)	0.055	0.074	0.067	0.025
					35. Percentage of households reporting land degradation by climate-related extremes during past 20 years	0.904	0.778	0.833	0.85

Main components	Farmers with IK and LK	Farmers with no IK and LK	Communal wards	Resettled wards	Sub-components	Farmers with IK and LK	Farmers with no IK and LK	Communal wards	Resettled wards
Water	0.333	0.317	0.327	0.324	36. Percent of household that collect water directly from natural water system	0.082	0.074	0.117	0
					37. Inverse of the average number of liters of water stored per household (range:>0–1)	0.81	0.798	0.799	0.819
					38. Percent of household that do not collect water from a reliable source	0.288	0.259	0.433	0.05
					39. Average number of boreholes in a village	0.20	0.214	0.187	0.23
					40. Average distance to water source	0.283	0.241	0.102	0.522
Climate hazards	0.294	0.262	0.294	0.273	41. Average number of floods, drought, and cyclone events in the past 20 years as accounted by the farmers (range: 0 – 10)	0.45	0.419	0.46	0.418
					42. Percent of households that did not receive a warning about the about expected natural disasters/event	0.479	0.481	0.4	0.6
					43. Percent of households with an injury or death as a result of the most severe natural disaster in the past 20 years	0.014	0.0	0.017	0.0
					44. Percent of households with losses to physical assets (house/ machinery) due to flooding and cyclones	0.233	0,148	0.30	0.075
Overall LVI	**0.379**	**0.412**	**0.373**	**0.404**					

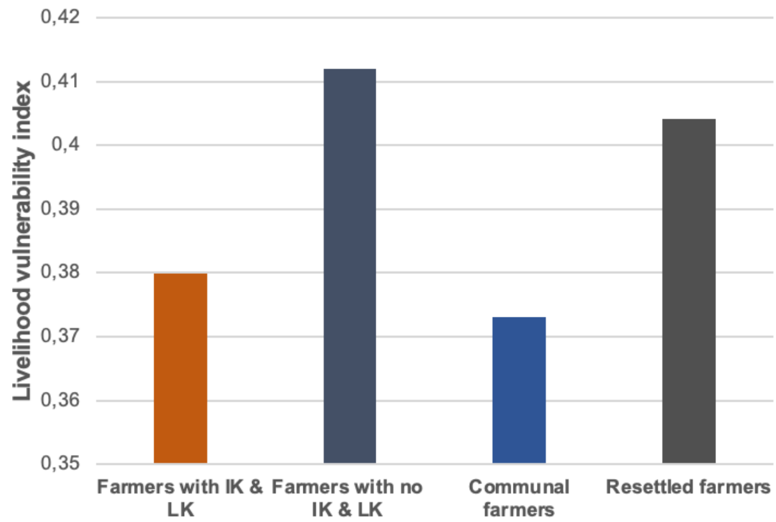

Figure 3-2: Overall livelihood vulnerability of various categories of smallholder farmers in Chiredzi: farmers with IK and LK; farmers with no IK and LK; farmers in communal areas; and farmers in resettled areas.

3.4.2. Differences in vulnerability focused on adaptive capacity: Applying the LVI–IPCC

LVI–IPCC was used to understand the differences in vulnerability due to differences in adaptive capacity. In agreement with the results of the LVI analysis, farmers with IK and LK were less vulnerable (LVI–IPCC = −0.131) than farmers with no IK and LK (LVI–IPCC = −0.119) (Table 3-4). This was driven by farmers with IK and LK having a higher overall adaptive capacity (0.622) than farmers with no IK and LK (0.553) (Table 3-4). For the components that constitute adaptive capacity, farmers with IK and LK had higher adaptive capacity than farmers with no IK and LK for all six adaptive capacity components (Table 3-4). The difference in sensitivity and exposure for farmers with versus with no IK and LK was smaller than for adaptive capacity, indicating that the overall difference in vulnerability was driven most by differences in adaptive capacity between farmers with IK and LK compared to farmers with no IK and LK (Table 3-4).

Farmers in communal and resettled areas had a similar livelihood vulnerability index (LVI–IPCC = −0,087 for communal areas and −0,085 for resettled areas) (Table 3-4). This is consistent with the results using LVI, as the main differences between resettled and communal areas were largely due to health, which does not constitute adaptive capacity in the LVI–IPCC. Communal areas had a higher adaptive capacity (0.5307) than resettled areas (0.4834).

Table 3-4: LVI-IPCC index for the four categories assessed: farmers with IK and LK, farmers with no IK and LK, farmers in resettled wards, and farmers in communal wards in Chiredzi rural district. Values range from -1 to 1 and lower values indicate lower vulnerability for a particular component or subcomponent. The figures are rounded to three decimal places.

Contributing factors	**Main components**	**Main components values**				**Number of subcomponents**	**Contributing factor values**			
		Farmers with IK and LK	**Farmers with no IK and LK**	**Communal wards**	**Resettled Wards**		**Farmers with IK and LK**	**Farmers with no IK and LK**	**Communal wards**	**Resettled Wards**
Adaptive capacity	Socio-demographic profile	0.6	0.594	0.414	0.333	4	0.622	0.553	0.531	0.483
	Livelihood strategy	0.705	0.661	0.307	0.3	6				
	Social networks	0.433	0.416	0.485	0.643	5				
	Indigenous and local knowledge	0.931	0.58	0.222	0.25	3				
	Education and training	0.575	0.519	0.475	0.563	4				
	Natural resources	0.519	0.519	0.525	0.513	2				
Sensitivity	Health	0.396	0.368	0.215	0.433	3	0.398	0.412	0.369	0.403
	Food	0.432	0.528	0.472	0.453	5				
	Water	0.333	0.317	0.327	0.324	5				
	Land	0.479	0.426	0.45	0.438	2				
Exposure	Natural disasters	0.294	0.262	0.294	0.273	4	0.294	0.262	0.294	0.273
LVI-IPCC for farmers with IK and LK		-0.131								
LVI-IPCC for farmers with no IK and LK		-0.119								

LVI-IPCC for in Communal Wards	-0.087
LVI-IPCC for in Resettled Wards	-0.085

4.1. 3.4.3. Exposure to climate variability and change in Chiredzi

El Niño years (1972/73 and 1991/92) recorded the lowest rainy season rainfall in Chiredzi while La Niña years (1999/2000) recorded extremely high rainfall (Figure 3-3b). The total annual rainfall was estimated to have increased by 2.2 mm per year and the rainy season total rainfall by 3.2 mm per year over the observed period, although the increasing trends in annual total rainfall and rainy season total rainfall were not statistically significant (Figure 3-3a, b). Rainy season onset for both maize and sorghum showed an increasing trend toward the later onset from 1972–2021, which was statistically significant (slope = 0.41, $p = 0.046$ for maize; slope = 0.833, $p = 0.001$ for sorghum) (Figure 3-3j and Supplementary Material 2 Figure 1). Standardized precipitation indices (SPI-3 and SPI-6) and the total number of agricultural rain days for maize showed increasing trends, suggesting wetter conditions, and the rainy season cessation date showed a trend toward later cessation date, but these were all statistically non-significant (Figure 3-3c, h, i, k). Rainy season length and number of storm days showed no statistically significant trends over time, and, within the rainy season, the longest consecutive dry days (CDD), the number of CDD events longer than 5 days, and the number of CDD events longer than 10 days also showed no statistically significant trends (Figure 3-3d, e, f, g,). Of the 49 rainy seasons analysed, 35% had a length of 100 days or less (Figure 3-3l), which made it difficult to support even short-season maize varieties that require between 115–135 days to reach physiological maturity in Zimbabwe under rainfed agricultural conditions.

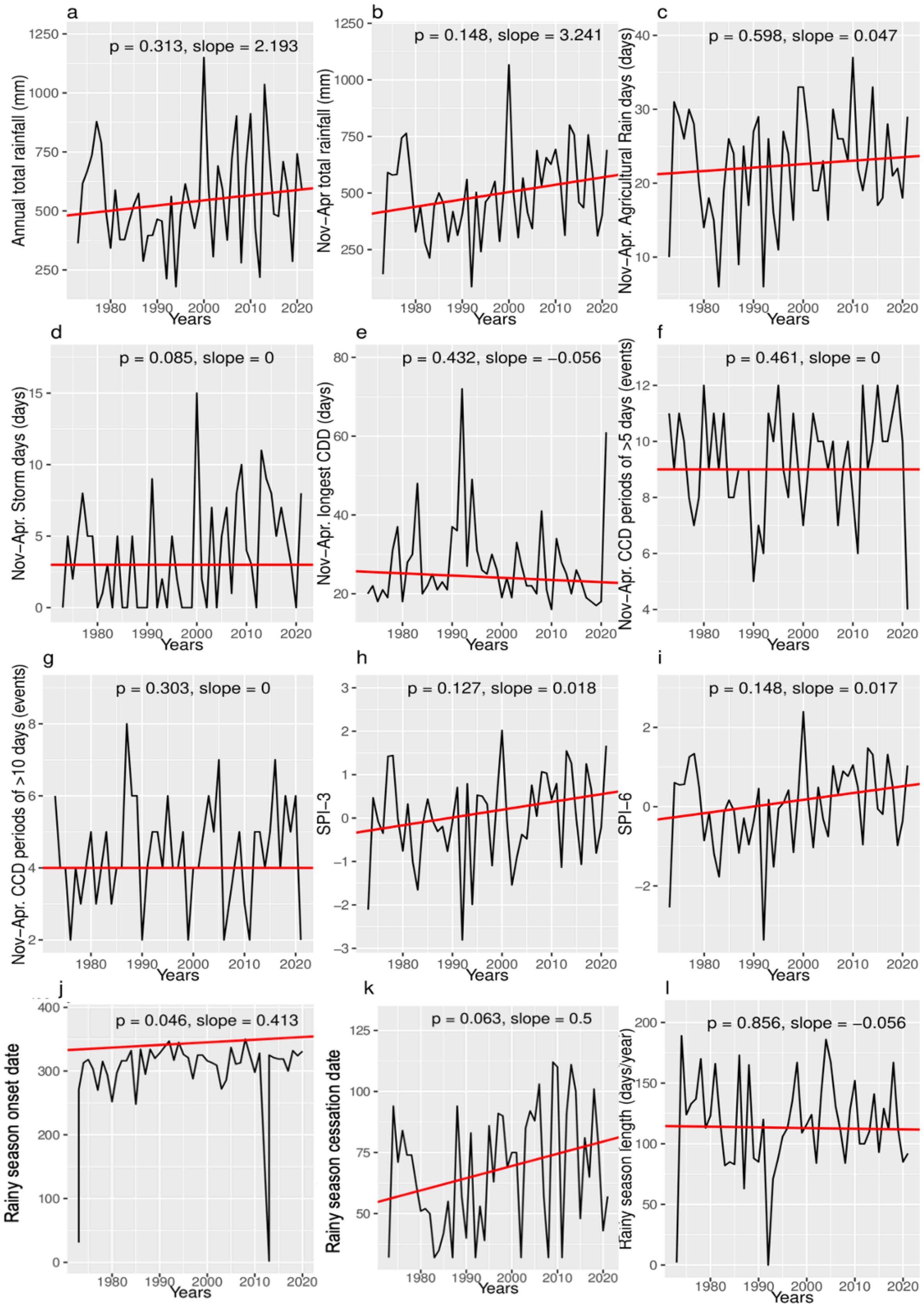

Figure 3-3: Interannual variability and trends in rainfall indices for Chiredzi district from 1972–2021. The red line indicates the fitted trend line using Mann–Kendall Sen's slope estimate for **a**) total annual rainfall, **b**) total rainy season rainfall (Nov–April), **c**) number of agricultural rainy days, **d**) number of storm days, **e**) longest period of consecutive dry days (CDD), **f**) CDD event of 5 days or more, **g**) CDD events of 10 days or more, **h**) Standardized Precipitation Index

over 3 months (SPI-3), **i**) SPI-6, **j**) rainy onset day (plotted in Julian days), **k**) rainy season cessation date (also plotted in Julian days) and **l**) rainy season length. Number of agricultural rain days, rainy season onset date, cessation date, and length are for maize (see Supplementary Material 2 Figure 2-1 for sorghum). The slope and significance value (P-value) at the 5% significance level are presented for each index.

The annual mean maximum temperature showed a statistically significant increasing trend of 0.12 ^{o}C per year ($p = 0.005$) between 2001 and 2021 (Figure 3-4c). The mean maximum rainy season temperature, mean annual temperature, the number of hot days during December–February for maize and sorghum, and the temperature of the hottest day all showed increasing but statistically non-significant trends (Figure 3-4b, c, f, g, k and Supplementary Material 2 Figure 1). The annual and rainy season minimum temperature and temperature of the coldest night all showed non-significant decreasing trends (Figure 3-4a, b, j).

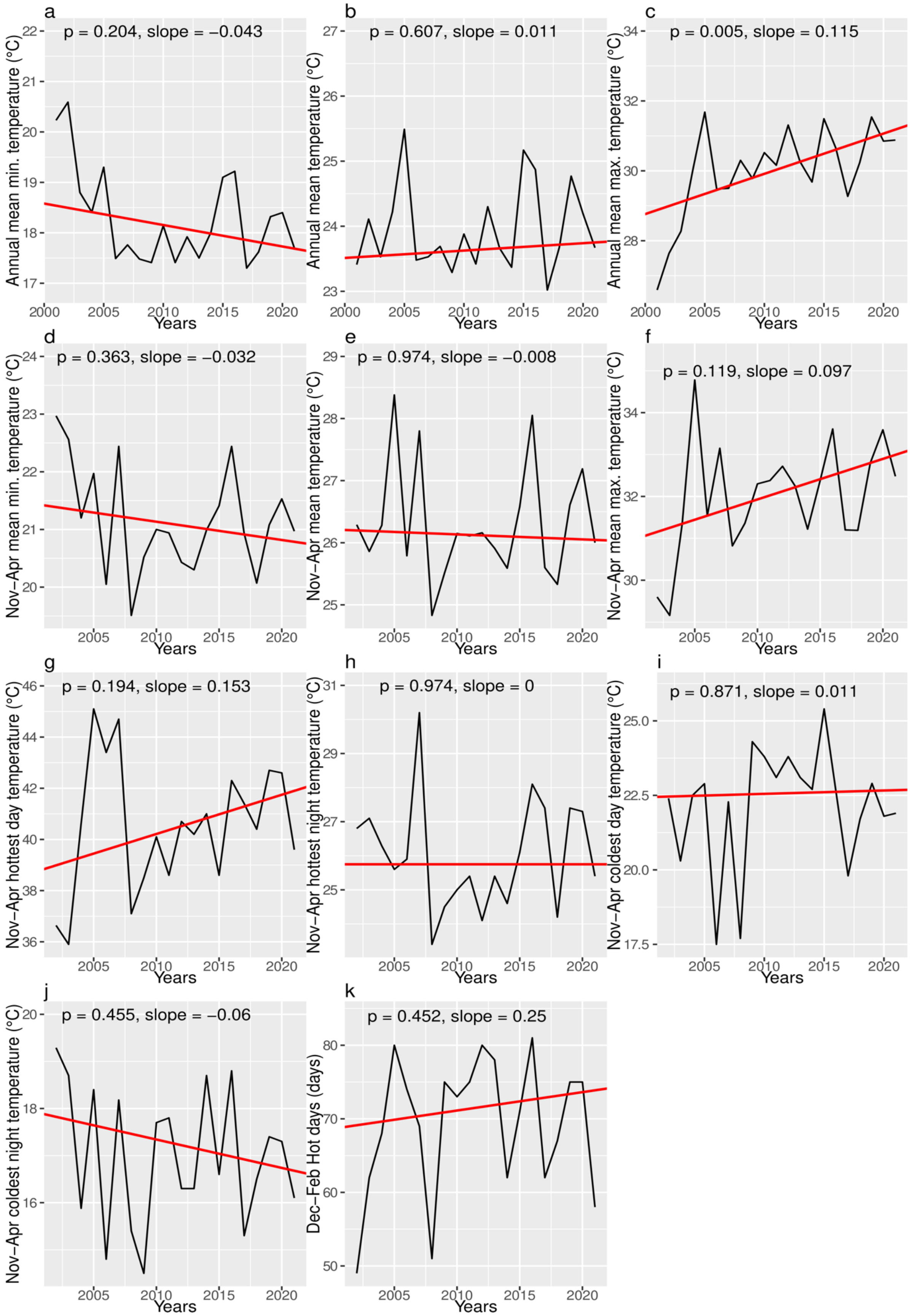

Figure 3-4: Interannual variability and trends in temperature indices for Chiredzi district between 2001 – 2021. The red line indicates the fitted trend line using Mann–Kendall Sen's slope estimate for **a**) mean annual minimum temperature, **b**) annual mean temperature, **c**) mean annual maximum temperature, **d**) mean rainy season minimum temperature, **e**) mean

rainy season temperature, **f**) mean rainy season maximum temperature. Rainy season extreme temperature events; hottest **g)** day and **h)** night temperatures; coldest **i)** day and **j)** night temperatures and **k**) number of hot days during the DJF months. The slope and significance value (P-value) at the 5% significance level are presented. The 30 °C threshold for hot days in **k** was for maize (see Supplementary Material 2 Figure 1 for sorghum).

3.4.4. IK and LK and climate perception of smallholder farmers in Chiredzi

To better understand farmers' perceptions of their exposure to climate variability and change, and how this drives vulnerability, we assessed farmers' perceptions of climate trends and hazards. The occurrence of droughts was perceived to have increased by 71% of the surveyed farmers, which was the highest percentage for any climate hazard (Table 3-5). The 2015/16 strong El Niño drought that affected Southern Africa could have influenced these perceptions. Temperatures were perceived to increase by 51% of the farmers, whereas 17% indicated that they perceived an increase in cold days over the last decade (Table 3-5). 30% perceived a delayed onset of the rainy season, 23% perceived a decrease in total rainfall during the rainy season, and 14% perceived an increase in total rainfall during the rainy season (Table 3-5).

We compared the seven main climate conditions perceived by farmers with indices of climate trends and extremes quantified from weather station data analysis (Table 3-5). Three of these showed alignment: delayed onset of the rainy season, unpredictable agricultural rainy days, and increased warming with results of observed data analysis (Table 3-5). Two of the indices, delayed onset of the rainy season and increased warming, showed statistically significant trends. This helps to understand the measures that farmers implement (in the adaptive capacity components – food, education and climate change training, and indigenous and local knowledge) in Chiredzi to reduce vulnerability. Evidence of misalignment between the climate trends in the weather station data and farmers' perceptions of total rainfall during the rainy season and the occurrence of droughts was observed (Table 3-5). This potentially increases farmers' vulnerability, for example, actions directed toward coping or adapting to reduced rainfall may not reduce vulnerability or exposure to climate risk. The other four conditions perceived by the farmers were not measured in the observed climate data analysis.

Table 3-5: Comparison of alignment or misalignment of climate perception of smallholder farmers with statistical analysis of observed climate data for Chiredzi.

Climate conditions/ indices		**Farmer perception**	**Frequency** (n = 100)	**Relationship with long term climate records**	**Description of the nature of relationship**
Rainfall	Rainy season Onset	Delayed onset	30	++	Aligns with the statistically significant increasing trend of later rainy season onset.
		Unpredictable onset	4	Not assessed	N/A
	Total rainfall in the rainy season	Reduced total rainfall amount	23	- -	A statistically non-significant trend in total annual rainfall and rainy season rainfall is misaligned with farmers who perceived a general decrease in total seasonal rainfall.
		Increased total rainfall amount	14	-	A statistically non-significant trend in total annual rainfall and rainy season rainfall is misaligned with the farmers who perceived increased rainfall. However, the non-significant trend in the total rainy season rainfall was an increasing trend.
	Predictability of rainy days	Unpredictability of agricultural rainy days	60	++++	No trend for CDD5 and CDD10 events, and a weak non-significant trend for longest CDD and number of agricultural rain days aligns with farmers' perception of unpredictable rainfall.
Temperature		Increased warming	48	+++	Aligns with a statistically significant increase in the mean annual maximum temperature.
		Increased cold summer days	17	Not assessed	N/A
Climate hazards		Increased occurrence of droughts	71	- - - -	Statistically non-significant trends in SPI-3 and SPI-6 misalign with farmer perception of increasing drought. However, with observed data not statistically significant the farmers perceptions might still be locally accurate.
		Increasing floods	2	Not assessed	N/A
		Increasing cyclones and storms	4	-	No trend for number of storm days suggests misalignment.
		Increasing heatwaves	2	Not assessed	N/A

+ indicates alignment and **–** indicates no alignment between farmers' climate perception and the results from the long-term observed climate data analysis. The strength of the relationship was measured based on the number of farmers who perceived a particular climate index and the statistical significance of the measured climate indices. We used the following classes (0–19 farmers perceived a change in agreement with the observations = +, 20–39 = ++, 40–59 = +++, and 60–100 = ++++) to determine the strength of agreement.

There was no statistical difference in the proportion of farmers with IK and LK and with no IK and LK who perceived changes in climate (Table 3-6). This means that whether farmers have IK and LK or not was not associated with how they perceive climate change.

Table 3-6: Statistical difference between farmers with IK and LK and with no IK and LK on climate perception for the main rainfall and temperature conditions.

Perception	Farmers with IK and LK (n = 73)	Farmers with no IK and LK (n = 27)	Frequency of perception	P- value
Delayed onset	19	11	30	0.24
Unpredictability of agricultural rainy days	49	12	61	0.40
Increased warming	37	14	51	0.70
Reduced total rainfall amount	15	8	23	0.49
Occurrence of droughts	54	17	71	0.41

3.5 Discussion

Vulnerability to climate variability and change for smallholder farmers in Chiredzi district is complex and determined by both climatic and non-climatic factors. Non-climatic factors at both household and community levels influenced smallholder farmers' vulnerability (Table 3-3; Table 3-4). Exposure to increasing temperatures and changes in the timing of the rainy season are expected to increase the risk of crop failure for rain-fed smallholder farmers in Chiredzi.

Adding an IK and LK lens to the LVI approach, we found that smallholder farmers with IK and LK were less vulnerable than farmers with no IK and LK (Table 3-3; Figure 3-2), extending our understanding of the role of IK and LK in reducing the vulnerability of smallholder farmers. This highlights the instrumental value of IK and LK in reducing vulnerability and cautions that IK and LK loss can have consequences beyond loss of intangible heritage values to have direct consequences in reducing adaptive capacity. Improved understanding of IK and LK in vulnerability to climate change also goes beyond the intrinsic heritage value of IK and LK or the loss and damage to heritage through loss or reducing efficacy of IK and LK, which has been a focus of much climate-heritage scholarship to date (Simpson, N.P. et al., 2022).

Farmers in communal areas were less vulnerable than those in resettled areas. Vulnerability across all categories of smallholder farmers in this study was higher in Chiredzi than in similar case studies of smallholder farmer vulnerability in other regions that also used the LVI approach in Africa (Adu et al., 2018; Asrat & Simane, 2017; Ebrahim, Miheretu & Alemayehu, 2022) and in Asia (Ho, Kuwornu & Tsusaka, 2022; Ho et al., 2021; Panthi et al., 2016; Rinzin et al., 2020).

3.5.1 **Livelihood vulnerability for IK and LK and no IK and LK farmers**

By incorporating IK and LK into the livelihood vulnerability assessment approach, our results advance our understanding of how IK and LK reduce the vulnerability of highly vulnerable groups to climate variability and change among smallholder farmers. The results indicate that farmers using IK and LK forecasts weather and climate diversify the number of crops they plant and implement more crop adaptation responses (Table 3-3), thereby diversifying the risk of crop failure and achieving food security, thus contributing to the resilience of farmers to climate variability and change. This highlights the important role of IK and LK in reducing the vulnerability of smallholder farmers in Chiredzi. This agrees with previous research in Chiredzi, which showed that farmers who relied on IK and LK forecasts implemented triple the number of adaptation responses that improved resilience compared to farmers with no IK and LK (Zvobgo, Luckson et al., 2023).

A major driver of lower livelihood vulnerability for farmers with IK and LK compared with those with no IK and LK was the differences in the food and IK and LK components of vulnerability (Table 3-3). The higher vulnerability of the food component of the LVI for farmers with no IK and LK was due to their lack of capacity to adapt in key food production activities compared with farmers with IK and LK (Table 3-3). This clearly demonstrates the role of IK and LK in improving the food security of farmers, which reduces their vulnerability to climate variability and change impacts. These results further our understanding of the role of IK and LK in food production for smallholder farmers that address climate risk from the usual understanding of the role of IK and LK in food provision through the utilisation of traditional and wild fruits in dryland areas to adapt to climate hazards, such as droughts (Egeru, 2012; Ghosh-Jerath et al., 2015; Kamwendo & Kamwendo, 2014; Okoye & Oni, 2017).

3.5.2 **Livelihood vulnerability for Communal and Resettled farmers**

Farmers in resettled areas had higher livelihood vulnerability than those in communal areas (Figure 3-2). The main difference in livelihood vulnerability between communal and resettled farmers was the difference in the health and social network components that were key to reducing smallholder farmers' vulnerability to climate variability and change hazards and impacts (Table 3-3). Good and strong social networks are critical for reducing the vulnerability of smallholder farmers by improving their adaptive capacity and strengthening their ability to access and mobilise resources to respond to environmental change (Chaudhury et al., 2017; Dapilah, Nielsen & Friis, 2020; Dumenu & Takam Tiamgne, 2020). The higher social network index contributing to higher vulnerability in resettled wards is explained by the weak social networks in these wards. Fewer farmers in resettled wards belonged to agriculture-based community groups or projects. This is because the area consists of newly erected communities that have not established strong social networks or interactions, yet these social interactions are key for sharing weather and seasonal climate forecasts and other agricultural information, such as planting dates in Chiredzi (Zvobgo, Luckson et al., 2023), which are required for the implementation of informed adaptation responses that reduce farmers' vulnerability. This demonstrates that poorly planned resettlement and relocation can disrupt community social networks (Centre for Conflict Management and Transformation, 2014) rooted in historical relationships between households in farming areas, which are key in the management of climate risks that reduce farmers' vulnerability (Alare et al., 2022; Chaudhury et al., 2017). The higher index for farmers not accessing government subsidies on key production inputs, social welfare and NGO programmes important for increasing adaptive capacity for smallholder farmers in resettled wards was because these farmers received less government support, which is vital to rainfed smallholder farmer production in Zimbabwe (Kang'ethe & Serima, 2014; Mapfumo, Paul et al., 2013; Zamchiya, 2013). This widens the gap between communal and resettled wards, thereby increasing the vulnerability of smallholder farmers in resettled areas. Conversely, farmers in communal areas received most government support (through subsidies on essential agricultural production inputs, such as seeds, fertilisers, and social welfare programs) and NGO donor support through various social security and safety net programs, which increased their adaptive capacity.

The higher health index in resettled areas was largely a result of the lack of access to health facilities. Most of the health facilities were, on average, 34.5 km away in resettled areas compared to 5.9 km in communal areas. The lack of access to health facilities in resettled areas was caused by a lack of infrastructure development in the newly resettled areas of Zimbabwe (Centre for Conflict Management and Transformation, 2014). Improved access to health infrastructure is critical for managing climate disasters (World Health Organisation, 2021). Thus, lack of access to healthcare negatively affects livelihood vulnerability for smallholder farmers in Chiredzi in the event of injuries from climate hazards, and farmers in resettled wards are more vulnerable to climate hazard-related injuries and other health complications because of their reduced access to health services. This demonstrates how a lack of access to health facilities in resettled farming areas due to the poorly planned resettlement of farmers by the government can compound the risks that smallholder farmers face from climate change. Other studies have also shown that reduced access to health services (for Australia's rural communities) compounded rural vulnerability to climate variability and change (Berry et al., 2011). More generally, many studies have also found that poorly planned government resettlement programmes increase the livelihood vulnerability of smallholder farmers (Abbink et al., 2014; Arnall, 2014; Haji & Legesse, 2017; Kothari, 2014) and can also introduce new risks and sources of vulnerability (Eriksen et al. (2021).

Taken together, the higher vulnerability in resettled wards due to differences in health access and social network demonstrates that social protection programs in Chiredzi are key to addressing livelihood vulnerability to climate risk for rainfed smallholder farmers. This extends the findings of continental-scale vulnerability analyses, where higher vulnerability to climate change in Africa has been found to be the result of the intersection of socioeconomic, political, and environmental factors (Ayanlade et al., 2023; Trisos et al., 2022). These findings demonstrate how social protection programs can reduce vulnerability, and social safety programs need to integrate vulnerability to climate risk to enhance benefits for development and climate adaptation. This observation is widely shared by scholars across Africa (Agrawal et al., 2019; Hallegatte et al., 2016; Niño-Zarazúa et al., 2012; Scognamillo, Mastrorillo & Ignaciuk, 2022; Trisos et al., 2022; Ulrichs, Slater & Costella, 2019), where the integration of climate adaptation components into social protection programs has led to the co-benefits of improved food security for smallholder farmers.

Given how IK and LK reduced vulnerability in Chiredzi (Table 3-3), our results show that farmers with IK and LK and staying in communal areas in Chiredzi have increased adaptive capacity and reduced vulnerability compared to farmers who are found at the intersection of no IK and LK and live in resettled areas (Figure 3-2). This demonstrates how different factors intersect in defining and compounding the vulnerability of communities to climate change.

3.5.3 **Exposure to climate variability and change in Chiredzi**

Smallholder farmers in Chiredzi are exposed to climate variability and change (Figure 3-3 and Supplementary Material 2). Our results showed that ENSO strongly influenced rainfall variability in Chiredzi, an observation generally shared by many precipitation analyses conducted in Zimbabwe (Gwimbi, 2009; Mazvimavi, 2010; Sibanda, Grab & Ahmed, 2020). Between 1972–2021, 35% of the seasons had a season length of 100 days or less (Figure 3-3l), which is too short to support at least short-season maize varieties grown in Zimbabwe which require 115-135 days to reach physiological maturity depending on variety (Nyabako & Manzungu, 2012). This indicates a high exposure of rain-fed maize crops in Chiredzi to climate-related crop failures. Together with a significant trend of later onset of the rainy season for maize and sorghum (Figure 4j and Supplementary Material 2), the further shortening of the rainy season increased the exposure of smallholder farmers in Chiredzi. Similar patterns of shrinking and shifting of the rainy season have been observed in other parts of Zimbabwe (Rurinda et al., 2014a; Sibanda, Grab & Ahmed, 2020).

Smallholder farmers in Chiredzi were also exposed to increasing maximum temperatures (Figure 3-4c). This agrees with previous research in Chiredzi (Jiri, Obert, Mafongoya & Chivenge, 2017), which observed a temperature increase of 0.04°C per year between 1980–2010, and for Zimbabwe, where the mean annual temperature increased by approximately 1.7°C from 1961–2010 (Engelbrecht et al., 2015). Increasing maximum temperatures, especially during the growing season, poses a severe risk for rainfed smallholder farmers who are unable to irrigate to reduce the risk of heat stress and crop yield losses (Aryal et al., 2020; Hasegawa et al., 2022; Maúre et al., 2018). The increasing trend (although not statistically significant) of an additional 0.25 days per year in the number of hot days (days with maximum temperature above 30 °C) in the December–February months poses a threat to maize crop production by smallholder farmers in Chiredzi because each degree-day spent at temperatures above 30 °C in semi-arid conditions in Africa, which includes the climate of Chiredzi, is estimated to reduce the final yield of maize by 1.7% under drought conditions (Lobell et al., 2011). Future warming will negatively affect food production in Africa by shortening growing seasons and increasing water stress, mostly for smallholder farmers under rainfed systems (Trisos et al., 2022). The increased exposure of maize to crop failure has increased the exposure of smallholder farmers to food insecurity in Chiredzi. Our results concur with earlier findings from other smallholder farming regions in Zimbabwe (Rurinda et al., 2014a), where the number of hot days in December–February increased, and this has huge implications as discussed above.

Taken together, increased exposure to higher temperatures and shifting rainy seasons can increase the chances of compound and cascading risks to smallholder farmers in Chiredzi. For example, in addition to the risk of crop failure, extreme heat presents a risk to livestock pasture availability, outdoor labour productivity for smallholder farmers, and heat-related mortality and morbidity (Bangira et al., 2015; Godde et al., 2021; Mabuya & Scholes, 2020; Wiru et al., 2019). Therefore, farmers, especially those in resettled areas with low access to health services, could be expected to face compounding risks to food security, labour productivity, and health (de Lima et al., 2021; IPCC, 2023b; Kjellstrom et al., 2016; Simpson, Nicholas P. et al., 2021b). These risks could cascade to negatively impact the school attendance of youth in the community, as drought and high temperatures negatively impact family incomes and undernutrition harms cognitive development (Marchetta, Sahn & Tiberti, 2019; Randell & Gray, 2016; Randell & Gray, 2019; Trisos et al., 2022). In rural Zimbabwe, experiencing drought conditions in early life has been associated with fewer years of schooling and a reduction in lifetime earning potential (Alderman, Hoddinott & Kinsey, 2006).

Wider support for adaptation, including adaptation responses integrating IK and LK, can reduce exposure and thereby reduce food insecurity risks for smallholder farmers. Adaptation options implemented with support of IK and LK that can reduce risk include the growth of indigenous drought-resistant crops; such as sorghum, sesame, and legumes; and irrigation along the Save and Mtirikwi Valleys. In terms of providing answers to the two most critical questions relevant to the adaptation planning of rainfed smallholder farmers on what is the best crop type and variety to grow, and when to plant (Tadross, M. et al., 2009; Tadross, M. A., Hewitson & Usman, 2005), our results suggest that maize production should be reduced and focus more on sorghum to improve food security, sesame for income generation of farmers, or during wetter seasons, early maturity maize varieties should be considered with planting dates carefully chosen to avoid severe mid-season consecutive dry days. Also, given the fundamental role of IK and LK weather and seasonal climate forecasts in the implementation of adaptation responses in Chiredzi (Jiri, O, Mafongoya & Chivenge, 2015; Zvobgo, Luckson et al., 2023), the inclusion of IK and LK in early warning systems can help reduce the exposure of smallholder farmers and crops.

3.5.4. **Perceptions of climate by smallholder farmers in Chiredzi**

The alignment of farmers' perceptions with climate data is important for adaptation planning, particularly when combined with understanding of human-caused climate change and when supported by actionable climate information. Perception of climate change in Africa affects climate risk perception and can lead to a higher sense of urgency for climate action, influencing how they respond to and cope with climate variability, which inherently defines their vulnerability (Mairura et al., 2021; Simpson, Nicholas P. et al., 2021a; Talanow et al., 2021; Trisos et al., 2022). IK and LK shape perceptions that are vital for managing climate risk in day-to-day activities and longer-term actions, especially for smallholder farmers (Ara Begum et al., 2022), this perception-to-action and its implications for implemented adaptation actions is important for understanding vulnerability, as we have shown here that IK- and LK-informed adaptation actions can reduce the level of vulnerability.

The alignment of farmers' climate perceptions with key precipitation and temperature indices (Table 3-5) has substantive and instrumental implications for farmers using IK and LK weather and climate forecasts, as this can improve the efficacy of the adaptation actions that farmers implement to address climate risk, which reduces their vulnerability. These results on the alignment of perceptions and climate data agree with some key regional findings, where alignment was found to be high for temperature and rainfall indices in Africa (Simpson, Nicholas P. et al., 2021a; Trisos et al., 2022). These findings therefore extend our understanding of the conditions under which adaptation measures are implemented and their consequences for reducing vulnerability. Thus, the potential implementation of appropriate informed adaptation responses required for transformative actions (Mitter et al., 2019; Simpson, Nicholas P. et al., 2021a). This can reduce the risk of maladaptation from uninformed implementation of adaptation responses. In Chiredzi, understanding farmers' perceptions is critical for understanding the implementation of anticipatory responses that address risks, such as late rainy season onset, among dry planting, crop variety selection, and crop area allocation, to manage anticipated climate risk based on their IK and LK forecasts and how they perceive the climate risks (Soropa et al., 2015; Zvobgo, Luckson et al., 2023).

The results also showed that the two most critical climate indices and hazard smallholder farmers are concerned with when making adaption decisions: total rainy season rainfall and the occurrence of droughts misaligns with farmers' perceptions in Chiredzi. These findings have implications on how farmers respond to climate impacts to reduce their vulnerability. Drought and rainfall perceptions in Chiredzi are highly likely to have been influenced by the 2015/16 strong El Niño drought that affected Southern Africa (Hove & Kambanje, 2019), as the impacts of the drought are still vivid in the memories of the farmers. In terms of smallholder farmer planning, information about total rainfall and drought is among the metrics useful to smallholder farmers when making decisions regarding which crop variety to grow (Leroy, García & Bocco, 2022; Zvobgo, Luckson et al., 2023). This could affect the types of responses that these farmers implemented when responding to reduced total rainy season rainfall and drought. These divergent perceptions potentially lead to inappropriate adaptation responses, resulting in maladaptation associated with response measures (Dhanya & Ramachandran, 2015), which increases the vulnerability of smallholder farmers in Chiredzi.

