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Perceived links between climate change and weather forecast accuracy: new barriers to tools for agricultural decision-making

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Abstract
The accuracy of weather forecasts has experienced remarkable improvements over the recent decades and is now considered important tools for developing the climate resilience of smallholder farmers, particularly as climate change upends traditional farming calendars. However, the effect of observations of climate change on the use of weather forecasts has not been studied. In an analysis of smallholder farming in Zambia, Kenya, and Jamaica, we document low weather forecast use, showing that perceptions of changes in the climate relate to views on forecast accuracy. Drawing on detailed data from Zambia, we show that weather forecast use (or not) is associated with perceptions of the accuracy (or inaccuracy) of the forecast, with rates of weather forecast use far lower among those who believe climate change impacts forecast accuracy. The results suggest a novel feedback whereby climate change erodes confidence in weather forecasts. Thus, in a changing climate where improvements in weather forecasts have been made, farmers thus experience a double disadvantage whereby climate change disrupts confidence in traditional ways of knowing the weather and lowers trust in supplementary technical forecasting tools.

Keywords Weather forecast · Smallholder agriculture · Climate change perceptions · Climate resilience · Climate-smart agriculture

1 Introduction

Meeting the Sustainable Development Goals (SDG) within the agriculture sector is a pressing global challenge (Garnett et al. 2013; UN 2016). Agriculture occupies about 40% of global land and is cultivated on more than 570 million farms worldwide, the vast majority of which are on small plots and are operated by farmers with limited resources (Lowder et al. 2016).

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Increases in population and food demand, along with climate change, threaten to undermine agricultural production and, in turn, livelihood security (Challinor et al. 2014; Suh et al. 2020). In many of the regions where agriculture is dominant, those with rural livelihoods routinely suffer from chronic food insecurity.

In recent decades, substantial improvements to crop yields have occurred in regions like Asia, but differences between potential and actual yields remain high in many regions (Suh et al. 2020). The yield gap has been attributed to a lack of capital, technology, and knowledge and information (Suh et al. 2020). Some information of potential agricultural benefit comes in the form of weather services, which provide historical information, real-time monitoring, and forecasts, including early warnings of extreme events. These services increase farm production in several ways. Directly, they can inform production decisions on the timing of planting, input use, and labor allocations (Stone et al. 2006; Hansen et al. 2011; Nissan et al. 2019). Indirectly, early warning forecasts allow farmers to prepare their fields to limit crop losses and limit damage to their productive assets. These applications can lead to livelihood stability and reduce year-to-year variability in sources of income and expenditures. For decades, weather services have been considered important tools to improve sustainable agriculture (Rijks 1992), and they are now considered fundamental to progress in the SDGs (GFDRR 2012; Thorpe and Rogers 2018).

In the past 40 years, science has made huge strides in predicting weather (Benjamin et al. 2018; Zhang et al. 2019). Five-day forecasts today are as accurate as 2-day forecasts were 25 years ago (Bauer et al. 2015), and skillful forecasts can be extended as far out as 10 days (Zhang et al. 2019). The annual economic value generated by weather forecasts for the USA alone is around US$31 billion (Lazo et al. 2009). Weather forecasts take on a greater importance in rain-fed systems, which account for approximately 80% of land cultivated worldwide and 96% of African agriculture (Rosegrant et al. 2009).

At the same time that great progress has been made in the ability to forecast the weather, there has been heightened awareness of changes in the climate. It is well-documented that farmers have observed disruptive changes in their local climates, and there is evidence that climate changes have eroded confidence in traditional decision-making cues (Roncoli et al. 2001; Ingram et al. 2002; Kalanda-Joshua et al. 2011; Funk et al. 2019). If climate change undermines confidence in traditional ways of knowing the climate, weather forecasts could provide alternative ways to manage climate risk.

Surprisingly, research on the use of forecasts in agricultural decision-making has focused more on climate timescales (i.e., months to decades) than on weather timescales (i.e., hours to days). In Africa, for example, there are more than six times as many published peer-reviewed articles since the 1980s on the use of seasonal forecasts for agricultural purposes than on the use of weather forecasts (Figure 1).

