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

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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. We 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% 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.

1. Introduction

Globally, there is increasing recognition of the potential value of Indigenous knowledge (IK) and local knowledge (LK) for climate change adaptation (IPCC, 2019, 2022b, 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 et al., 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 (Hansen

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et al., 2011; Africa Adaptation Initiative, 2018; 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; Turek-Hankins et al., 2021; Williams et al., 2021; Leal Filho et al., 2022b; Trisos et al., 2022). How individuals and societies anticipate and respond to climate change risk is important, as inappropriate responses can increase vulnerability and lead to maladaptation (Schipper, 2020), and thus, can be a potential driver of increased climate change risk (Simpson 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., 2021; Thomas et al., 2021; Leal Filho et al., 2022b). 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 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 (Ray et al., 2019; Sultan et al., 2019; Ortiz-Bobea et al., 2021), 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 (Rosenzweig et al., 2014; Moore et al., 2017; Franke et al., 2020). 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 (Pauline et al., 2017; Sonwa et al., 2017; Krell et al., 2021; Leal Filho et al., 2022b).

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 et al., 2013; Zuma-Netshiukhwi et al., 2013; Nkomwa et al., 2014; Grey, 2019; Mekonnen et al., 2021). 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 et al., 2020), Malawi (Joshua et al., 2017; Ngongondo et al., 2021; Bucherie et al., 2022; Streefkerk et al., 2022), Namibia (Schnegg, 2019), South Africa (Vilakazi et al., 2019; Ubisi et al., 2020; Kom et al., 2022; Rankoana, 2022), Zambia (Mbewe, 2019), and Zimbabwe (Jiri et al., 2015; Soropa et al., 2015; Gwenzi et al., 2016; Tanyanyiwa, 2018; Mafongoya et al., 2021). 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 et al., 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 and Bewket, 2017; Nyadzi 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 change do not necessarily translate into adaptation (Waldman et al., 2019; Simpson et al., 2021a).

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 et al., 2020; Zvobgo, 2023), it is important that smallholder farmers use climate and weather forecasts to improve decision-making for informed 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.

2. Methods

2.1. Study area

The study was conducted in Chiredzi district in the southeast lowveld region of Zimbabwe. The Chiredzi district is located in the semi-arid Natural Region V, which is the driest of Zimbabwe's Agro-Ecological Zones with highly variable rainfall patterns (Chikodzi and Mutowo, 2012; Mugandani et al., 2012) and is among the regions in Zimbabwe that are most vulnerable to climate variability and change (Unganai and Murwira, 2010). Smallholder farming is the main economic activity in many rural areas of Chiredzi. In the absence of reliable scientific weather forecast information, farmers in the region use indigenous methods to predict the seasonal quality (Jiri et al., 2015). There are three weather stations in the Chiredzi district (see Fig. 1), despite the area being 380 km^2.

2.2. Data collection

Five out of the total 32 wards in Chiredzi rural district (wards 1, 3, 25, 27, and 32) were strategically selected for data collection based on their accessibility, as well as the characteristics of farmer settlement and geography (Fig. 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 et al., 2003; Ndhlovu, 2018). We 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, we aimed for a minimum sample of 80 farmers, and our available resources enabled us to survey 100 farmers. A sample of 100 farmers from five communal and resettled wards was surveyed. We used