Although the results of farmers' perceptions of particular climate conditions affect the responses they implement, which has a bearing on the vulnerability of the farmers (Table 3-3), the perceptions of farmers with IK and LK and with no IK and LK were not statistically different (Table 3-6). This means that whether farmers have IK and LK or not has no effect on how they perceive climate change. This means that sources of vulnerability between farmers with IK and LK and those with no IK and LK were statistically less likely to be affected by how they perceive changes in the climate.

3.5.5 **Theoretical contributions of our empirical findings**

This study contributes to an understanding of vulnerability and the effectiveness of actions shaped by IK and LK in reducing climate risk. The results of the LVI in this study were not only important in understanding the vulnerability of smallholder farmers in Chiredzi but also in advancing our understanding of the different elements of sensitivity, exposure, and adaptive capacity and their relationships in vulnerability assessments, highlighting how IK and LK can reduce smallholder farmers' vulnerability. This study integrated IK and LK into LVI and showed the forms of IK and LK that contribute to the adaptive capacity that reduces smallholder farmers' vulnerability. In the future, IK and LK should be fully incorporated into LVI assessments, and specific elements should be explored to broaden our understanding of smallholder farmers' vulnerability and what IK and LK can do or fail to do to reduce vulnerability. This study clearly link the nexus: IK and LK to climate risk perception to implementation of adaptation responses and how this is crucial in assessing the vulnerability of smallholder farmers, addressing the lack of empirical evidence in the current vulnerability literature.

The study also highlights the importance of vulnerability assessments going beyond the current scholarship that focuses on the lack of adaptive capacity in understanding the vulnerability of smallholder farmers to include implemented adaptation responses in vulnerability assessment. This study contributes to the understanding of the relationships between implemented adaptation actions and vulnerability, aligning with the new IPCC climate risk framing that considers the role of implemented responses in understanding risk and vulnerability (Ara Begum et al., 2022). The LVI applied in this study builds on a framework for vulnerability developed during the IPCC 4th Assessment cycle. Some components of adaptive capacity in our framework, include adaptation responses (e.g., seasonal and weather climate forecasting, and social welfare and safety net programmes) which in the updated IPCC 6th Assessment risk framework are identified as a separate driver of risk (Ara Begum et al., 2022; Simpson, Nicholas P. et al., 2021b). Further work is therefore required to align LVI approaches with updated IPCC framings of climate risk.

3.6. Conclusion

Smallholder farmers in Chiredzi are highly vulnerable to climate variability and change. Vulnerability in Chiredzi varies depending on many local factors, emphasising the importance of local-level vulnerability assessment. This study found that farmers with IK and LK and performing weather and seasonal forecasts had a high adaptive capacity and were less vulnerable than farmers with no IK and LK. This demonstrates the important role of IK and LK in increasing the adaptive capacity of smallholder farmers. Farmers in communal areas are less vulnerable than farmers in resettled areas. This was mainly due to the lack of social safety nets in the resettled areas explaining government failures of the land reform programme. These results are important for developing Zimbabwe's National Adaptation Plan (NAP), where vulnerability assessments are identified as the cornerstone of a successful NAP process (Government of Zimbabwe, 2019). Smallholder farmers in Chiredzi are exposed to climate variability and change. The rainy season in Chiredzi slowly shifts forward while shrinking for staple crops (maize and sorghum) between 1972–2021. This has increased farmers' exposure to crop failure, resulting in difficult climate decision-making processes and increased vulnerability. Government policies and initiatives in Chiredzi should promote the growing of drought-resistant small-grain crops to address high crop exposure levels to climate variability and change. This is important for ensuring food security for smallholder farmers. Additionally, planting of short-term maize varieties can be promoted to reduce exposure levels in Chiredzi. The alignment of farmers' perceptions of the climate and observed data is crucial for adaptation planning and implementation of effective and appropriate adaptation responses by smallholder farmers in Chiredzi. To address the higher livelihood vulnerability in Chiredzi, it is vital that other developmental projects integrate climate risk management components in their planning and implementation. Thus, climate-resilient development should take the lead in the planning of all projects and programmes in Chiredzi. This study also recommends the implementation of tailored adaptation measures based on vulnerability levels in the area to increase the efficacy of climate adaptation and effectively reduce climate risk in Chiredzi.

*“**Their radio is our radio**.”*

~ A smallholder farmer in Chiredzi, 2021 during an Interview referring to how they access conventional (scientific) weather and climate forecasts.

4. IK and LK Seasonal Forecasts and Climate Adaptation

Role of Indigenous and local knowledge in seasonal forecasts and climate adaptation: A case study of smallholder farmers in Chiredzi, Zimbabwe*

Abstract

Accessible, reliable, and diverse sources of climate information are needed to inform climate change adaptation at all levels of society, particularly for vulnerable sectors, such as smallholder farming. Globally, many smallholder farmers use Indigenous knowledge (IK) and local knowledge (LK) to forecast weather and climate; however, less is known about how the use of these forecasts connects to decisions and actions for reducing climate risks. The article examined the role of IK and LK in seasonal forecasting and the broader climate adaptation decision-making of smallholder farmers in Chiredzi, Zimbabwe. The data were collected from a sample of 100 smallholder farmers. Seventy-three of the 100 interviewed farmers used IK and LK weather and climate forecasts, and 32% of these farmers relied solely on IK and LK forecasts for climate adaptation decision-making. Observations of cuckoo birds, leaf-sprouting of Mopane trees, high summer temperatures, and Nimbus clouds are the main indicators used for IK and LK forecasts. The use of IK and LK climate forecasts was significantly positively associated with increasing farmer age and farmland size. Farmers using IK and LK forecasts implemented, on average, triple the number of adaptation measures compared with farmers not using IK and LK. These findings demonstrate the widespread reliance of farmers on IK and LK for seasonal forecasts, and the strong positive link between the use of IK and LK and the implementation of climate adaptation actions. This positive association between IK and LK usage and the implementation of adaptation actions may be widespread in smallholder farming communities throughout Africa and globally. Recognition and inclusion of IK and LK in climate services is important to ensure their continued potential for enhancing climate change adaptation.

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4.1. Introduction

Globally, there is increasing recognition of the potential value of Indigenous knowledge (IK) and local knowledge (LK) for climate change adaptation (IPCC, 2019b; IPCC, 2022b; IPCC, 2022c). For example, case studies from Brazil have highlighted how the causal and mechanistic explanations provided by IK and LK for perceived local environmental changes can prove accurate and more nuanced than scientific and academic explanations (El-Hani, Poliseli & Ludwig, 2022). The IPCC defines IK as the "understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings" (IPCC, 2022a: p 2912) and LK as "understandings and skills developed by individuals and populations, specific to the places where they live" (IPCC, 2022a: p 2914). For many indigenous peoples and local communities, IK and LK inform decision-making about fundamental aspects of life, from day-to-day activities to longer-term actions (IPCC, 2022a). Recognising epistemic differences between knowledge systems and triangulating their value for local decision-making is key to extending climate services and informed climate change adaptation to the currently underserviced smallholder farmers. This is especially crucial in most African countries, where climate and weather recording and forecasting infrastructure and context-specific climate information services are often lacking (Africa Adaptation Initiative, 2018; Hansen et al., 2011; Singh et al., 2018; Trisos et al., 2022).

Communities in Africa across multiple sectors, geographies, and scales are responding to climate change (Graham et al., 2021; Leal Filho et al., 2022a; Trisos et al., 2022; Turek-Hankins et al., 2021; Williams et al., 2021). How individuals and societies anticipate and respond to climate change risk is important, as inappropriate responses can increase vulnerability and lead to maladaptation (Schipper, E. Lisa F., 2020), and thus, can be a potential driver of increased climate change risk (Simpson, Nicholas P. et al., 2021b). Current evidence shows that adaptation is generally in the nascent stages of implementation, with little evidence of risk reduction under recent climate change conditions, particularly for rainfed smallholder farmers (Berrang-Ford et al., 2021b; Leal Filho et al., 2022a; Thomas, Adelle et al., 2021). This demonstrates the importance of easily accessible and reliable climate information to smallholder farmers for climate adaptation decision-making which the smallholder farmers in Africa are acquiring through indigenous and local knowledge of interpreting the environment, surroundings, personal and shared experiences. These types of forecasts are important to rainfed farmers, considering that in smallholder farming, climate decision-making occurs mainly at the household level and is affected by several factors, including climate information quality and availability to decision makers (Waldman, Kurt B. et al., 2021).

In many African countries, the majority of farmers are smallholder entities engaged in household agricultural production (FAO, 2018), consisting mainly of rainfed and subsistence agriculture. African farmers are already experiencing economic and non-economic losses and damage, mainly through impacts on livelihoods from crop losses due to climate change (Trisos et al., 2022). These include yield reduction and lower productivity of the staple crops. For example, there has been a reduction in maize yield by 5% in Southern Africa, a 10–20% yield loss for millet and 5–15% yield loss for sorghum in West Africa (Ortiz-Bobea et al., 2021; Ray et al., 2019; Sultan, Defrance & Iizumi, 2019), as well as livestock pasture losses (Sloat et al., 2018; Stanimirova et al., 2019). In addition to these climate impacts, the projected increased climate risk to food systems associated with increases in global warming will likely have increasingly severe impacts on smallholder farmers across Africa. Increased global warming is projected to decrease the yields of maize, rice, wheat, and soybean in Sub-Saharan Africa, especially if the levels of global warming exceeds 2 °C above pre-industrial levels (Franke et al., 2020; Moore et al., 2017; Rosenzweig et al., 2014). African smallholder farmers are generally more vulnerable to climate change because of their limited access to production and adaptation resources, including financial, land, technological, and climate services (Krell et al., 2021; Leal Filho et al., 2022a; Pauline et al., 2017; Sonwa et al., 2017).

When adapting to climate impacts, smallholder farmers in Sub-Saharan Africa have relied on available knowledge sources that they trust in climate decision-making, including using IK and LK for weather and climate forecasting (Filho et al., 2022) and the implementation of adaptation measures (Ajani, Mgbenka & Okeke, 2013; Grey, 2019; Mekonnen et al., 2021; Nkomwa et al., 2014; Zuma-Netshiukhwi, Stigter & Walker, 2013). Case studies investigating how communities and smallholder farmers use various IK and LK systems to forecast weather have increased in the Southern African region over the past decade, including in: Botswana (Kolawole et al., 2014; Mogomotsi, Sekelemani & Mogomotsi, 2020), Malawi (Bucherie et al., 2022; Joshua et al., 2017; Ngongondo et al., 2021; Streefkerk et al., 2022), Namibia (Schnegg, 2019), South Africa (Kom et al., 2022; Rankoana, 2022; Ubisi, Kolanisi & Jiri, 2020; Vilakazi, Zengeni & Mafongoya, 2019), Zambia (Mbewe, 2019), and Zimbabwe (Gwenzi et al., 2016; Jiri, O, Mafongoya & Chivenge, 2015; Mafongoya, O., Mafongoya & Mudhara, 2021; Soropa et al., 2015; Tanyanyiwa, 2018). A common conclusion from these case studies is that IK and LK weather and climate forecasting by smallholder farmers is important for increasing farmers' general understanding of the weather and season ahead. For example, IK and LK are relied upon by smallholder farmers in Chiredzi (the study site in south-eastern Zimbabwe) for both short-term and seasonal rainfall predictions (Jiri, O, Mafongoya & Chivenge, 2015; Soropa et al., 2015). This has led to increased recognition of the potential value of appropriate IK and LK to inform climate-relevant decisions and actions, particularly for rainfed smallholder farmers (Alemayehu & Bewket, 2017; Nyadzi, Emmanuel et al., 2021). However, little is known about the connection between IK and LK forecasts, and how using IK and LK to forecast seasonal weather and climate translates into the decisions taken and actions implemented by smallholder farmers for climate risk reduction. There are also limitations to the impact of climate information, as perceptions of climate risk do not necessarily translate into action (Simpson, Nicholas P. et al., 2021a; Waldman, K. B. et al., 2019).

This study focuses on climate decisions currently being made and the response options being implemented based on IK and LK climate forecasts by smallholder farmers in Chiredzi, Zimbabwe. Given the risk of increased seasonal rainfall variability in Chiredzi District (Sibanda, Grab & Ahmed, 2020; Zvobgo, Luckson et al., 2023), it is important that smallholder farmers use climate and weather forecasts to improve decision-making for informed climate adaptation actions. We also assessed the contribution of IK and LK weather and climate forecasts to the overall climate adaptation of farmers in Chiredzi. The findings broaden our understanding of how IK and LK systems shape household-level decision making for smallholder farmers' climate adaptation. The discussion and conclusion highlight the value of IK and LK in Africa, which is at risk from climate change, and the utility of a blended approach with scientific knowledge of climate information services that draws on the strengths of IK and LK to enhance the implementation of adaptation responses to climate change.

4.2. Methods

4.2.1. Characteristics of the Study Area

Smallholder farming is the main economic activity in many rural areas of Chiredzi. Chiredzi District is among the regions in Zimbabwe that are most vulnerable to climate variability and change (Unganai, Leonard S & Murwira, 2010). In the absence of reliable scientific weather forecast information, farmers in the region use indigenous methods to predict the seasonal quality (Jiri, O, Mafongoya & Chivenge, 2015). A detailed description of the study area can be found in Section 1.5.1, Section 3.3.1.

4.2.2. Data collection

Wards sampled were strategically selected for data collection based on their accessibility, as well as the characteristics of farmer settlement and geography (Figure 1-1). The wards were selected from communal and resettled farming areas. Communal wards consisted of farmers who have stayed in one area for several decades and longer than for resettled wards who consisted of farmers that since 2000 were reallocated land under Zimbabwe's land reform programme in formerly commercially managed ranches that had not been previously tilled (Chaumba, Scoones & Wolmer, 2003; Ndhlovu, Emmanuel, 2018). The study sampled these two different types of farming areas because the IK and LK in communal areas were anticipated to be multigenerational and endemic due to wards in communal areas having farmers staying in the same community and farming in the same area for several decades. IK and LK in resettled areas were anticipated to be younger and syncretic of exogenous knowledge systems, including knowledge brought about by resettled farmers, and potentially adapted with local IK and LK over the past 15-20 years to the local context.

To enable us to run a binary logistic regression with sufficient statistical power, study aimed for a minimum sample of 80 farmers, and the available resources enabled us to survey 100 farmers. A sample of 100 farmers from five communal and resettled wards was surveyed. The study used two main factors to select the wards to sample from both communal and resettled areas: the proximity of a ward to the main river valleys in the study area (Save and Mtirikwi Valley), and the dryland conditions of a ward, specifically whether it had water available for irrigation. This sampling design was used to estimate the effects of access to irrigation for farmers in the Save and Mtirikwi valleys on the use of IK and LK for climate adaptation in Chiredzi. For resettled areas, one ward along the Mtirikwi Valley was selected (ward 27), and one ward from dryland conditions was selected (ward 32). For communal areas, two wards along Save Valley (wards 1 and 25) were selected, and one ward from dryland conditions (ward 3). Four villages were selected from each ward to ensure uniform sampling across the ward. In each village, five farmers were randomly selected for interviews. Ethical clearance was obtained from the university (FSREC 002 – 2021). Permission from the headman was obtained before conducting the surveys in each village. Free informed consent was obtained before every interview with the farmers. Interviews were conducted in the local language (Shona) to ensure maximum participation and engagement with the farmers. Farmers' participation was anonymous.

Data were collected in October 2021 using face-to-face, in-depth, semi-structured interviews in five wards. October was strategically selected for the interviews because the growing season usually starts from mid-November to early December. Therefore, October is a critical month in which climate-relevant farming decisions are top-of-mind for respondents, as smallholder farmers are preparing for the upcoming planting and growing season. During that time, farmers use various indigenous and local indicators, such as observing how flora and fauna behave and applying the information to forecast the expected weather and climate of the incoming season, including dates of rainy season onset, season quality and length, cessation dates, and the possibility of drought (Jiri, O, Mafongoya & Chivenge, 2015; Soropa et al., 2015). Forecasts are used to make decisions on when to perform key farm operations, such as dry planting, considering options between drought-resistant crops, such as cotton, sorghum, and millet crops, as well as the selection and allocation of crops per cultivation area (Soropa et al., 2015).

The interview guide (Supplementary Material 3) was structured to explore four main areas: i) how smallholder farmers use IK and LK to perform weather and seasonal climate forecasting, ii) farmers' reliance on IK and LK forecasts, iii) the influence of IK and LK forecasts on farmers' decision-making for preparedness for potential climate risks, and iv) the connection of IK and LK forecasts to climate adaptation actions implemented by smallholder farmers. Sociodemographic data (Table 4-1) of the respondents were also collected for use in the binary logistic regression model to assess which sociodemographic factors are associated with an increased or decreased probability of farmers using IK and LK forecasts.

Data collection focused on the types and varieties of knowledge used to forecast the weather and climate conditions of the forthcoming season, specifically storms, heavy precipitation, rainy days, season quality and length, and onset and cessation periods of the rainy season. Data on the level of farmers' reliance on IK and LK forecasts by scoring the degree (on a scale of 1–5) to which they relied on IK and LK forecasts in their decision was also collected. Using the farmers' responses, we analysed the types of actions and measures that they were taking to react to IK and LK weather and climate forecasts. This was to establish the contribution of IK and LK to household- and local-level decision making in climate adaptation.

4.2.3. Determinants of the use of IK and LK climate forecasts

The study used a binary logistic regression model (Van Huynh et al., 2020) to test the sociodemographic factors that influence smallholder farmers' use of IK and LK for weather and climate forecasts in Chiredzi. The model contained 13 independent variables (age, education, farming type, gender, wealth level, access to irrigation, access to scientific weather information, perception of climate variability, livelihood diversification, access to extension services, farmland size, LOS, and family size) (Table 4-1). The assumption is that if a farmer uses IK and LK in forecasting, they are likely to make climate decisions to prepare for or adjust to the expected climate risks based on that forecasting. The binary logistic regression analysis was performed as follows:

$$Ln\left[\frac{P}{1-P}\right] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 \ldots\ldots\ldots + \beta_{13} x_{13} \qquad (1)$$

where $\left[\frac{P}{1-P}\right]$ is the odds ratio.

P is the probability of a farmer in Chiredzi to forecast climate using IK and LK methods.

$1 - P$ denotes the probability of not using IK and LK to forecast climate.

β_0 is the intercept.

x_1, x_2, x_3…, and x_{13} are the independent variables.

β_1, β_2, β_3…, and β_{13} are partial regression coefficients.

Table 4-1: Description and justification of the predictor variables for a binary logistic regression model considered in this study.

	Variable	Variable code	Justification for the variable	Expected sign
x_1	Age	Continuous	Older farmers are hypothesized to be more likely to use IK and LK weather forecasting than younger farmers, as they have better knowledge of weather information, particularly indigenous and local indicators of climate forecasting (Belay et al., 2017; Tunde & Ajadi, 2019).	+
x_2	Farmland size	Continuous	Farmers with larger farms are hypothesized to be more likely to use IK and LK weather and climate forecasts. The assumption is that farmers with large farmlands would grow many crops; hence, they are more likely to implement several adaptation responses and use IK and LK forecasts.	+
x_3	Number of years living in the area	Continuous	Farmers who have lived in an area for a longer time are hypothesized to be more likely to understand indigenous and local environments and indicators better. Therefore, they are more likely to use IK and LK forecasting than farmers who have lived in an area for a short period (Van Huynh et al., 2020).	+
x_4	Access to scientific weather forecasting information	Yes = 1 No = 0	Farmers with access to scientific weather forecasts are more likely to use these forecasts (Bryan et al., 2013b). Therefore, they are hypothesized to be less likely to use IK and LK weather and climate forecasts.	-
x_5	Level of Education	Tertiary = 3 Secondary = 2 Primary = 1	More educated farmers are more likely to understand and appreciate scientific weather and climate forecasts, and hence are hypothesised to be less likely to use IK and LK forecasts (Belay et al., 2017).	-

		No education = 0		
x_6	Gender	Male = 1 Female = 0	Male farmers are hypothesized to be more likely to understand the IK and LK systems and use them for weather and climate forecasting (Tunde & Ajadi, 2019). This is because men in the study area are more involved in activities that allow them to share/receive IK and LK, mostly traditional gatherings where storytelling on societal experiences took place with the older generation. This is because of the patriarchal system that believes men are household heads who should make relevant agricultural/farming decisions.	+
x_7	Access to irrigation	Yes = 1 No = 0	Access to irrigation reduces the reliance of a farmer on rainfed systems and allows the farmer to try strategies such as repeated sowing that do not follow the natural rainfall seasons (Varadan & Kumar, 2014). Therefore, it is hypothesised that farmers with access to irrigation are less likely to use IK and LK climate forecasts because of their lower reliance on rain-fed systems.	-
x_8	Perception of climate variability and change	Yes (if perceive increased climate variability) = 1 Not = 0	Farmers who perceive climate variability and change are hypothesized to be more likely to use IK and LK forecasts to plan, prepare, and adjust to anticipated risk (Van Huynh et al., 2020).	+
x_9	Farming type	Communal = 1 for Resettled = 0	Resettled farmers are hypothesized to be less likely to use IK and LK forecasts than farmers in communal areas because of their limited knowledge and time spent in the local environment (although indigenous knowledge can be transferred from place to place through resettlement).	-
x_{10}	*Livelihood diversification	Yes = 1 No = 0	Farmers that diversify their livelihoods are hypothesized to be less likely to use IK and LK seasonal forecasts because they have other means of living away from smallholder farming (Bryan et al., 2013b)	-
x_{11}	Access to agricultural extension services	Yes = 1 No = 0	Access to extension services has been shown to increase farmers' exposure to scientific forecasts and knowledge and may reduce reliance or trust in IK and LK, where a blended approach is not adopted.	-
x_{12}	Family size	Continuous	Farmers with larger families have more members who are fit to work in the field, thereby intensifying production. Therefore, this is hypothesized to increase the probability of	+

			using IK and LK forecasts to make strategic decisions to buffer farming systems.	
x_{13}	Wealth level	*'Relatively better off' = 1 Poor = 0	Relatively better off farmers in this study were those with asbestos roofed houses, livestock (cattle), and owning television or radio, where they could access scientific/meteorological climate updates. Therefore, farmers who are better off are hypothesized to be less likely to use or rely on IK and LK forecasts to make climate adaptation and farming decisions.	+/-

*Livelihood diversification in this study was measured by farmers engaged in other off-farm activities that support their livelihood, such as trading, contract jobs in neighbouring villages, buying and selling to support household food security during the dry season, drought, and other climate hazards.
*'Relatively better off' in this study was measured based on farmers ownership of a house with asbestos roofing, farmer owning a TV or radio to access scientific forecasts, number of livestock owned by the farmer (at least four cattle – cattle are sold in the study area during climate related hazards such as droughts). This study adopted the approach of Rurinda et al. (2014a), who used two different classes– resource-endowered farmers and poor farmers – to determine the impact of resources on adopting adaptation measures.

4.3. Results

4.3.1. Socio-economic profile

The mean age was 48.7 (S.D. = 14.5). The mean length of stay (LOS) in communal wards was 36.53 (S.D. = 19.36), and that for the resettled wards was 18. 03 (S.D. 6.16). The mean family size was 7.3 (S.D. = 3), and the mean farmland size was 3.8 (S.D. = 2.4) hectares. Most farmers (59%) were women, and 48% had primary education as the highest formal education qualification. The majority (54%) of the farmers were classified in the poverty- poor category of wealth level (i.e., they did not have asbestos roofed houses, had three or fewer cattle, and did not have a radio/television to directly access weather updates). Seventy percent of farmers diversified their farming practices through mixed farming (crops and livestock). Only 23% of the farmers used irrigation. A high percentage (88%) reported having either direct access (from their own radio, TV, phone, or Malilangwe Conservancy Trust weather station, 31%) or indirect access (from agricultural extension officers, neighbours, social groups such as community gatherings, 57%) to scientific weather and climate forecasts. 74% of the farmers had access to agricultural extension services. Almost all the farmers (96%) perceived increasing climate variability and change (Table 4-2).

Table 4-2: Socio-demographic and other variables of the farmers (n = 100).

Variable	Mean	SD
Age (years)	48.73	14.45

LOS in an area (years)		
Communal	36,53	19.36
Resettled	18.03	6.16
Family size	7.31	3.03
Farmland size (ha)	3.75	2.37
Variable	**Percentage**	
Age category (years)		
20-29	11	
30-39	19	
40-49	24	
≥ 50	46	
Gender		
Female	59	
Male	41	
Education		
No Formal Education	18	
Primary	48	
Secondary	34	
Tertiary	2	
Farming type		
Resettled	40	
Communal	60	
Wealth Level		
'Poor'	54	
'Relatively better off'	46	
Use Irrigation		
No	77	
Yes	23	
Access to scientific weather information		
No	12	
Yes	88	
Perception of increasing climate variability and change		
No	4	
Yes	96	
Livelihood diversification		
No	30	
Yes	70	
Access to extension services		

No	26
Yes	74

Ninety-seven percent of the households surveyed in Chiredzi rural district relied on rainfed subsistence farming as their main source of livelihood. Twenty-three percent supplemented rainfed farming with small-scale irrigation in the Save and Mtirikwi Valley. The main crops grown were sorghum, maize, millet, sesame, groundnuts, and bambara nuts. Maize and sorghum are staple crops, while cotton and sesame are cash crops. Cowpeas, groundnuts, and Bambara nuts are edible crops.

4.3.2. IK and LK weather and climate forecasting in Chiredzi

Seventy-three out of the 100 smallholder farmers stated that they used IK and LK weather and seasonal climate forecasts. The weather and climate conditions most forecasted by farmers using the IK and LK forecasts were rainy season onset (63 farmers), followed by storms and rainy days (45 farmers), and rainy season quality and length (21 farmers) (Figure 4-1). Most forecasts made using IK and LK were short-term (hours for storms, days for rainy season onset and rainy days; and 4–6 weeks for rainy season onset) and with fewer mid-term climate forecasts (4–6 months for season length and quality, and droughts) (Figure 4-1).

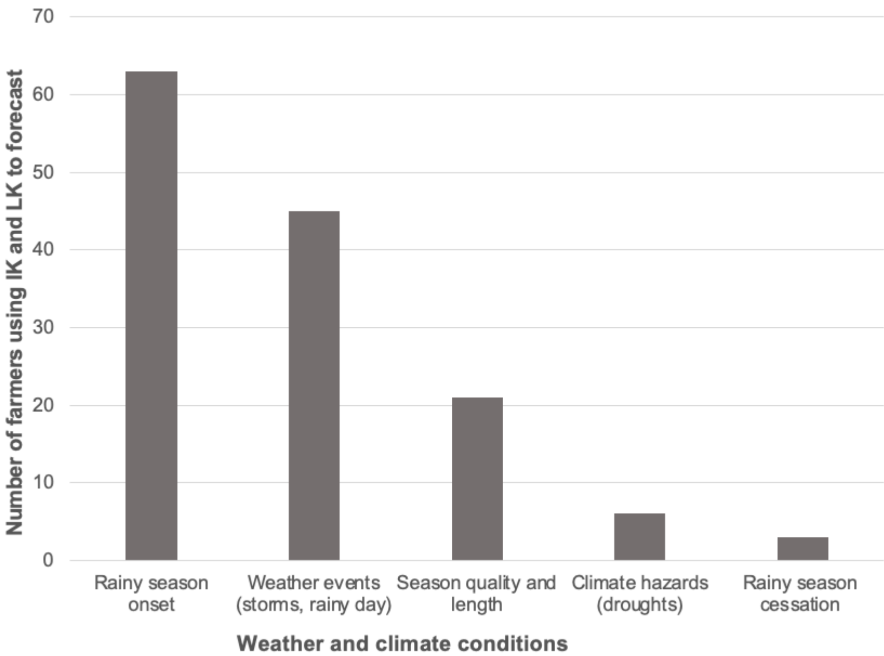


Figure 4-1: Weather and climate conditions that are forecasts by smallholder farmers in Chiredzi using IK and LK (n = 73).

Observing the summer temperatures, bird behaviour (mostly cuckoo), cloud characteristics (cloud type, appearance, development, and movement), tree flowering, fruiting, and vegetation leaf-out of local and indigenous tree species (mostly Mopane trees) are the most common indicators used for weather and climate forecasting in the Chiredzi district (Table 4-3). To predict the onset of the rainy season, farmers relied mostly on observing the direction of the nimbus clouds. To predict storms, farmers mostly relied on observing the sound of the southern ground hornbill. Some farmers revealed changes in the availability of important indicators used for IK and LK forecasts, such as the use of cuckoo birds to predict the onset of the rainy season.

Table 4-3: Common IK and LK indicators used by smallholder farmers in Chiredzi to forecast weather events and climate conditions.

Climate conditions	**Indicators**	**How perception of environmental variable is interpreted by IK and LK for seasonal forecasting**	**Percentage of responses indicating use of the indicator (%)**	**Degree of reliance on IK and LK for decision-making** (0-5)
Rainy season onset	Summer temperatures	Very hot summer days indicate the imminent arrival of the onset rain	26%	4.4
	Leaf-sprouting of Mopane trees (*Colophospermum mopane*); Rain tree (*Philenoptera violacea*), Baobab and other indigenous tree species	The shooting of brownish leaves indicates imminent rain.	25%	4.1
	Clouds (Nimbus clouds)	The appearance of moving nimbus clouds indicated good onset rain.	23%	4.5
	Birds mostly Cuckoo (*Cuckoo Cuculiformes*)	Continuous calls indicates imminent rain.	22%	4.4
	Human body	Interpretation of human body pain, back pain, and leg pain indicates imminent onset rain.	12%	4.3
	Wind direction	Wind constantly blowing from the east (from the Indian ocean via Mozambique) means onset rains are close	5%	4.5
	Christmas beetle (*Cicadas*)	Continuous call indicates imminent rains	4%	4.3
	Tropical rose mallow (*Hibiscus vitifolius*)	Abundant flowering before the rainy season indicates a delayed onset of rain	2%	4.5
Weather events	Clouds	Dark clouds indicate a rainy day or a very intense storm	25%	4.1

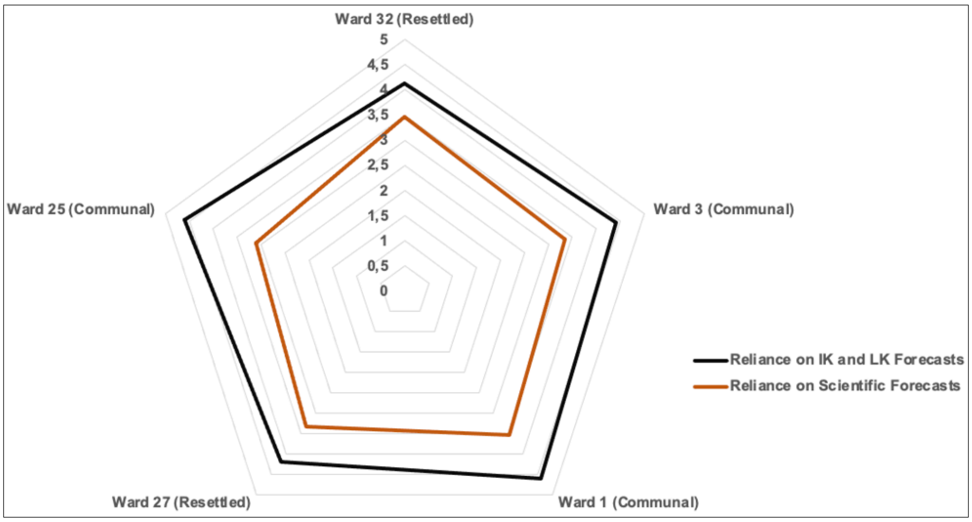
(storms, rainy day)	Birds (southern ground hornbill)	Sounding means imminent storm	16%	4.7
	Wind temperature and direction	Warm winds and wind blowing from east to west indicate that a storm is close	8%	4.4
	Human body	Human body pain, sweating, and aching (mostly elderly) mean that rainy days or storms are coming soon	5%	4.8
	Frogs	Continuous sounding indicates the coming of a storm or rainy days	4%	5
	Observations of the environmental surroundings	Reddish sunsets indicate imminent storm	4%	4.7
	Moon	Appearance of 1st and last quarter of the moon indicates that rainy days are close	3%	4
Growing season quality and length	Trees (*Acacia nigrescens)*	Abundant white flowering observed in September indicated a good incoming rainy season, and abundant red flowers indicated a dry season	8%	4.5
	Dreams	Dreams on whether a season is good or bad by individuals recognised to be 'weather dreamers.'	5%	4.9
	Trees (*Sclerocarya birrea*)	Profuse fruiting in February and March indicates a bad rainy season or drought ahead.	3%	4
	Trees (mahogany - *Afzelia qunzeisis*), mango tree	Abundant flowering and fruiting (observed prior to the start of the rainy season) indicated a good incoming rainy season	3%	4
	Stars	The large shining star on the western side indicates a good rainy season	3%	4.5
	Grasshoppers (*Schistocerca americana*)	Appearing in large numbers or swarms indicates an abundance of food	3%	4
	Wind direction	Frequent winds from east to west indicated high rainfall	3%	4.9
	Whirlwind	The regular occurrence of strong whirlwinds indicates high rainfall and a perfect temporal distribution of rain during the entire season.	2%	4.9
Rainy season cessation	Cold temperatures	Decrease in summer temperatures.	4%	4.5
	Cold rainfall	Cold rainfall indicates the end of rainy season and marks the beginning of the winter season	3%	4
	Clouds (cirrus)	The appearing of cirrus clouds indicates that no more rain is coming	3%	4
	Mist	The occurrence of mist and light showers indicates that the rainy season is ending	2%	4.5
Droughts	Stars	The large shining star on the eastern side forecast drought.	4%	4.5

	Marula tree (*Sclerocarya birrea*), bush fruits	Abundant fruiting indicates a dry season or a drought	4%	4.7
	Dreams	Dreamer in a village can foretell years of drought	3%	4.5

The degree of reliance on IK and LK was based on the ranking of each IK and LK forecast used by a farmer on a scale of 1–5 on how much they rely on the forecasts in decision-making. 1 = “I use them but do not rely on them”, 2 = “Barely rely on the IK and LK predictions”, 3 = “Sometimes I rely on them”, 4 = “I rely on them”, 5 = “I strongly rely on them.” The reliance score for each indicator was averaged to provide a representative degree of reliance, as indicated in the last column.

Comparing reliance ratings for weather and seasonal forecasts between IK and LK and scientific forecasts for climate decision-making by farmers, it is apparent that smallholder farmers in Chiredzi rely more on IK and LK forecasts than scientific forecasts (Figure 4-2a). At the ward level, farmers in communal wards (1, 3, 25) had a higher reliance on IK and LK forecasts than farmers in resettled wards – 27 and 32 (Figure 4-2a, b). Looking at the five weather and climate conditions and hazards forecasted by farmers, higher reliance on IK and LK forecasts is observed for communal wards (1,3 and 25) for four conditions: – onset rains (highest in ward 1), rainy season cessation (highest in wards 1 and 3), rainy season quality (high in wards 3 and 25), and storms and rainy days (ward 25). The highest reliance on IK and LK forecasts in resettled wards was observed for ward 32 only for droughts (Figure 4-2).

a)



b)

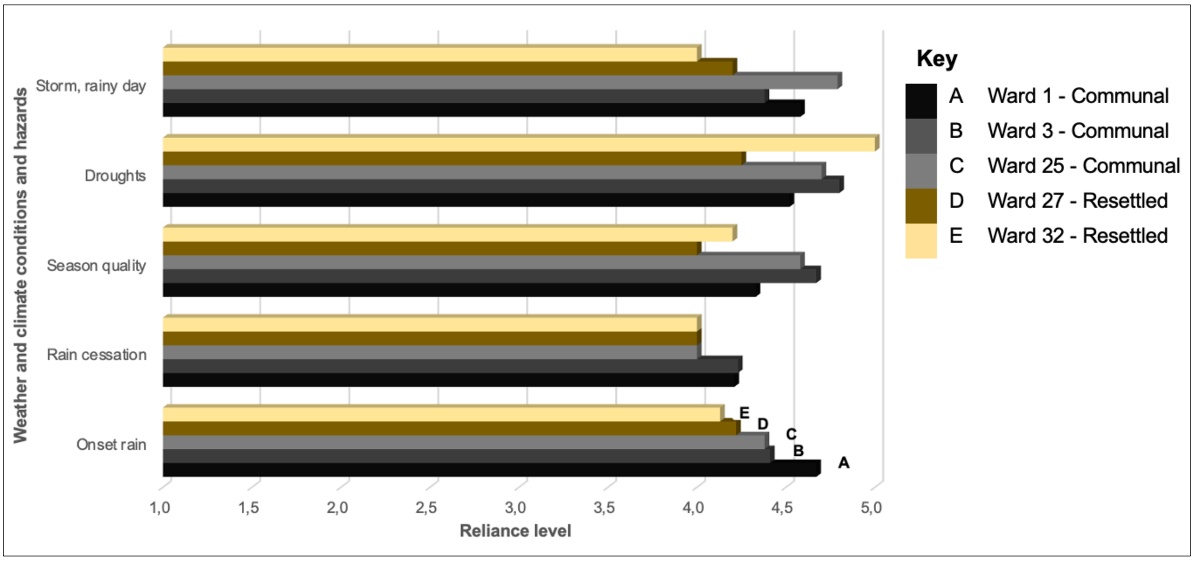


Figure 4-2: Differences in farmers reliance on IK and LK and scientific forecasts in Chiredzi: **a**) Reliance on IK and LK and scientific weather forecasts at the ward level by smallholder farmers in Chiredzi, and **b**) Reliance on IK and LK forecasts separated into five climate conditions and hazards by communal and resettled wards. Reliance here was based on the average ranking of forecast types used by a farmer from a scale of 1–5, reflecting how well they rely on the forecasts in decision-making (see Table 2 for the description of the reliability scale).