In this research, we are motivated by the lack of focus on weather forecasts given their purported societal benefits. We focus on smallholder farming systems in the countries of Zambia, Kenya, and Jamaica to address three questions. First, we ask: what is the extent to which smallholder farmers use weather forecasts? Our finding of low usage across these diverse contexts motivates our second research question: what are the reasons for their limited use? In interpreting the results of this question, we are cognizant of several important socio-behavioral observations, namely, that farmers' perceptions are predictors of their behaviors (Lazo et al. 2009) and that numerous studies have documented that individuals associate extreme weather events with climate change (Capstick and Pidgeon 2014; Roxburgh et al. 2019), conflate weather and climate, and confuse seasonal and weather forecasts (Letson et al. 2001; Moser 2010). We therefore ask a third question: do observations of climate changes

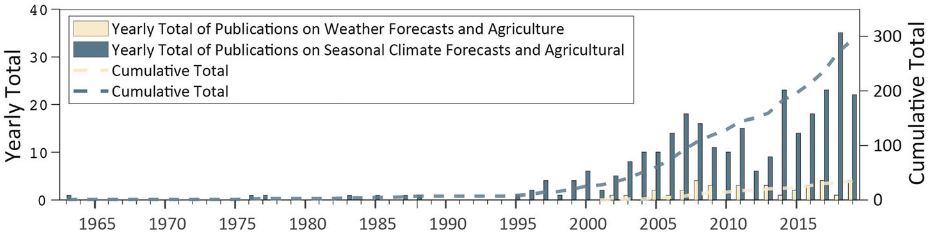

Fig. 1 Time series of the annual number and cumulative total number of published peer-reviewed articles focused on agricultural applications of weather forecasts and seasonal climate forecasts. We conducted a Scopus database search using the following criteria. For weather forecasts, we searched on "weather forecast*" OR "short-range weather forecast*" AND Africa AND agricult* OR farm*. For SCF, we used "seasonal climate forecast*" OR "seasonal forecast" OR "seasonal climate outlook" OR "climate outlook" OR "seasonal outlook" OR "long-term weather forecast*" AND Africa AND agricult* OR farm*. We confined the search to titles, keywords, and abstracts written in English. The original search yielded 89 articles related to the weather forecast criteria. We then read each abstract, and sometimes the article, to determine if the article focused on agricultural applications of weather forecasts. This resulted in 36 studies. 2019 covers the calendar year through September 19, 2019

influence weather forecast use? For this final question, we draw on a large sample of Zambian smallholder farmers to show robust, significant relationships between Zambian farmers' use of weather forecasts, their views on weather forecast accuracy, and measures of their perceptions of a changing climate.

The results provide evidence that farmers associate the meaning of climate and weather in ways that appear to undermine their use of weather forecasts despite improvements in the technical accuracy, or skill, of weather forecasts. The results thus lead to the central proposition of our analysis: that experiences of a changing climate reduce the use of weather forecasts by altering farmers' perceptions of the forecasts' accuracy. Links between weather and climate thus suggest a novel feedback, whereby climate change creates uncertainty about the future, which erodes confidence in weather forecasts. Farmers may therefore be experiencing a double disadvantage: climate change both disrupts confidence in traditional ways of knowing the weather and lowers trust in tools that can supplement traditional approaches. This feedback has implications for the development and benefits of climate-smart agriculture and resilience programs.

In pursuing these questions, we make a distinction between weather and climate that is core to the climate science and meteorological communities. Each concept brings different, although related, knowledge bases, sensitivities to environmental processes, methods of analysis, and science outputs. Perhaps the most evident difference relates to the methods of future projection. Bothe (2019) writes that climate begins when "the sum of our experiences and the resulting expectation of the typical weather describe the system more reliably than a deterministic forecast starting from our experience of the current state of the system." To quantify these timeframes, weather forecasts generally pertain to minutes to days, whereas climate projections relate to seasonal to century temporal scales. Given our results, we argue for a more careful separation of these ideas in the development of climate resilience.