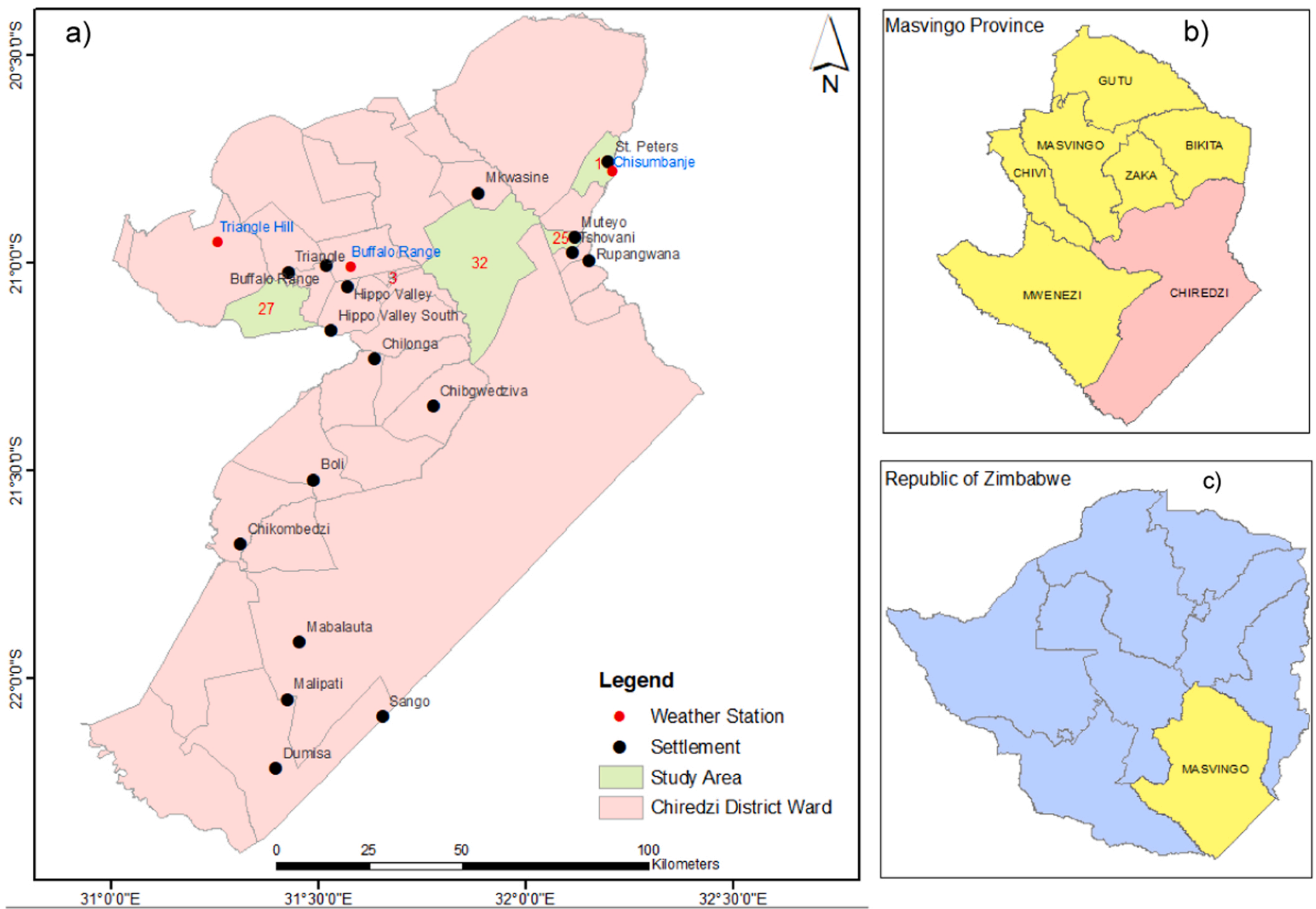

Fig. 1. Map showing the five wards in Chiredzi considered in this assessment and the weather stations in the district: a) Chiredzi district map, b) Masvingo provincial map showing the location of Chiredzi district in relation to other districts in the province, and c) is the map for Zimbabwe showing the location of Masvingo in relation to other provinces.

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 the 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 of Cape Town, approved by the Faculty of Science Research Ethics Committee (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 et al., 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) 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 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. We also collected 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. Using the farmers' responses, we analysed the

Table 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 hypothesised 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 and Ajadi, 2019).	+
x_2	Farmland size	Continuous	Farmers with larger farms are hypothesised 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 hypothesised 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., 2013). Therefore, they are hypothesised to be less likely to use IK and LK weather and climate forecasts.	-
x_5	Level of Education	Tertiary = 3 Secondary = 2 Primary = 1 No education = 0	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).	-
x_6	Gender	Male = 1 Female = 0	Male farmers are hypothesised to be more likely to understand the IK and LK systems and use them for weather and climate forecasting (Tunde and 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 the 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 and 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 hypothesised 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 hypothesised 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 hypothesised 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., 2013)	-
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 hypothesised to increase	+

(continued on next page)

Table 1 (*continued*)

	Variable	Variable code	Justification for the variable	Expected sign
			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 hypothesised 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. (2014), who used two different classes– resource-endowered farmers and poor farmers – to determine the impact of resources on adopting adaptation measures.