4.3.3. Determinants of use of IK and LK climate forecasts in Chiredzi

The binary logistic regression model explained between 19.7% (Cox and Snell R^2) and 28.6% (Nagelkerke R^2) of the variance in the use of IK and LK climate forecasts and correctly classified 79% of the cases (Table 4-4). The use of IK and LK climate forecasts was significantly positively associated with increasing farmer age and farmland size (Table 4-4). This implies that in Chiredzi, farmers with greater experience as farmers in an area are more likely to have trusted IK and LK and are therefore able to manage and maximise benefits working on farmland area implement, consistently IK and LK adaptation responses. The level of education of the farmer, access to irrigation, farming type (communal vs. resettled), and access to scientific weather forecasting information were found to be positively associated with farmers' probability of using IK and LK climate forecasts but were not statistically significant (Table 4-4). Family size, LOS in an area, farmers' perception of climate variability and change, access to extension services, wealth level, gender, and livelihood diversification were negatively associated with farmers' probability of using IK and LK forecasts, but were not statistically significant.

Table 4-4: Factors influencing smallholder farmers' probability of using IK and LK climate forecasting in Chiredzi.

					95% CI		
Variables	***β***	**S.E.**	**Wald**	**OR**	**Lower**	**Upper**	***p*** **- value**
Age (years)							
30–39	0.649	0.891	.531	1.914	0.334	10.969	0.466
40–49	2.974	1.146	6.737	19.576	2.072	184.978	0.009*
50 and above	1.622	1.057	2.355	5.064	0.638	40.189	0.125
Education							
Primary	1.136	0.760	2.236	3.114	0.703	13.799	0.135
Secondary or higher	0.967	0.942	1.053	2.630	0.415	16.678	0.305
Farming Type (*Resettled*)	2.158	1.158	3.472	8.655	0.894	83.781	0.062
Gender (*Female*)	-0.139	0.590	.055	0.871	0.274	2.769	0.814
Wealth Level (*Poor*)	-0.328	0.617	.283	0.720	0.215	2.413	0.595
Access to Irrigation (*no access*)	0.713	0.795	.804	2.040	0.430	9.680	0.370
Access to scientific weather information (*No access*)	1.091	0.839	1.690	2.977	0.575	15.413	0.194
Perception (*not perceiving changes in climate*)	-0.991	1.669	.352	0.371	0.014	9.785	0.553
Livelihood diversification (*not diversified)*	-0.594	0.755	.618	0.552	0.126	2.427	0.432
Access to extension services (*no access*)	-0.030	0.664	.002	0.971	0.264	3.568	0.964
Farmland Size	.513	.214	5.727	1.671	1.097	2.543	0.017*
LOS in an area	-.009	.024	.152	0.991	.946	1.038	0.697
Family Size	-.026	.103	.066	0.974	.796	1.192	0.797
Constant	-3.346	2.090	2.562	0.035			0.109
Cox and Snell R Square	0.197						
Model Nagelkerke's R^2	0.286						
Model correct prediction	79						
Number of respondents	100						

Note: The baseline state of a factor is provided in brackets where relevant. β is the estimated coefficient, SE is the standard error, Wald is Wald Chi-Squared Test, OR is the coefficient of determinations, p is the p value. * signifies $p < 0.05$. The italics shows the reference levels, for age the reference level was 0–29, for education it was no formal education.

4.3.4. Role of IK and LK in household climate decision making

Of the 73 out of 100 smallholder farmers who used IK and LK for weather and climate forecasting, 44 combined IK and LK forecasts and scientific forecasts to make climate decisions, 23 depended solely on IK and LK forecasts for climate decision-making on risk preparedness, and seven did not take any action in response to the available IK and LK forecasts (Figure 4-3).

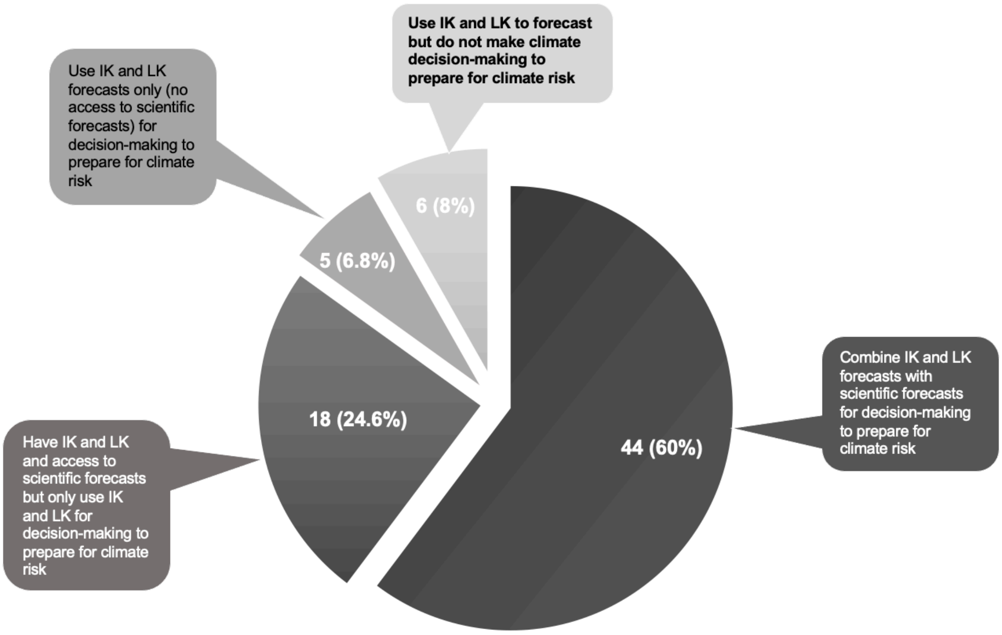


Figure 4-3: How smallholder farmers are relying on IK and LK weather and climate forecasts for decision-making to prepare for the climate risk in Chiredzi district. (n = 73).

A total of 23 decisions responding to various IK and LK forecasts were made by smallholder farmers in the Chiredzi district (Figure 4-4). Fifteen of these were climate decisions that contributed to the adaptation responses implemented by farmers in Chiredzi (Figure 4-4). Onset rain forecasts contributed the most decisions made by farmers – one third (9), followed by a storm and rainy day forecasts (5), climate hazards – cyclones, droughts (4), growing season quality (3), and rainy season cessation (3) (Figure 4-4). Most of these decision responses were related to planning the agricultural calendar, including 51% of the farmers implementing land preparation responses, 30% making crop variety selection actions, 43% preparing indigenous seeds, and 32% implementing dry planting measures (Figure 4-4). Figure 4-4 also shows that rainy season onset forecasting is the most critical parameter forecasted by farmers, as many decisions are made compared to other parameters.

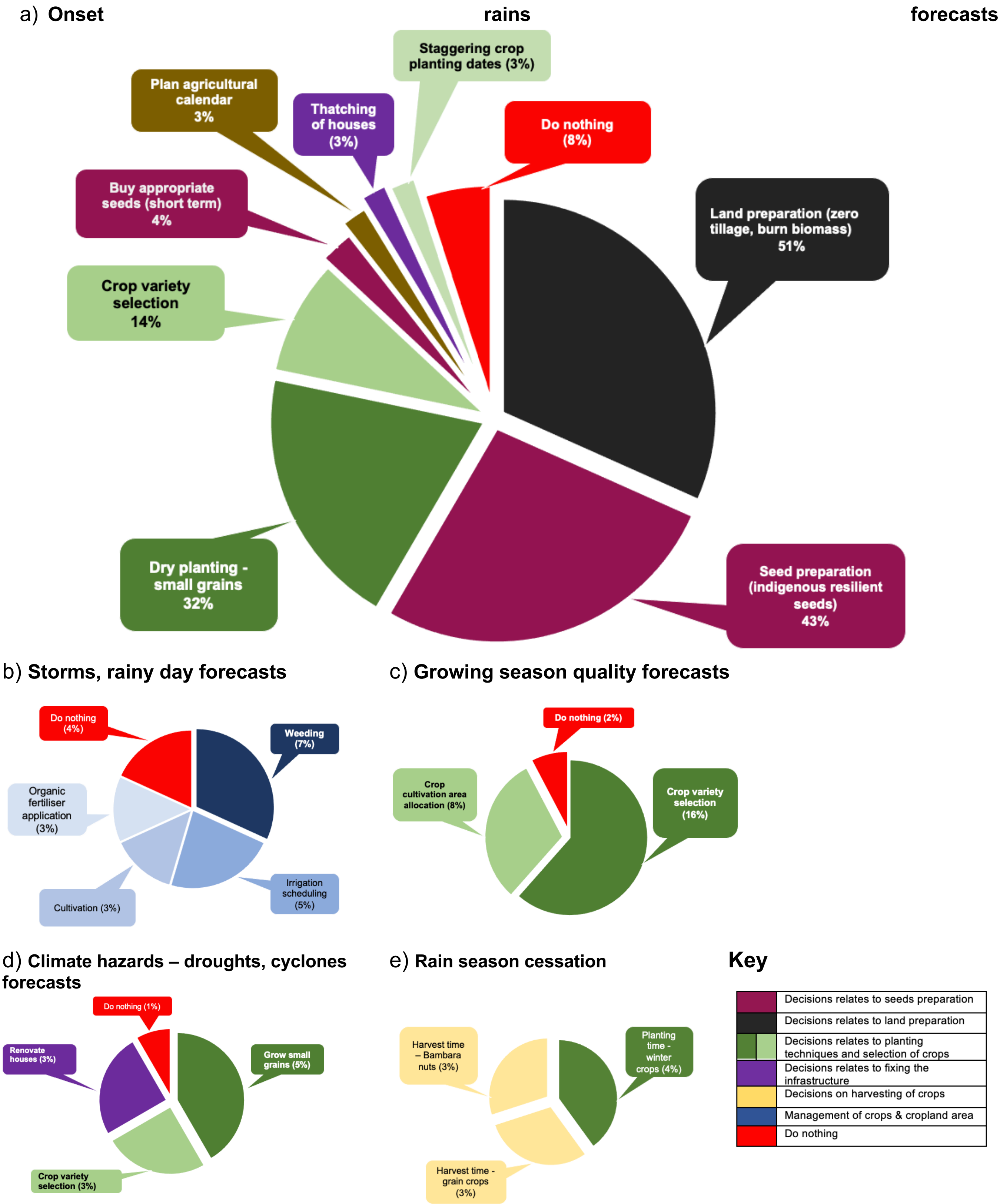


Figure 4-4: Smallholder farmers decisions made from the various IK and LK forecasts to prepare for the anticipated weather and climate outcomes for climate risk preparedness in Chiredzi district: **a**) decisions from rainy season onset predictions, **b**) decisions associated with storms, rainy day forecasts, **c**) decisions from rainy season quality forecasts, **d**) decisions from climate hazards, – droughts, cyclone forecasts, and **e**) decisions from rainy season

cessation forecasts. Pie-chart sizes are proportional to the number of decisions made and the percentage of farmers making those decisions. Detailed explanations of the decisions for each category are provided in the Supplementary Material 3.

4.3.5. Climate adaptation and IK and LK in Chiredzi

Smallholder farmers implemented seven different climate adaptation response types to cope with and adapt to drought and rainfall variability (Table 4-5). Specific farmers' coping and adaptation responses included increasing the area under small grains in anticipation of a dry season or drought (12%), growing drought-tolerant crops (8%), dry planting (21%), zero tillage for conservation agriculture (15%), smallholder irrigation (20%), selling livestock (9%), and working in neighbouring communities (19%). Farmers are also diversifying livelihoods through off-farm activities, such as trading (7%) and fishing – in the Save and Mtirikwi Rivers (7%) (Table 4-5). These measures have been implemented to cope with droughts, increased rainfall variability, and summer temperature risks.

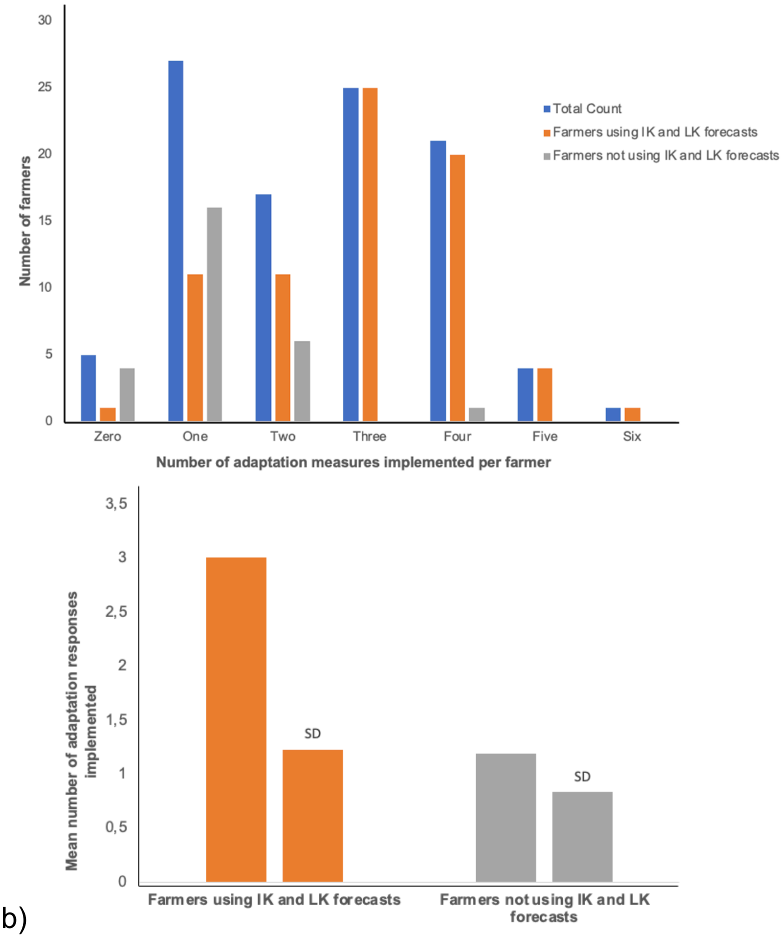
Table 4-5: The adaptation measures implemented by smallholder farmers to cope and adjust to climate risk in Chiredzi.

Adaptation type	Specific adaptation actions	Climate variability and hazards adapted to	Percentage of farmers implementing the response (%)
Crop variety selection	Growing small grains (e.g., sorghum, millet)	Drought, poor rainfall distribution, increasing mid-season dry spells	16%
	Growing drought resistant crops and varieties (e.g. cotton, sesame).	Droughts, increasing mid-season dry spells	8%
	Growing short term varieties.	Shortened growing season and early season dry spells	4%
	Growing indigenous varieties e.g., indigenous maize seeds.	Delayed onset	5%
Cropping area management	Reduce cultivation of high water demand crops such as maize when anticipating a drought.	Droughts, shortened growing season	10%
	Increase area under small grains.	Droughts and poor seasonal rainfall distribution	12%
Agricultural calendar planning	Dry planting	Delayed and unpredictable rain onset	21%
	Early planting	Mid-season dry spells; early cessation	6%

	Staggering planting dates	Increased mid-season dry spells, poor season rainfall distribution and increased variability	16%
Farm operational measures	Irrigation	Droughts, increased summer temperatures, increasing mid-season dry spells	20%
	Zero tillage for rain water conservation on plant stations.	Reduced seasonal rainfall amount	15%
	Intercropping	Increased rainfall intensity, storms'/	12%
Management measures	Fertilisation; organic manuring	Poor rainfall distribution	16%
	Rainwater harvesting and conservation	Poor rainfall distribution	10%
Off – farm activities	Fishing in the Save and Mtirikwi rivers	Droughts	7%
	Brick making	Droughts	3%
	Trading (buying and selling)	Droughts	7%
	Remittances	Droughts	3%
	Migrate to other areas and countries	Droughts	2%
Livelihood diversification	Sell livestock to buy family food	Droughts	9%
	Provide casual labour in neighbouring communities - sugarcane fields, commercial and irrigation plots	Droughts, poor and unpredictable rainfall	19%
Do nothing			5%

Ninety-five percent of the farmers surveyed were implementing at least one adaptation response, and 5% were doing nothing. The most frequently reported number of adaptation responses was the implementation of a single response (27 farmers), followed by 25 farmers implementing three adaptation responses and 21 farmers implementing four adaptation responses. The highest number of adaptation measures implemented by farmers was six (Figure 4-5a). Farmers that use IK and LK climate forecasts implement, on average, three times more adaptation responses (3.01, SD = 1.23) than farmers that do not use IK and LK to forecast weather and climate (1.19, SD = 0.83) (Figure 4-5b).

a)



b)

Figure 4-5: Smallholder farmers in Chiredzi using IK and LK forecasts implemented more climate adaptation responses: **a**) number of adaptation responses implemented per farmer by farmers using IK and LK climate forecasts and farmers not using IK and LK climate forecasts, and **b**) mean number of adaptation responses for farmers using IK and LK climate forecasts and farmers not using IK and LK climate forecasts.

4.4. Discussion

Most smallholder farmers in Chiredzi use IK and LK for weather and climate forecasting. The findings demonstrate the critical role of IK and LK forecasts in climate adaptation, as farmers using IK and LK forecasts in Chiredzi implemented, on average, triple the number of adaptation measures compared with farmers not using IK and LK (Figure 4-5). This highlights the important role of IK and LK in the implementation of climate adaptation responses at the local level, thus agreeing with the recent regional and global findings by Trisos et al. (2022), Berrang-Ford et al. (2021b) and IPCC (2022c). This further cements recent IPCC findings on how IK and LK provide a rich foundation for climate adaptation at the local level in Africa (Trisos et al., 2022).

Farmers use IK and LK forecasts to make context-specific climate decisions that are important for climate risk preparedness and resilience to climate risks (Figure 4-3) While understanding the use of IK and LK forecasts by smallholder farmers in Chiredzi, the study found that farmers aged 41–50 years, especially in communal wards, developed strong IK and LK systems for both climate forecasting and adaptation. This was confirmed by the regression analysis results, as the use of IK and LK forecasts was significantly positively associated with the farmers aged 41–50 (Table 4-4). This means that the age group is more likely to use IK and LK forecasts, which also increases their probability of adapting, as farmers using IK and LK forecasts implemented more adaptation responses than farmers not using IK and LK. The results on the significant association of IK and LK weather and climate forecast use with the 41–50 age group agreed with other studies in Africa (Tunde & Ajadi, 2019), where age distribution analysis revealed a significant relationship between the household use of indigenous knowledge for forecasting and climate variability adaptation for the 41–50 years category. However, farmers' LOS in an area was found to have no significant influence on their use of IK and LK. This qualifies the generalisability of LOS in an area as a determinant of IK and LK use that has been proposed by previous qualitative studies such as Chisadza, B. et al. (2013), and the results suggest that farmers move with their Indigenous and local knowledge systems, practices, and ways of doing things to new areas they inhabit, especially when the movements occur in short spaces such as movements within districts or provinces. It also suggests that there may be dimensions of IK and LK that are not constrained by place, enhancing their potential applicability and transferability to new contexts under conditions where knowledge holders have sufficient life experience to do so.

Also, the regression results confirmed that farmland size was also significantly positively associated with the increased probability of farmers using IK and LK for seasonal forecasting (Table 4-4). Farmers with larger farms were more likely to use IK and LK weather forecasts, as farm size appears to influence the extent of weather or climate-related damage or losses that a farmer may incur from extreme weather or climate events. In contrast to observations of Vietnamese farmers by Van Huynh et al. (2020), we did not find that years living in the area, farm-monthly income, or perception of climate change correlated with farmers' use of indigenous climate change adaptation practices. Although we found age to be an important determinant of farmers' use of IK and LK climate forecasts, global concerns about whether current and future generations could use IK and LK forecasts effectively, because of increased intergenerational disconnections, remain a grey area as far as the use of IK and LK is concerned with indigenous communities and smallholder farmers (Álvaro et al., 2021; Cameron, 2012). This is crucial for establishing the consistency and effectiveness of future knowledge as well as its relevance to climate adaptation.

Regarding the accessibility and use of climate information services, the higher reliance on IK and LK forecasts compared to scientific weather forecasts was explained by the majority of farmers having direct access to, and interpretation of IK and LK forecasts compared to scientific forecasts, where the majority of farmers access these through secondary sources (e.g., from agricultural extension officers, neighbours, and social groups such as community gatherings). This further highlights that easy access to climate-information services is vital for enhancing the implementation of timely decisions and responses. The findings support the notion that the use of and reliance on climate forecasts among smallholder farmers depends on how well individuals relate to the source providing forecast information. This validates the finding of Churi et al. (2012) that the lack of direct access to scientific weather information updates and how forecasts are shared between farmers affects the use of and reliance on scientific climate forecasts. Although we established farmers' higher reliance on IK and LK forecasts, the reliability of these forecasts has not yet been established. It is important that, in the future, the reliability of IK and LK forecasts is established in the study area and other regions where IK and LK forecasts form the majority of climate services. Research on the reliability of forecasts will further establish the potential future contributions of IK and LK to climate forecasting and adaptation. This is because the reliability of climate forecasts determines the relevance of actions implemented based on weather and climate forecasting (Guido et al., 2021).

4.4.1. Blending IK and LK and scientific forecasts

The study note that, despite the majority of the farmers relying on IK and LK forecasts, the forecasts did not provide more specific information, such as the total expected seasonal rainfall, which is also important in the climate decision-making and adaptation of smallholder farmers. However, the forecasts remain a priority and basis for decision-making for these farmers. Therefore, it would be helpful if farmers receive more reliable constant climate forecast information for accurate decision-making regarding how to cope with current variability and implement adaptation measures. This calls for an approach that promotes the use both of IK and LK and scientific forecasts.

To address the shortcomings of IK and LK forecasts and to improve access, use, and relevance of weather and climate forecasts for climate decision-making to smallholder farmers, a blended approach of various forecast sources is proposed. The study expect a coordinated approach that promotes blending of forecasts to increase the reliability and uptake of climate services by smallholder farmers in Chiredzi. Other blended approaches, such as integrated probability forecasting, have shown that integrating Indigenous and scientific forecasting improves smallholder farmers' climate forecasting and decision making (Nyadzi, Emmanuel et al., 2022). Because most of the IK and LK forecasts described in this study are short-term predictions (from hours to 90 days), the blended approach recommend can be applied in the following specific terms: (i) complement IK and LK short-term weather forecasting with daily (short-term) scientific forecasts for more informed short-term immediate decision-making for day-to-day management of climate risk, and (ii) higher use of scientific forecasts for long-term (up to one year or beyond) climate forecasting to increase the resilience of farmers. However, it is important that scientific forecasts be conveniently conveyed to smallholder farmers to address the challenges related to the delay and inaccessibility of scientific forecasts for the success of the blending process. This can be achieved through various mechanisms and technological interventions such as the use of mobile phones to supplement IK and LK forecasts with up-to-date scientific forecasting.

Challenges related to the intervention include, costs such as buying mobile data and smallholder farmers lacking access to smartphones. Given that most farmers own mobile phones, one way to overcome these challenges could be for farmers to use their existing phones to receive scientific climate forecasts through uncharged SMS text messages. The communication of climate services using SMS has recently become common and instrumental in smallholder farmers' decision making (Yegbemey & Egah, 2021). In Senegal, the use of SMS and community radio, together with other tools such as 'word of mouth,' increased access to climate information for over 3.9 million people in the five regions (Lo & Dieng, 2015). Issues such as language decryption of the forecasts are essential for converting the forecasts from probabilistic and complex jargon (Bacci, Ousman Baoua & Tarchiani, 2020; Unganai, Leonard S. et al., 2013; Yegbemey & Egah, 2021) to plain language, which farmers can easily understand for decision making. The use of mobile SMS text will also address some costs related to frequent visits by government agricultural extension officials to the less accessible communities in Chiredzi, by decreasing such visits by replacing them with the use of mobile phones. The visits of agricultural extension officers can be limited to periodic gatherings to discuss long-term scientific forecasts by farmers.

Smartphones can be used to further improve day-to-day access to scientific forecasts, and platforms such as WhatsApp and Telegram can be used to convey forecasts on a wider scale. This can be achieved by linking the available weather station to a weather application on a smart mobile phone or by sending regular updates to the WhatsApp or Telegram numbers of the farmers. In other regions, such mobile apps have been developed for smallholder farmers mostly under rainfed systems similar to Chiredzi, such as the use of CropMon in Kenya and

CommonSense in Ethiopia (van der Burgt, van Pelt & Lobbrecht, 2018), the Agricloud app in South Africa[3], and the Weather4Farmers app in Bangladesh[4]. Technological interventions for blending forecasts using smartphone applications have cost implications. Funding models for such initiatives can be developed through government working with multilateral funding institutions and the private sector to leverage funds for the development and set up of the technology. Other countries have used such financing models, for example, HydroNET in South Africa, where private sector partners with government departments provide different climate services to different sectors, including agriculture[5]. Establishing a blended forecast approach would be helpful in the event that some of the IK and LK indicators are affected by climate change, such as wildlife used for IK and LK going locally extinct due to climate impacts (e.g., cuckoo birds mentioned in Section 3.2), and the complementary scientific forecasts received through mobile phones can still provide useful updates for farmers' decision-making.

4.4.2. IK and LK climate forecasting and decision making

Most farmers use IK and LK forecasts to make various climate risk preparedness decisions. With most of the IK and LK used for short-term weather and climate forecasts (from hours to 90 days), most decisions are important for the day-to-day management of climate risk and the implementation of short-term climate coping responses. It is important to note that, with the existing IK and LK climate forecasting, few long-term farm plans and decisions go beyond a single growing season that can be made from the forecasts. Although these decisions are short-term in nature (from hours to 90 days), the study revealed that they are critical to farmers' everyday climate adaptation and decision making. For example, measures such as the selection of a suitable crop type and variety and the use of indigenous seeds based on IK and LK predictions of the rainy season onset and season quality and length (Figure 4-4) were among the most implemented adaptation responses by farmers in the study areas. Other examples include dry planting dates and selection of crop area management, which are among the most implemented adaptation responses in the Chiredzi district (Table 4-5). Most decisions are made based on rainy season onset forecasts. This means that the Meteorological Department and the government, through agricultural extension officers, can use these results to decide how to package the weather and climate forecasts when

[3] https://www.grainsa.co.za/get-this-weather-app-on-your-cell-phone

[4] https://www.weatherimpact.com/wi-app/

[5] https://www.hydronet.co.za/

disseminating scientific forecasts to the farmers to enhance farmers' decision-making that is required for informed climate adaptation in Chiredzi and Zimbabwe.

According to this study's sample, farmers in Chiredzi District combine IK and LK climate forecasts with scientific weather forecasts to implement adaptation responses to increase their resilience to climate risks. Farmers in Chiredzi showed higher reliance on IK and LK forecasts than on scientific forecasts (Figure 4-2a). This agrees with previous research in Zimbabwe and other parts of Africa (Fitchett & Ebhuoma, 2018; Grey, 2019; Streefkerk et al., 2022; Tanyanyiwa, 2018), where farmers have relied more on IK and LK weather forecasts. The majority of smallholder farmers in Chiredzi use IK and LK to forecast the onset of rain, mid-season storms, and quality of the growing season (Figure 4-1). These are the climatic conditions most commonly predicted by smallholder farmers (Fitchett & Ebhuoma, 2018; Gwenzi et al., 2016). These variables are important for rainfed smallholder farmers for both the planning and implementation of climate adaptation measures (Nkomwa et al., 2014). Farmers in Chiredzi use IK and LK forecasts for short-term agricultural planning and decision making, which are critical for climate adaptation. The unique indigenous knowledge resource found in Chiredzi, which was used to forecast key climate forecasts, was weather dreamers. Unlike most cases where a farmer makes a decision using personal interpretations and beliefs of the local environment and experiences, the unique character of weather dreamers in Chiredzi is their sphere of influence. On average, these dreamers influenced 5–10 households in terms of agricultural decision-making. The advice from weather dreamers is more specific; for example, the issuing of specific crop types to grow and the size of crop area management according to how they received the dreams. Advice plays a key role in farmers' coping mechanisms. Importantly, this advice, in some cases, conflicts with the advice from government extension officers. It is critical to note that the farmers in Chiredzi rely highly on forecasts and advice from weather dreamers in making climate decisions, with the indicators scoring highest on reliability (Table 4-3).

Changes in the availability of cuckoo birds, which are important for predicting the onset of the rainy season (Table 4-3) were attributed to increased climate variability and change. The results here are consistent with other regional and global case studies, in which many indigenous knowledge holders notice changes in the IK and LK indicators used for weather and climate forecasts, thus reducing their reliance on the IK and LK forecasts of that indicator for climate decision-making (Ankrah, Kwapong & Boateng, 2022; Leal Filho et al., 2022b; Radeny et al., 2019; Speranza et al., 2010). The attribution of the lack of availability of cuckoo birds to climate variability agrees with other studies that have shown how increased climate variability and change affect the indicators used for IK and LK climate forecasting, such as the extinction of some plants and animals in East Africa that are used for IK climate forecasts (Radeny et al., 2019). This presents challenges in the future regarding the reliability of IK and LK forecasts by smallholder farmers who rely more on forecasts for climate decision-making. This, also explains the compound impacts of climate change on climate forecasts and biodiversity as indicated by Simpson, Nicholas P. et al. (2021b) on compound risk from climate change.

4.4.3. Role of IK and LK on climate adaptation in Chiredzi

The major observation from the empirical evidence in this case study is how critical the IK and LK contributions are to the planning, selection, and implementation of adaptation responses and actions by smallholder farmers in Chiredzi (Figure 4-5). The findings strongly agree with regional analysis of the contribution of IK and LK forecasts to climate adaptation by farmers and communities (Filho et al., 2022; Leal Filho et al., 2022b; Trisos et al., 2022). The case study further emphasises how IK and LK are relevant and responsible for the implementation of the majority of behavioural and cultural adaptation measures. This was revealed by the nature of the adaptation measures implemented by farmers using IK and LK in Chiredzi. Most of them have focused on agricultural calendar year planning, crop type and variety selection, crop area management, and farm operational and management measures, such as irrigation scheduling, weeding, and fertiliser application. This has revealed the critical role and influence of indigenous and local knowledge on decision making that informs farmers about how they respond to climate variability risks. However, there is potential for some adaptation responses to reach soft and hard limits due to increased climate variability and change, such as the sale of livestock in response to food insecurity due to droughts. The increase in the frequency and intensity of droughts in recent years has affected the availability of livestock pasture. Furthermore, the efficacy of IK- and LK-based climate adaptation responses in reducing climate risk is yet to be established in the study area. The risks of maladaptation associated with the IK and LK climate adaptation responses also need to be established. This further highlights the gap of IK and LK identified by Zvobgo et al. (2022) across the African continent regarding the lack of evidence in the scientific literature showing the efficacy of IK- and LK-associated climate adaptation responses.

These results also highlight the importance of indigenous foods in climate adaptation, as the use of indigenous seeds, and the growing of indigenous crops, such as sorghum, and millet are among the most common climate adaptation responses in Chiredzi (Table 4-5). The results indicate the important role of indigenous seeds and varieties in improving the food security of vulnerable communities in arid and semi-arid regions of Sub-Saharan Africa. This is highlighted by other global studies: the use of indigenous food in India Ghosh-Jerath et al. (2015), the importance of indigenous seeds and food in adapting to climate change impacts, such as droughts, for example, the traditional drying of food and harvesting of wild fruits and vegetables by smallholder farmers in Africa – Tanzania, Zimbabwe, Ghana, and Malawi (Codjoe, Owusu & Burkett, 2014; Egeru, 2012; Kamwendo & Kamwendo, 2014; Okoye & Oni, 2017).

4.4.4. Policy implications of the study findings

The results on the contribution of IK and LK to smallholder farmers' climate adaptation highlight key issues and opportunities related to policy and planning at national and global levels. Given the important contribution of smallholder agriculture to livelihoods in many African countries, IK and LK on climate adaptation in this critical part of the food system can be instrumental in informing key climate change policies at the national level, such as adaptation commitments made by governments in Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs). Climate-resilient development processes that link IK and LK with other knowledge (scientific, practitioner, among others) can be more effective in avoiding maladaptation and leading to more locally appropriate and legitimate adaptation actions (IPCC, 2022c). In Zimbabwe, the results are relevant to the National Climate Response Strategy and when developing frameworks for operationalising the National Climate Policy, where Weather, Climate Modelling, and Change is one of the five thematic areas the policy focuses on (Government of Zimbabwe, 2017). For example, IK and LK forecasts can be integrated into national early warning systems for more localised climate risk and disaster management. The results also inform adaptation objectives and commitments for the first revised NDC and NAP planning for Zimbabwe.

In the revised first NDC for Zimbabwe submitted to the UNFCCC in 2021, early warning systems are identified as a top adaptation priority; hence, the results help develop processes for achieving effective early warning systems that are required for the implementation of informed climate adaptation responses in the agricultural sector. With the Zimbabwe NAP roadmap developed and finalized in 2019 (Government of Zimbabwe, 2019), the results are crucial for providing the Meteorological Services Department with local, accurate, and useful information for the implementation of effective and informed adaptation strategies through IK and LK fit for climate services. Lastly, in the global context, the fundamental role of IK and LK in climate adaptation, especially in developing countries from global south regions, is being increasingly recognised, and the integration of IK and LK into planned and institutional adaptation is very important (IPCC, 2019b; IPCC, 2022b). Therefore, we recommend a full chapter on IK and LK in future IPCC assessments or a special report on IK and LK for climate adaptation and mitigation as part of IPCC's 7th assessment cycle. If conducted in an inclusive manner, IPCC assessment could be a significant opportunity to further integrate IK and LK into climate change policy, given the crucial role of IPCC assessments in knowledge brokering across science, policymaking, governments, and other international and regional climate adaptation actors.

4.5. Conclusion

Indigenous and local knowledge plays a key role in weather and climate forecasting and household climate decision making, shaping smallholder farmers' adaptation to climate variability risks in Chiredzi. This study highlights the important link between IK and LK, and the increased implementation of adaptation actions. This is crucial for the operationalisation of the Zimbabwe National Climate Policy and the implementation of the key adaptation measures set in the revised first NDC among the adoption of an effective early warning system to manage climate risk. The IK and LK weather and climate forecasts performed by smallholder farmers are mostly used for short-term (from hours to 90 days) forecasting, which influences immediate crop cultivation, livelihood decision making, and adaptation responses. IK and LK forecasts are also used for medium-term forecasting (up to seasonal forecasting), which has a greater influence on the resilience of smallholder farmers to climate risk. Concretising the significant role IK and LK can play in climate change adaptation, as they demonstrate the importance of recognising the instrumental values of IK and LK and how a blended approach to using multiple knowledge systems can improve interventions targeting resilience for climate-exposed communities such as smallholder farmers. Therefore, this study recommends the IPCC 7th Assessment Special Report or a full chapter in the 7th assessment report on IK and LK. This will promote the integration of IK and LK into policy space and institutional adaptation for transformative, effective, and inclusive adaptation. The study have demonstrated how technological interventions can be explored to improve access to scientific climate forecasts that can promote the blending of scientific, and IK and LK forecasts at different temporal scales. Evidence from this study strongly indicates that IK and LK are important for smallholder farmers' resilience to current climate risks. However, concerns about the accuracy of IK and LK climate forecasts in Chiredzi and globally are not known, nor is the effectiveness and efficacy of the associated climate adaptation measures in reducing climate risk. Future research addressing the effectiveness of the IK and LK climate adaptation responses is required.

"From my experience; if I plant sorghum, and plant it early, I obtain a good harvest despite many dry spells we experience during dry years."

~ A smallholder farmer in Chiredzi, 2022 during an Interview referring to how she used her indigenous knowledge of planting sorghum early was effective in reducing climate risk.

Reliability and effectiveness of Indigenous and local knowledge in reducing climate risk: a case of smallholder farmers in Chiredzi, Zimbabwe*

Abstract

The reliability of using Indigenous Knowledge (IK) and local knowledge (LK) for weather and seasonal climate forecasts for adaptation decision-making has received increasing attention in the past decade. However, little is known about the effectiveness of responses informed by IK and LK in reducing climate risk. We developed a framework to assess the effectiveness of adaptation-related responses informed by IK and LK based on changes in exposure to climate hazards, conditions of vulnerability, adaptation capacity, and impact on other adaptation response outcomes. We applied the framework using a survey of 210 smallholder farmers in Chiredzi, Zimbabwe (2021–2022). IK and LK forecasts were most reliable for near-term weather and seasonal conditions (0–90 days). Eighteen IK- and LK-informed crop-related responses were implemented, with 22% of the responses showing evidence of high effectiveness in reducing climate risk by reducing the exposure of crops and farmers' livelihood vulnerability, another 22% showing moderate effectiveness, and 28% showing less evidence of effectiveness. IK and LK forecasts reduced both cropland exposure and length of time of exposure by informing strategic crop variety and type section and staggering planting dates; traditional irrigation reduced the exposure of crops to dry spells and late rainy-season onset; growing indigenous, drought-resistant small-grain crops reduced vulnerability to droughts; and IK and LK forecasts informed selection of drought-resistant cash crops provided income benefits for women and children. These findings show that the implementation of adaptation responses that consider IK and LK can effectively reduce climate risk for smallholder farmers. Effective IK- and LK-informed adaptation should be prioritised by adaptation projects to ensure social acceptance of adaptation and IK and LK forecasts should be incorporated into climate services to increase the implementation of more informed adaptation responses.