2 Background: perceptions of climate change and the use of forecasts

Research on climate change perceptions and climate risk management provides insights into the motivations and conditions that constrain the use of weather forecasts in agricultural decision-making. In the USA, where climate change has been used as a political wedge issue, stronger climate change beliefs among farmers are associated with more adaptive and mitigative action (Arbuckle et al. 2013). This is in contrast to developing countries, where there is a widespread perception that the climate is changing and that weather variability is increasing (Waldman et al. 2020). In many developing countries, climate change is generally perceived to be a significant threat to local livelihoods, and this perceived threat is generally greater than in more developed countries (Lee et al. 2015). Despite these perceptions, however, environmental concerns like climate change often are not the main motivators for what we often think of as climate adaptive behaviors; instead, salient motivators relate more to immediate concerns like income needs and food insecurity (Waldman et al. 2019a). Even though climate change influences these issues, the cause and effect are obscured by complicated processes that relate to how individuals perceive the environment and process information.

Perceptions about climate change can affect an individual's behavior. For example, Jain et al. (2015) found that cognitive factors like perceptions of changing trends in rainy season onset and aversion to risk were important predictors of adaptation behavior. Singh et al. (2020) further stated that farmers manage climate risk by seeking new information and adopting new technologies and practices, finding that a willingness to use climate forecasts was positively associated with farmers who had recently observed more variable or unusual weather on their farms. A lot of research has also gone into characterizing the numerous drivers of climate change perceptions. They have been related to personal experiences (Mase et al. 2017); individual risk assessment (Menapace et al. 2013); and political ideology, age, gender, and nationality and the role of different processing modes in climate change perception (Weber 2016). In addition to perceptions about climate change, climate risk mitigating behaviors are also influenced by institutional, individual, and inter-personal endowments. This aligns with some frameworks of agricultural decision-making (e.g., Jain et al. 2015) that categorize the determinants of decision-making as related to cognitive processes, as well as biophysical, social, and economic conditions. Social network relationships (Gareau et al. 2020), access to productive assets like seed varieties (Waldman et al. 2017), extension activities (Dayamba et al. 2018), and institutional support programs (Eakin 2005) have all been identified as either constraints or enablers in farm management. Across heterogenous populations, therefore, the variety of influences lead to diverse responses, albeit in a manner that has generally combined to limit climate risk mitigating behaviors (Wise et al. 2014).

The weather and climate risk management scholarship, particularly as it pertains to agricultural decision-making, recognizes that famers have complex decision-making algorithms. Nonetheless, a common view is that technical information can reduce uncertainty about environmental conditions as well as help inform action to respond to environmental change (Singh et al. 2020). Within this frame, perceptions of the information's reliability and accuracy are particularly important for information use (Mase and Prokopy 2014).

Roncoli (2006) reviewed ethnographic and participatory research on farmers' perceptions of weather and climate forecasts across varied socioeconomic contexts, finding evidenced for both declines in the perceived reliability of traditional forecasts in some locations as well as contrary evidence in others. More recently, Metcalfe et al. (2020) researched farming and fishing communities in Mexico, reporting that changes in climate had affected the acceptance and use of traditional weather cues and cultural practices. At the same time, the use of technical forecasts has been offered as a supplement to traditional forms of environmental decision-making (Roncoli et al. 2002; World Bank 2015; UNESCO 2019).

The accuracy of technical forecasts is often assessed statistically by comparing a forecast to the true atmospheric state as well as a reference forecast such as a climatological average (the level of accuracy is referred to as “skill”). An individual’s perception of the weather, however, does not always align with observations (e.g., Waldman et al. 2019b), and therefore, a technical assessment of accuracy is less instructive for an understanding of farmer decision-making than the perception of its accuracy: better technical accuracy does not necessarily mean better forecast use (Dilling and Lemos 2011). Although surprisingly little research has been conducted on the associations of weather forecast accuracy and use among smallholder farming, several studies are instructive. Burgeno and Joslyn (2020) stated that weather forecast inaccuracy reduces trust, and Tall et al. (2018) reported that African farmers who perceive the seasonal forecasts to have high levels of accuracy also had high levels of trust in them. In a review article of agricultural decision-making in the USA, Australia, and Canada, Mase and Prokopy (2014) reported that the most commonly cited barrier to using seasonal forecasts was perceptions of the low accuracy of the forecasts.