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.

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

We 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 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:

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

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.

$\beta_1, \beta_2, \beta_3, ...,$ and β_{13} are partial regression coefficients.

Table 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	

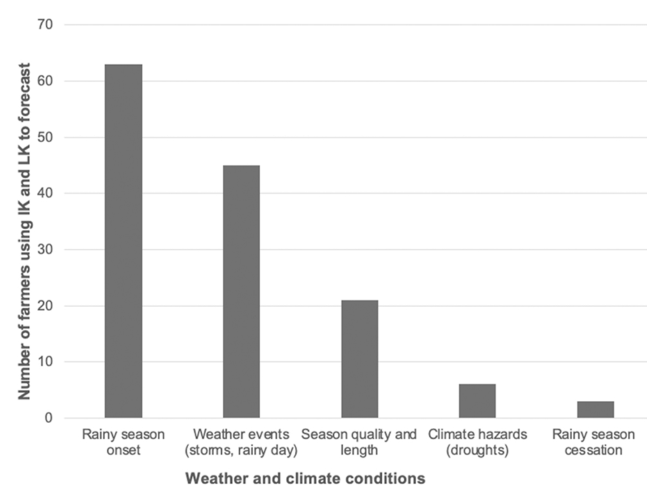

Fig. 2. Weather and climate conditions that are forecasts by smallholder farmers in Chiredzi using IK and LK (n = 73).

3. Results

3.1. Socio-demographic 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

Table 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 indicated 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 (storms, rainy day)	Clouds	Dark clouds indicate a rainy day or a very intense storm	25%	4.1
	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 forecasts 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.

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 2).

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.

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) (Fig. 2). 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) (Fig. 2).

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 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.

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 (Fig. 3a). 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 (Fig. 3a, 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 (Fig. 3b).

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). The use of IK and LK climate forecasts was significantly positively associated with increasing farmer age and farmland size (Table 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). 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.

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 (Fig. 4).

A total of 23 decisions responding to various IK and LK forecasts were made by smallholder farmers in the Chiredzi district (Fig. 5). Fifteen of these were climate decisions that contributed to the adaptation responses implemented by farmers in Chiredzi (Table 5). 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) (Fig. 5). 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 (Fig. 5). Fig. 5 also shows that rainy season onset forecasting is the most critical parameter forecasted by farmers, as many decisions are made compared to other parameters.

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 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 5). These measures have been implemented to cope with droughts, increased rainfall variability, and summer temperature risks.

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 (Fig. 6a). 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) (Fig. 6b).

4. Discussion

Most smallholder farmers in Chiredzi use IK and LK for weather and climate forecasting. Our 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 (Fig. 6b). 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. (2021) 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