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Zvobgo L, Johnston P, Meyer Schwarz A, Trisos. C. H and Simpson. N. P: Reliability and Effectiveness of Indigenous and local knowledge in reducing climate risk: A case of smallholder farmers in Chiredzi, Zimbabwe. (to be submitted).

5.1. Introduction

The United Nations has declared 2020–2030 the "decade of action" for climate change[6]. This theme calls for increased implementation of innovative and sustainable solutions to adapt to climate change and effectively reduce climate risk. According to the Intergovernmental Panel on Climate Change (IPCC), effectiveness of adaptation was defined as "the extent to which an action reduces vulnerability and climate-related risk, increases resilience, and avoids maladaptation" (IPCC, 2022c, p. 7). Research on adaptation effectiveness has typically focused on ecosystem-based adaptation, especially for coastal systems (Calliari, Staccione & Mysiak, 2019; Chausson et al., 2020; Ferrario et al., 2014; Narayan et al., 2016; Reid et al., 2018; Tamura et al., 2019), with a recent assessment for water adaptation responses (Mukherji & Kumar, 2021), and in the global north—for example, flood defences reduced flood damages and early warning systems reduced heat-related mortality in parts of Europe (Bednar-Friedl et al., 2022). Many of these studies have been conducted in the context of cost–benefit analysis and the estimated effectiveness of the measures used to justify investments in ecosystem-based adaptation or nature-based solutions. Recent continental and global-scale assessments have found that the integration of Indigenous knowledge (IK) and local knowledge (LK) increases the effectiveness of a range of options for water- and food-related adaptation implemented by communities (Ara Begum et al., 2022; O'Neill et al., 2022; Trisos et al., 2022).

However, relatively few studies have assessed the effectiveness of adaptation responses for crop production in the global south (Berrang-Ford et al., 2021b; Owen, 2020). Furthermore, little is known about the effectiveness of adaptation responses in the context of reducing climate risks to food security for smallholder farmers who use IK and LK to inform their adaptation actions. In addition, the knowledge gap is perpetuated at regional and global scales on the effectiveness of IK- and LK-informed adaptation responses in reducing climate risk. The dearth of literature that assesses the effectiveness of adaptation responses is not limited to IK and LK but extends to most adaptation responses, particularly in the agricultural sector. With an increased understanding of the important role played by IK and LK in climate adaptation globally and in Africa, assessing the effectiveness of IK and LK-informed adaptation actions is critical for the implementation of appropriate and informed adaptation responses that reduce climate risk for the most vulnerable populations, including smallholder farmers (IPCC, 2019b; IPCC, 2022b; IPCC, 2023a; Leal Filho et al., 2022b; Schlingmann et

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[6] https://www.un.org/sustainabledevelopment/decade-of-action/

al., 2021). This is particularly important for smallholder farmers because they use IK and LK forecasts to inform climate adaptation actions in many Africa regions (Leal Filho et al., 2022a; Leal Filho et al., 2023; Nyadzi, Emmanuel , Ajayi & Ludwig, 2021; Petzold et al., 2020). Therefore, assessing the effectiveness of IK and LK for climate adaptation by smallholder farmers entails understanding both the reliability of IK and LK forecasts to correctly predict weather and climate conditions and the potential risk reduction of IK- and LK-informed climate adaptation responses. This combined approach is especially needed to develop evidence of the effectiveness of IK and LK adaptation responses from the perspective of rainfed smallholder farmers, given that approximately 90–95% of cropland in Africa is rainfed (Adams, 2018) and are heavily exposed to changes in precipitation (Seneviratne et al., 2021; Trisos et al., 2022). There is a need to develop empirical evidence on effectiveness of IK and LK adaptation responses from the perspective of rainfed smallholder farmers.

One way to assess the reliability of IK and LK forecasts is to compare them with observed climate data for a particular timeframe or season (Chisadza, Bright et al., 2014; Chisadza, Bright et al., 2015; Gilles et al., 2022; Guye, Legesse & Mohammed, 2022; Nkuba et al., 2022). However, there are knowledge gaps on in terms of very few studies that have used this approach to assess the reliability of IK and LK forecasts in Zimbabwe and in Sub-Saharan Africa, despite most of vulnerable communities use these forecasts for responding to climate risk.

The lack of evidence on the effectiveness of IK and LK-informed adaptation responses can be attributed in part to the lack of a comprehensive framework that assesses the risk-reduction element of climate adaptation (Zvobgo et al., 2022). Due to the highly contextual nature and temporal dimensions of adaptation for people, regions, and sectors, assessing the effectiveness of adaptation at different scales and over different timeframes is challenging (Ara Begum et al., 2022; Dilling et al., 2019; Eriksen et al., 2011; Eriksen et al., 2021; Ford, James D. et al., 2013; IPCC, 2022b; O'Neill et al., 2022). This lack of evidence of effectiveness can be attributed to several factors: human adaptation to climate change is in the early stages of implementation (Berrang-Ford et al., 2021b) and the lack of specific and commonly agreed upon metrics to measure adaptation (Christiansen, Martinez & Naswa, 2018; Dilling et al., 2019; IPCC, 2022c; Leiter et al., 2019; Morgan, Nalau & Mackey, 2019; O'Neill et al., 2022; Owen, 2020).

This study intends to fill the gaps identified above in three ways: (i) by developing a framework for assessing the effectiveness of IK- and LK-informed adaptation responses for smallholder farmers, (ii) establish the reliability of IK and LK seasonal climate forecasts, and (iii) apply the proposed framework to assess the effectiveness of IK and LK adaptation responses using empirical evidence from Chiredzi. The framework is applied in the context of the effectiveness of IK and LK adaptation responses in reducing food insecurity risks faced by smallholder farmers due to climate variability and change impacts in the Chiredzi district in Zimbabwe.

5.1.2. Framing Adaptation Effectiveness

A Local and Indigenous Knowledge Adaptation Effectiveness Assessment (LIKAEA) framework was developed to assess the effectiveness of IK- and LK-informed crop related adaptation responses of smallholder farmers. The effectiveness of adaptation responses in this study was framed by the IPCC 6th Assessment Cycle framing of adaptation effectiveness as well as the broader conceptual framing of effectiveness (Ara Begum et al., 2022; IPCC, 2022c; O'Neill et al., 2022; Simpson, Nicholas P. et al., 2021b). The framework is centred on how adaptation responses address the components of climate risk—hazard, exposure, vulnerability, and response—including how dimensions of vulnerability of farmers (poverty, gender, age and migration) can affect response implementation, which affects the effectiveness of the response and how different adaptation responses interact to address possible risk of maladaptation from implementation of responses (IPCC, 2022c; Schipper, E. Lisa F., 2020; Simpson, Nicholas P. et al., 2021b). Extending the 11 conceptual framing of assess effectiveness of adaptation from a multi-criteria approach developed by Singh et al. (2022), the framework in this study considered two conceptual framings to assess the effectiveness of IK and LK-informed adaptation responses which are: adaptation responses should (1) reduce risk and vulnerability and (2) support the achievement of material and subjective well-being. These two conceptual framings were selected because they were the most relevant for assessing the effectiveness of IK and LK-informed adaptation responses for rainfed smallholder farmers. The ability of the responses to increase farmers' income was added (Owen, 2020; Williams et al., 2021). Thus, the IK- and LK-informed climate adaptation responses in this study were considered successful if exposure and vulnerability to climate risks were reduced or the response had adaptation mitigation co-benefits, response implementation was less affected by the dimensions of vulnerability, and positively contributed to the five adaptation outcomes in Table 5-1, including the economic or financial benefits for smallholder farmers (Ayanlade et al., 2023; Carr & Nalau, 2023; Mukherji & Kumar, 2021; Owen, 2020; Singh et al., 2022; Williams et al., 2020). Crop related adaptation responses in this study refer to measures that involve crops in the implementation, or measures implemented to reduce the risk associated with crop production. Therefore, effectiveness of climate adaptation responses referred to the ability of IK and LK adaptation responses to exposure and vulnerability of crops and farmers and contribute to food security or improved informed decision making for farmers.

A multi-criteria approach was adopted when developing this framework, which simultaneously reported several different biophysical and socioeconomic attributes (Ara Begum et al., 2022). Several aspects are involved in assessing the effectiveness of adaptation responses. The framework proposed here applies to crop-related adaptation measures, although it can be modified for application in other sectors, such as pastoral and coastal flooding assessments. The framework is not geographically limited, which addresses the lack of systematic methods for assessing general adaptation effectiveness (Ara Begum et al., 2022). The framework utilised a combination of 11 indicators to assess the four climate risk components of the key risks in IPCC AR6– hazard, exposure, vulnerability and responses (Table 5-1). We further developed indicator questions that assess the impact of dimensions of farmer vulnerability on the IK and LK responses, as well as the interactions and trade-offs between responses (Table 5-1). Using the five indicators developed by Owen (2020) and the adaptation outcomes approach applied by Mukherji and Kumar (2021), plus the expert knowledge on IK and LK and smallholder farmers' adaptation, the framework developed five adaptation outcomes relevant to IK and LK-informed climate adaptation

Table 5-1: The LIKAEA framework developed to assess the effectiveness of IK and LK adaptation responses in reducing climate risk for smallholder farmers in Chiredzi.

Adaptation response	Response indicator on Hazard	Response indicator on Exposure (of crops)	Response indicator on Vulnerability	Impact of dimensions of Vulnerability on response implementation	Interactions between responses	Adaptation response' outcomes
What is the IK- and LK-informed adaptation response?	1. **Frequency of hazard**: How does the response reduce or increase the occurrence of climate risk? – Assess the role of the response in altering risk occurrence, thus affecting the climate physical processes or atmospheric emissions that increase, for example, extreme rainfall that can result in floods. Such practices include agroforestry from a smallholder farmer perspective. Whether the response addresses the mitigation components or any evidence of the mitigation co-benefits from the response.	1. **Duration of exposure:** How does the response reduce or increase the duration of exposure to climate risk? For example, how the response reduces the number of days crops are exposed to the risk, such as irrigation or other measures that supplement/conserve moisture for crops, such as mulching and other crop cover techniques.	1. **Crop vulnerability**: How does the response change crop vulnerability? This assesses the ability of the response to reduce the vulnerability of crops, for example, how the response reduces the vulnerability of crops to increased seasonal dry conditions. This includes decisions that promote drought-resistant crops from IK and LK seasonal forecasts or the planting of indigenous selective breeds that stand harsh climatic conditions in semi-arid regions.	1. **Limited access to resources**: How does poverty affect the implementation of such a response? This reciprocates the dimension of vulnerability such as poverty. How can poverty impede the implementation or adoption of IK- and LK-informed adaptation responses? This includes how lack of financial resources and other production resources affects the implementation of the responses. For example, can lack of draught power affects farmers' implementation of early planting response to utilise early rains/moisture.	**Trade-offs**: Is the response negatively affected by the implementation of other responses? Assesses the trade-offs between/ among the responses, whether the implementation of the response blocks or limit the implementation of the other response for example, by increasing the area under irrigation, the household reduces or stops growing drought-resistant crops to focus on irrigation, OR **Co-benefits**: the implementation of the response triggers the implementation of another response. For example, the IK and LK climate forecasts inform the implementation of	What are the outcomes of the adaptation response in the context of food security for smallholder farmers? Five relevant outcomes were identified. Whether the adaptation response contributed to one or more of the following outcomes. i. Improving farmers' food security, thus improving their livelihoods. ii. Improve crop yields obtained by farmers. iii. Financial/ economic benefits realised by farmers that improve their livelihoods. iv. Improve farmer weather and seasonal climate forecasting. v. Informed climate decision-making process for farmers.
	2. **Magnitude of Hazard**: How does the response reduce or increase the magnitude of climate hazards? Responses' ability to reduce the extent of a risk, for example, the responses reduce the chances of flooding or increase the magnitude of	2. **Area of exposure**: How does the response change the area exposed? The ability of the response to reduce the area of cropland exposed to the risk, for example, a response that reduces the maize crop area exposed to dry conditions in semi-arid regions or areas becoming drier due to	2. **Address poverty**: How does the response change farmers' poverty levels? This assesses the evidence of the response to address other key components of livelihood and humankind outside the food security and provision, such as the sale of proceeds	2. **Human mobility impact**: How does migration affect response implementation? This assesses the impact of mobility on reducing or increasing the adoption and implementation of IK- and LK-informed responses, for example, shift of labour requirements due to		

	hazard; for example, a response that promotes overutilisation of vegetation and destroy land cover leading to increased flooding when excess rainfall is received.	climate variability and change by applying cover to the area exposed or other practices such as ridging to conserve moisture/harvest water.	from crops to buy basic needs that improve their wellbeing, such as a radio or television, which can be used to access climate forecasts or buy livestock that can be sold during a drought to buy family food.	economic migration leading to a household not being able to implement the adaptation response, for example, cannot implement zero tillage due to lack of labour power as young, active family members that can do manual labour required for zero tillage have migrated to towns or abroad for employment.	other critical responses. The aim is to assess any potential maladaptation caused by the interaction between adaptation responses.	
		3. **Number of Crops exposed**: How many crops with exposure reduced? Evidence of the response to reduce of crops exposed (crop types and varieties), for example, the number of crops under intercropping.	3. **Equity and justice**: Who are the people involved in the implementation or who benefits from the adaptation response? Assess the involvement of underprivileged groups such as women in both planning and implementation or the benefits for women and children, for example, evidence of women and children benefiting from the response e.g., women and children needs addressed such as income for children's school fees.	3. **Age and gender**: How do age and gender limit response implementation? This assesses the gendered impact of the response; for example, women cannot implement the response because of lack of power or skills that are restricted to men in an area due to cultural norms and customs that discourage women from implementing the same response. How age affects response implementation; for example, old-aged farmers do not implement IK and LK responses, such as zero tillage because, they lack the required manpower.		

5.2. Methods

5.2.2. Characteristics of the Study Area

Chiredzi district is located in Natural Region V of the Zimbabwe Agro-Ecological Zones, which is the driest region in Zimbabwe. It is a semi-arid region that receives average total annual rainfall of 500 mm per annum (Chikodzi & Mutowo, 2012; Mugandani, R et al., 2012). Rainfall patterns in Chiredzi are highly variable (Jiri, Obert, Mafongoya & Chivenge, 2017; Manatsa et al., 2020), making it one of the most vulnerable to increased climate variability (Unganai, Leonard S & Murwira, 2010). Food insecurity is a common challenge for smallholder farmers in Chiredzi, and has been linked to climate hazards such as increased droughts, rainfall variability, and high temperatures (Chafa, Jaka & Chazireni, 2021; Defe & Matsa, 2021; UNDP, 2012). To adapt to climate risk in Chiredzi, smallholder farmers use various IK and LK weather and seasonal forecasts for critical climate decision-making and to implement climate adaptation responses, although the reliability of these forecasts has not been evaluated (Chafa, Jaka & Chazireni, 2021; Jiri, O, Mafongoya & Chivenge, 2015; Soropa et al., 2015; Zvobgo, Luckson et al., 2023).

5.2.3. Data Collection

Five of the 32 wards in Chiredzi rural district – Wards 1, 3, 25, 27, and 32 were strategically selected for data collection. We considered these five wards because of the resources available, time allocated for data collection, ward accessibility, and the presence of the key infrastructure for climate adaptation, such as the presence of continuous water supply from the Save and Mtirikwi Valleys. These wards were selected from communal and resettled farming areas. Data were collected over 12 months, covering the 2021–22 rainy season. Two data collection visits to the study area were conducted with interviews conducted prior the start of the rainy season and again after the end of the rainy season.

The main purpose of the interviews prior to the start of the rainy season was to understand various IK and LK forecasts performed by the farmers for the incoming rainy season. Data collection before the start of the rainy season was conducted in September and October 2021, because the rainy season usually starts from mid-to the end of November. Therefore, September and October are critical months where IK and LK forecasts are top-of-mind for respondents. During September and October, farmers used different local and indigenous indicators to observe and interpret environmental patterns (vegetation, birds, animals, insects, wind, moon, stars, clouds, and other atmospheric conditions). The forecasts were compared with observed precipitation data for the 2021–22 season (Table 5-2). A multistage sampling method (Sedgwick, 2015) was used to select study participants. One hundred smallholder farmers were interviewed at this stage with the sample consisting of 20 farmers per ward. Four villages were selected from each ward to ensure uniform sampling across each ward. In each village, five farmers were randomly selected for the interviews. Ethical clearance was obtained from the Faculty of Science Research Ethics Committee of the University of Cape Town (FSREC 002 – 2021).

Another round of interviews was conducted in June and July 2022, just after the rainy season. The June and July months were used because farmers would still have a fresh recollection whether their IK and LK weather and climate forecasts provided reliable predictions; whether the decisions and actions they took after forecasting effectively addressed climate risk; and if the overall adaptation responses they implemented could increase crop yields. A cross-sectional survey was conducted on 110 smallholder farmers by repeating the sampling procedure for September and October fieldwork, but with 22 smallholder farmers interviewed per ward. Different sets of farmers were selected from the same wards sampled in September and October to ensure sufficient coverage of the wards and to improve the richness of the collected IK and LK data. The interviews in June and July focused on the reliability of the IK and LK seasonal climate forecasts and the decisions made based on these forecasts in preparation for the 2021–22 rainy season. The survey further probed how adaptation responses implemented contributed to the food security of the farmer, and how they reduced other climate-related risks. This is important for establishing the effectiveness of the implemented climate adaptation responses. In total, 210 farmers were interviewed between 2021 and 2022. The effectiveness of the IK and LK adaptation responses was assessed at three levels: (1) reliability of the IK and LK forecasts, (2) adaptation responses reducing climate risk, and (3) contributing to the five adaptation response outcomes of improved food security, crop yields, economic benefits, improved forecasting and improved decision-making Table 5-1.

5.2.4. Reliability of IK and LK seasonal climate forecasts

A hindcast comparison technique (Chisadza, Bright et al., 2014) was applied, where IK and LK forecasts were evaluated against how the season turned out. We focused on four seasonal climate indices that are the most frequently forecasted by smallholder farmers in Chiredzi (Zvobgo et al., 2022) and that are crucial indices for rainfed smallholder farmers' climate decision-making (Jiri, O, Mafongoya & Chivenge, 2015; Soropa et al., 2015; Zvobgo, Luckson et al., 2023) (Table 5-2). Single-season data for the IK and LK seasonal climate forecasts made by smallholder farmers were compared with observed precipitation data to establish the reliability of the IK and LK seasonal forecasts in Chiredzi. Precipitation data (1972–2022) were obtained from a local meteorological weather station at the Malilangwe Conservancy Trust located opposite ward 32. Four climate indices were computed from the observed data for the baseline period (1972–2021) and compared with the 2021–22 season analysis for the same indices. The results of this comparison were used to establish the status of the 2021–22 season (Table 5-2). The 2021–22 season analysis was compared with the IK and LK seasonal climate forecasts (Jiri, O, Mafongoya & Chivenge, 2015; Soropa et al., 2015; Zvobgo, Luckson et al., 2023).

Table 5-2: IK and LK seasonal climate forecasts made by smallholder farmers and the climate indices used for comparison between the forecasts and observed precipitation data to establish the reliability of the IK and LK forecasts.

IK and LK seasonal climate forecasts (from the farmers)	**Equivalent climate indices used for comparing the reliability of IK and LK forecasts with weather station data.**	**How the indices were measured for observed precipitation data**	**Source of the scientific climate index**	**How observed baseline data (1972–2021) was compared with the 2021–22 season.**	**Source of the scientific explanation of what is late, delayed or early/ short**	**How observed data for 2021–22 season compared with K and LK seasonal forecasts.**
First rain for planting	Rainy season onset	25 mm of accumulated rainfall in 10 days (after August 1), without 10 consecutive dry days (rainfall <2 mm) occurring in the next 20 days.	(Tadross, M. et al., 2009)	Early onset: rains start 1 dekad (10 days) earlier or more than the average baseline. Normal onset: rain occurs within 1 dekad of the baseline average onset. Late onset: rain came 1 dekad later or more when compared to the baseline average.	(Shukla et al., 2021)	Compare the three categories in column 5 with the number of farmers who forecasted early, average and late start of the first rain for planting.
Length of the growing season	Rainy season length	The number of days between the rainy season onset and cessation dates.	(Mupangwa, Walker & Twomlow, 2011)	Short season: length shorter than 14 days or more compared to the baseline average length. Normal: length falls within 14 days of the baseline average length. Long: length of 14 days longer or more than the average length from baseline.	(Dunning, Black & Allan, 2016)	Compare the three categories in column 5 with the number of farmers that forecast short, average or long growing season.
Drought	Standardised Precipitation Index (SPI-6: Nov-April)	SPI is continuously negative and reaches an intensity of -1.0 or less.	(McKee, Doesken & Kleist, 1993)	Moderate drought (−1.5 to −1) Severe drought (−2 to −1.5) Extreme drought (≤-2)	(Tirivarombo, Osupile & Eliasson, 2018)	Compare the three categories in column 5 with the number of farmers that forecast a drought or a normal season.
End of rainy season	Rainy-season cessation	3 consecutive dekads, each with <20 mm (d after 1 Feb).	(Tadross, M. et al., 2009)	Early cessation: termination occurred 14 days earlier or more compared with baseline average. Normal cessation: termination falls within 14 days of the baseline average. Late cessation: termination is 14 days late or more from baseline.	(Ferijal et al., 2022)	Compare the three categories in column 5 with the number of farmers that forecast early, average or late rainy season end.

5.2.5. Effectiveness of IK and LK Adaptation responses

The LIKAEA framework developed in Section 1.2 (Table 5-1) was applied to assess the effectiveness of IK- and LK-informed adaptation responses implemented by smallholder farmers in reducing climate risk. For the adaptation outcomes of interest, farmers were asked to state the responses that contributed to the outcomes. Where one response contributed to more than one outcome, farmers were asked to rank them according to the most contributed outcome. A questionnaire survey was prepared to collect data from farmers for each IK and LK adaptation response identified following the framework developed in this study (Supplementary Material). Four evidence categories of effectiveness of adaptation responses: high evidence of effective (if 70% or more of the farmers implementing the response mentioned it as effective in addressing one of the three components of climate risk in Table 5-1; medium evidence of effectiveness (if 50–69% of the farmers implementing the response mentioned it as effective), low evidence of effectiveness (if 25–49% of the farmers implementing mentioned it as effective) and very low evidence of effectiveness if 1–24% of the farmers implementing the response mentioned it as effective.

It is important to note that the effectiveness of the adaptation responses assessed here was based solely on the analysis of data collected from farmers' perceptions and self-assessed description of effectiveness of adaptation expressed during the interviews. A quantitative analysis of some of the effectiveness indicators and adaptation outcomes could be conducted in future to obtain results independent of farmer perceptions. Adding quantitative analysis when applying the framework developed here, such as quantifying the yields obtained, could strengthen future assessment of the effectiveness of adaptation responses.

5.3. Results

Eighteen IK and LK-informed adaptation responses were identified as the crop-related adaptation responses implemented by smallholder farmers in the Chiredzi rural district. Among the 18 IK and LK adaptation responses, growing drought-resistant small-grain crops (sorghum and millet) was the most frequently implemented, followed by IK and LK weather and seasonal climate forecasts (Table 5-3). Irrigation, dry planting, zero tillage, and growing drought-resistant cash crops such as sesame were also among the most frequently implemented responses (Table 5-3).

5.3.2. Effectiveness of IK and LK adaptation responses

Of the 18 IK and LK responses reported by smallholder farmers, four (22%) showed high evidence of effectiveness in reducing exposure of crops and one or more dimensions of vulnerability (represented by dark blue in Table 5-3), four (22%) showed medium evidence of effectiveness in reducing exposure of crops and one or more dimensions of vulnerability (represented by light blue in Table 5-3) and further five (28%) responses responses were showed low evidence of effectiveness (represented by yellow in Table 5-3). Growing drought-resistant small grain crops, including the use of indigenous seeds for these crops, was frequently reported by smallholder farmers to effectively reduce the vulnerability of crops to persistent seasonal droughts. Income from crop sales of drought-resistant cash crops were effective in reducing poverty. Drought-resistant legumes (although implemented by few farmers and on small areas) are highly effective in addressing both exposure and vulnerability components due to legume cover crops, such as cowpeas, which reduced the direct exposure of soil to solar radiation, thus reducing the soil moisture evaporation. Growing of drought-resistant cash crops (such as sesame and cotton) benefit the most vulnerable groups – both women and children – as women tend to buy household goods for their families and children have their school fees paid from income sales of the crop (Table 5-3).

Traditional irrigation was reported more evenly distributed, addressing both the vulnerability and exposure components than any other adaptation response assessed (Table 5-3). Dry planting, zero tillage, and early planting showed negligible evidence of reducing climate risk in Chiredzi for the three key risk components. Regarding the dimensions of vulnerability assessed (gender, age, poverty, and human mobility), poverty reduce the effectiveness of most of the IK- and LK-informed measures implemented, followed by age and gender (indicated by grey colour in Table 5-3). This has implications on the implementation of other highly effective adaptation responses, such as drought-resistant small grain crops (indicated by green colour in Table 5-3). The use of IK and LK forecasts and the implementation of irrigation influenced other response implementations through negative trade-offs or beneficial synergies, for example, IK and LK forecasts positively influence crop decision making on type (plant more indigenous sorghum than maize), size of crop area to cultivate, stager planting dates that reduce risk (Table 5-3). In some cases, the implementation of irrigation had negative trade-offs with other responses with high evidence of effectiveness. Farmers adopting irrigation were reduced the implementation of these effective responses, such as the growing of indigenous drought-resistant crops (Table 5-3) thus potential of maladaptation.

Table 5-3: Effectiveness of IK and LK-informed adaptation responses in Chiredzi using the LIKAEA framework. The 0 values indicates that no farmers mentioned that particular aspect of risk.

Adaptation category	Specific adaptation responses	Total Count	Reduced hazard		Reduced exposure of crops			Reduced vulnerability of crops and livelihood			Impact of dimensions of vulnerability on responses			Trade-offs or synergies between responses: Irrigation			Trade-offs or synergies between responses: IK & LK forecasts		
			H1	H2	E1	E2	E3	V1	V2	V3	VR1	VR2	VR3	P (+)	N	Neg (–)	P (+)	N	Neg (–)
Crop type and variety selection	Drought resistant – SM, indigenous seeds	88	0	0	0	0	1	83	1	1	44	5	8	0	N/A	18	48	N/A	N/A
	Grow drought resistant cash crops	31	0	0	0	0	1	0	29	29	6	1	1	0	N/A	6	9	0	N/A
	Grow drought resistant legumes	7	0	0	7	7	7	0	5	5	2	1	1	1	N/A	2	5	N/A	N/A
	Grow short term varieties	12	0	0	3	0	0	4	0	0	2	0	0	N/A	N/A	N/A	7	N/A	N/A
	Appropriate crop type & variety selection	11	0	0	0	0	0	4	0	0	4	0	0	4	N/A	N/A	6	N/A	N/A
Timing of planting	Dry planting	36	0	0	0	1	0	0	0	0	10	1	2	2	N/A	5	19	0	N/A
	Early planting	19	0	0	1	0	0	0	0	0	6	0	2	10	4	1	11	0	N/A
	Delay planting / timing of planting	9	0	0	0	0	0	0	0	0	1	0	0	N/A	N/A	N/A	9	N/A	N/A
	Staggering of planting dates	8	0	0	4	0	0	1	0	0	3	0	0	N/A	N/A	N/A	3	N/A	N/A
Crop support measures	Irrigation	38	0	0	33	27	24	0	19	19	11	1	2	N/A	N/A	N/A	6	N/A	N/A
	Organic manure (to keep soil moisture)	7	0	0	0	0	0	0	0	0	0	0	0	2	N/A	N/A	0	N/A	N/A
	Rainwater harvesting - for irrigation	3	0	0	1	0	0	0	0	0	0	0	0	1	N/A	N/A	N/A	N/A	N/A
	Intercropping and early thinning	4	0	0	0	1	0	0	0	0	0	0	0	N/A	N/A	N/A	N/A	N/A	N/A
Land/ land use management	Zero tillage	34	0	0	8	0	0	1	0	0	2	0	1	2	N/A	10	22	N/A	N/A
	Crop area selection	10	0	1	0	0	0	0	0	0	2	0	0	3	N/A	N/A	9	N/A	N/A
	Soil moisture retention	10	0	0	1	2	0	0	0	0	0	0	1	N/A	N/A	N/A	1	N/A	N/A
	Reduce the area under maize crops	6	0	0	0	0	0	0	0	0	1	0	0	N/A	N/A	N/A	5	N/A	N/A
Forecasts (CL)	Climate seasonal forecasts	80	0	0	10	50	15	21	2	0	0	0	7	5	N/A	0	N/A	N/A	N/A

Effectiveness of response to address risk category

Evidence Level	Description of the effectiveness evidence	Colour Code
No evidence	Zero count for the response	
Very low evidence	Between 1–25% of the total count of the response	
Low Evidence	Between 26–49% of the total count of the response	
Medium evidence	Between 50–69% of the total count of the response	
High evidence	Over 70% of the total count of the response	

Vulnerability impact on response

Impact Level	Description of the impact level	Colour Code
No evidence	Zero count for the response	
Very low impact	Affect less than 25% of the total count of the response	
Low impact	Affect between 26-49% of the total count of the response	
Medium impact	Affect between 50-69% of the total count of the response	
High impact	Affect over 70% of the total count of the response	

Trade-offs and synergies between responses

Nature of Interaction	Description of the nature of response interactions	Response type: Irrigation	Response type: Forecast
Positive (+)	Response observed to promote implementation of other responses		
Neutral	Response implementation has no observed effect on the implementation of other responses		
Negative (-)	Response observed to negatively impact implementation of other responses		
N/A	No data	N/A	N/A

Code	Full Indicator Name	Description of indicator
H1	Frequency of hazard	Is the response reducing or increasing the occurrence of the climate risk? e.g., reduce flood occurrence
H2	Magnitude of Hazard	Is the response reducing or increasing magnitude of hazard? e.g., intensify the magnitude of flooding
E1	Duration of exposure	Is the response reducing or increasing duration of exposure? e.g., reduce the number of days that crops are exposed to dry days
E2	Area of exposure	Is the response change the area exposed? e.g., reduce the area of cropland that exposed to dry conditions
E3	Number of crops exposed	Is the response change the number crops exposed? e.g., number of crops under intercropping/ crops rotated
V1	Crop vulnerability	Is the response reduce vulnerability of crops? e.g. response promoting drought resistant crops or drought resistant legumes or indigenous selective breeds
V2	Address poverty	Is the response change farmer poverty levels? e.g., farmer selling proceeds from crops to buy basic needs that improve their wellbeing.
V3	Equity and justice	Number of women, children benefiting from the response e.g., women and children needs addressed such as income for children's school fees
VR1	Limited access to resources	Impact of poverty on response implementation? i.e. lack of financial and other key production resources that affect implementation of response, e.g., lack of draught power on early planting response or limited access to indigenous drought resistant seeds. This affects the adaptive capacity of the household.
VR2	Human mobility impact	How human mobility issues affect implementation of response? e.g., household not able to implement zero tillage due to lack of labour as young, active family members migrate to towns/abroad for employment due to climate impacts such as droughts.
VR3	Age and gender	Is age and gender effecting implementation of responses? e.g., not been able to implement draught power related measures due to old age or not allowed to implement certain adaptation options due to patriarchal reasons and cultural norms for women. These reduce the adaptive capacity of the farmers.
RR	Trade-offs and synergies	Is the response affect choice of other responses? e.g., due to increase of the area under irrigation, a farmer reduce or stopped growing drought resistant crops

5.3.3. Adaptation outcomes

A total count of 414 adaptation outcomes were realised by 91 farmers with IK and LK. Among these, 31% were improved food security outcomes, 28% improved farmers' yields, 16% improve weather and climate forecasting, 14% improved climate decision-making, and 11% improved the financial and economic status of smallholder farmers' livelihoods. Figure 5-1 shows the adaptation responses that contributed to the five adaptation outcomes investigated (improved crop yields; improved food security; financial and economic benefits; improved forecasting; informed decision making), and how farmers ranked the responses in the order they contributed to a particular outcome. The growing of drought-resistant crops, irrigation, and zero tillage were ranked the most in terms of their contribution to the two most critical outcomes – improve crop yields and food security (Figure 5-1). All 75 farmers who used IK and LK forecasts the 2022/23 season mentioned that the forecasts result in informed decision making to manage climate risk. (n = 91).

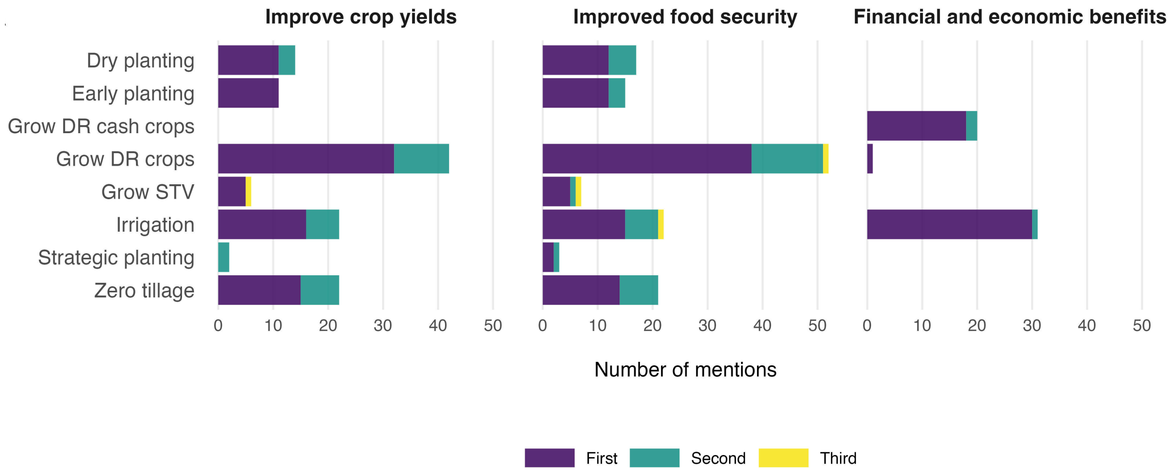

Figure 5-1: How the five adaptation outcomes from the IK- and LK-informed adaptation responses implemented by smallholder farmers were distributed and how farmers ranked them in the order of most realised per adaptation response. **a**) Bar charts are outcomes associated with crop-based adaptation responses.
*DR is drought resistant crops, STV is grow short term varieties, W & C is IK and LK weather and climate forecasts. (n = 91).

Although dry planting, early planting, and zero tillage showed negligible evidence for reducing the climate risk for the three components (in Table 5-3), here they have showed evidence of contributed to two important outcomes: food security and better yields (Figure 5-1). Growing drought-resistant crops improved both the yield and food security of farmers, who ranked them the most (Figure 5-1a). Drought-resistant cash crops such as sesame and cotton have contributed to these financial outcomes. Irrigation contributed more to the three outcomes (improved yield, food security, and financial benefits) than any other adaptation response (Figure 5-1a). 100% (75) of the farmers that used IK and LK seasonal climate forecasts the mentioned that the forecasts resulted in informed decision making to manage climate risk (Figure 5-1b).

5.3.4. Reliability of IK and LK seasonal climate forecasts

Most farmers surveyed use IK and LK for weather and seasonal climate forecast. Of the 210 farmers interviewed, 71% used IK and LK to forecast weather and seasonal climate for the 2021–22 season. For the 100 farmer interviews conducted prior to the beginning of 2021–22, 73 used IK and LK to make various seasonal climate forecasts for the upcoming rainy season. Observing and interpreting the summer temperatures, bird behaviour (mostly cuckoo), cloud characteristics (cloud type, appearance, development, and movement), tree flowering, fruiting, and vegetation leaf-out of local and indigenous tree species (mostly Mopane trees) are the most common indicators used by smallholder farmers to perform IK and LK seasonal climate forecasts in Chiredzi. The four main seasonal forecasts were the rainy season onset and cessation periods, length and quality of the rainy season, and drought (Table 5-4). IK and LK forecasts show high reliability for near-term forecasts (forecasts between 0–90 days), but their reliability is reduced for long-term forecasts (from three to six months). The IK and LK rainy season onset forecasts were highly reliable (high agreement when compared to the observed precipitation data) (Table 5-4). The IK and LK season climate forecasts correctly predicted the drought conditions for the 2021-22 season. Medium-term forecasts (three to four months) – rainy season quality and length show less reliability (medium agreement), and the forecasts were not reliable for longer-term forecasts (up to six months from the period of forecasting), as no agreement for rainy season cessation was observed (Table 5-4).

Table 5-4: Reliability of IK and LK seasonal climate forecasts in Chiredzi for a single season for data collected before the beginning of the 2021–22 rainy season. Reliability is determined by how closely the forecasts predicted key precipitation indices using the observed data for Chiredzi between 1972–2021 as the baseline. (n = 73).