The literature demonstrates that numerous determinants for agricultural decision-making, including forecast use, are influenced by individual perceptions and endowments. However, what is known about forecast use among smallholders is largely drawn from studies on seasonal climate forecasts (SCF), with a far more limited focus on weather forecasts (Figure 1), and the limited studies on weather forecast use are matched by an equally limited view on how perceptions of climate change affect the use of weather forecasts. We therefore position our analysis within these discussions, hypothesizing that perceptions about climate change are associated with perceptions of weather forecast accuracy and their use.

3 Methods

3.1 Study locations

Our study focuses on smallholder farming systems in Zambia, Kenya, and Jamaica. The three countries were part of separate projects studying the application of weather and climate information among smallholder farmers. The lead author led the survey development in each country. Each survey provided insights that expanded the subsequent questionnaire, with the order progressing from Kenya, to Jamaica, to Zambia. The questions that were common to two or more countries remained largely the same, with small changes to account for local language nuances.

In each country, weather forecasts are at least available for 1- and 3-day periods and disseminated by the National Meteorological Services. They are also disseminated and available from third parties, like the World Meteorological Organization (WMO), regional climate centers, and a variety of private and third-party weather applications. In our surveys, we defined forecast *use* as explicitly linked to an action. For farmers who stated they used the weather forecast, we inquired how (see Suppl. Table S3 for response options).

Because insights into the uses of weather forecasts from the Kenya and Jamaica surveys led to the addition of new questions to the Zambia survey, Zambia had the most comprehensive results, which allowed us to investigate whether observations of climate changes influence weather forecast use. We therefore devote more discussion to the Zambia results. Nevertheless, we include all three countries in this analysis because the substantive content overlap allows us to investigate dynamics across different geographic locations, spanning contexts with different primary crops (e.g., maize and coffee), market orientations (e.g., export and local), and climate.

The total number of completed surveys in Zambia, Kenya, and Jamaica were 1084, 601, and 294, respectively. In the Supplemental material, we describe the smallholder agriculture and climate contexts and provide summary statistics of the farmers we surveyed in each country. We further provide in the Supplemental material the survey questions and response options asked in each country.

3.2 Survey sampling design, data collection, and methods of analysis

In Kenya, we conducted a survey of 601 farming households between June and July 2018 in agricultural communities on the northwest side of Mount Kenya. Farmers were selected in order to continue a longitudinal dataset that began in 2016 to investigate agriculture and water management. A multilingual team of six women and two men conducted the survey in Kiswahili, Kikuyu, or Kimeru, depending on the respondent's preferred language. The survey questionnaire was designed from a sustainable livelihoods approach that recorded demographic information, agricultural farming practices, and information about weather and climate information use, among other topics. Each household interview lasted 1–1.5 h. A more complete description of the sampling method is described in Guido et al. (2020b).

A household survey of Jamaican coffee growers was conducted by phone survey between September 2018 and February 2019 during a 5-year project. Farmer recruitment for this survey was inherited from an initial household survey administered in 2016 that targeted farmers living in the 20 primary coffee farming communities in the Blue Mountains, the main coffee-growing region in Jamaica (Guido et al. 2020a). In each community, a random sampling protocol targeted 15% of the households. Graduate students from the University of West Indies conducted 434 household surveys in person, with a response rate of 84%. The 2018–2019 survey, which this analysis draws on, surveyed those farmers in original dataset who were available by phone in addition to a random sampling of participants from workshops in nine of the 20 communities. The workshops had been convened to discuss coffee management and climate risks. Local leaders and coffee extension agents with whom the project had built relationships helped recruit the workshop participants. These workshops are described in further detail in Guido et al. (2019b). The workshops were convened at least 8 months prior to the 2019 phone survey, and the participants we contacted had volunteered their phone numbers to be contacted at a future date. The final sample size of 294 households was smaller than the original dataset of 434 due to attrition from disconnected phone numbers, unanswered calls, or an inability to participate in the phone survey.