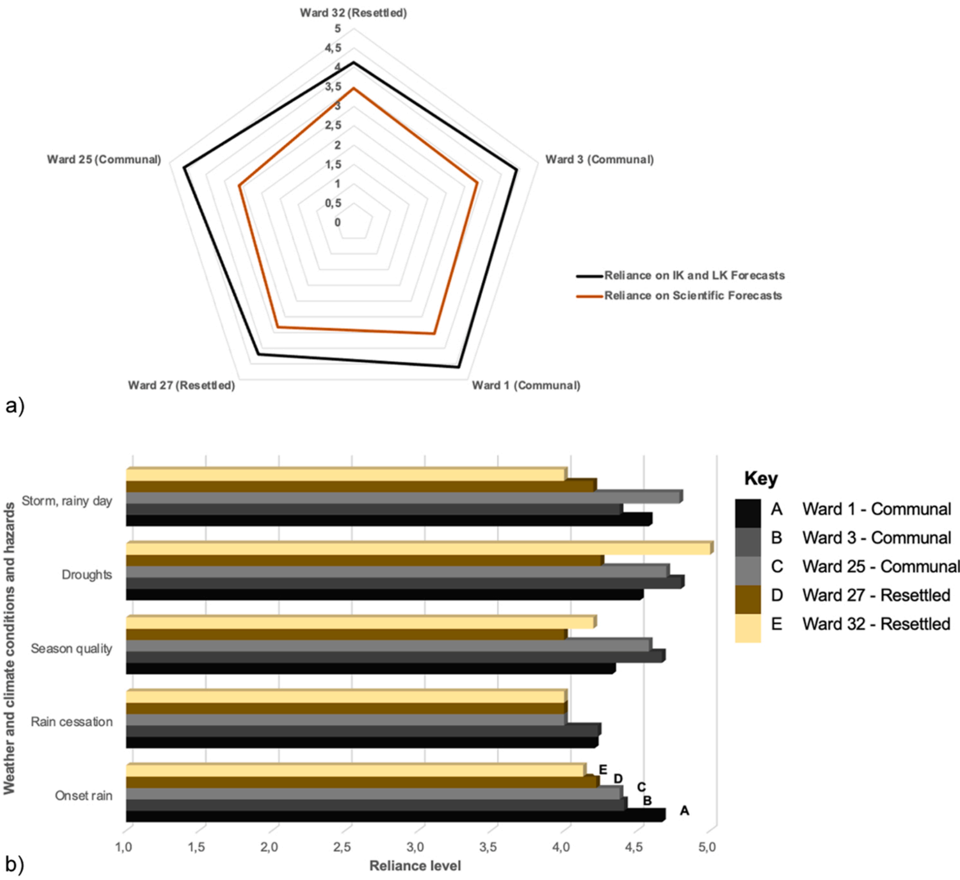

Fig. 3. Differences in farmers reliance on IK and LK and scientific forecasts in Chiredzi: (a) Reliance on IK and LK and scientific weather forecasts at the ward level by smallholder farmers in Chiredzi; (b) Reliance on IK and LK forecasts separated into five climate conditions and hazards by communal 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).

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

Variables	β	S.E.	Wald	OR	95% CI Lower	95% CI Upper	p - value
Age (years)							
30–39	0.649	0.891	0.531	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	0.055	0.871	0.274	2.769	0.814
Wealth Level (*Poor*)	-0.328	0.617	0.283	0.720	0.215	2.413	0.595
Access to Irrigation (*no access*)	0.713	0.795	0.804	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	0.352	0.371	0.014	9.785	0.553
Livelihood diversification (*not diversified*)	-0.594	0.755	0.618	0.552	0.126	2.427	0.432
Access to extension services (*no access*)	-0.030	0.664	0.002	0.971	0.264	3.568	0.964
Farmland Size	0.513	0.214	5.727	1.671	1.097	2.543	0.017*
LOS in an area	-0.009	0.024	0.152	0.991	0.946	1.038	0.697
Family Size	-0.026	0.103	0.066	0.974	0.796	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.

to climate risks (see Fig. 5). While understanding the use of IK and LK forecasts by smallholder farmers in Chiredzi, we 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 farmers aged 41–50 (see

Table 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. Our 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 and 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 et al. (2013), and our 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). 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, becaused 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 (Cameron, 2012; Álvaro et al., 2021). 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. Our 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).

4.1. Blending IK and LK and scientific forecasts

We 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 of both IK and LK and scientific forecasts.

To address the shortcomings of IK and LK forecasts and to improve the 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. We expect a coordinated approach that promotes blending of forecasts to increase the reliability and uptake