Climate indices	**2021-22 IK and LK seasonal climate forecasts**	**Number of farmers per forecast**	**Total count**	**Overall IK and LK forecast**	**Average long-term observed 1972–2021**	**Calculated observed 2021–22**	**Comparison between the average observed and 2021–22**	**Comparison with 2021–22 observed climate data analysis**
Rainy season onset	Early onset	3	63	Late rainy season onset	309 days / (5-Nov)	326 days / (22-Nov)	Rainy season onset delay by 17 days	
	Normal onset	7						
	Late onset	53						
Rainy season length	Short	10	23	Normal rainy season length	116 days	115 days	Fall within 14 d range	
	Normal	12						
	Long	1						
Rainy season cessation	Early cessation	9	12	Early cessation	67 days / (8-Mar)	76 days / (17-Mar)	Fall within 14 d range	
	Normal	3						
	Late cessation	0						
Droughts	Drought year	1	73	No drought	N/A	1.1	No drought (SPI-6 above 0)	
	No drought	72						

High agreement		Medium agreement		No agreement	

Rainy season onset and cessation are expressed in the Julian days and the Gregorian Calendar. High agreement means that over 70% of the majority forecast agrees with observed data, medium agreement means 50%–69% of the majority forecast agrees with observed data, low agreement means less than 50% of the majority forecast agree with observed data, and no agreement means that over 70% of the majority forecast disagrees with observed data.

5.3.5. **Actions implemented from IK and LK forecasts.**

From the data collected after the 2021-22 rainy season on IK and LK seasonal forecasts and how farmers reacted to the forecasts, 92 of the 110 interviews had IK and LK. Only 75 farmers of the 92 applied their IK and LK for seasonal climate forecasting of the 2021–22 season. A total of 111 decision actions were implemented by smallholder farmers, based on how they had forecasted the season. Figure 5-2 shows the seasonal forecasts made and used by the farmers and the response actions implemented. Nineteen actions are taken by farmers to manage risks, including no action decisions, depending on seasonal forecasts (Figure 5-2). Most actions were related to the timing of planting, tillage type, crop type, and variety selection. Wet season forecasts were key for tillage, crop type and variety selection actions, such as zero tillage, whereas dry season forecasts were mostly associated with actions to manage the cropland area, selection of crop type and varieties, and timing of planting, such as early planting (Figure 5-2).

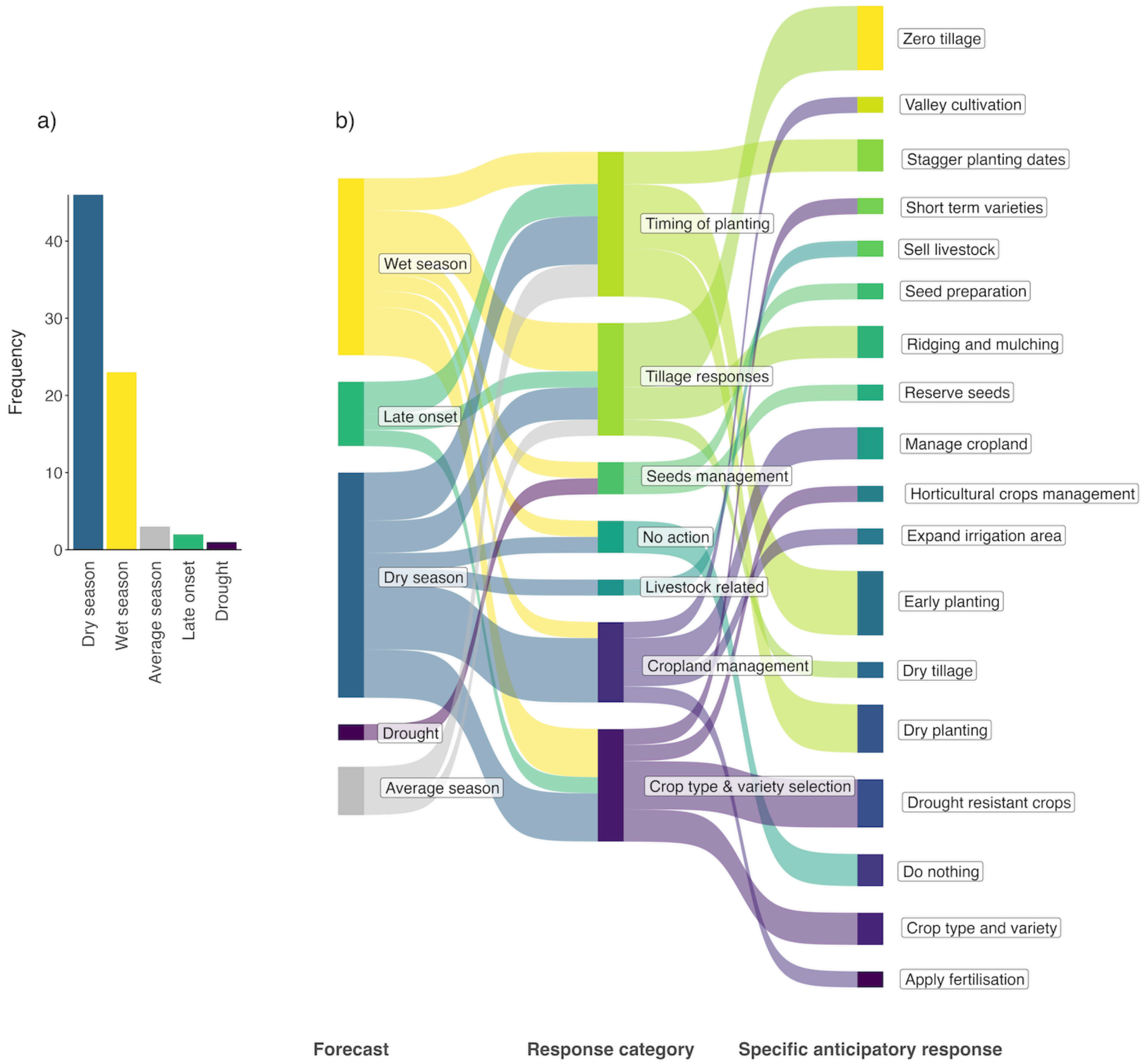

Figure 5-2: The forecasts farmers made for 2021–22 for data collected after the rainy season: **a**) the frequency of the four main forecasts made, and **b**) the relationship between the forecasts made and the actions farmers took to manage risk. (n = 75).

5.4. Discussion

The analysis of the 18 IK and LK adaptation responses in Chiredzi showed moderate to high effectiveness (44% of the 18 responses assessed showed evidence of effectiveness) (Table 5-3), This is consistent with Africa and global assessment on the evidence of climate adaptation, which shows the effectiveness of irrigation and drought-resistant crops in reducing climate risk for smallholder farmers (IPCC, 2022c; IPCC, 2023b; Mukherji & Kumar, 2021; Pörtner et al., 2022; Trisos et al., 2022). The level of effectiveness of IK and LK-informed adaptation responses in this assessment demonstrates why including IK and LK in adaptation planning and implementation of responses is critical for the effective offset of climate risk. This agrees with regional and global findings on how the inclusion of IK and LK increases the effectiveness of adaptation (Ara Begum et al., 2022; Berrang-Ford et al., 2021b; IPCC, 2022c). Based on the level of effectiveness demonstrated in this study, coupled with the absence of transformative adaptation responses under current global warming levels, smallholder farmers can cope, but the risk remains high and poses a potential threat. The evidence here suggest that under the projected global warming levels of 2 °C, poses the effectiveness of these measures will be reduced thus a high risk to Africa's food security (Trisos et al., 2022), as these IK and LK responses will not be able to address the climate risk with their effectiveness arguably reduced to negligible levels (IPCC, 2022c) leading to "redundancy adaptation" as they reach adaptation limits (Trisos et al., 2022). The IK- and LK-informed responses presented here should not be implemented alone, integrating them with responses informed by other knowledge sources can effectively buffer crops and the livelihoods of smallholder farmers (Apraku, Morton & Apraku Gyampoh, 2021; Ndalilo, Wekesa & Mbuvi, 2020).

We observed a lack of mitigation co-benefits of adaptation responses for all IK and LK responses assessed for Chiredzi. This highlights the fact that all IK and LK in Chiredzi only had adaptation benefits. These responses can be strengthened by complementing the current IK and LK measures with mitigation-benefit responses (Bryan et al., 2013a; Chandra, Dargusch & McNamara, 2016; Martinez-Baron et al., 2018), such as agroforestry, to achieve adaptation-mitigation co-benefits, as in other parts of Africa (Altieri & Nicholls, 2017; Bezner Kerr, Rachel et al., 2019; Leakey, 2020; Webb et al., 2017). The potential IK- and LK-informed responses in Chiredzi that can address this have not been implemented on scale, such as intercropping and the use of organic manure from livestock (Table 5-3). The same responses have produced adaptation-mitigation benefits for smallholder farmers in other areas (Bezner Kerr, Rachel et al., 2019).

The LIKAEA framework has the potential for wide application in sectors where IK and LK play key role in adaptation, for example, in the context of communities affected by flooding (Acharya & Prakash, 2019; Lai et al., 2023; Mavhura et al., 2013). Although the results from our framework are based on farmers' perceptions of the responses implemented, the framework provides an opportunity and an ideal foundation for understanding the effectiveness of IK and LK, mostly in the global south. Some limitations associated with the framework proposed here relate to the lack of time frame consideration to which the IK and LK adaptation response achieves its intended outcomes, yet this is key in assessing the effectiveness of adaptation (Ara Begum et al., 2022). Future research is therefore recommended to combine qualitative and quantitative assessments, for example, by running randomised trial pits in the study area under rainfed conditions to see if the crops grown early produce better yields compared to crops grown later. The same can be applied to dry planting as well as to other main adaptation responses implemented by farmers.

5.4.2. Effectiveness of specific IK and LK adaptation responses in Chiredzi

Our results show that irrigation in Chiredzi is highly effective in addressing both the exposure and vulnerability components (Table 5-3). This result agrees with regional and global findings in IPCC AR6 on how effective irrigation is in addressing the current climate risk (Bezner Kerr, R. et al., 2022; Caretta et al., 2022; IPCC, 2022c; IPCC, 2023b; Pörtner et al., 2022; Trisos et al., 2022). However, proper planning and management is important to avoid potential adverse outcomes, which can include accelerated depletion of groundwater and other water sources and increased soil salinization that leads to maladaptation (Caretta et al., 2022; IPCC, 2022c; IPCC, 2023b; Pörtner et al., 2022). Irrigation was the only response by smallholder farmers in Chiredzi, where IK and LK evenly addressed components of risk assessed.

Similar to the regional findings in some parts of Africa (Harmanny & Malek, 2019), our results also improves household food security. However, not many farmers have access to irrigation because of the lack of financial and technical expertise to irrigate (Trisos et al., 2022). Those who have access to it in Chiredzi use outdated technology informed by the IK and LK practices, such as the use of bunds and riverbed cultivation in Save, Mtirikwi, and other small streams around the district. These have the potential for maladaptation; for example, riverbed irrigation causes the siltation of rivers in the long term. Such maladaptation patterns have been observed where valley or streambank cultivation by Indigenous and local smallholder farmers negatively affects long-term river flow owing to siltation (Magesa et al., 2023; Ncube-Phiri, Mundavanhu & Mucherera, 2014). Streambank cultivation also increases the vulnerability of crops to future river flooding (Zvobgo et al., 2022). Thus, careful consideration is important for the current IK and LK irrigation practices practiced by smallholder farmers in Chiredzi. The adoption of safe, reliable, and efficient irrigation in Chiredzi can be improved through technological interventions by the government or NGOs' support; however, careful consideration and feasibility assessment are key.

The effectiveness of drought-resistant crops, mostly sorghum, is vital for Chiredzi to improve food security. The substitution of small grains for maize has been suggested as a viable adaptation option in the face of climate variability and change (Dunjana et al., 2022; Lobell et al., 2008). However, given the yield difference between maize and sorghum per hectare with maize having more yields, the adoption of sorghum should be carefully considered (Rurinda et al., 2014b). These can potentially implicate food security if not carefully planned and taken out of context. The government can use these results to promote farming initiatives that subsidise drought-resistant seeds and other inputs to encourage the growing of small grains such as sorghum and millet in Chiredzi and other dryland areas in Zimbabwe, and particularly seeds that's are locally adapted.

The results are also crucial for the government to reconsider its traditional and outdated policies which have shown a continual inclination towards growing of maize in semi-arid areas (Mango et al., 2015; Mukarumbwa & Mushunje, 2010). The results are also important for the revision of the current "*pfumvudza*" initiative and others that promoting the growing of maize crops even in semi-arid regions such as Chiredzi through providing maize seeds and related agricultural inputs to smallholder farmers in Chiredzi (Mavesere & Dzawanda, 2022; Mutonodzo-Davies & Magunda, 2011; Zerbe, 2001). The government can rather promote the increased production of sorghum in the semi-arid regions of Zimbabwe by subsiding inputs such as seeds and pesticides required for growing sorghum and investing in improving the varieties to short maturity. With the historical marginalisation of sorghum crop, especially in Zimbabwe, the sensitisation of smallholder farmers on why adopting sorghum crop is best suited for adapting to increased climate variability for regions such as Chiredzi is important. Some of the factors that should be considered to improve the sorghum adoption include strengthen local networks of kinships (Musara et al., 2019), increase awareness, improving market access, policy development, and availability of more locally adapted sorghum varieties are requisite factors in addressing the prevailing constraints limiting sorghum (Dunjana et al., 2022; Musara et al., 2019).

Adaptation responses contributing to highest adaptation outcomes in (Figure 5-1), should prioritise for implementation by farmers and government-led adaptation projects. Farmers implementing a combination of responses, such as growing drought-resistant cash crops while irrigating will likely to have "effective adaptation". Our results highly recommend mixing the implementation of adaptation responses, prioritising those with evidence of addressing the key components of the risk reduction framework. Vulnerability characteristics such as gender, age, poverty and migration affect the effectiveness of adaptation responses (Table 5-3) and adaptation planning should consider these factors. This agrees with recent findings for Africa where dimensions of vulnerability such gender, and migration compound with each other to affect risk (Ayanlade et al., 2023), thus reducing the effectiveness of adaptation responses. Our results provide key evidence that support the global conclusion that IK and LK provide important understanding for acting effectively on climate risk (Ara Begum et al., 2022).

For policymakers from the global south, these results are relevant when mobilising for adaptation funds and resources – both local and international funds, by providing an understanding of activities to priorities. For multilateral international funding institutions, such as the Green Climate Fund, Adaptation Fund, Global Environmental Facility, and others, the results provide insights on how to structure project activities, ensuring that the adaptation projects they fund for smallholder farmers have included important aspects of mitigation to ensure adaptation-mitigation co-benefits. Multilateral-funded project activities with such co-benefits will result in utilising limited available funds by maximising funded activities to have more impact, while effectively addressing climate risk (World Bank, 2021).

5.4.3. Reliability of IK and LK seasonal climate forecasts in Chiredzi.

Our results on reliability of IK and LK seasonal forecasts confirmed their relevance for short-term forecasting (Gilles et al., 2022; Gwenzi et al., 2016; Irumva, Twagirayezu & Nizeyimana, 2021; Zvobgo, Luckson et al., 2023). However, they also showed that their reliability decreases for long-term forecasts (usually forecasts for six months or more from time of forecasting) (Mahoo et al., 2015). The high reliability of near-term forecasts can be explained by two factors: the type of indicators used for forecasting and recent climate trends in Chiredzi. Indicator variables used for forecasting, such as summer temperatures, bird behaviour, clouds, and vegetation, are most suitable for short-term forecasting (Kalanda-Joshua et al., 2011; Zuma-Netshiukhwi, Stigter & Walker, 2013).

Observed climate data analysis for Chiredzi showed a statistically significant delayed onset of the rainy season between 1972–2021 (Zvobgo, Luckson et al., 2023); thus, the likelihood of farmers forecasting a late rainy season onset for the 2021/22 increase. High reliability of the IK and LK forecasts on rainy season onset is important for reducing the climate risk as information on onset is critical for rainfed smallholder farmers making informed decisions regarding when and what to plant (Tadross, M. et al., 2009; Tadross, M. A., Hewitson & Usman, 2005) that reduces crop failures associated with mid-season conditions from poor timing of planting. The high reliability of IK and LK rainy season onset forecasts are widespread in global south (Chisadza, Bright et al., 2014; Gilles et al., 2022; Radeny et al., 2019). IK and LK forecasts can be used together with conventional scientific forecasts, complementing each other to improve decision-making and implementation of informed adaptation responses by smallholder farmers. Where meteorological and scientific forecasts are remodelled and tailored with the input of IK and LK, they have performed better, with high adoption by smallholder farmers (Bucherie et al., 2022; Nyadzi, Emmanuel et al., 2022; Streefkerk et al., 2022). As reliability of IK and LK seasonal forecasts reduces longer-term forecasts, one way of integrating these forecasts with scientific forecasts is to merge specific forecast information where this can be provided by conventional forecasts, such as expected total rainfall amount which is often difficult to forecast using IK and LK (Gilles et al., 2022;

Iticha & Husen, 2019; Luseno et al., 2003). This will increase the relevance of the forecasts for improved decision making that is required for effective adaptation.

Our approach is an improved way to assess the reliability of IK and LK forecasts compared to previous qualitative approaches (Ankrah, Kwapong & Boateng, 2022), where the reliability of IK and LK forecasts was confirmed using methods such as relying on the majority of farmers using only IK and LK forecasts in a particular area (Adanu, Abole & Gbedemah, 2022; Chisadza, B. et al., 2013; Gwenzi et al., 2016; Iticha & Husen, 2019), which basically interpret the reliance of the forecast producer to the forecasts (Joshua et al., 2017; Zvobgo, Luckson et al., 2023). However, our approach can be strengthened by repeating the process for several successive years (up to five years) to establish probabilities for robust and reliable results (Gilles et al., 2022). We also propose that this approach can be applied to specific IK and LK weather forecasting indicators; for example, where farmers use wind direction or speed to forecast rainy season onset or storms, such data can be collected and compared with observed data for wind and precipitation to see if rainfall was received for those particular days/ time forecasted. This should shape future research on IK and LK forecasts, so that more informed responses supported by data are implemented in areas where smallholder farmers lack access to conventional weather forecasts.

Considering that IK and LK seasonal forecasts are highly useful for the implementation of several actions for farmers to prepare and manage risk (Figure 5-2), the reliability of such forecasts remains vital when managing climate risk. The direct link between forecast and decision actions taken by farmers (Figure 5-2), the reliability of such forecasts remains vital when managing climate risk. The direct link between forecast and decision actions taken by farmers (on Figure 5-2) demonstrates their importance for the adaptation responses recorded in Table 5-3. A smaller number of farmers forecasting the rainy season cessation in Chiredzi can explain two things: information about season end is not a priority for these farmers or that farmers are much concerned about the current (i.e., the rainy season onset and if it was a drought year, considering that the data collection was conducted towards the beginning of the rainy season–September and October–when preparations for the incoming growing season were at their peak).

5.4.3.1. Policy implications of the reliability of IK and LK seasonal forecasts

Evaluations of the reliability of IK and LK forecasts using observed climate data are very few in the African region and this study represents one of the few efforts to validate IK and LK seasonal forecasts to establish their reliability by comparing producer perceptions with multiple years of observed precipitation data. This is vital for governments and national climate services to accept IK and LK (Gilles et al., 2022). Our results are important for informing policy development in key areas related to climate services, including information dissemination, strategic planning, and decision-making processes at the local level for smallholder farmers. Such strategic approaches can be achieved by complementing IK and LK forecasts with scientific forecasts for specific aspects where IK and LK forecasts do not perform better, such as long-term rainy-season cessation forecasting (Nyadzi, Emmanuel et al., 2022; Zvobgo, Luckson et al., 2023). By illustrating the reliability of IK and LK forecasts using scientific data, our results increase the acceptance of IK and LK climate forecasts by the scientific community, academia, and policymakers in climate services (Ziervogel & Opere, 2010). Our results further demonstrates the potential for the co-production of forecasts using both IK and LK and meteorological/ scientific forecasts in future planning of the agricultural sector's early warning systems for actions targeted for smallholder farmers.

5.5. **Conclusion**

We assessed the effectiveness of 18 IK and LK adaptation responses in reducing climate risk in Chiredzi. Using the LIKAEA framework developed in this study, we showed that most IK and LK responses were supportive measures. Positive and promising evidence of the effectiveness of IK and LK adaptation responses was observed in Chiredzi. Growing drought-resistant cereal crops, irrigation, and drought-resistant cash crops addresses the vulnerability and exposure of crops and humans to climate risk. Notably, all IK and LK responses failed to record the mitigation co-benefits of the adaptation responses. Thus, complementing the current IK and LK adaptation responses with responses such as agroforestry may lead to adaptation-mitigation co-benefits. This ensures that approaches to tackling climate risk are significantly improved with limited available resources. These results provide a basis for understanding the effectiveness of current responses and the potential threats from these responses. IK and LK seasonal climate forecasts were more reliable for near-term forecasts, and their accuracy was reduced for longer-term forecasts (up to six months or more from the time of forecasting); thus, the forecasts need to be complemented with scientific forecasts, especially for key longer-term indices that are relevant for informed climate decision making of rainfed smallholder farmers.

The results of this study have wide implications for various stakeholders: for smallholder farmers, they are critical for advising them on responses to priorities; for multilateral international funding institutions, the results are critical when structuring funding activities, thus promoting initiatives where mitigation co-benefits of adaptation are realised and merging existing IK and LK adaptation responses with innovative technological responses. The framework proposed in this study can be the basis for considering programs to be implemented at the local or community level by non-governmental organisations, and local and national governments. Additionally, these adaptation responses can be included in other social security and safety programs and projects in Chiredzi. Importantly, these results for policymakers in Zimbabwe provide insights into the planning and development of the National Adaptation Plan, providing evidence that IK and LK responses can be promoted and integrated into national climate adaptation programs and planning. Future research could use quantitative data to assess some of the indicators suggested in this study to provide robust evidence for the effectiveness of adaptation responses.

6. Synthesis, Conclusions and Recommendations

6.1. Synthesis of findings

The overarching research question of this thesis was to understand “what role do IK and LK play in smallholder farmers’ adaptation to climate variability and change risks?” Empirical evidence from the Chiredzi Rural District was used to understand smallholder farmers’ use of IK and LK to adapt to climate variability and change. In total, 210 farmers were engaged over a period of two years. Enormous data and insights were collected from farmers on IK and LK weather and seasonal climate forecasting, climate decision-making, and overall climate adaptation, including the effectiveness of IK and LK-informed responses in addressing climate risk. The data were corroborated by long-term precipitation and temperature data to understand the exposure of farmers and confirm the reliability of the IK and LK forecasts.

Key findings of the study are synthesised in this Chapter in light of the results presented across the four empirical chapters. Drawing on the synthesis of the findings, this chapter further outlines the proposed conceptual framework that can potentially facilitates the integration of IK and LK into institutional and planned adaptation. The discussion was largely drawn from the key findings of the study and the lessons from engaging wider scholarship from the researcher’s experience and involvement in IPCC AR6 Working Group II, where he was the Contributing Author of ‘Box 9.2 | Indigenous knowledge and local knowledge’ of Chapter 9: Africa and as IPCC Chapter Scientist for Chapter 9: Africa during the same period.

The five research questions in Chapter 1 were explored in Chapters 2–5, investigated and presented as research papers. Below is a summary of the research questions, the chapters in which they were investigated and how the findings are connected.

1. What are the current knowledge trends and gaps in Africa's IK and LK academic literature for water sector, and to what extent is IK and LK considered in national policy focusing on Nationally Determined Contributions (NDCs) submitted by African governments? (in Chapter 2). The knowledge gaps and opportunities explored were fundamental in the framing of Chapters 3–5.
2. How vulnerable are smallholder farmers in the Chiredzi District to climate variability and change risks? Are smallholder farmers that use IK and LK more or less vulnerable than smallholder farmers relying on other forms of knowledge in

the district? (Chapter 3). Farmers using IK and LK had increased adaptive capacity and reduced vulnerability because of the IK and LK weather and seasonal forecasts they used to make climate-informed decisions, thus introducing the research question 3 that was explored in Chapter 4.

3. What IK and LK that are used by smallholder farmers for weather and seasonal climate forecasts and what is their influence on climate decision-making in Chiredzi? (Chapter 4). On-farm adaptation responses related to 23 identified decision types from IK and LK weather and climate forecasts, including crop variety selection (e.g., drought-resistant crops), cropping area management (e.g., water conservation measures), and agricultural calendar planning and management (e.g., zero tillage, dry planting, or irrigation). This triggered the research question in Chapter 5 regarding the effectiveness of these decisions in reducing climate risk.
4. What is the role of the IK and LK weather and climate forecasts in informing the climate adaptation responses implemented by smallholder farmers in Chiredzi? (Chapter 4). Farmers using IK and LK forecasts implemented, on average, triple the number of adaptation measures than farmers using other climate forecasts.
5. How reliable are IK and LK seasonal climate forecasts, and what is the effectiveness of IK and LK adaptation responses in reducing the climate risk in Chiredzi? (Chapter 5). The IK and LK seasonal forecasts were most reliable for near-term forecasts (forecasts between 0–90 days). Eighteen IK and LK adaptation responses were identified, 44% of these responses showed medium to high evidence of effectiveness in reducing climate risk. This opened the discussion to integrate IK and LK into institutional, planned adaptation explored in Chapter 6: Section 6.1.6 to increase the effectiveness of adaptation to increase resilience, thus reduce the climate risk for smallholder farmers.
6. How can IK and LK be integrated into planned and institutional adaptation to increase the resilience of smallholder farmers to manage climate risk? (Chapter 6). A conceptual framework was proposed that can potentially improve the integration of IK and LK into planned adaptation processes at national level.

6.1.1. IK and LK Regional knowledge trends and gaps

As Africa is among the regions with the highest evidence of IK and LK for climate adaptation recorded in academic literature (Berrang-Ford et al., 2021b; IPCC, 2022b; Mukherji & Kumar, 2021; Petzold et al., 2020; Schlingmann et al., 2021), it is important to explore the role of IK and LK in Africa's key livelihood sectors, such as the water sector. Furthermore, it is important to understand how IK and LK climate adaptation contributes to effective adaptation, which reduces climate risk (Ford, J. D. et al., 2015). Therefore, the following research question was explored in the academic literature for Africa regarding IK and LK for climate adaptation.

> **"What are the current knowledge trends and gaps in Africa's IK and LK literature on water sector adaptation responses?"**

The assessment of academic literature (2013–2020) in Chapter 2 for water sector adaptation responses in Africa reveals the potential of IK and LK to contribute to effective adaptation. The analysis slowly highlighted the potential of IK and LK in reducing climate risk for water adaptation responses in Africa. The analysis showed that the water adaptation responses informed by IK and LK recorded higher evidence of risk reduction than responses without IK and LK. This is consistent with the IPCC global findings in AR6, where IK and LK is understood to play an important role in effectively reduce climate risk and helping diversify knowledge that may enrich adaptation policies and practices (Ara Begum et al., 2022). Evidence of IK and LK in the implementation of water adaptation responses was high in West, East, and Southern Africa, with Zimbabwe displaying the highest evidence (77.8%). This was consistent with the global evidence mapping of the academic literature on IK and LK for climate adaptation, which identified Zimbabwe as one of the countries with the highest evidence of the role of IK and LK in climate adaptation (Petzold et al., 2020). To better understand the extent of the contribution of IK and LK in Zimbabwe, a more local-level assessment of the role of IK and LK was conducted for smallholder farmers in the Chiredzi district (Chapters 3–5).

Given the key role of IK and LK in climate adaptation in Africa and its importance in climate risk management, the literature assessment further analyses the considerations of IK and LK in national policy formulation; thus, Africa's NDCs were reviewed. NDCs were considered for this assessment, as they determine national policy planning for countries. NDCs contain countries' adaptation priorities and long-term planning, they inform countries climate actions. To achieve this, the study asked the following sub-research question.

> **"To what extent is IK and LK included in NDCs submitted by African governments to UNFCCC?"**

The analysis of iNDCs shows that the most implemented water adaptation actions recorded in academic literature were consistent with the water sector adaptation targets set by most

African governments. This demonstrates the important role of NDCs in influencing national climate adaptation discourse (Abanda et al., 2022; Bjørn et al., 2022; Fuso Nerini et al., 2019). Despite this direct link of commitments in NDCs to drive national adaptation, the analysis of the iNDCs showed that only 10.4% of the African countries (33 countries assessed) included IK and LK in their national adaptation planning (Table 2-5). These results reveal the limited consideration of IK and LK in the national adaptation discourse for African countries. This confirms what has been emphasized in the literature on how IK and LK in Africa is often neglected in national adaptation planning processes (Adenle et al., 2017; Chah et al., 2022; Ogunyiola, Gardezi & Vij, 2022; Trisos et al., 2022). This was one of the key gaps identified by the literature assessment and what this thesis intended to address by proposing a conceptual framework that could assist the inclusion of IK and LK in adaptation planning. This limited consideration of IK and LK can be explained by the lack of a framework that can easily facilitate their inclusion in planned institutional adaptation (Mycoo et al., 2022).

6.1.2. Gaps and opportunities identified.

Although water adaptation responses informed by IK and LK showed higher evidence of climate risk reduction than water adaptation responses informed by other knowledge sources for locally led adaptation (Table 2-4), the lack of a comprehensive framework that assesses current IK and LK responses in reducing climate risk was identified as a huge gap and obstacle in assessing the effectiveness of IK and LK adaptation responses. This provided an opportunity for this study to develop a framework to address this gap. The lack of a framework was also identified in IPCC AR6 as a key challenge limiting global assessment of the effectiveness of adaptation (O'Neill et al., 2022). This is partly attributed to the highly localised, context specific, and the time bound of characteristics of climate adaptation responses (Ara Begum et al., 2022; Christiansen, Martinez & Naswa, 2018; Singh et al., 2022). Thus, the research questions in Chapters 3–5 of the study explored these gaps to address the gaps at a local scale, such as a district. With a clear gap in the limited consideration of IK and LK in national adaptation planning, Chapter 2 also recommends a coordinated approach that integrates multiple knowledge systems, including IK and LK, to ensure the sustainability of both current and proposed climate adaptation responses in Africa. This study attempted to address this gap by proposing a conceptual framework that can facilitate the integration of IK and LK into institutional adaptation, mostly in the African context (Section 6.1.6, Figure 6-1).

6.1.3. Vulnerability of smallholder farmers to climate variability and change in Chiredzi

Globally and across Africa, smallholder farmers are among the most vulnerable populations to climate variability and change (IPCC, 2023b; Trisos et al., 2022). This is because of their livelihoods, which rely highly rely on climate-sensitive sectors among rainfed agriculture (IPCC, 2022b; IPCC, 2023b). Although there is a tendency to focus more on vulnerable groups, such as smallholder farmers, there is still limited engagement with local perspectives and knowledge (Ayanlade et al., 2023). Hence, this study explored the following question to understand the vulnerability of smallholder farmers in Chiredzi on a local scale:

> **"How vulnerable (absolute) are smallholder farmers in Chiredzi District to climate variability and change risks?"**

A locally calibrated livelihood vulnerability assessment method was developed to understand the level of farmers' livelihood vulnerability. This was corroborated by precipitation and rainfall data analysis (1972–2021) to understand the exposure of farmers to climate variability and change. Overall, vulnerability of smallholder farmers was high (between 0.37 for the least and 0.41 for the highest in Chiredzi District. This was relative to a range scale of 0 (which is for the least) to 0.5 (for the most vulnerable) (Hahn, Riederer & Foster, 2009). In terms of absolute vulnerability, this was considered high compared with other results for smallholder farmers elsewhere that have used the LVI approach in Africa (Adu et al., 2018; Asrat & Simane, 2017; Ebrahim, Miheretu & Alemayehu, 2022) and Asia (Ho, Kuwornu & Tsusaka, 2022; Ho et al., 2021; Panthi et al., 2016; Rinzin et al., 2020). Higher vulnerability levels of smallholder farmers in Chiredzi can be explained by higher exposure levels to climate variability and change. Higher exposure was confirmed by analysing the observed long-term precipitation and temperature data. Smallholder farmers were exposed to increasing temperatures and significant changes in the timing of the rainy season (Section 3.4.3; Figure 3-2; 3-3; Supplementary Material 2). This increases the risk of crop failure for rainfed smallholder farmers. Climate data analysis showed that 35% of the seasons failed to reach a rainy season length of 100 in Chiredzi, which cannot support short-term maize varieties grown in Zimbabwe (Mutungwe, Mvumi & Manyiwo, 2017). The higher exposure to climate variability and change for smallholder farmers in Chiredzi has implications on two critical questions relevant for adaptation planning regarding the best crop type and variety to grow, and when to plant (Tadross, M. et al., 2009). The results of the study suggest that strategic decisions to reduce maize production and plant more sorghum should be adopted to improve food security, add sesame to the crop list for income generation of farmers, or consider more maize crops during wetter seasons, preferably early maturity varieties. Increased warming means that crops need high moisture replenishment to compensate for the moisture lost through evapotranspiration. This is a big challenge for smallholder farmers under rainfed conditions, as most farmers lack access to irrigation (Table 4-5, Table 5-3). Increased warming can potentially lead to a reduction in maize yields in Chiredzi, as each degree-day with temperatures above 30 ^{o}C reduces the final yield by 1.7% under drought conditions (Lobell et al., 2011).

To further understand the levels of livelihood vulnerability of smallholder farmers in Chiredzi, the livelihood vulnerability assessment was explored for farmers with different societal experiences and knowledge (farmers with IK and LK and with no IK and LK) and under different farming and settlement types (farmers in communal farmers areas vs. resettled farming areas) to establish relative vulnerability (Birkmann, J. et al., 2022). The aim was to understand how aspects of poverty, access to basic infrastructure, social networking, government support farmers and relevant knowledge and experiences affect smallholder farmers' livelihood vulnerability. Two sub-research questions below were explored:

> **"Are smallholder farmers that use IK and LK more or less vulnerable than other smallholder farmers in the district?"**

Applying the IK and LK lenses in LVI analysis, the study found that despite being exposed to the same climate risk, smallholder farmers with IK and LK were less vulnerable than those without IK and LK (see Section 3.4.1; Figure 3-2; Table 3-3). The study clarified the elements of IK and LK that reduced vulnerability of smallholder farmers and unpack how it reduces vulnerability of smallholder farmers. Farmers with IK and LK planted diverse crops and increased crop adaptation responses, which reduced their vulnerability specifically on food. This was because farmers with IK and LK forecasted the climate, use the forecasts information to make climate-informed decisions in selecting appropriate crop varieties, timing of planting, and use indigenous drought-resistant seeds. This show the role of IK and LK in increasing adaptive capacity that reduce vulnerability of smallholder farmers (see Sections 3.3.4.1; 4.3.5; Figure 4-3, Figure 4-4, Figure 4-5). This broadens the understanding of the role of IK and LK in reducing vulnerability of smallholder farmers from the much generalised regional and global perspectives (Bezner Kerr, R. et al., 2022; IPCC, 2022c; Mbow et al., 2019; Trisos et al., 2022). The study concludes that if a farmer have IK and LK in Chiredzi, they reduce their vulnerability from the baseline of relative vulnerability set by other smallholder farmers, thus highlighting the important role of IK and LK in reducing smallholder farmers' long-term livelihood vulnerability to climate change (Castellanos et al., 2022; Oppenheimer et al., 2019).

"Are the livelihood of smallholder farmers in Chiredzi equally vulnerable to climate variability and change?"

Farmers in communal areas were less vulnerable than those in the resettled areas (see Section 3.4.1; Table 3-3). This was because of the lack of social safety nets in resettled areas, weak social network and lack of health infrastructure due to resettlement, thus demonstrating the importance of other social and developmental activities in addressing the vulnerability of farmers, mostly programs that address poverty, health and gender inequality (Ayanlade et al., 2023; Cissé et al., 2022; Schipper, E.L.F. et al., 2022). These results illustrates how social and economic inequities linked to geographic location compound vulnerability to climate change (Schipper, E.L.F. et al., 2022). What these results are telling is that to reduce vulnerability differences between communal and resettled wards' relative vulnerability, incorporating climate risk management in social protection programs (whether government or NGO projects) can reduce vulnerability, and social safety programs need to integrate vulnerability to climate risk to enhance benefits for development and climate adaptation. Results elsewhere have demonstrated widely this across Africa (Agrawal et al., 2019; Hallegatte et al., 2016; Niño-Zarazúa et al., 2012; Scognamillo, Mastrorillo & Ignaciuk, 2022; Trisos et al., 2022; Ulrichs, Slater & Costella, 2019).

This study concludes that a farmer staying in a communal area that use IK and LK forecasts has a higher chance of being able to implement several adaptation responses, while receiving help from the government or NGOs reduces their vulnerability, despite being exposed to the same risks with a farmer in a resettled area and do not use IK and LK forecasts. These are intersectional differentiations of vulnerabilities that are often not understood at local scales in Africa (Ayanlade et al., 2023), despite a much improved understanding of vulnerability at the regional scale (Trisos et al., 2022).