In Zambia, we conducted a household survey during June and July 2019, following the maize harvest. The farmers surveyed were part of a longitudinal study that began in 2016, which sought geographic representation and to speak with the head of the household (Waldman et al. 2019b). The original survey, and therefore our 2019 survey, occurred in three distinct precipitation zones mapped by Waldman et al. (2019b) and in all provinces except the Western province and the Luapula province on the country's northern border (Figure 2). Farmers were originally selected with help from the project's partnership with the Zambia Agricultural Research Institute (ZARI), who contacted agricultural extension officers to facilitate access to individual farmers. The 2019 survey interviewed in person as many of the same households as possible. The ZARI organized the Zambian enumerators, and surveys were conducted in the preferred language of the interviewee. We surveyed 55 clusters representing different towns and villages. Surveys included sections on demographics, socio-economic conditions, and—pertaining to the 2018–2019 agricultural season—farming practices, perceptions of weather and climate, and forecast uses. We surveyed 1121 households in 2019 but excluded 37 households from analysis (18 as a result of various quality control issues and 19 because the cultivated area in 2018–2019 was greater than 10 hectares), resulting in a total of 1084. Table 1 presents the summary statistics for the weather and climate questions analyzed for this analysis.

We analyze our three research questions using a combination of statistical techniques. Descriptive statistics answer our first research question of whether farmers use weather forecasts. To address our second and third research questions (what are the reasons for the limited use of weather forecasts, and do observations of climate changes influence their use?), we also use independent means tests and chi square tests. For these statistical tests, we report values of significance at the 0.05, 0.01, and 0.001 levels.

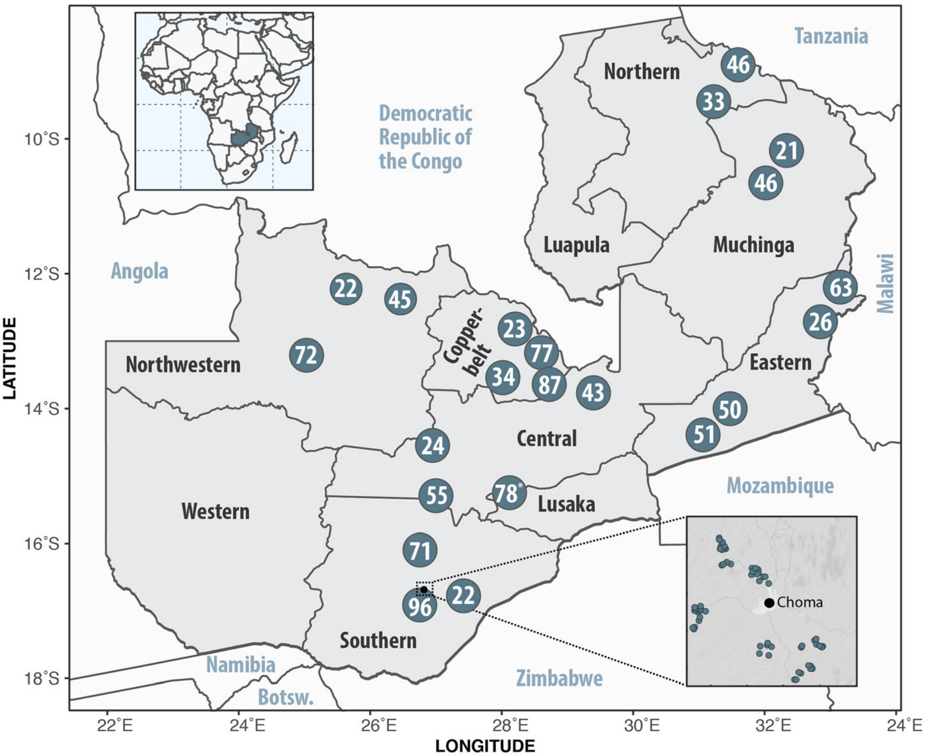

Fig. 2 Location map of the general clustered locations of the household's surveyed in Zambia during the summer of 2019. Numbers inside the circles denote the total number of surveys in the area. Seventy-eight surveys, or ~7% of the sample, did not have valid GPS coordinates. They were assigned to the Zambia capital city Lusaka in the Lusaka province (denoted as 78* on map); no surveys were conducted in Lusaka. The Choma inset displays a representative survey around the urban area of Choma where 60 surveys were completed. For question 4*, the response options were different slightly for each country; we include the response options for Zambia, which is also the most comprehensive set