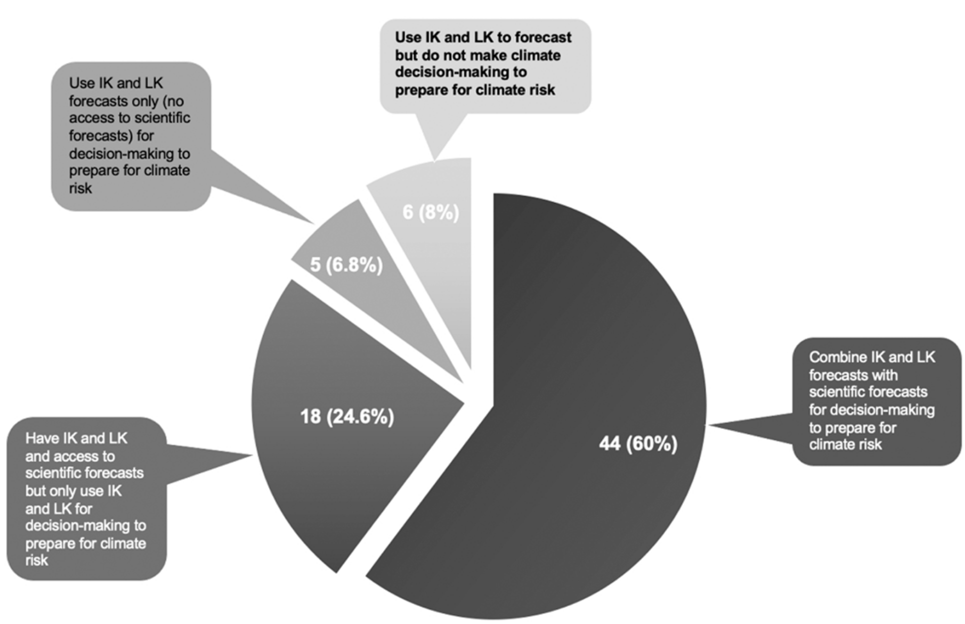

Fig. 4. How smallholder farmers are relying on IK and LK weather and climate forecasts for decision-making to prepare for the climate risk in Chiredzi district. (n = 73).