6.1.4. IK and LK Weather and Climate forecasts and climate adaptation.

Given the role of IK and LK weather and seasonal climate forecasts in informing decision making on selection of appropriate crop varieties and timing of planting that reduce exposure, increase adaptive capacity and reduce vulnerability of smallholder farmers in Chiredzi (discussed in Section 6.1.2; Chapter 3; Table 3-3; Table 3-4). The Chapter 4 of this thesis focuses on linking the forecasts with relevant climate decision-making that contributes to the overall climate adaptation of farmers. This following sub-research question was explored.

"What IK and LK are used by smallholder farmers for weather and seasonal climate forecasts in Chiredzi?"

This study established that the majority of smallholder farmers in Chiredzi used IK and LK to make various weather and seasonal climate forecasts (Figure 4-1). Smallholder farmers in Chiredzi relied more on IK and LK forecasts than on scientific forecasts for planning agricultural activities (Figure 4-2a). The availability and easy accessibility of IK and LK forecasts explain why they are preferable for many smallholder farmers. These results are consistent with several case studies in many parts of Africa, where smallholder farmers prefer IK and LK because of their easy accessibility and lack of scientific forecasts (Barihaihi & Mwanzia, 2017; Basdew, Jiri & Mafongoya, 2017; Jiri, Obert et al., 2016; Jost et al., 2015; Mapfumo, P., Mtambanengwe & Chikowo, 2016; Nyadzi, Emmanuel et al., 2022; Radeny et al., 2019; Tume, Suiven John Paul, Kimengsi & Fogwe, 2019). The results demonstrated the importance of incorporating IK and LK weather and seasonal climate forecasts into mainstream climate services. Where IK and LK are part of mainstream climate services in providing indicators for contextually relevant conventional climate forecasting, the overall performance and usage of weather and seasonal climate forecasts by smallholder farmers have improved (Bucherie et al., 2022; Nyadzi, Emmanuel et al., 2022; Streefkerk et al., 2022). The findings of this study recommend a complementary approach can be pursued in Chiredzi, where IK and LK and scientific forecasts are considered and used together to improve farmers' decision-making. To achieve this, specific recommendations were made such as adopting the mobile phone forecasts communication to increase access to scientific forecasts for farmers to complement with IK and LK forecasts (see Section 4.4.1). To link the forecasts with relevant climate decision-making that contributes to the overall climate adaptation of the farmers in climate risk management, the following sub-research question was explored.

> **"How are these forecasts informing farmers' climate decision-making that increase implementation of climate conscious actions in Chiredzi?"**

This was a pilot study in which the connection between IK and LK forecasts, climate decision-making, and the implementation of adaptation responses was comprehensively explored. Although past research has demonstrated the connection between IK and LK climate forecasts and the implementation of adaptation responses (Leal Filho et al., 2022b; Mapfumo, P., Mtambanengwe & Chikowo, 2016; Nkomwa et al., 2014; Nkuba, Michael Robert et al., 2020; Soropa et al., 2015; Vilakazi, Zengeni & Mafongoya, 2019), the types and nature of the decisions farmers make and how they influence their climate adaptation have not been fully explored. The study found that 32% of the farmers solely used IK and LK for climate decision-making, despite the majority (88%) of the sampled farmers having direct or indirect access to scientific forecasts (Figure 4-3). A total of 23 climate decision response types were made by smallholder farmers in Chiredzi District (Figure 4-4). In understanding the nature of the decisions being made in the context of climate adaptation, 15 of these decisions were contributing directly to the adaptation response types implemented by farmers to enhance crop management when adapting to the climate risk (Table 4-5, Table 5-3). This demonstrates the importance of IK and LK forecasts in climate risk management of rainfed smallholder farmers. Given the strong link between the actions farmers took after the IK and LK weather and seasonal climate forecasts, this study further explores the role of forecasts in overall farmer adaptation. To achieve this, the following research question was explored:

> **“What is the role of the IK and LK weather and climate forecasts in informing the climate adaptation responses implemented by smallholder farmers in Chiredzi?”**

The study found that, on average, farmers who used IK and LK climate forecasts in Chiredzi implemented triple the number of climate adaptation measures compared with farmers who did not use IK and LK climate forecasts (Figure 4-5). The significance of this is that the IK and LK forecasts inform a wide range of local coping and adaptation measures implemented by smallholder farmers. This is consistent with the IPCC regional findings on how the diversity of Africa’s IK and LK systems plays a critical role in providing a rich foundation for local-scale climate adaptation (Trisos et al., 2022). These results demonstrate that IK and LK play an important role in the micro-level climate adaptation of smallholder farmers to growing climate variability and change risks. They also explain, at the global level, why the recognition of IK and LK in planned and institutional adaptation is required and urgent alluded to by Castellanos et al. (2022). Despite the vital role of IK and LK in local-level climate adaptation for smallholder farmers, the effectiveness of IK and LK climate adaptation is not fully known (O'Neill et al., 2022; Trisos et al., 2022; Zvobgo et al., 2022). This highlights the need to assess the effectiveness of IK and LK climate adaptation responses in reducing climate risk in Chiredzi.

6.1.5. Reliability and Effectiveness of IK and LK adaptation

The evidence in Chapter 3 suggests that IK and LK are fundamental in addressing the vulnerability of smallholder farmers and improving their adaptive capacity. Chapter 4 highlights the importance of IK and LK forecasts in the implementation of adaptation responses by smallholder farmers. However, with gaps identified both locally and regionally in Chapters 2 and 4, it suggests that less is known and less has been done to assess the reliability of IK and LK seasonal forecasts, as well as the effectiveness of IK and LK adaptation responses in addressing climate risk. Additionally, the AR6 Regional Africa Chapter emphasises the need to evaluate the potential effectiveness and limits of adaptation options in the region’s agriculture sector under future climate change, including smallholder farmers (Trisos et al., 2022). To explore this, the study investigated the following two critical sub-research questions:

> **"How reliable are smallholder farmers' IK and LK seasonal climate forecasts for effective decision making?"**

A single-season comparison between the IK and LK seasonal forecasts and observed precipitation data (1972–2022) showed that the IK and LK seasonal forecasts are most reliable for near-term forecasts, and their reliability becomes fuzzy for longer-term (usually over 90 d) forecasts (Table 5-4). High reliability of IK and LK forecasts was observed for the rainy season onset and drought forecasts for the 2021–22 season. These results confirm two crucial points about the IK and LK forecasts used by smallholder farmers; the forecasts are most relevant for short-term forecasting, which has been argued in the literature (Garay-Barayazarra & Puri, 2011; Gwenzi et al., 2016; Ziervogel & Opere, 2010; Zvobgo, Luckson et al., 2023), and that the reliability of IK and LK seasonal forecasts decreases for long-term forecasts (usually six months or above forecasts from the time of forecasting) (Mahoo et al., 2015). The results reinforce findings from previous research that examined the reliability of IK and LK forecasts, which found smallholder farmers accurately forecast rainy season onset and drought conditions, confirming the high reliability of short-term forecasting (Chisadza, Bright et al., 2014; Gilles et al., 2022; Guye, Legesse & Mohammed, 2022; Radeny et al., 2019). With the reliability of IK and LK seasonal forecasts becoming fuzzy for longer-term forecasts (Table 5-4), integration of IK and LK forecasts with scientific forecasts in Chiredzi can be done by merging IK and LK rainy season onset with scientific forecasts on other indices that conventional/scientific forecasts can provide more detailed information, such as expected total rainfall amount and rainy days for the season. This will increase the relevance of forecasts for improved decision-making which is required for effective adaptation. In terms of policy influence, these results in Chiredzi are important for governments and national climate services for the acceptance of IK and LK into agricultural-related early warning systems that are required for the implementation of informed adaptation responses:

> **"What is the effectiveness of IK and LK-informed adaptation responses in reducing the climate risk in Chiredzi?"**

Addressing the gap identified in Chapter 2 regarding the lack of a framework that comprehensively assesses the effectiveness of IK and LK adaptation responses in reducing climate risk, a framework was developed, the Local and Indigenous Knowledge Adaptation Effectiveness Assessment (LIKAEA), and was applied to assess the evidence of effectiveness of IK and LK-informed responses implemented by smallholder farmers in Chiredzi. This also addressed the global gap on the lack of a global assessment evidence of effectiveness of adaptation (O'Neill et al., 2022) by providing sectoral-based analysis of the effectiveness of adaptation that provides evidence required for global assessments. Although adaptation is highly contextual and time-bound (Eriksen et al., 2021; O'Neill et al., 2022), the LIKAEA framework can be applicable in other areas where local contexts are taken into consideration; for example, in an area where climate forecasts are effectively communicated, the focus can be placed on other adaptation outcomes to assess the effectiveness of IK and LK. This framework was the first attempt to comprehensively assess the effectiveness of IK and LK responses based on empirical evidence. Existing studies have used secondary data based on review of academic literature (Mukherji & Kumar, 2021; Schlingmann et al., 2021). The important lessons learned here can shape future research agendas for studies on the effectiveness of IK and LK adaptation responses.

Of the 18 IK- and LK-informed adaptation responses identified in Chiredzi, 44% showed medium to high evidence of effectiveness of reducing climate risk. These were mostly irrigation, growing drought-resistant small-grain crops including the use of indigenous seeds, IK and LK seasonal climate forecasts, staggering of planting dates, drought-resistant legumes and cash crops effectively reduced climate risk. Traditional irrigation effectively reduced the exposure of crops to late-season onset and dry spells and reduced cropland exposed to climate variability risks. Evidence of the effectiveness of the irrigation response in Chiredzi agrees with regional and global findings in IPCC AR6, where irrigation was observed to effectively address the current climate risk (Bezner Kerr, R. et al., 2022; Caretta et al., 2022; IPCC, 2022c; IPCC, 2023b; Pörtner et al., 2022; Trisos et al., 2022). Drought-resistant small-grain crops effectively addressed vulnerability to seasonal droughts while drought-resistant cash crops effectively addressed poverty, and cash benefits to women and children. Although not implemented on scale, drought resistant legumes are highly effective in addressing both exposure and vulnerability components (Table 5-3). No IK and LK adaptation response had mitigation benefits. It can be concluded that IK and LK adaptation responses have showed limited, positive and promising signs of effectiveness, which is consistent with regional and global assessments of the evidence of climate adaptation (IPCC, 2022c; Mukherji & Kumar, 2021; Trisos et al., 2022).

With the projected risks for the food sector under future global warming levels (2 °C and 4 °C), these measures will not be sufficient to offset the risk in Africa if smallholder farmers rely solely on them (Trisos et al., 2022). This is because most of the IK and LK-informed measures in Chiredzi were supportive responses implemented at the local scale. This is consistent with previous regional and global analyses of adaptation responses implemented by smallholder farmers between 2013–2020 (Berrang-Ford et al., 2021b; Trisos et al., 2022). Unless the measures are integrated with technological and institutional adaptation, there is a higher possibility of reaching adaptation limits for these measures (Trisos et al., 2022). In terms of policy, the results illustrate the importance of just- and equity-adaptation planning, where IK and LK are equally considered and incorporated into institutional adaptation to implement transformative responses (IPCC, 2022c; Mycoo et al., 2022).

6.1.6. Proposed conceptual framework for improving IK and LK integration in planned adaptation.

With the relevance of IK- and LK-informed adaptation unknown for most of the future climate risk (Bezner Kerr, R. et al., 2022; Trisos et al., 2022) and the evidence of the effectiveness of IK and LK adaptation responses to current climate risks in Chapter 5 (Table 5-3), it is important that IK and LK and scientific knowledge sources coalesced to increase the sustainability and feasibility of adaptation actions to current and projected climate risk. This is because the integration of IK and LK can potentially increases the effectiveness of scientific and technological interventions in communities with smallholder farmers (Bezner Kerr, R. et al., 2022; IPCC, 2019a; Mycoo et al., 2022; Pörtner et al., 2022; UNESCO, 2018). However, evidence of the lack of integration of IK and LK in adaptation strategies, institutional adaptation and national adaptation planning processes still exists (Chapter 2; Table 2-5; Mycoo et al., 2022).

The findings discussed in Sections 6.1.2, 6.1.3, and 6.1.4 and Chapters 3–5 suggest that IK and LK is fundamental in addressing climate risk at local scales. There is potential for the lessons learned to be transferred to other areas and regions, and sectors that rely on IK and LK for decision making in Africa. Thus, the equal consideration of this knowledge becomes critical for effective adaptation. To facilitate this, a conceptual framework is proposed (Figure 6-1). This allows the incorporation of IK and LK into national decision-making process as an equal contributor for planned adaptation. This can help align other adaptation solutions with cultural values and increase the legitimacy of climate adaptation with Indigenous and local communities (Ara Begum et al., 2022; Cooley et al., 2022). To achieve this, the study addressed the following research question aims to increase the integration of IK and LK in planned adaptation.

“How can IK and LK be integrated into planned and institutional adaptation to increase the resilience of smallholder farmers to manage climate risk?”

A conceptual framework is proposed (Figure 6-1) to demonstrate how the integration of IK and LK into the planned, (policy and institutional) can be improved. The purpose of the proposed framework is to guide and provide insights into how the integration of IK and LK into planned and institutional adaptation can be addressed in terms of the process. The research undertaken in this study has enabled the development of this conceptual framework. It was established in Chapter Four that IK and LK is crucial for smallholder farmers’ weather and climate forecasting, which informs decision making on the adaptation responses to implement. Chapter Three shows that IK and LK responses reduce the vulnerability of smallholder farmers to climate impacts. Chapter Five further highlighted that IK and LK adaptation responses were effective in reducing risk. However, the review of Africa’s policy documents (NDCs) in Chapter Two highlights the limited inclusion and recognition of the role of IK and LK in climate action planning. Therefore, this section synthesise the results from each of the preceding chapters to propose a conceptual framework for the effective integration of IK and LK into planned adaptation. The conceptual framework assumes that through a policy framework where both IK and LK and scientific knowledge at par can increase the potential of IK and LK to contribute to planned adaptation.

Previous research has addressed the lack of IK and LK in subnational and national policy frameworks relevant for planned adaptation, which influences international climate adaptation research and policy fora (Bohensky & Maru, 2011; García-Del-Amo, Mortyn & Reyes-García, 2020; Mustonen et al., 2021). Thus, the proposed framework was developed by taking lessons from the literature, as well as empirical findings from the study. The two proposed frameworks in literature consist of a knowledge co-production framework (Hill et al., 2020; Klenk et al., 2017; Latulippe & Klenk, 2020) and the “two-eyed seeing” knowledge complementary framework (Abu, Reed & Jardine, 2020) that brings together indigenous and scientific/western science perspectives on an equal basis. In an effort to understand knowledge integration, previous research has attempted to discuss how knowledge integration builds resilience in theory and offers little explanation of how different knowledge is actually or could potentially be brought together (Bohensky & Maru, 2011). Here, the empirical findings from the study have provided additional evidence to support the theoretical framing in the literature.

Based on the empirical evidence generated in this study, the basis of the proposed framework is that mutual recognition and integration of IK and LK with scientific knowledge potentially increases the effectiveness of adaptation responses that are locally led (Adger et al., 2014; Caretta et al., 2022; Castellanos et al., 2022; Shaw et al., 2022). If more evidence is gathered on what IK and LK locally led adaptation responses are effective, scaling up these measures through inclusion in national policy planning frameworks, such as the NAPs and NDCs, can critically increase the adoption of IK and LK in national climate discourse. Thus, the interactions between scientific and IK and LK (Figure 6-1) have been expanded to include processes, such as building evidence of the effectiveness of IK and LK, as well as their reliability to increase contribution to growing evidence that is critical for the implementation of long-term adaptation in the international frameworks – NDCs and NAPs (Figure 6-1). Thus, more robust evidence of IK and LK accumulates through research and constant assessments, which helps bring IK and LK at par with scientific knowledge. Knowledge co-production through the proposed framework and equal recognition of such knowledge can potentially play a critical role in decolonising climate adaptation research, especially in the global South (Whyte, 2017; Wilkens & Datchoua-Tirvaudey, 2022). It is critical to ensure that IK and LK are not lost during this integration process with scientific knowledge.

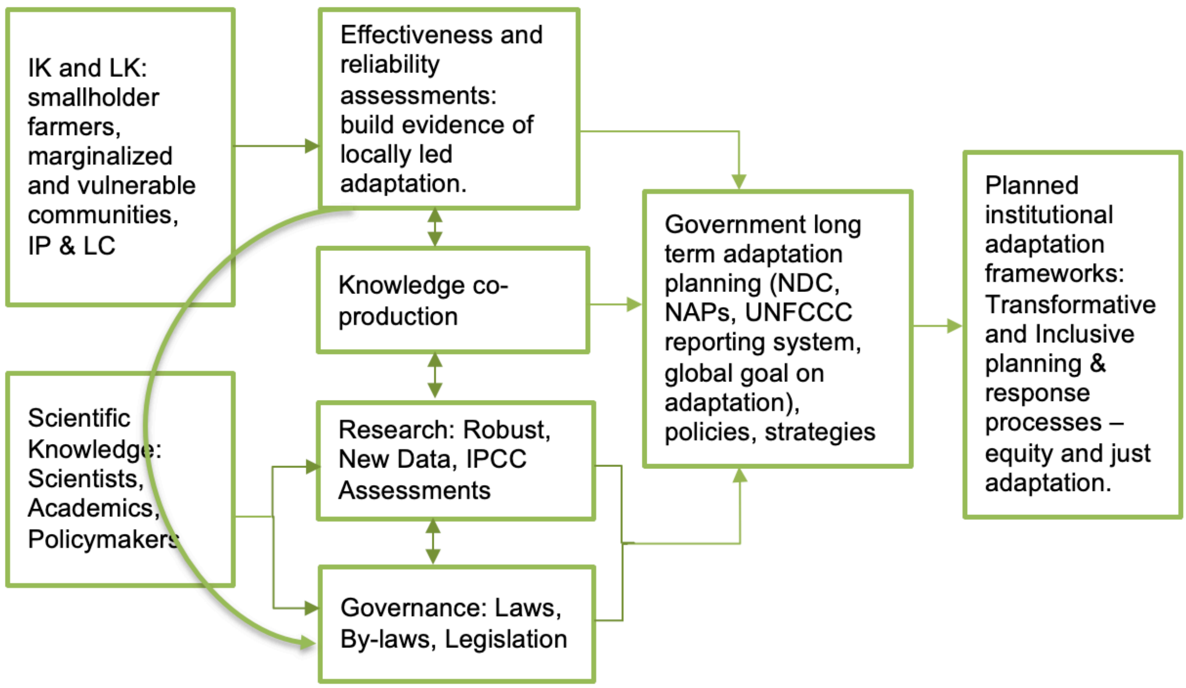

Figure 6-1: The proposed conceptual framework for effective integration of IK and LK into planned institutional adaptation. IP&LC means Indigenous Peoples and Local Communities.

The proposed framework engages critical actors and multiple stakeholders in the process – scientists, state actors, IP&LC, and smallholder farmers. Likewise, the co-production that usually takes place in scientific research is extended to communities on IK and LK. This knowledge production process should then be assimilated into various climate-policy framework processes. The proposed framework has the potential to improve two aspects: the uptake of IK and LK weather and climate forecasts, which have shown evidence of reliability when synchronised with technology-based forecasting methods (Bucherie et al., 2022;

Nyadzi, Emmanuel et al., 2022; Streefkerk et al., 2022). Thus, promoting the value and adoption of forecasts as part of national climate services and early warning systems informs how communities should prepare and respond to the anticipated risk. Second, the framework provides a platform to mainstream effective IK and LK adaptation practices into national climate adaptation planning policy tools – NDCs, and NAPs (Zvobgo et al., 2022).

Similar to any other framework, there are caveats associated with the proposed framework. These include the following: since the gathering of evidence is based on what IK and LK is reliable, for example, in climate and weather forecasting, it becomes a challenge for some IK and LK practices that are difficult to scientifically validate. In addition, it may be difficult to bring all stakeholders to a common understanding during knowledge co-production, as one form of knowledge may emerge as superior, particularly where IK and LK-informed adaptation is difficult to assess its effectiveness. Thus, it is necessary to follow the co-production pathways proposed by Hill et al. (2020). It is important that more case study-based research is conducted to build sufficient evidence of the effectiveness and reliability of IK and LK to support the proposed framework.

6.2. Conclusions

This study has sufficiently demonstrated the role of IK and LK in climate adaptation and how it supports specific elements of the UNFCCC adaptation iterative cycle of the global goal on adaptation (GGA) framework. The study demonstrated how IK and LK is important in reducing farmers' livelihood vulnerability to climate change impacts, its role in planning, and implementation of adaptation responses. This was demonstrated through empirical evidence from smallholder farmers in Chiredzi district in Zimbabwe. The study findings broaden the understanding of current scholarship on what exactly IK and LK can do, and further attempt to elaborate what could be the limitations of these responses under the projected future global warming levels. This highlights how IK and LK crucially contributes to the achievement of GGA. This potentially elevates IK and LK in national policies, regional and global climate adaptation discourse, which is required for the implementation of effective adaptation that reduce increased and projected climate risk. It was abundantly demonstrated that IK and LK are key in reducing the livelihood vulnerability of smallholder farmers. This is because IK and LK play a fundamental role in weather and seasonal climate forecasting. These forecasts are important for informing different actions and adaptation measures implemented by smallholder farmers. Thus, this study provides the fundamental body of literature required to initiate the full consideration and inclusion of IK and LK in climate services for planning and implementing coordinated actions that effectively address climate risk.

This study also demonstrated how IK and LK contribute to the long-term climate resilience of smallholder farmers. Thus, IK and LK should constitute part of the discourse and scholarship on climate-resilient development. The unpacking of the role of IK and LK weather and climate forecasts in climate decision-making allows a better understanding of how forecasts can be enhanced for effective climate adaptation responses. It also promotes co-production of knowledge for reliable and actionable climate services. Although the results demonstrated limited evidence of the effectiveness of IK and LK responses in reducing climate risk, they provide much-needed evidence of adaptation effectiveness, mostly from the global south, where adaptation is the most critical component of climate action.

6.3. Recommendations

Specific policy and science recommendations in each empirical chapter are provided in Sections 2.5, 3.6, 3.6, 4.4.4, 4.5, 5.4.3.1, and 5.5. The following are the broad and general recommendations:

- Based on empirical evidence of reducing exposure, vulnerability and effectiveness of IK and LK responses, this study recommends the growing of drought-resistant small-grain crops – sorghum and millet in Chiredzi. This recommendation applies to other semi-arid regions in Southern Africa with similar conditions where rainfed agricultural system support livelihood of farmers. This is critical for improving the food security of smallholder farmers at the household and regional scales. Important stakeholders such scientist, government institutions and private sector can invest in improving sorghum and millet varieties that can adapt to the climate risk anticipated for the projected global warming of 1.5 °C or 2 °C pre-industrial levels. Farmers in these regions are recommended to reduce the growing of maize crops. It is, therefore, imperative for policymakers and governments should develop policies that promote the growing of drought-resistant crops by incentivising and subsidising seeds and other key production inputs. With the historical marginalisation of sorghum crop, especially in Zimbabwe, the sensitisation of smallholder farmers on why adopting sorghum crop is best suited for adapting to increased climate variability for regions such as Chiredzi is important.
- This study recommends the co-production of climate services, where smallholder farmers, scientists, policymakers, and government authorities work together to

generate reliable and usable climate forecasts and services that are informed by IK and LK together with science for the implementation of effective climate adaptation responses that are required to reduce risk. In the co-production of climate services, this study further proposed combining IK and LK with conventional early warning systems to define climate hazard impacts on a much more localised scale – to a level of ward. For example, using IK and LK and hazard impact experiences, smallholder farmers and scientists can recalibrate local climate hazards, taking into consideration localised impacts of specific hazards, such as the magnitude of a certain rainfall event that can cause flooding with devastating localised impacts on crops and livestock, which the conventional climate forecasts at sub-regional or national forecasts can fail to detect as a significant climate hazard event due to concentrated localised nature of hazard impacts. This is important for providing early warming information that is more relevant to the local scale, such as a ward or village.

- Considering the fundamental role of IK and LK in climate adaptation, mostly in developing countries from the global south regions, the holistic integration of IK and LK in planned and institutional adaptation is very important. Thus, the recognition of IK and LK in academic and policy spaces is vital for this integration to take place. Therefore, this study recommends a full Chapter on IK and LK in future IPCC assessments or a special report on IK and LK for climate adaptation and mitigation in future assessments. If conducted in an inclusive manner, the IPCC assessment could be a significant opportunity to further integrate IK and LK into climate change policy, given the crucial role of IPCC assessments in knowledge brokering across science, policymaking, governments, and other international and regional climate adaptation actors.

6.4. Limitations of the results and study

There are limitations of the study. These are mainly limitations that affected key study components such as data availability, collection and methodological, which limits the extent to which results can be relied to. These limitations are related to the availability of data, financial and other resources, time, and methodological limitations. The context to which these factors limit the study, and the results is explained in this section. This is to acknowledge that although the findings can provide crucial academic and scholarship in the IK and LK literature, these limitations should be noted, and future research can explore them to improve the depth of our understanding of the subject. The results of this study can be broadly applicable beyond the case study area – Chiredzi, Zimbabwe, to smallholder farmers in other regions, particularly in the global South, for communities that rely on IK and LK.

Given the resources required to have a representative sample for some of the quantitative analyses performed in Chapter 4 of the study, the results may be limited in that aspect, as sample representativeness was not achieved. This was because of limited resources, as sampling 10% of the population in the study area required substantial resources – finance and human effort – and more time, which was also a constraint, as this PhD research was supposed to be completed in three years. This limits the extent to which the results can be relied upon for this specific section.

To effectively establish the effectiveness of some of the IK and LK weather and climate forecasts (Chapter 5), it is important to run this comparison for several seasons/years. This was not possible because of the limited time allocated for data collection and time limits for the researcher to complete the PhD. This potentially limits the accuracy of IK and LK climate forecasting results. Also, data on assessing the effectiveness of IK and LK adaptation responses require multiple years, which was not achieved for the same reasons explained in the previous sentence. Thus, the results can be improved by repeatedly conducting the assessment consecutively over several seasons.

Data constraints – climatic and socio-economic at the local level – hindered projections and assessment of future vulnerability, limiting the thesis to current vulnerability analysis. The results are limited to 210 farmers in a district with more than 10 000 farmers. Thus, more resources are required, which are costly and time consuming. Increasing the number of farmers participating in the study increases the accuracy of the results mostly on the statistical analysis performed in Chapter 4. The observed temperature data analysis in Chapter 3 was constrained by the availability of long-term climate data, which limited the analysis to 21 years. This was because of the lack of completeness of climate data beyond 21 years. These limitations are critical for shaping the future research need to pursue IK and LK for climate adaptation beyond its role in climate adaptation discourse, mostly from local to national and international level especially on the methodological limitations.

6.5. Future research and wider application of the results

Building on the key findings of this study, further research should advance the framework developed to improve the understanding of the effectiveness of IK and LK in reducing climate risk, thereby improving smallholder farmers' resilience to climate impacts. Further research on approaches to scale-up some of the effective IK and LK adaptation responses in the study areas and nationally can be important for informing other global adaptation policies and frameworks, such as the goal of climate adaptation in the Paris Agreement. If more evidence is generated through these studies in the future across Africa, where IK and LK have shown evidence in effective adaptation, there is potential to influence global processes, policy and in global assessments such as IPCC. There is potential for further research to assess the effectiveness of IK and LK adaptation responses under future climate risk and project climate impacts.

Although the results are more localised, there are important lessons, observations and findings from the study that can be applied to other regions in the global South to improve our understanding of the subject. However, these should not be taken out of context, and the local conditions and purpose of the study should be carefully considered. For example, the framework developed in Chapter 5 for assessing effectiveness of adaptation of IK and LK responses can be applied to other regions and setups to examine the effectiveness of IK and LK. Thus, establishing the effectiveness of IK and LK interventions beyond climate adaptation to other sectors, where IK and LK is relevant in informing decisions and actions, such as environmental management, natural resource management and traditional health actions and interventions. This is because the frameworks clearly determine how IK and LK interventions can reduce the problem, and the elements of IK and LK that are effective depending on the subject under study. The conceptual framing of IK and LK integration into planned adaptation through policy influence could potentially be the basis for framing IK and LK in NDCs. However, further research is required to understand how this can be operationalised.

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Supplementary Material

Supplementary Material 1: The role of indigenous knowledge and local knowledge in water sector adaptation to climate change in Africa: a structured assessment.

SM 1.1.1

Definition of the relevant GAMI codes used in this study. These should be read together with methods and results sections where summary of the sectors, climate hazards, type of responses, climate risk reduction, limits to adaptation and actors are listed.

SM Table 1-1: The seven sectors identified by GAMI that are crucial for understanding and tracking climate adaptation.

Sector	**Definition**
Terrestrial and freshwater ecosystems	Freshwater, lake, river, watershed, pond, wetland, stream, terrestrial, taiga, tundra, grasslands, forest, tropical, temperate
Ocean and coastal ecosystems	Marine, mangrove, tidal, estuary, lagoon, reef, coral, sea, ocean, benthic, salt, coast
Water and sanitation	Water, hydrology, basin, watershed, flood, drought, landslide, sanitation
Food, fibre, and other ecosystem products	Food, fibre, nutrition, medicine, aquaculture, fisheries, agroforestry, agroecology
Cities, settlements, and key infrastructure	Cities, urban, infrastructure, industry, settlements
Health, well-being, and communities	Health, wellbeing, well-being, wellness, disease, illness, medicine, epidemics, vector, vector borne, vector-borne, cardiovascular, respiratory, allergies, mental health, heat stress, psychosocial, nutrition, asthma, displacement, cultural integrity, migration, cultural heritage, identity, social capital, mobility, conflict, war
Poverty, livelihoods, and sustainable development	Poverty, livelihood, sustainable development, wealth, resilience, justice, equity, discrimination, conflict, diversification

SM Table 1-2: Description of the climate hazards that were identified in the papers.

Hazard	**Definition**
Sea level rise	Includes coastal flooding and storm surges
Extreme precipitation and inland flooding	
Increased frequency and intensity of extreme heat	Includes urban heat island effect
Precipitation variability	
Drought	
Rising ocean temperature and ocean acidification	Includes loss of coral cover
Loss of Arctic Sea ice	
General climate impacts	No specific hazard identified
Other	Other

SM Table 1-3: Classification of climate adaptation responses.

Adaptation response type	**Definition**
Behavioural/cultural	Enabling, implementing, or undertaking lifestyle and/or behavioural change
Ecosystem-based	Enhancing, protecting, or promoting ecosystem services
Institutional	Enhancing multilevel governance or institutional capabilities
Technological/infrastructure	Enabling, implementing, or undertaking technological innovation or infrastructural development

SM Table 1-4: Description of the actors identified in the literature assessed.

Actor	Definition
International or multinational governance institutions	Global or regional treaty body or agency (e.g., UN institutions/ organizations, EU institutions, Organization of American States, African Union)
Government (national)	Countries officially recognized by the UN
Government (sub-national)	Domestic, sub-national governing unit. Terms include state, province, territory, department, canton, Lander
Government (local)	Terms include municipality, local government, community, urban, urban regions, rural
Private sector (corporations)	Large national or international companies
Private sector (SME)	Small- and medium-enterprises
Civil society (international, multinational, national)	Voluntary civil society organizations. Includes charities, non-profits, faith-based organizations, professional organizations (e.g., labour unions, associations, federations), cultural groups, religious groups, sporting associations, advocacy groups (e.g., NGOs).
Civil society (sub-national or local)	Formal community associations
Individuals or households	Including informal community networks

SM Table 1-5: Codes used for assessing the reduced risk and limits to adaptation in the literature papers.

Category	Question	Instructions	Codes	Definition
Reduced risk	Is there any evidence (implicitly or explicitly) provided that activities successfully reduced risk or vulnerability?	Select one. If yes, describe the approach in the open field. If no write "None" in open field.	Yes	The change must be documented to respond 'yes' for this question. Anticipated or expected reduction is not sufficient for this question. Note that these don't need to be quantitative, but could involve theory of change, narrative justifications of change, or other.
			No	
			Open field	If answered yes, copy relevant text here. If none write "None."
Adaptation limits	Does the article/ document identify and describe constraints or limits to adaptation?	Select one.	Yes	Constraints are defined as: "factors that make it harder to plan and implement adaptation actions." (IPCC AR5 WG2, Chap. 16, pg. 923). Constraints can be categorized as: (1) Economic: existing livelihoods, economic structures, and economic mobility. (2) Social/cultural: social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support. (3) Human capacity: individual, organizational, and societal capabilities to set and achieve adaptation objectives over time including training, education, and skill development. (4) Governance, Institutions and Policy: existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity, and absorption capacity. (5) Financial: lack of financial resources. (6) Information/Awareness/Technology: lack of awareness or access to information or technology. (7) Physical: presence of physical barriers; and (8) Biological: temperature, precipitation, salinity, acidity, and intensity and frequency of extreme events including storms, drought, and wind.

SM 1.1.2

Articles used in the review with evidence of water adaptation responses implemented are found here: https://link.springer.com/article/10.1007/s11625-022-01118-x. List of the countries where the 200 articles with evidence of water adaptation responses. These are distributed in 31 African countries. (Include excel file with GAMI coded water adaptation response articles).

SM Table 1-6: Expanded list of articles with evidence of water adaptation responses.

Country	Number of articles with water adaptation responses	Number of articles with IK and LK evidence
Algeria	2	-
Angola	1	1
Benin	3	2
Botswana	2	-
Burkina Faso	7	1
Cameroon	3	1
Chad	1	1
Cote d'Ivoire	1	1
Egypt	1	-
Ethiopia	30	4
Ghana	28	15
Gambia	2	-
Kenya	26	12
Lesotho	1	1
Malawi	5	-
Mali	2	-
Morocco	1	1
Mozambique	4	1
Namibia	4	1
Niger	6	2
Nigeria	19	4
Rwanda	1	-
Senegal	3	1
South Africa	16	5
Sudan	2	-
Swaziland	2	-
Tanzania	11	3
Tunisia	4	-
Uganda	11	3
Zambia	4	-
Zimbabwe	9	7

Evidence levels in Literature assessed

Using the IPCC guidelines, we assessed the evidence levels for both the water adaptation responses and the IK and LK (see the methods section - framing of water adaptation responses and IKLK). This was based on the counts each adaptation response is mentioned in the articles per sub-region (southern, east, west, north, and central Africa).

SM Table 1-7: Evidence levels used to assess the water adaptation responses recorded in the literature assessed.

Strong evidence	> 20 counts per adaptation measure in the region
High evidence	10 - 19 counts per adaptation measure in the region
Medium evidence	6 - 9 counts per adaptation measure in the region
Low evidence	1 - 5 counts per adaptation measure in the region
No data	No evidence of specific adaptation measure in the region

SM Table 1-8: Evidence levels used to assess the influence of IK and LK per adaptation response

Strong evidence	> 10 counts per adaptation measure in the region
High evidence	6-9 counts per adaptation measure in the region
Medium evidence	3-5 counts per adaptation measure in the region
Low evidence	1-2 counts per adaptation measure in the region
No data	No evidence of specific adaptation measure in the region

SM Table 1-9: Evidence of human adaptation across sectors in Africa in the literature assessed.

Sector	**Total number of publications**	**Water Adaptation responses**	**IK and LK in water adaptation**
Food fibre and other ecosystems	409	146	56
Poverty, livelihoods, and sustainable development	349	129	59
Health, well-being, and communities	142	47	18
Water and sanitation	92	21	7
Terrestrial and freshwater ecosystems	53	18	6
Cities settlements and key infrastructure	39	11	3
Ocean and coastal ecosystems	25	4	2
	n = 570	*n = 200*	*n = 73*

SM 1.1.3

Articles that were reviewed for IK and LK application in the implementation of water adaptation measures are found here: https://static-content.springer.com/esm/art%3A10.1007%2Fs11625-022-01118-x/MediaObjects/11625_2022_1118_MOESM2_ESM.xlsx. Extension codes were developed on attributes of indigenous and local knowledge for articles with evidence of IK and LK. The attributes of IK and LK were adapted from Petzold et al. 2020.