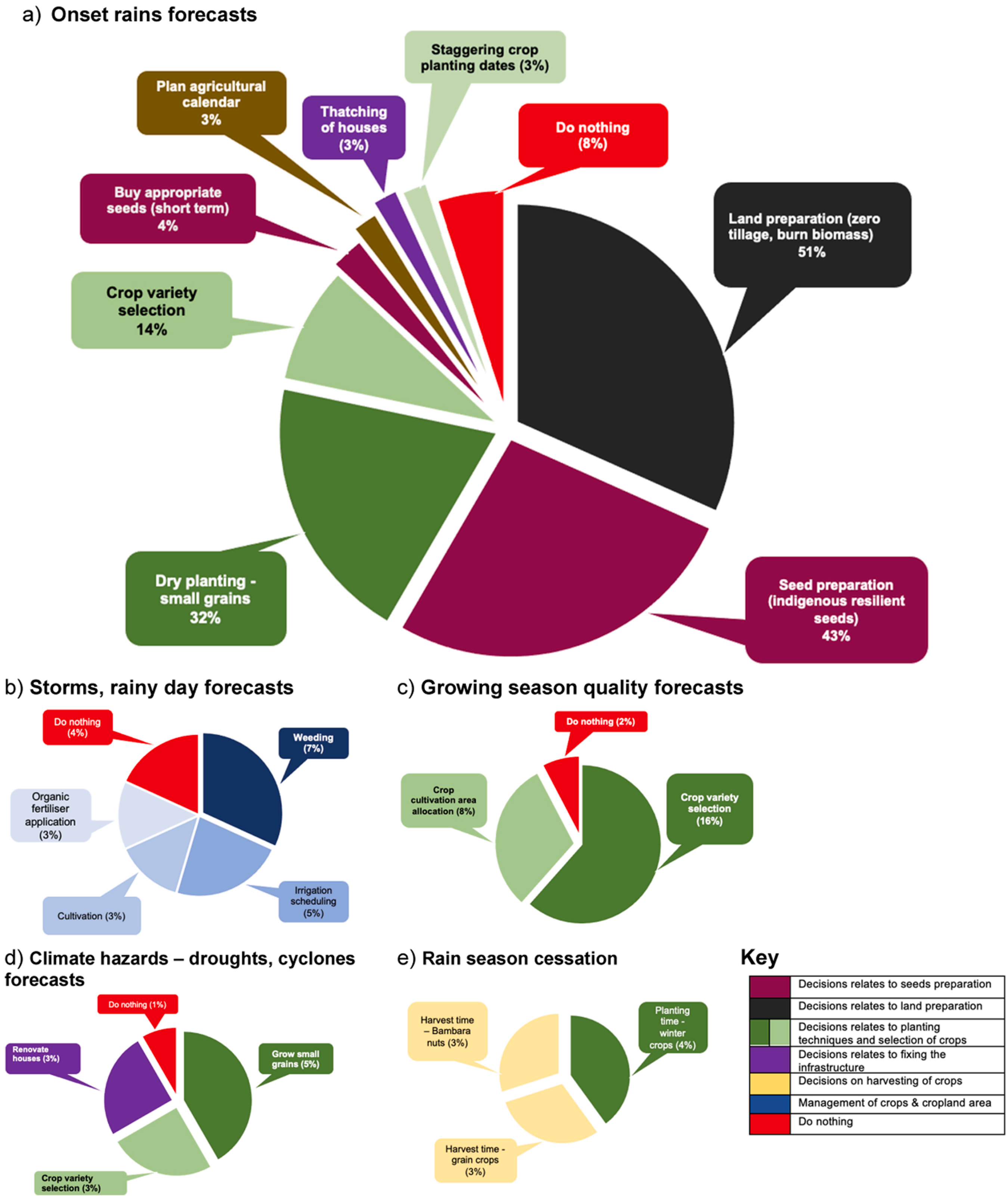

Fig. 5. Smallholder farmers decisions made from the various IK and LK forecasts to prepare for the anticipated weather and climate outcomes for climate risk preparedness in Chiredzi district: a) decisions from rainy season onset predictions, b) decisions associated with storms, rainy day forecasts, c) 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.

Table 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%

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 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 we 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 and 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 and Dieng, 2015). Issues such as language decryption of the forecasts are essential for converting the forecasts from probabilistic and complex jargon (Unganai et al., 2013; Bacci et al., 2020; Yegbemey and 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 farmers' long-term scientific forecasts.

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 et al., 2018), the Agricloud app in South Africa,[1] and the Weather4Farmers app in Bangladesh.[2] 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.[3] 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.

4.2. 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

[1] https://www.grainsa.co.za/get-this-weather-app-on-your-cell-phone.
[2] https://www.weatherimpact.com/wi-app/.
[3] https://www.hydronet.co.za/.