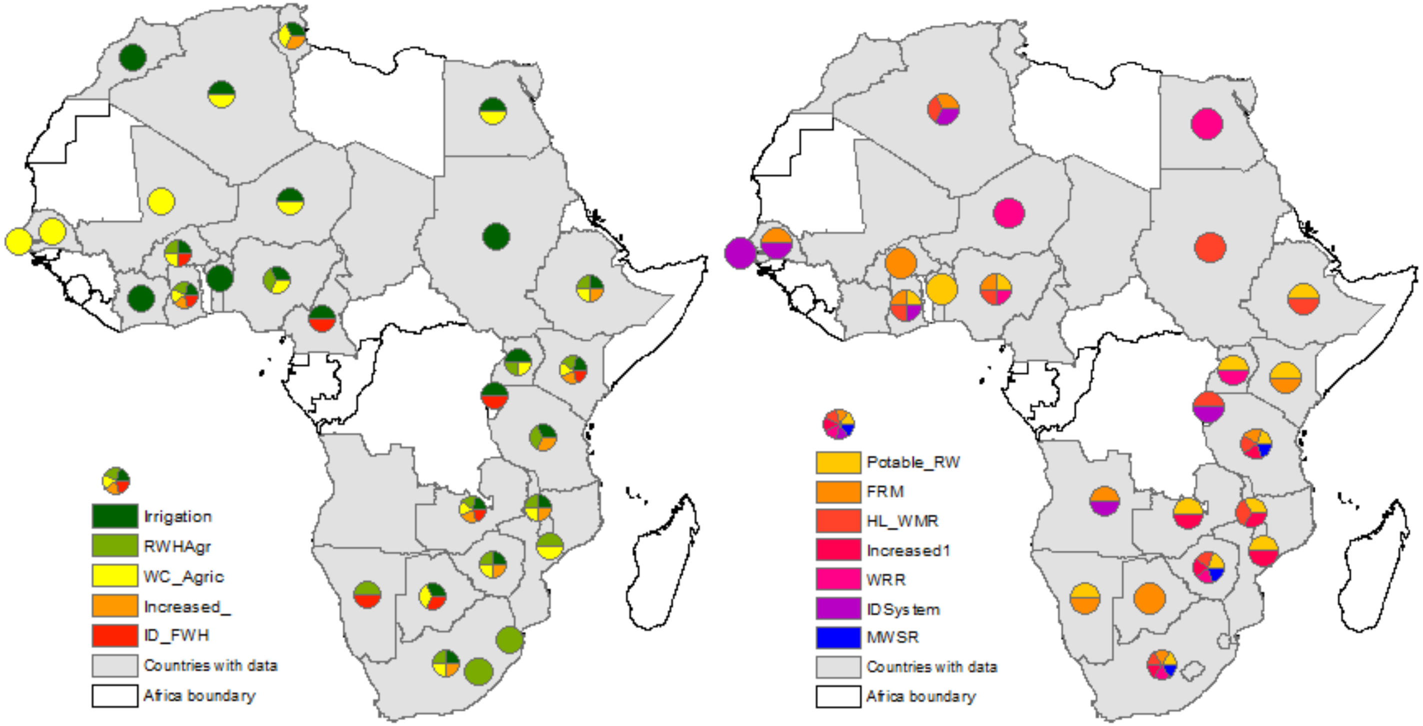
SM Table 1-10: Definition of IK and LK attribution used in this review

Attribute	**Definition**

Factual knowledge about the environment and environmental changes	These were observations, monitoring of weather, land, place, habitat, ecosystem used to adapt to climate change impacts such as droughts, floods, precipitation variability.
Factual knowledge about the use of the environment	These were water management practices, land use, land use change, carrying capacity, resource conservation for climate adaptation.
Governance and social capital	These were social norms, customary rules and institutions, land tenure, networks of reciprocity in communities used to strengthen/ promote the adaptation process.
Cultural values and worldviews	These were moral and ethical statement about the use of the environment, taboos, religious beliefs, folklore knowledge.
Other	This consisted of other practices used by farmers and communities which are relevant for water-climate-adaptation.

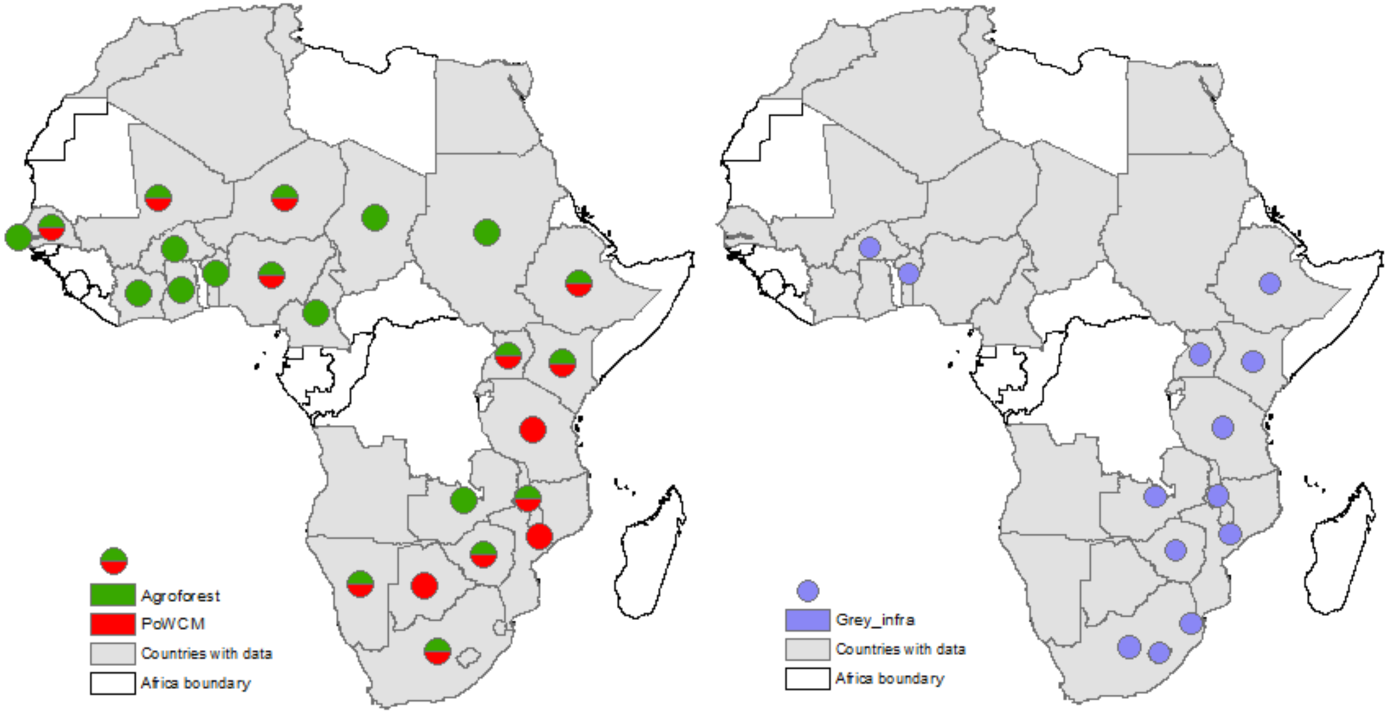
SM 1.1.4

Geographic distribution of specific water adaptation responses per country are presented in supplementary material 4.



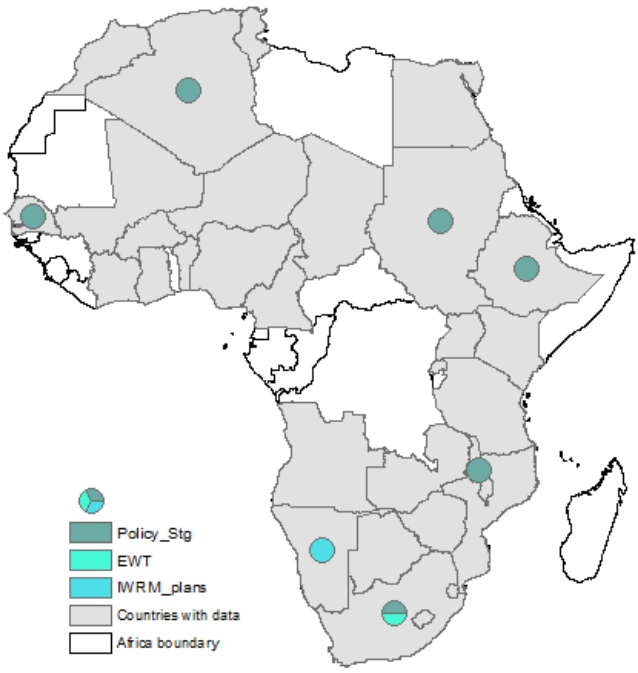
SM Figure 1-1: Panel (a) is the distribution of water adaptation responses in agriculture, (b) is the distribution of in domestic and potable water adaptation responses

Key: RWHAgric = Rainwater harvesting in agriculture, WC_Agric = water conservation, ID_FWH = Flood water control (harvesting, diverting, drainage) Incresead_= increased groundwater abstraction in agriculture, Potable RW = potable rainwater harvesting, FRM = Flood relief responses, HL_WMR = household level water management and resilience, Increased1= increased groundwater abstraction for domestic water supply, WRR = water recycling, reuse, IDSystem = Improve drainage systems for flood water removal, MWSR = municipal level water supply rationing.



SM Figure 1-1: Panel (c) is the distribution of ecosystem-based adaptation responses, (d) is the distribution of grey water adaptation responses

Key: PoWCM = Protection of watersheds and catchment management, Grey_infra = grey inrstructure development



SM Figure 2-1. Panel (e) is policy, strategy and enabling environment responses.

Key: Policy_Stg. = Policy, strategy and enabling conditions responses, EWT = effective water tariffing, IWRM_plans = integrated water resources management plans implementation.

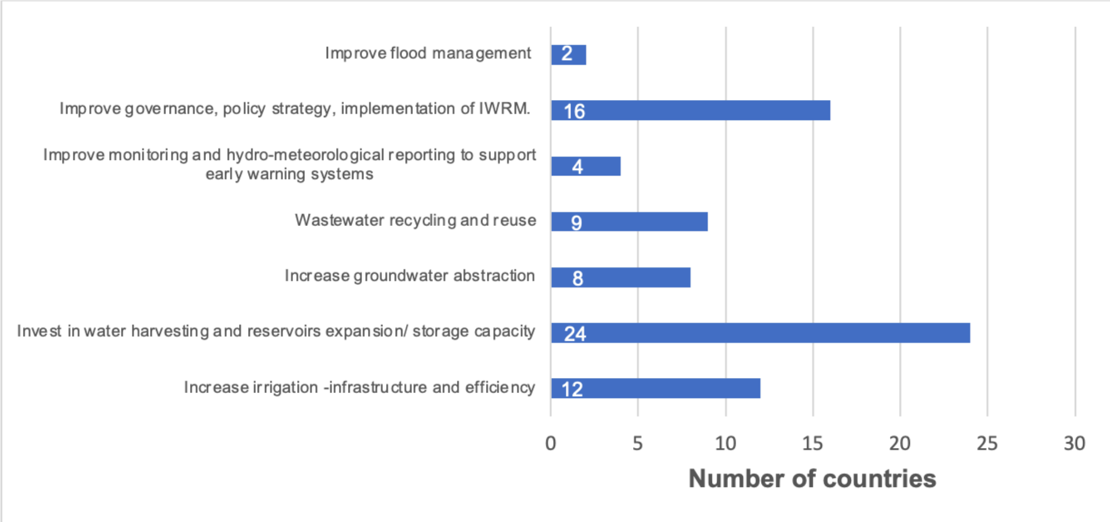
SM 1.1.5

SM Table 1-11: List of countries with iNDCs covered in this study and the respective water adaptation targets

Country	Water sector adaptation priorities
Algeria	Integrate the impacts of climate change into sectorial strategies among water management.
Angola	Increase water availability, promote IWRM, water harvesting, construct flood protection barriers along major rivers
Benin	Improve water access, promote water conservation, reduce vulnerability to water stress and floods, promote good water management (IWRM)
Botswana	Improve water supply infrastructure, enhance conjunctive groundwater-surface water use, reduce water loss
Burkina Faso	Implement soil and water conservation strategies, develop master plans for water development and management, development of water reservoirs, combating the silting of water sources, implementation of water-efficient irrigation techniques
Burundi	Develop small- and large-scale irrigation and improve its efficiency, develop, rehabilitate, and manage hydro-agricultural developments
Central African	Improvements on sustainable management of water resources (IWRM), improve potable water supply, improvements on the monitoring of groundwater
Chad	Develop water infrastructure (reservoir), expand irrigation infrastructure, implement IWRM.
Djibouti	Improve access to water.
Egypt	Increase water storage capacity, improve irrigation and drainage, rainwater harvesting, increased use of deep groundwater reservoirs
Eritrea	Implementation of solar powered improved water systems interventions and provide clean and adequate water to all, promote sustainable utilisation.
Ethiopia	Enhance irrigation systems through rainwater harvesting and conservation of water, including improved water use efficiency. Ensure the uninterrupted availability of water services
Gambia	Improve water supply infrastructure (reservoir), implement IWRM,

Ghana	Implement IWRM, strengthen equitable distribution and access to water for the population living in climate change risk communities.
Guinea	Preserve the quality and quantity of water resources, set up a system of hydro-ecological monitoring, use controlled irrigation.
Guinea-Bissau	Capture and storage of rainwater (water retention basins and mini dams) for water management in the dry season
Kenya	Implementing the National Water Master Plan (2014).
Lesotho	Secure village water supply for vulnerable communities, increase irrigation efficiency, increase rainwater and sustainable ground water harvesting, constructing multipurpose dams to enhance water storage, implement IWRM.
Liberia	Protection of water catchments around hydro-power sources, improve irrigation
Malawi	construction of multipurpose dams, implementation of water harvesting technologies, capacity building in integrated water resources management (IWRM), catchment management, promotion of irrigated agriculture
Morocco	Improve irrigation efficiency by adopting localised irrigation systems, desalination, construct water storage facilities, transfer water to other dry regions, improve potable water access.
Mozambique	Improve the capacity for IWRM including building climate resilient hydraulic infrastructures
Namibia	Establishing of irrigation schemes along the perennial rivers of Namibia, improve rural water supply, rationalization of the use of water resources for different economic sectors
Niger	No clear set water sector goals.
Nigeria	Increase use of irrigation systems that use low amounts of water; increase rainwater and sustainable groundwater harvesting for use in agriculture
Rwanda	Increase investment in irrigated agriculture to increase production (irrigation), harness freshwater resources while ensuring food security to its population.
Sierra Leone	No cleat water sector adaptation goals
Somalia	Implement IWRM, construction of large-scale water capture and storage facilities and equitable distribution and access systems,
South Africa	Water Conservation and Demand Management strategy
Sudan	Implement IWRM, water harvesting, increase monitoring and provide hydrological information.
Swaziland	Artificial groundwater recharge, implement IWRM, water harvesting, construct more storage reservoirs, water recycling and reuse
Tanzania	Promote IWRM, wastewater recycling and reuse, exploit and develop groundwater resources
Togo	Protect water resources, improve agriculture water management, rainwater harvesting, improve groundwater management, wastewater reuse.
Tunisia	Wastewater transfer and reuse, improve and secure the water supplies of large urban centres
Uganda	Improving water efficiency, water harvesting and storage, implement IWRM
Zambia	Improve water storage through a network of dams and weirs, adopt and promote IWRM, promote rainwater harvesting
Zimbabwe	Promoting and supporting water harvesting, developing, rehabilitate and maintain surface and groundwater resources, promoting efficient water use practices, improve monitoring, strengthen IWRM

Analysis of iNDCs' water sector adaptation targets set by African governments.



SM Figure 1-2: Summary of the water sector adaptation targets submitted to UNFCCC by African governments. (n = 36).

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Supplementary Material 2: Indigenous and local knowledge in the vulnerability of smallholder farmers to climate variability and change in Chiredzi, Zimbabwe.

This file contains Supplemental Material of the following:

1. The file also contains the November to April rainy season onset, cessation, length, and hot days for the sorghum crop and the additional monthly temperature and rainfall plots.
2. Detailed explanations of the livelihood vulnerability assessment components and sub-components, including the questions used to investigate each sub-component and how this relates to vulnerability assessment in Chiredzi.
3. Questionnaire survey guide used to collect socioeconomic data from the farmers. Dataset with survey information is found here: https://doi.org/10.17632/T87ZPHVS5X.1.

2.1. Sorghum rainy onset, cessation, and length

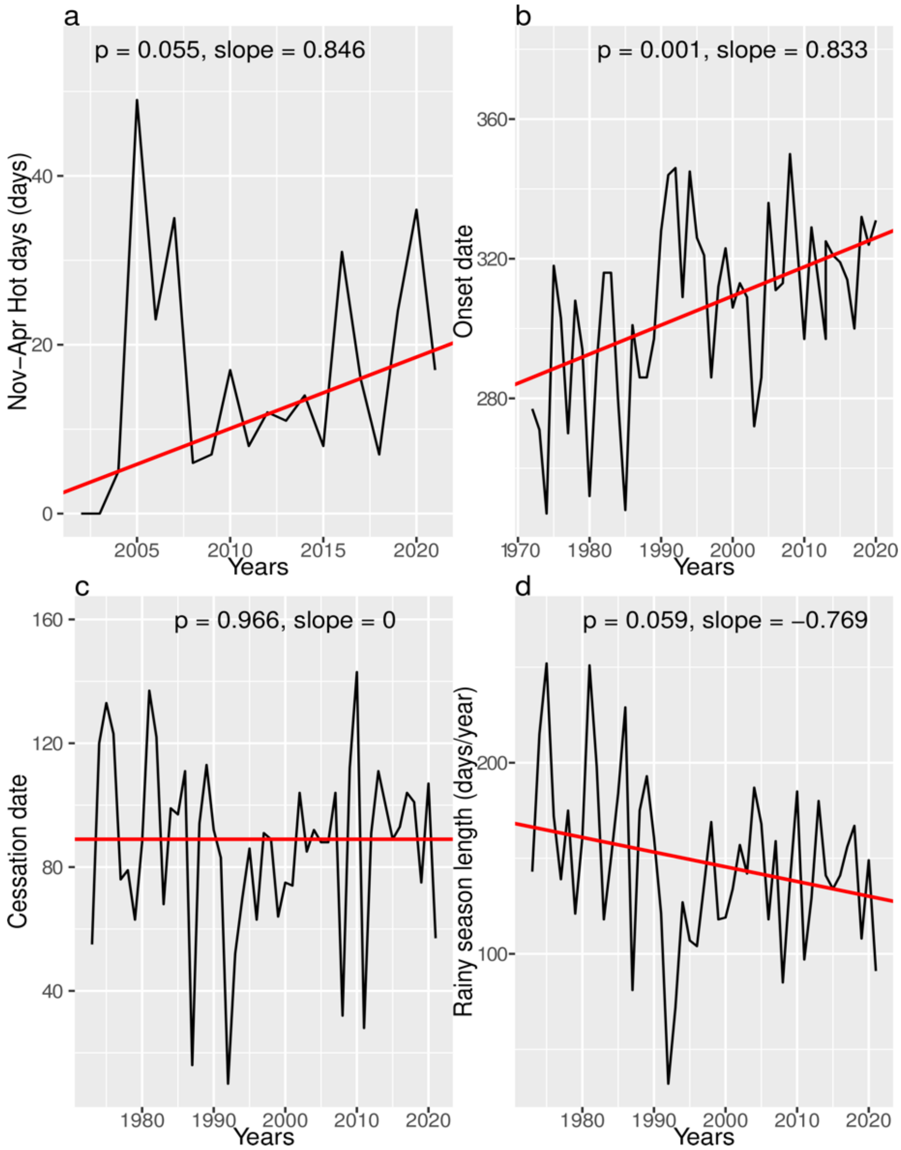
Additional Methodology

It is important to assess the growing conditions of sorghum because it is a staple crop that is increasingly grown by rainfed smallholder farmers in the Chiredzi rural district. We used the following thresholds (SM Table 2-1) to calculate onset, cessation, and season length of the rainy season for sorghum grown in semi-arid regions.

SM Table 2-1: Definition of indices for rainfall requirements under semi-arid and arid conditions for sorghum crops.

Climate index	Description	Reference
Rainy season onset	Cumulative rainfall of ≥2 cm/ 20mm within 10 days in the sowing period (after 1 Aug for southern Africa)	(Wolf, Ouattara & Supit, 2015)
Rainy season cessation	The last day between 1 January and 30 June that accumulates 10 mm or more rainfall	(Mupangwa, Walker & Twomlow, 2011)
Rainy season length	The number of days between onset and cessation of rain dates	(Byakatonda et al., 2018)
Hot days	The number of days with maximum temperature above 38 °C between November - April months of the growing season	(Huda et al., 1984)

Sorghum onset, cessation, length of rainy season and hot days

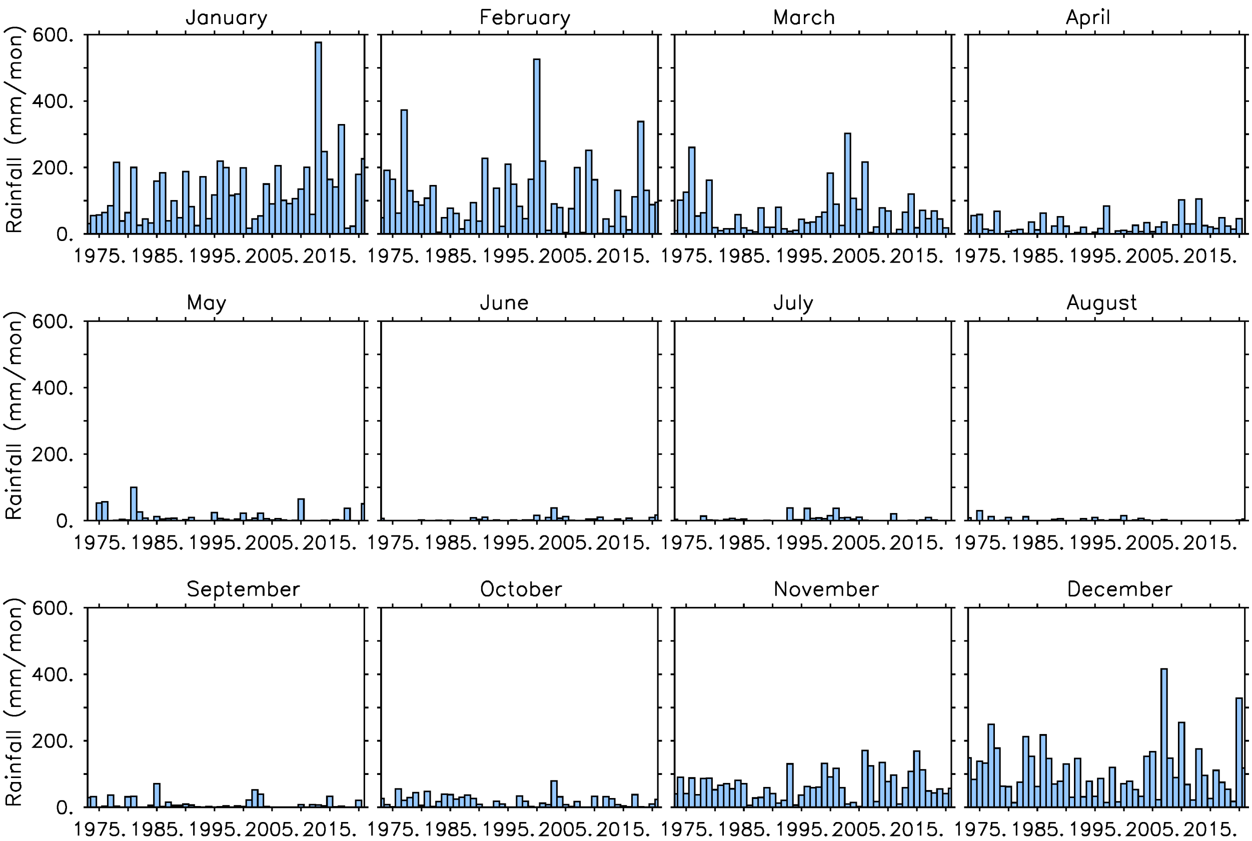


SM Figure 2-1: Inter-seasonal variability and trends in temperature and rainfall indices for sorghum in Chiredzi District between 1972–2021. The red line indicates the fitted trend line using the Mann–Kendall Sen's slope estimate for **a**) number of hot days, **b**) onset of the rainy season (plotted in Julian days), **c**) cessation dates of the rainy season (also plotted in Julian days), and **d**) length of the rainy season. The slope and significance value (P-value) at the 5% significance level are presented for each index. The rainy season onset showed a statistically significant increasing trend ($p = 0.001$) to a delayed start, whereas cessation showed no trend. The combination of a significantly delayed rainy season onset and decreasing rainy season length strongly suggests shrinking of rainy season for sorghum. The hot days showed a statistically insignificant increasing trend, although we observed 0.846 days/year.

Monthly rainfall and temperature plots.

Monthly precipitation plots

Total monthly rainfall plots (1972–2021) for Chiredzi are presented in SM Figure 2-2.



SM Figure 2-2: Total monthly rainfall for Chiredzi (1972–2021). Total monthly rainfall received in January has increased from 2000, while the February rainfall totals decreased simultaneously. This suggests a forward shift of the rainy season. This means that the dry spells traditionally experienced in January have now moved to February.

Monthly temperature analysis

Monthly mean minimum, average, and maximum temperature plots (2001–2021) for Chiredzi (SM Figure 2-3).

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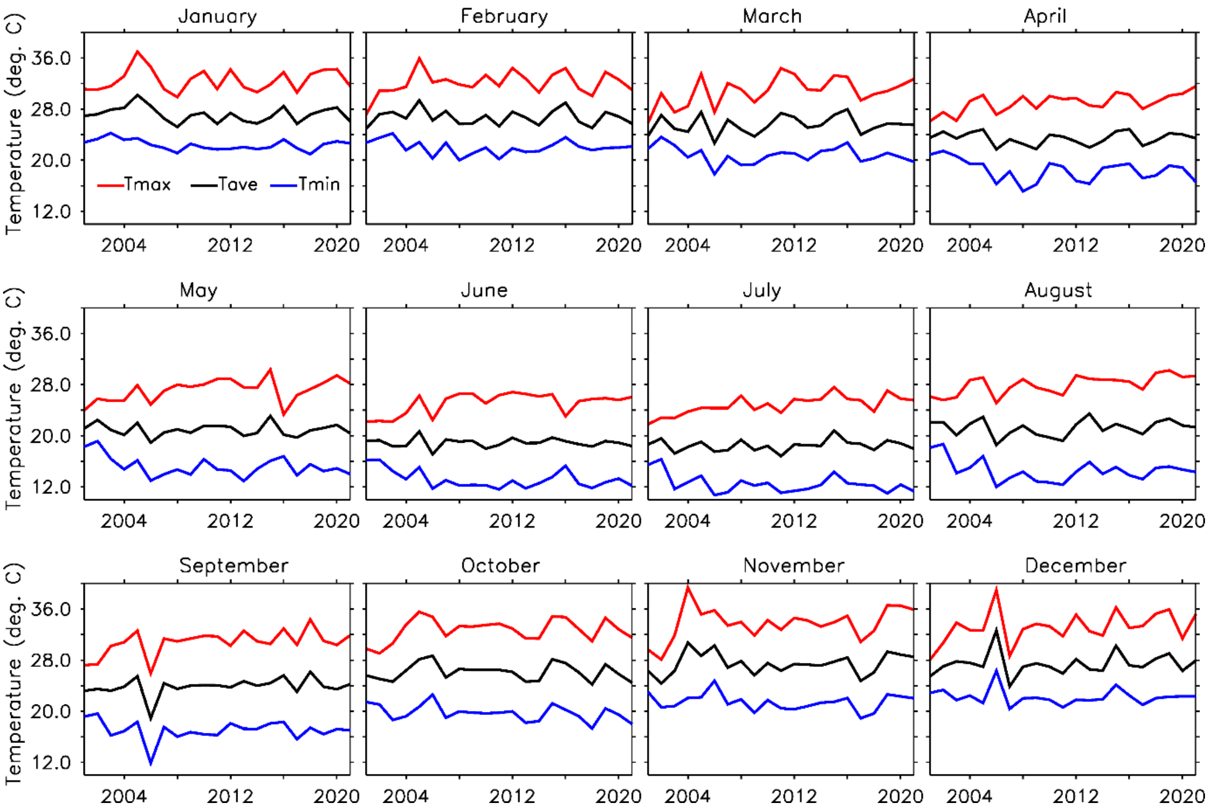

SM Figure 2-3: Mean monthly minimum, average, and maximum temperature trends for rainfall (2001–2021). The blue lines represents the mean monthly minimum temperature, the black lines represents the monthly average temperature, and the red lines are the mean monthly maximum temperature. the maximum temperature for April, July, and August is constantly increasing, while the minimum temperature for the same months is decreasing. Also, the minimum temperatures in June and May are constantly decreasing. This suggests that Chiredzi is increasingly warming with all winter months, showing that the minimum temperature is decreasing. The highest warming in October–February was observed between 2005-07.

2.2. Detailed Livelihood Vulnerability Index for Chiredzi

SM Table 2-2: Expanded table of the LVI main and sub-components developed for Chiredzi and their link to vulnerability assessment of the smallholder farmers Chiredzi.

Capitals	Main	Sub-components	Explanation of sub-components	Status in LVI	Unit	Source	Survey question	Relationship with vulnerability to climate risk
Human	Food	1. Percent of households dependent on family farm for food	Percentage of households that get their food primarily from their personal farms	Existing	Percent	(Hahn, Riederer & Foster, 2009)	Where does your family get most of its food?	High dependence of family food on farm produce indicates high sensitivity to droughts and climate variability-related crop failure, and therefore, high vulnerability (Twongyirwe et al., 2019). The limited ability to save crops from preceding harvests reflects the sensitivity of the earlier season to unfavourable production conditions, including the climate. A higher inverse average crop diversity means fewer crops are grown, limiting the potential of the farmer to spread risk to climate-related crop failures, such as droughts (Lin, 2011). The higher the indicators for food, the more sensitive households are and the higher the vulnerability (Hahn, Riederer & Foster, 2009; Williams, Crespo & Abu, 2020).
		2. Average number of months households struggle to get food (range: 0–12)	Average number of months households struggle to obtain food for their family	Existing	Months	(Hahn, Riederer & Foster, 2009)	Does your family have adequate food for the whole year or are there times during the year that your family does not have enough food? How many months a year does your family have trouble getting enough food?	
		3. Percent of households who do not save crops	Percentage of households that do not save crops from each harvest	Existing	Percent	(Huong, Yao & Fahad, 2019)	Does your family save some of the crops you harvest to eat during a different time of year?	
		4. Average Crop Diversity Index (range: >0–1)	The inverse of (the number of food crops grown by a household +1). e.g., A household that grows pumpkin, maize, groundnuts, millet, beans, and Bambara buts will have a Crop Diversity Index = 1/(6 + 1) = 0.14.	Modified	1/no. crops	(Hahn, Riederer & Foster, 2009)	How many crops does your household grow? Please list.	
		5. Percent of households that do not sell/ barter trade crops for other food supplies	Percentage of households unable to trade self-grown crops	Existing	Percent	(Shah et al., 2013)	Do you trade the food you grow with others for different food? Do you sell the crops you grow for money to buy other food goods?	
	Livelihood strategy	6. Percent of households without family member working in a different community in Zimbabwe	Percentage of households that report at least 1 family member who works outside of the community for their primary work activity.	Modified	Percent	(Hahn, Riederer & Foster, 2009)	How many people in your family go to a different community to work?	Households with members in the diaspora in Chiredzi are likely to receive remittances, which could lead to less dependence on agriculture for livelihood, and therefore, less vulnerable (FAO, 2017; Mupakati & Tanyanyiwa, 2017). The higher dependence on crops only for livelihoods indicates a household's high sensitivity to climate risk. The diversification of income sources increases adaptive capacity and decreases the risk of loss. Practicing
		7. Percent of households without family member working in diaspora	Percentage of households that report at least 1 family member working in diaspora	New	Percent	Developed for this study	Do you have any family member working in the diaspora? How often they send money back home? Under what circumstances do you usually sell your livestock?	
		8. Percent of households dependent solely on crops production as source of income	Percentage of households that report only crop production a source of income	Modified	Percent	(Hahn, Riederer & Foster, 2009)	Do you or someone else in your household collect food from the bush, the forest, or lakes and rivers to sell?	

Capitals	Main	Sub-components	Explanation of sub-components	Status in LVI	Unit	Source	Survey question	Relationship with vulnerability to climate risk
		9. Percent of households do not practice mixed farming	Percent of households that rely on mixed farming	New	Percent	Developed for this study	Do you or someone else in your household raise animals? How many cattle, goats, sheep, and chickens do you have? How often do you sell cattle?	mixed farming for smallholder farmers in Africa reduces their vulnerability to climate hazards risks (Trisos et al., 2022). The higher the Average Agricultural Livelihood Diversification Index, the lower the livelihood diversification and, hence, the higher the vulnerability of the farmer to climate risk. Therefore, a higher value of the overall livelihood strategy indices reflects lower adaptive capacity, and hence, higher vulnerability.
		10. Percent of households without non-agricultural livelihood income contribution	Percentage of households reporting livelihoods other than agriculture/ fishing/hunting as the main source of income	Existing	Percent	(Shah et al., 2013)	Obtained from the analysis of the survey	
		11. Average Agricultural Livelihood Diversification Index (range: 0.20 –1)	The inverse of (the number of agricultural livelihood activities +1) reported by a household, e.g., A household that farms, keep livestock, and utilises climate sensitive natural resources for livelihood will have a Livelihood Diversification Index = 1/(3 + 1) = 0.25.	Existing	1/no. livelihoods	(Hahn, Riederer & Foster, 2009)	Integrate answers from 8, 9 and10	
	Health	12. Average distance to a health facility	Average distance households to get to the nearest health facility	Modified	Meters	(Hahn, Riederer & Foster, 2009)	How long are you from a health facility?	The longer the distance to a health facility, the more families are ill or miss school/work, and the more sensitive and vulnerable they are (Hahn, Riederer & Foster, 2009; Panthi et al., 2016). The indicators show how health impacts family and higher indices imply higher sensitivity.
		13. Percent of households with family member with chronic illness	Percentage of households that report at least 1 family member with chronic illness. Chronic illness was defined subjectively by respondent	Existing	Percent	(Hahn, Riederer & Foster, 2009)	Is anybody in your family chronically ill (they get sick very often)?	
		14. Percent of households where a family member had to miss work or school in the last 2 weeks due to illness	Percentage of households that report at least 1 family member who had to miss school of work due to illness in the last 2 weeks.	Existing	Percent	(Hahn, Riederer & Foster, 2009)	Has anyone in your family been so sick in the past 2 weeks that they had to miss work or school?	
	Education and climate change training (modified)	15. Percent of households where household head has not attended school	Percentage of households where the head of the household reports that they have attended 0 years of school	Existing	Percent	(Hahn, Riederer & Foster, 2009)	Did you ever go to school?	Education improves awareness and the ability to adopt operational and crop management practices that increase adaptive capacity. Hence, they are less vulnerable to climate change. Education is the highest predictor of climate change literacy in Africa (Simpson, Nicholas P. et al., 2021a). The higher the education level, the more likely it is to have climate change literacy which influence the urgency of farmers to act and likelihood to adapt (Simpson, Nicholas P. et al., 2021a; Trisos et al., 2022), thus reducing their vulnerability. Therefore, the higher the education and climate change training the lower, the adaptive capacity and
		16. Percent of households where household head just passed primary school	Percentage of households where the head of the household reports that they have attended secondary school as their highest qualification	Existing	Percent	(Huong, Yao & Fahad, 2019)	If yes, what is the highest education level?	
		17. Percent of households where household head did not attend tertiary learning.	Percentage of households where the head failed to proceed to tertiary level	New	Percent	Developed for this study	If yes, what is the highest education level?	
		18. Percent of households where a family member did not receive any training on climate change	Percent of households where a family member did not receive any training or information shared to them on climate change impacts and its causes..	New	Percent	Developed for this study	Did you ever receive any training or information about climate change including its causes? Where did you receive the training? By who?	

Capitals	Main	Sub-components	Explanation of sub-components	Status in LVI	Unit	Source	Survey question	Relationship with vulnerability to climate risk
								the higher the vulnerability of the farmer/ household.
	Indigenous and local knowledge (new)	19. Percent of households do not use indigenous and local knowledge for weather forecasting	Percentage of households dot not use IK neither have access to scientific weather forecasts	New	Percent	Developed for this study	Do you forecast weather events and climate? If yes, how?	Having the indigenous and local knowledge of weather and seasonal forecasting means a farmer can make informed climate decisions in Chiredzi (Zvobgo, Luckson et al., 2023), hence implemented several adaptation responses to adapt to the anticipated risk (Zvobgo, Luckson et al., 2023), thus reducing the vulnerability and improves adaptive capacity. Lack of indigenous and local knowledge reverse all said above. Also, limited access to weather and climate forecasts means that uninformed decisions are made and there is less chance to adapt. The higher the indicator, the higher is the vulnerability of the farmer to climate risks.
		20. Percent of farmers that do not implement planning and adaptation measures from indigenous knowledge.	Percentage of households that do not implement any IK measures to adapt to the climate risk.	New	Percent	Developed for this study	What practices (both management and operational) measures you implement because of the IK forecasts?	
		21. Average Crop Adaptation Response (CAR) Index (range: 0 –1)	The inverse of (the total number of adaptation responses implemented +1) reported by a household, e.g., A household that implement a total of 3 adaptation responses will have an AR Index = 1/(3 + 1) = 0.25.	New	Percent	Developed for this study	List the number of crop adaptation responses that you are implementing	
		22. Percent of households that do not have access to scientific weather forecasting	Percentage of households that have no access to scientific weather forecasts	New	Percent	Developed for this study	Do you have any access to scientific weather and climate forecasts? If yes, what device do you access with?	
Social	Socio-demographic profile	23. Dependency ratio	Ratio of the population under 18 and over 65 years of age to the population between19 and 60 years of age	Modified	Ratio	(Hahn, Riederer & Foster, 2009)	Could you please list the ages and sexes of every person who eats and sleeps in this house?	The higher the number of dependents, the lower the capacity of the households to adapt. Women in Africa typically have a lower capacity to adapt (Ayanlade et al., 2023; Trisos et al., 2022). Fewer family members means limited capacity to adapt, as smallholder farmers depend on family labour to implement adaptation responses, most of which are labour intensive (Atube et al., 2021; FAO, 2015). The higher the number of members requiring dependent care, the fewer the members of the family that can be involved in agricultural production. Therefore, higher percentages of socio-demographic profile indicators reflect a lower capacity of households to adapt and higher the vulnerability.
		24. Percent of female-headed households	Percentage of households where the primary adult is female. If a male head is away from home > 6 months per year the female is counted as the household head.	Existing	Percent	(Hahn, Riederer & Foster, 2009)	Are you the head of the household?	
		25. Average number of family members in a household	Average number of family members in a household	Existing	Persons	(Huong, Yao & Fahad, 2019)	Could you please list the ages and sexes of every person who eats and sleeps in this house?	
		26. Percent of households with members needing dependent care	Percentage of households with at least one member requiring daily care because of age, physical or mental condition, illness, or disability	Existing	Percent	(Shah et al., 2013)	Do any members of your household require daily care because of age? physical or mental condition, illness, or disability?	
	Social network	27. Average Receive: Give ratio (range: 0–15)	Ratio of (the number of types of help received by a household in the past month + 1) to (the number of types of help	Existing	Ratio	(Hahn, Riederer & Foster, 2009)	In the past month, did relatives or friends help you and your family:(e.g., Get medical care or medicines, sell animal products or other goods produced by	High participation in farm-related community organisations/ groups and increased access to information through communication devices

Capitals	Main	Sub-components	Explanation of sub-components	Status in LVI	Unit	Source	Survey question	Relationship with vulnerability to climate risk
			given by a household to someone else in the past month + 1)				family, Take care of children). In the past month, did you and your family help relatives or friends: (same choices as above)	improves individuals' awareness of impending hazards (Chaudhury et al., 2017; Dapilah, Nielsen & Friis, 2020). Access to social safety nets for farmers is crucial for improving adaptive capacity and is one of the adaptation responses available to smallholder farmers, which reduces their vulnerability (Agrawal et al., 2019; Hallegatte et al., 2016; Scognamillo, Mastrorillo & Ignaciuk, 2022; Trisos et al., 2022; Ulrichs, Slater & Costella, 2019). Strong social network indicators strengthen the capacity to adapt for farmers but higher constraints of this result in lower vulnerability (Chaudhury et al., 2017; Dapilah, Nielsen & Friis, 2020; Dumenu & Takam Tiamgne, 2020).
		28. Percent of households not having access to government subsidies on agricultural production inputs in the past 12 months and other social welfare assistance including NGO support.	Percentage of households that reported that they have not received support from local government for any assistance in the past12 months with agricultural inputs, social welfare and other NGO support.	Modified	Percent	(Williams, Crespo & Abu, 2020)	In the past 12 months, did your household received subsidies from the government on agricultural inputs, social welfare and other NGO support?	
		29. Percent of households not associated with any farmer-based organization (FBO)	Percentage of households that do not belong to any farmer-based group.	Existing	Percent	(Williams, Crespo & Abu, 2020)	Are you a member of any farmer group or society?	
		30. Percent of households not having communication devices	Percentage of households that do not have a TV, radio or cellphone that can receive weather updates	Existing	Percent	(Williams, Crespo & Abu, 2020)	Do you own any of the following: TV, radio or cellphone that connect FM radio?	
		31. Percent of households not associated with any community social group	Percentage of households that do not belong to any social excluding farmer-based groups.	Existing	Percent	(Williams, Crespo & Abu, 2020)	Are you a member of any social group including WhatsApp group?	
Natural	Natural resources	32. Percent of households that depend on (exploit) natural resources	Percentage of households that survive on natural resources either for food or selling products.	Existing	Percent	(Huong, Yao & Fahad, 2019)	Do you exploit any natural resource for either selling or for consumption?	Higher percentages of farmers depend on exploiting natural resources for livelihood indicate greater reliance on climate-sensitive resources, which increases household vulnerability to negative climate impacts that affect the natural resource base (IPCC, 2023b).
		33. Percent of households using only Forest-based energy for cooking purpose	Percentage of households that use wood only for cooking and lighting.	Existing	Percent	(Huong, Yao & Fahad, 2019)	What energy source do you use to cook at your house?	
	Land	34. Percent of households with small farmland (0.1–0.5 ha)		Existing	Percent	(Huong, Yao & Fahad, 2019)	What is the approximate size of your farmland?	Limited access to land hinders production, which reduces the capacity of smallholder farmers to adapt and increases their vulnerability (Bryceson, 2019; FAO, 2015). The higher the percentage of farmers who record signs of degradation, the less suitable the land is for agriculture, thus increasing the vulnerability of farmers (Olsson et al., 2019; UN, 2018; Webb et al., 2017). Thus, the higher the land component, the lower the farmer's capacity to adapt hence high vulnerability.
		35. Percentage of households reporting land degradation by climate-related extremes during past 20 years		Existing	Percent	(Huong, Yao & Fahad, 2019)	Did you see any gully or land destruction related to climate hazards between 2000 and 2020?	
	Water	36. Percent of household that collect water directly from natural water system	Percentage of households obtaining water from wells, rainwater, pool, or hole as their primary source	Existing	Percent	(Shah et al., 2013)	Where do you collect your water from?	High reliance on households to natural water systems means reduced access to potable water during

Capitals	Main	Sub-components	Explanation of sub-components	Status in LVI	Unit	Source	Survey question	Relationship with vulnerability to climate risk
		37. Inverse of the average number of liters of water stored per household (range:>0–1)	The inverse of (the average number of liters of water stored by each household + 1)	Existing	1/Litre	(Hahn, Riederer & Foster, 2009)	What containers do you usually store water in? How many? How many liters are they?	drought or flooding events. An increase in the distance to water sources for households means limited access to potable water and climate hazards can be a barrier to access potable water for households. The higher the percentage of water indicators, the higher the sensitivity of the water component to climate hazards and the more vulnerable households are.
		38. Percent of household that do not collect water from a reliable source	Percentage of household that are using reliable and protected water source	New	Percent	Developed for this study	Depending on the answers provided in Q35, if it's a well, the follow up question is: Is your well covered with a lid?	
		39. Average number of boreholes in a village	Average number of boreholes that are in a village	New	Count	Developed for this study	How many boreholes are in your village?	
		40. Average distance to water source	Average distance from households to primary water source.	Existing	Meters	(Williams, Crespo & Abu, 2020)	How long does it take to get to your water source?	
	Climate hazards	41. Average number of floods, drought, and cyclone events in the past 20 years (range: 0 –10)	Total number of floods, droughts, and cyclones that were reported by households in the past 20 years	Existing	Count	(Hahn, Riederer & Foster, 2009)	How many times has this area been affected by a flood/ cyclone/ drought in 2010–2020?	The higher the number of climate hazards listed by the farmers, the higher the exposure of the farmers, and hence, the higher their vulnerability to climate variability and change. Lack of access to early warning systems for farmers means that they cannot prepare for the hazards, thereby increasing their vulnerability (Shiferaw et al., 2014). A higher percentage of households with members injured or died from climate hazards indicates high exposure of farmers to climate risk. Higher index values for climate hazards reflect higher exposure and increased vulnerability to climate hazards.
		42. Percent of households that did not receive a warning about the about expected natural disasters/event	Percentage of households that did not receive a warning about the most severe flood, drought, and cyclone event in the past 20 years.	Existing	Percent	(Hahn, Riederer & Foster, 2009)	Did you receive a warning about the flood/ cyclone/ drought before it happened?	
		43. Percent of households with an injury or death as a result of the most severe natural disaster in the past 20 years	Percentage of households that reported either an injury to or death of one of their family members as a result of the most severe flood, drought, or cyclone in the past 20 years.	Existing	Percent	(Hahn, Riederer & Foster, 2009)	Was anyone in your family injured in the flood/cyclone drought? Did anyone in your family die due to flood/ cyclone/ drought?	
		44. Percent of households with losses to physical assets (house/ machinery) due to flooding and cyclones	Percentage of households that have suffered losses of physical assets that causes loss/damage of livelihood	Existing	Percent	(Shah et al., 2013)	In the last 10 years, what physical assets have you lost or been severely damaged due to flooding/ storm events?	

2.3. Questionnaire survey guide for farmers

Questionnaire survey guide for assessing livelihood vulnerability for smallholder farmers in Chiredzi, Zimbabwe

Demographic data

Ward	
Village	
Age of the house head (range)	
Number of people below 18 and above 60: 19-59 years	
Length of stay in the area	
Education (of the household head)	
Gender (of the household head)	
Family size	
Size of the farmland?	

Food

Question	**Responses**
Where does your family get most of its food?	
How many crops does your household grow? Please list.	
Does your family have adequate food for the whole year or are there times during the year that your family does not have enough food?	
If not, how many months you struggle to put food on the table	
How much crop do you save?	
Do you trade the food you grow with others for different food?	
Do you trade the food you grow with others for different food?	
Do you sell the crops you grow for money to buy other food goods?	

Livelihood strategy

Question	**Responses**					
Do you have livestock?						
How many cattle, goats, sheep, and chickens that you have? Please list.	Cattle	Goats	Donkey	Sheep	Chickens	Others
How often do your sell livestock?						
Under what circumstances do you usually sell your livestock?						

How many people in your family go to a different community to work?	
Do you have any family member working in the diaspora?	
How often they send money back home?	
Do you collect something from the bush, the forest, or lakes and rivers to sell?	

Water

Question	Responses
Where do you collect your water from?	
What containers do you usually store water in? How many? How many liters are they?	
Depending on the answers provided in row 1, if it's a well, the follow up question is: Is your well covered with a lid or protected?	
How many boreholes are in your village?	
How long does it take to get to your water source?	

Natural resources

Question	Responses
Do you exploit any natural resource for either selling or consumption?	
What energy source do you use to cook at your house?	

Land

Question	Responses
Did you see any gully or land destruction related to climate hazards between 2010 and 2020?	
What is the approximate size of your farmland?	

Socio-demographic data

Question	Responses
Could you please list the ages and sexes of every person who eats and sleeps in this house?	
Are you the head of the household?	
Do any members of your household require daily care because of age? physical or mental condition, illness, or disability?	

Social networks

Question	Responses
In the past month, did relatives or friends help you and your family:(e.g., Get medical care or medicines, sell animal products or other goods produced by family, Take care of children). In the past month, did you and your family help relatives or friends: (same choices as above)	
In the past 12 months, have you or someone in your family gone to your community leader for help?	
Are you a member of any farmer group or society?	
Do you own any of the following: TV, radio or cellphone that connect FM radio?	
Are you a member of any social group including a WhatsApp group?	

Education and training

Question	Responses
Did you ever go to school?	
If yes, what is the highest education level?	
If yes, what is the highest education level?	
Did you ever receive any training or information about climate change including its causes? Where did you receive the training? By who?	

Indigenous and local knowledge

Question	Responses
Do you forecast weather events and climate? If yes, how?	
What practices (both management and operational) do you implement because of the IK forecasts?	
List the number of crop adaptation responses that you are implementing.	
Do you have any access to other forecasts? If yes, what device do you access with?	

Natural disasters

Question	Responses
How many times has this area been affected by a flood/ cyclone/ drought in 2000–2020?	

Did you receive a warning about the flood/ cyclone/ drought before it happened?	
Was anyone in your family injured in the flood/cyclone drought?	
Did anyone in your family die due to flood/ cyclone/ drought?	
In the last 10 years, what physical assets have you lost or been severely damaged due to flooding/ storm events?	

Health

Question	Responses
How long are you from a health facility?	
Is anybody in your family chronically ill (they get sick very often)?	
Has anyone in your family been so sick in the past 2 weeks that they had to miss work or school?	

Part B: Farmers' perceptions of climate variability and change

How do you assess the weather and climate over the recent past years?

What evidence do you see that suggest any change or variability of the climate?

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Supplementary Material 3: Role of Indigenous and local knowledge in seasonal forecasts and climate adaptation: a case study of smallholder farmers in Chiredzi, Zimbabwe.

This file contains the following supplementary material:

i. Questionnaire guide for smallholder farmers
ii. Details description of the farmer decisions
iii. Expanded binary logistic regression model results.

The dataset with information from farmer surveys are found here: https://doi.org/10.17632/DNZCSZDNC2.4

3.1. Questionnaire guide for smallholder farmers

Below is the questionnaire survey guide used during the interviews with smallholder farmers in Chiredzi.

A. Socio-demographic and livelihood data

Ward	
Village	
Age of the respondent (range)	
Number of people below 18 and above 60: 19-59 years	
Length of stay in the area	
Education level (of the respondent)	
Gender (of the respondent)	
Family size	
Size of the farmland?	

1. Food

Question	Responses
What is the household's source of food?	
How many crops do you grow?	
Is the harvest enough for the whole year?	
If not, how many months you struggle to put food on the table	
How much crop do you save?	
Do you trade the food you grow with others for different food?	
Do you sell the crops you grow for money to buy other food goods?	

2. Livelihood strategy

Question	Responses
Do you have livestock?	

How many cattle, goats, sheep, and chickens that you have?	Cattle	Goats	Donkey	Sheep	Chickens	Others
How often do your sell livestock?						
Under what circumstances that you sell your livestock?						
How many people in your family go to a different community to work?						
Do you have any family member working in the diaspora?						
How often they send money back home?						
Do you collect something from the bush, the forest, or lakes and rivers to sell?						

3. Social networks

Question	Responses
Are you a member of any farmer group or society?	
Do you own any of the following: TV, radio or cellphone that connect FM radio?	
Are you a member of any social group including a WhatsApp group?	

4. Education and training on climate and weather

Question	Responses
Did you ever receive any training about climate change?	
If yes, is there any of that knowledge you are using to improve your climate decision making	

B. Role of indigenous and local knowledge in weather & climate forecasts and climate adaptation

1. Do you forecast weather and climate? If yes, please complete question the 2 below.
2. How do you forecast the following?

Weather and climate hazards	**Indigenous & local knowledge**		**Scientific forecasts**	
	Yes	No	Yes	No
Weather events (storms, heavy precipitation, rainy day, excessive temperature)				
Droughts, floods, heatwaves				
Season quality and length				
Rain onset				
Cessation rains				

If **YES** to one of the above on Indigenous knowledge (IK) & local knowledge (LK) forecasts

3. What IK & LK do you use to forecasts what you listed above? On a scale of 1 to 5, please rate how you reliably depend on IK and LK forecasts for each weather events climate hazards you listed.

Indicator category	**Indicator type**	**Weather events and climate indices**	**Reliance score**
Weather/ Meteorological			
Fauna			
Fauna			
Astrological			

Reliability: 1 = I use them but do not rely on them, 2 = Barely rely on the IK and LK predictions, 3 = Sometimes I rely on them, 4 = I rely on them, 5 = I strongly rely on them.

4. Are there any decisions you make based on these forecasts? If yes, please list the actions you take to improve your farming:

5. What are the climate adaptation measures you implement based on these IK and LK forecasts? Please list below:

6. Do you also use scientific forecasts to make farming decisions related to climate adaptation? **Yes/No**
7. What other adaptation responses that you are implementing not linked to IK & LK listed on question 5?

8. Do you have access to Meteorological Service Department forecasts? Yes/ No
9. If **YES**,
   i. How do you receive them?

Radio	

TV	
Extension/ government agencies	
Social groups and neighbours	
Other (please list)	

ii. On a scale of 1 to 5, how do you rely on the predictions?

1	I do not trust them, but I use them
2	I use them but I do not rely on them
3	I sometimes use them and rely on them
4	I rely on them
5	I strongly rely on them

iii. What are the adaptation responses that you implement based on the forecasts?

C. Farmer perception on climate variability and change

1. How do you assess the weather and climate over the past 5 years?

2. Do you see any evidence that suggest any increased variability or change of the items you mentioned above?

3.2. Details description of the farmer decisions

SM Table 3-1: detailed description of the decisions that farmers in Chiredzi are making from IK and LK weather and climate forecasts (support the Figure 5 of the article).

Climate indices and hazards	IK and LK supported responses for climate risk preparedness
Onset rains	Land preparation (zero tillage, burn biomass from previous crops to decrease soil carbon and kill weeds for farmers practicing conservation agriculture)
	Seed preparation (indigenous seeds for small grains - sorghum and millet, groundnuts, and Bambara nuts)
	Dry planting (of small grains - millet and sorghum, cotton, and Bambara nuts)
	Crop variety selection
	Buy appropriate seed varieties (for crops that farmers use certified seed) e.g., maize varieties (consider short term varieties when anticipating a short season)
	Plan agricultural calendar
	Prepare housing (roofing/thatching)
	Staggering crop planting dates
	Do nothing, ignore the forecasts
Weather events (storms, rainy day)	Weeding
	Irrigation scheduling
	Cultivation
	Organic fertiliser application dates and timing
	Do nothing, ignore the forecasts
Growing season quality	Crop variety selection
	Cultivation area allocation per crop
	Staggering of planting dates
Climate hazards (floods, droughts, cyclones)	Grow small grains when anticipating a drought
	Crop variety selection
	Prepare housing - cyclones
	Do nothing, ignore the forecasts
Rain cessation	Planting time - winter crops
	Time to harvest grain crops to avoid rotting of yields
	Time to harvest groundnuts and Bambara nuts when the ground is still wet

3.3. Expanded binary logistic regression model results.

SM Table 3-2: Full results from the BLR model with reference per variable

				95% CI		
	B	S.E.	OR	Lower	Upper	p-value
Age (years)						
20-29 (Ref)						0.063
30-39	0.649	0.891	1.914	0.334	10.969	0.466
40-49	2.974	1.146	**19.576**	**2.072**	**184.978**	**0.009**
50 and above	1.622	1.057	5.064	0.638	40.189	0.125
Education						
No Formal Education (Ref)						0.327
Primary	1.136	0.760	3.114	0.703	13.799	0.135
Secondary or higher	0.967	0.942	2.630	0.415	16.678	0.305
Farming Type						
Communal	2.158	1.158	8.655	0.894	83.781	0.062
Resettled (Ref)						
Gender						
Male	-0.139	0.590	0.871	0.274	2.769	0.814
Female (Ref)						
Wealth Level						
Good	-0.328	0.617	0.720	0.215	2.413	0.595
Poor (Ref)						
Access to Irrigation						
Yes	0.713	0.795	2.040	0.430	9.680	0.370
No (Ref)						
Access to scientific weather forecasts						
Yes	1.091	0.839	2.977	0.575	15.413	0.194
No (Ref)						
Perception						
Yes	-0.991	1.669	0.371	0.014	9.785	0.553
No (Ref)						
Livelihood diversification						
Yes	-0.594	0.755	0.552	0.126	2.427	0.432
No (Ref)						
Access to extension services						
Yes	-0.030	0.664	0.971	0.264	3.568	0.964
No (Ref)						

Farmland Size	.513	.214	**1.671**	**1.097**	**2.543**	**0.017**
Length of stay	-.009	.024	0.991	.946	1.038	0.697
Family Size	-.026	.103	0.974	.796	1.192	0.797
Constant	-3.346	2.090	0.035			0.109

*Ref means reference

4.3.2. SPSS output of the BLR model

```
LOGISTIC REGRESSION VARIABLES Farmer use of IK forecast
  /METHOD=ENTER Age Cat Education 2, Farming type, Gender, Wealth Level, Irrigation,
    Access to scientific weather information, Perception, Livelihood diversification,
Access to extension services, Farm Size, Length of stay, Family Size
  /CONTRAST (AgeCat)=Indicator(1)
  /CONTRAST (Education2)=Indicator(1)
  /CONTRAST (Access to extension services)=Indicator(1)
  /CONTRAST (Farming type)=Indicator(1)
  /CONTRAST (Gender)=Indicator(1)
  /CONTRAST (Wealth Level)=Indicator(1)
  /CONTRAST (Irrigation)=Indicator(1)
  /CONTRAST (Access to scientific weather information)=Indicator(1)
  /CONTRAST (Perception)=Indicator(1)
  /CONTRAST (Livelihood diversification)=Indicator(1)
  /CLASSPLOT
  /PRINT=CI(95)
  /CRITERIA=PIN(0.05) POUT(0.10) ITERATE(20) CUT(0.5).
```

Logistic Regression

Dependent Variable Encoding

Original Value	Internal Value
No	0
Yes	1

Categorical Variables Coding

			Parameter coding		
		Frequency	(1)	(2)	(3)
Age Category	20-29 years	11	.000	.000	.000
	30-39 years	19	1.000	.000	.000

	40-49 years	24	.000	1.000	.000
	50 and above years	46	.000	.000	1.000
Education 2	No Formal Education	18	.000	.000	
	Primary	48	1.000	.000	
	Secondary or higher	34	.000	1.000	
Farming type	Resettled	40	.000		
	Communal	60	1.000		
Gender	Female	59	.000		
	Male	41	1.000		
Access to extension services	No	26	.000		
	Yes	74	1.000		
Irrigation	No	80	.000		
	Yes	20	1.000		
Livelihood diversification	No	30	.000		
	Yes	70	1.000		
Perception	No	4	.000		
	Yes	96	1.000		
Access to scientific weather information	No	12	.000		
	Yes	88	1.000		
Wealth Level	Poor	54	.000		
	Good	46	1.000		

Block 1: Method = Enter

Omnibus Tests of Model Coefficients

		Chi-square	df	Sig.
Step 1	Step	21.894	16	.147
	Block	21.894	16	.147
	Model	21.894	16	.147

Model Summary

Step	-2 Log likelihood	Cox and Snell R Square	Nagelkerke R Square
1	94.758[a]	.197	.286

a. Estimation terminated at iteration number 6 because parameter estimates changed by less than .001.

Variables in the Equation

	B	S.E.	Wald	df	Sig.

Step 1[a]	Age Category			7.303	3	.063
	Age Category(1)	.649	.891	.531	1	.466
	Age Category(2)	2.974	1.146	6.737	1	.009
	Age Category(3)	1.622	1.057	2.355	1	.125
	Education 2			2.237	2	.327
	Education 2(1)	1.136	.760	2.236	1	.135
	Education 2(2)	.967	.942	1.053	1	.305
	Farming type(1)	2.158	1.158	3.472	1	.062
	Gender(1)	-.139	.590	.055	1	.814
	Wealth Level(1)	-.328	.617	.283	1	.595
	Irrigation(1)	.713	.795	.804	1	.370
	Access to scientific weather information(1)	1.091	.839	1.690	1	.194
	Perception(1)	-.991	1.669	.352	1	.553
	Livelihood diversification (1)	-.594	.755	.618	1	.432
	Access to extension services(1)	-.030	.664	.002	1	.964
	Farmland Size	.513	.214	5.727	1	.017
	Length of stay	-.009	.024	.152	1	.697
	Family Size	-.026	.103	.066	1	.797
	Constant	-3.346	2.090	2.562	1	.109

Variables in the Equation

			95% C.I.for EXP(B)	
		Exp(B)	Lower	Upper
Step 1[a]	Age Category			
	Age Category(1)	1.914	.334	10.969
	Age Category(2)	19.576	2.072	184.978
	Age Category(3)	5.064	.638	40.189
	Education 2			
	Education 2(1)	3.114	.703	13.799
	Education 2(2)	2.630	.415	16.678
	Farming type(1)	8.655	.894	83.781
	Gender(1)	.871	.274	2.769
	Wealth Level(1)	.720	.215	2.413
	Irrigation(1)	2.040	.430	9.680
	Access to scientific weather information(1)	2.977	.575	15.413
	Perception(1)	.371	.014	9.785
	Livelihood diversification (1)	.552	.126	2.427
	Access to extension services(1)	.971	.264	3.568

	Farmland Size	1.671	1.097	2.543
	Length of stay	.991	.946	1.038
	Family Size	.974	.796	1.192
	Constant	.035		

a. Variable(s) entered on step 1: Age Category, Education 2, Farming type, Gender, Wealth Level, Irrigation, Access to scientific weather information, Perception, Livelihood diversification , Access to extension services, Farmland Size, Length of stay, Family Size.

```
         Step number: 1

                Observed Groups and Predicted Probabilities

        8                                                                            +
+
          I
I
          I
I
F                                                                                    I
I
R      6 +                                                                           Y
+
E        I                                                                           Y
I
Q        I                                                                           Y
YY      I
```

```
U       I                                                                       Y
YY      I
E        4  +                                                           Y       Y
Y YYY     +
N          I                                                            Y       Y
Y YYY     I
C         I                                         N               Y       Y      Y Y
Y       Y Y Y YYYY  YI
Y         I                                         N               Y       Y      Y Y
Y       Y Y Y YYYY  YI
       2 +                                       N         N    Y    Y NY Y  N YY Y Y
Y N YY Y     Y Y Y YYYYY Y+
         I                                       N         N    Y    Y NY Y  N YY Y Y
Y N YY Y     Y Y Y YYYYY YI
         I                    N    Y          Y  NN YN    NNN YNN   YYNNY Y NNYYN
YNYYNYYNYNN Y  Y YYYYNY YYNYYYYI
         I                    N    Y          Y  NN YN    NNN YNN   YYNNY Y NNYYN
YNYYNYYNYNN Y  Y YYYYNY YYNYYYYI
Predicted  ---------+---------+---------+---------+---------+---------+---------+---
------+---------+----------
  Prob:    0        .1        .2        .3        .4        .5        .6        .7
.8        .9         1
  Group:
NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYYY
YYYYYYYYYYYYYYYYY

          Predicted Probability is of Membership for Yes
          The Cut Value is .50
          Symbols: N - No
                   Y - Yes
          Each Symbol Represents .5 Cases.



DESCRIPTIVES VARIABLES=Age Lengthofstay FamilySize FarmSize
  /STATISTICS=MEAN STDDEV MIN MAX.
```

Descriptives

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Age	100	20	80	48.73	14.447
Length of stay	100	5	70	29.13	17.928
Family Size	100	2.00	14.00	7.3100	3.02747
Farmland Size	100	.00	11.00	3.7530	2.36602

Valid N (listwise)	100				

```
FREQUENCIES VARIABLES=Farming type, Education, Gender, Wealth Level, Irrigation,
    Access to scientific weather information, Perception, Livelihood diversification,
Access to extension services,
    Farmer use of IK forecast AgeCat Education2 FamilySize2 FarmSize2 LengthofStay2
  /ORDER=ANALYSIS.
```

Frequencies

Statistics

		Farming type	Education	Gender	Wealth Level	Irrigation	Access to scientific weather information
N	Valid	100	100	100	100	100	100
	Missing	0	0	0	0	0	0

Statistics

		Perception	Livelihood diversification	Access to extension services	Farmer use of IK forecast	Age Category
N	Valid	100	100	100	100	100
	Missing	0	0	0	0	0

Statistics

		Education 2	Family Size 2	Farm Size 2	Length of Stay 2
N	Valid	100	100	100	100
	Missing	0	0	0	0

Frequency Table

Farming type

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Resettled	40	40.0	40.0	40.0
	Communal	60	60.0	60.0	100.0
	Total	100	100.0	100.0	

Education

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No Formal Education	18	18.0	18.0	18.0

		Frequency	Percent	Valid Percent	Cumulative Percent
	Primary	48	48.0	48.0	66.0
	Secondary	32	32.0	32.0	98.0
	Tertiary	2	2.0	2.0	100.0
	Total	100	100.0	100.0	

Gender

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Female	59	59.0	59.0	59.0
	Male	41	41.0	41.0	100.0
	Total	100	100.0	100.0	

Wealth Level

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Poor	54	54.0	54.0	54.0
	Good	46	46.0	46.0	100.0
	Total	100	100.0	100.0	

Irrigation

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No	80	80.0	80.0	80.0
	Yes	20	20.0	20.0	100.0
	Total	100	100.0	100.0	

Access to scientific weather information

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No	12	12.0	12.0	12.0
	Yes	88	88.0	88.0	100.0
	Total	100	100.0	100.0	

Perception

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No	4	4.0	4.0	4.0
	Yes	96	96.0	96.0	100.0
	Total	100	100.0	100.0	

Livelihood diversification

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No	30	30.0	30.0	30.0
	Yes	70	70.0	70.0	100.0
	Total	100	100.0	100.0	

Access to extension services

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No	26	26.0	26.0	26.0
	Yes	74	74.0	74.0	100.0
	Total	100	100.0	100.0	

Farmer use of IK forecast

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No	27	27.0	27.0	27.0
	Yes	73	73.0	73.0	100.0
	Total	100	100.0	100.0	

Age Category

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	20-29 years	11	11.0	11.0	11.0
	30-39 years	19	19.0	19.0	30.0
	40-49 years	24	24.0	24.0	54.0
	50 and above years	46	46.0	46.0	100.0
	Total	100	100.0	100.0	

Education 2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	No Formal Education	18	18.0	18.0	18.0
	Primary	48	48.0	48.0	66.0
	Secondary or higher	34	34.0	34.0	100.0
	Total	100	100.0	100.0	

Family Size 2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	0-5	33	33.0	33.0	33.0
	6-10	48	48.0	48.0	81.0
	11 and above	19	19.0	19.0	100.0
	Total	100	100.0	100.0	

Farm Size 2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1-5	60	60.0	60.0	60.0
	6-10	39	39.0	39.0	99.0

		Frequency	Percent	Valid Percent	Cumulative Percent
	11 and above	1	1.0	1.0	100.0
	Total	100	100.0	100.0	

Length of Stay 2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1-10	13	13.0	13.0	13.0
	11-20	37	37.0	37.0	50.0
	21-30	13	13.0	13.0	63.0
	31-40	16	16.0	16.0	79.0
	41 and above	21	21.0	21.0	100.0
	Total	100	100.0	100.0	

Supplementary Material 4: Reliability and Effectiveness of Indigenous knowledge and local knowledge in climate adaptation: a case of smallholder farmers in Chiredzi, Zimbabwe

This file contains the following supplementary material:

i. Questionnaire guide for smallholder farmers
ii. Detailed description of the actions implemented from IK and LK seasonal forecasts.

6.6. Questionnaire survey guide for smallholder farmers

1. Demographic data

Ward	
Village	
Age (range)	
Number of people below 18 and above 60: 19-59 years	
Length of stay in the area	
Education	
Gender	
Family size	
Size of the farmland?	

2. **Reliability of indigenous and local knowledge-based climate forecasting and implementation of anticipatory responses**

Did you forecast weather or climate for the just ended 2021/22 season? **Yes/No**

If yes, what did you use to forecast the weather or climate? If it was based on your experiences, cultural, social interactions with the environment **(indigenous and local knowledge)**

What was your forecast for the 2021/22 season?

What are the anticipatory response measures that you implemented?

How do you rate each of the anticipatory measures you implemented?

1	They were not useful at addressing the climate hazard
2	They were partially useful at addressing the climate hazard
3	They were very useful/ relevant at addressing the climate hazard

Did you combine this knowledge with other advice from government extension officers, operational NGOs in the area? **Yes/ No**

Do you intend to use **indigenous and local knowledge** climate forecasting next season or recommend your neighbour to use them? **Yes/ No**
Do you share any of the forecasting with other farmers? **Yes/ No**

3. **Effectiveness of indigenous and local knowledge-based climate adaptation responses to reduce risk to food security and other associated risks**

Do you have any prior knowledge from your experiences, cultural, social interactions with the environment (indigenous or local) that you use to manage the climate risk and plan agricultural activities? If **yes**, please list this knowledge. What are the adaptation responses that you are implementing based on this knowledge?

If yes, please list this knowledge	**Specific forecasting-informed adaptation action**	**Climate hazard**

NB: Ask specifically about forecasting

For each response measure, how are they affecting the climate hazard, farmers' exposure to the hazard, their vulnerability, and other responses farmers take.

Effect of the response on hazard

Description	**Indicator questions**	**Indicator**	**Answer**
Role of the response at reducing or	How the response is reducing or increasing the occurrence of the climate hazard?	The effect of the response on the frequency of the hazard.	

increasing the magnitude/ frequency of the hazard?	How is the response is reducing or increasing magnitude of the hazard?	e.g., ploughing along the slope that can increase chances of flooding or planting in reverbed to increase water access for irrigation increases the chances of crops wiped during flooding.	

Effect of response on exposure

Description	Indicator questions	Indicator	Answer
Role of the response at reducing or increasing the exposure to climate risks.	How the response reduce or increase duration of exposure to the climate hazard,	Reduce time /length of exposure of crops to climate risk	
	How the response is changing the area exposed?	Size of the area where the crop based measures are implemented e.g., the area under irrigation	
	The amount of livestock exposed?	Number of livestock that are mitigated	
	The amount of crops exposed?	Number of crops that are mitigated e.g., the number of crops under intercropping	

Effect of response on vulnerability

Description	Indicator questions	Indicator	Answer
Role of the response in affecting the vulnerability characteristics	What are the crop types and how does the response reduce or increase their vulnerability?	The crop types e.g., response promoting the drought resistance of maize or legumes (e.g. indigenous selective breeding)	
	How is the response changing the poverty levels of the farmer	Responses that address poverty, e.g., growing of drought resistant cash crops such as cotton to address the drought risk	
	Who are the people involved in the implementation or benefit from the adaptation responses	Number of women, children benefiting from the response e.g., the response reduce the time women go to fetch water or only men involved in the implementation	
	Did the response improve access to health	Access to clinic / access to maternal health	

	How is the response improving the education and societal learning		
	How is the response encourage the participation of children (under 18) and old generation (over 65)		

Effect of vulnerability on response implementation

Description	Indicator questions	Indicator	Answer
Effect of vulnerability on the implementation of the response	How does poverty affect the implementation of the response?	Lack of resources affect the implementation of a response e.g., lack of draught for early planting to address late rain season onset	
	How issues of migration of effect the implementation of the responses?	How things like migrant status affect the implementation of responses e.g., men that possess the indigenous and local knowledge relocate to towns or abroad looking for employment leaving women behind that cannot implement some laborious responses	
	How age and gender affect the implementation of the responses?	Some of the old folks with knowledge useful for the implementation of adaptation are too old to work in the fields or due to age their efficiency to execute the duties is reduced	

Effect of response on other responses

Description	Indicator questions	Indicator	Answer
The impact of the response on the implementation of other measures	How is the response affect the choice of other responses?	e.g. because of using irrigation then the farmer do not use drought-resistant crops	

Adaptation responses outcomes

Assessing the outcomes of the **indigenous and local knowledge** adaptation responses. Rank the adaptation responses for each outcome if it is more than 1

Adaptation outcomes impact	**Indicator question**	**Key Adaption Action linked to outcome**	**Answer**
Reduced the risk to food security (Improved the livelihoods)	If you don't implement the above indigenous and local knowledge adaptation measures, will you be able to get enough food for the whole year?		
Better crop yields	How much yield do you get after implementing the measures (in terms of quantity and quality)		
Improve climate/ weather forecasting	*Obtained from previous sections*		
Improve the climate decision making process	*Obtained from previous sections*		
Financial/ economic improvements of the livelihoods	Do you sell any surplus that you obtain after the implementation of indigenous and local knowledge response measures		

Other than the indigenous and local knowledge, what other sources (scientific knowledge - SK) that provide you with climate forecasts and advise on climate adaptation responses? Please list the adaptation measures that you implement based on the advise

Source	**Type of the advice**	**Adaptation responses implement**

4. **Intergeneration transferability of IK and LK to assess to its effectiveness.**

How did you acquire the above **indigenous and local knowledge** you mentioned?

How is IK and LK traditionally passed on to the next generation?

Who is the youngest person in this community that uses IK and LK?

Are you sharing this knowledge with your children or younger generation

SM Table 3:

Forecast	Frequency	Category	Specific anticipatory response	Frequency	Total responses
Dry season (dry season and limited rainfall)	46	Timing of planting	Dry planting	16	63
			Early planting	9	
			Stagger planting dates	2	
		Crop type &variety selection, drought/small grain crops	Crop type, variety	4	
			Drought resistant/ small grain crops	3	
			Focus on horticultural crops in community gardens	1	
		Tillage and land preparation	Zero tillage	13	
			Ridging and mulching	2	
		Livestock related	Sell livestock	1	
		Cropping area management	Focus/expand irrigation area	3	
			Apply organic manure on planting station	2	
			Reduce area under specific crops	2	
			Grow crops in the valley	1	
		No action	Do nothing	4	
Average season (usual wet and dry season)	3	Tillage and land preparation	Zero tillage	3	8
		Timing of planting	Dry planting	3	
			Early planting	2	
Late rainy season onset	2	Timing of planting	Early planting	1	4
		Tillage and land preparation	Zero tillage	1	
		Seed and seed preparation	Select seed variety to plant for short term	1	
		Crop type & variety selection	Grow a lot of sorghum	1	
Wet season	23	Timing of planting	Dry planting	6	33
			Early planting	6	
			Stagger planting dates	1	
		Crop type &variety selection, drought/small grain crops	Crop type and variety	1	
			Drought resistant/ small grain crops	2	
			Grow short term varieties	1	
		Tillage and land preparation	Zero tillage	7	
			Winter/dry tillage	3	
			Ridging	3	
		Cropping area management	Increase area under maize crop	1	

			Increase the total cultivation area	1	
		Seed and seed preparation	Prepare enough seeds to plant on bigger area	1	
		No action	Do nothing	1	
Drought	1	Seed and seed preparation	Keep seeds for next season	1	1