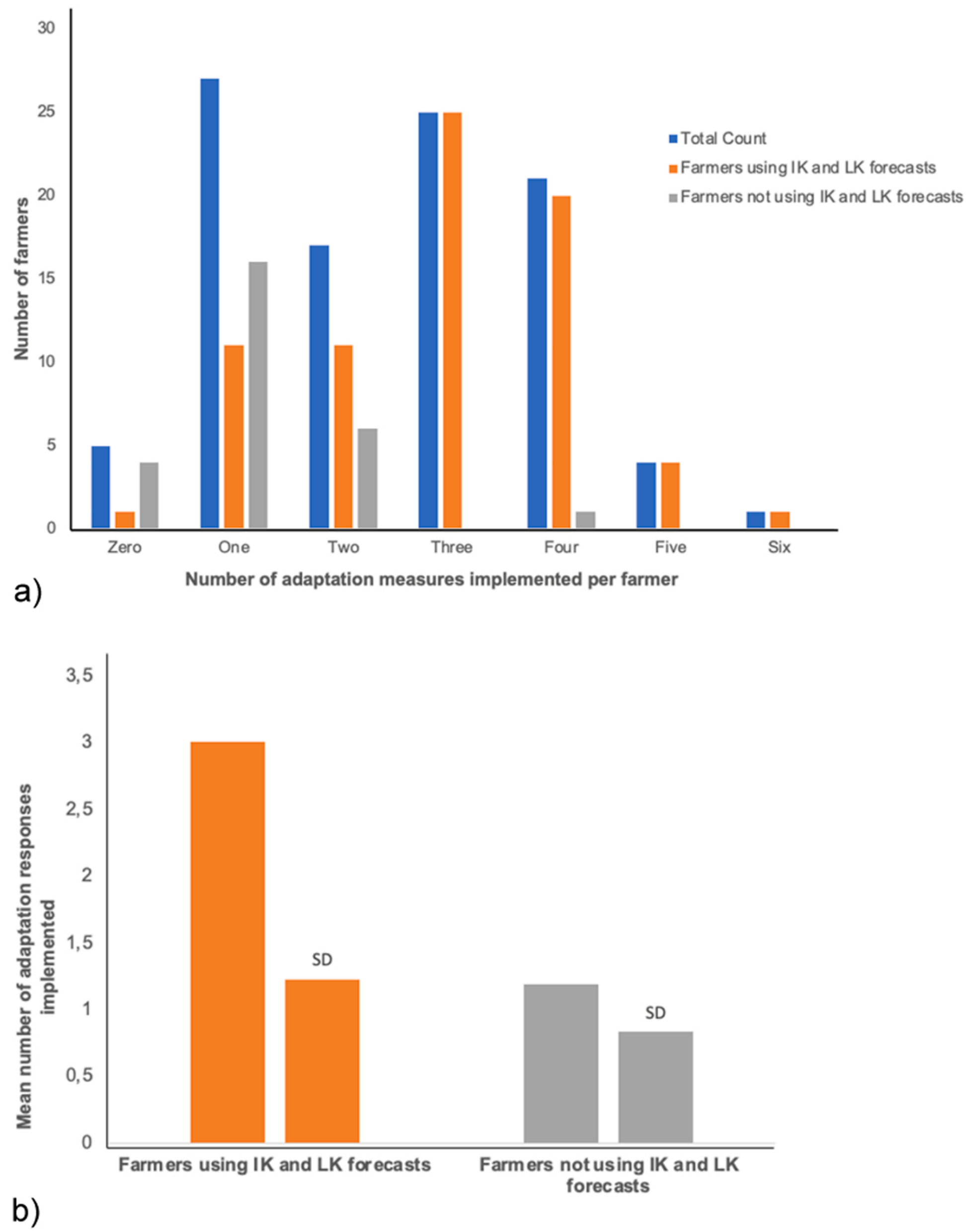

Fig. 6. Smallholder farmers in Chiredzi using IK and LK forecasts implemented more climate adaptation responses: (a) number of adaptation responses implemented per farmer by farmers using IK and LK climate forecasts and farmers not using IK and LK climate forecasts, b) mean number of adaptation responses for farmers using IK and LK climate forecasts and farmers not using IK and LK climate forecasts.

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), our 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 (Fig. 5) 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 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 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 (Fig. 3a). This agress with previous research in Zimbabwe and other parts of Africa (Fitchett and Ebhuoma, 2018; Tanyanyiwa, 2018; Grey, 2019; Streefkerk et al., 2022), 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 Fig. 2). These are the climatic conditions most commonly predicted by smallholder farmers (Gwenzi et al., 2016; Fitchett and Ebhuoma, 2018). 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 (see Table 3).

Changes in the availability of cuckoo birds, which are important for predicting the onset of the rainy season (see Table 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 (Speranza et al., 2010; Radeny et al., 2019; Ankrah et al., 2022; Leal Filho et al., 2022a). 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 et al. (2021b) on compound risk from climate change.

4.3. Role of IK and LK in 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 (Fig. 6a). Our 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., 2022a; 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 (see Table 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 (Egeru, 2012; Codjoe et al., 2014; Kamwendo and Kamwendo, 2014; Okoye and Oni, 2017).

4.4. Policy implications of the study findings

Our 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, our 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, our 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 finalised in 2019 (Government of Zimbabwe, 2019), our 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, 2019, 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.

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. We 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 our case 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.

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CRediT authorship contribution statement

Luckson Zvobgo: Conception and design of study, acquisition of data, analysis and/or interpretation of data, Drafting the manuscript, Approval of the version of the manuscript to be published. **Peter Johnston:** revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **Oladapo M. Olagbegi:** analysis and/or interpretation of data, Approval of the version of the manuscript to be published. **Nicholas P. Simpson:** revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **Christopher H. Trisos:** revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published.

Declaration of Competing Interest

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

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2023.03.017.

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