Table 1 Zambian farmer responses to household survey questions concerning weather forecast use

Question	Response options	#	%	*N*
1. Use of weather forecasts[1]	Used	284	26.2	1084
	Did not use	768	70.9	
	Can't recall	32	3.0	
2. Awareness of weather forecasts[1,a]	Aware	575	71.9	800
	Not aware	192	24.0	
	Unsure	33	4.1	
3. Reasons for not using weather forecasts[2,a]	Prefer own observations	511	66.8	765
	No one can predict weather	121	15.8	
	Information not accessible	145	19.0	
	Other reasons*	278	36.3	
4. Perceived accuracy of the weather forecasts[1]	Always	141	13.0	1084
	Mostly	280	25.8	
	Sometimes	251	23.2	
	Not very	184	13.7	
	Unsure	264	24.4	
5. Importance of weather forecasts now compared to past[1]	More important	561	51.8	1084
	Less important	170	15.7	
	About same	124	11.4	
	Don't know	229	21.1	
6. Reasons for change in importance of weather forecasts[2,b]	Perceived lower accuracy	71	9.8	724
	Perceived higher accuracy	156	21.6	
	Weather is more predictable	205	28.3	
	Weather is less predictable	352	48.6	
	Weather is more variable	148	20.4	
7. Climate change affects weather forecast accuracy[1]	Yes	400	42.7	936
	No	234	25.0	
	Unsure	302	32.3	
8. Changes observed in the weather and climate during approximately the last 10 years[2]	Decreasing rainfall	789	83.1	950
	More frequent and/or severe drought	428	45.1	
	Warmer temperatures	378	39.8	
	Changes in growing season length	215	22.6	
	Cooler temperatures	116	12.2	
	More intense rainfall	103	10.8	
	Increasing rainfall	51	5.4	
	No changes	37	3.9	

[1] and [2] refer to a single choice response and the ability to choose multiple responses, respectively. On single choice responses, rounding can cause the cumulative total to be greater than 100%.

[a] Question given only to those who responded to question 1 with "did not use" or "can't recall" using weather forecasts; this accounts for the lower N.

[b] Question analyzed for only those reporting a change in the importance of weather forecasts from question 5; this accounts for the lower N.

* Seven response options account for this percentage, with the highest value for any one option being 12%.

3.3 Data collection limitations

Several aspects of our survey approaches influence the interpretation of our results. First, each survey was part of a longitudinal study, causing the research design to be inherited from the origin of the study. The approach in Kenya, for example, was originally designed to characterize agriculture and community water management in a relatively small region, whereas in the Blue Mountains of Jamaica, the goal was to represent the entire population of coffee farmers. This introduced differences among the three samples relating to geographic representation and the ability to generalize. Second, we relied on local partners such as extension agents to help recruit participants, at least in part. This likely introduced bias for which we did not explicitly account. Finally, we asked a slightly different set of questions in each country, which prevents us from extending the more complete analysis for Zambia to the other two countries. Notwithstanding these shortcomings, we believe the results provide important new insights about the smallholder groups in three distinct agricultural contexts.

4 Results

4.1 Smallholder farmers' views and use of weather forecasts in Zambia, Jamaica, and Kenya

There were differences in the use of weather forecasts across the countries (Figure 3). The lowest rates of weather forecast use were in Zambia and Jamaica at 29%, compared with use rates of 56% in Kenya. The Jamaican results may also be biased in favor of using the weather forecasts as a consequence of about a third of those surveyed being participants in group discussions about weather and climate approximately 8 months prior to the survey (Guido et al. 2019). In Zambia, around two-thirds of the farmers who did not use weather forecasts said it was because they "prefer own observations" (Table 1).

We further explored farmers' views of weather. The vast majority of farmers surveyed in all three countries (between 70 and 80%) report that weather is becoming more difficult to predict (Figure 3). Moreover, nearly all of the farmers (between 88 and 98%) stated that they have observed climate changes during their principal growing season (Figure 3). These perceived climate changes appear to affect farmers' perceptions of weather forecasts. In each country,

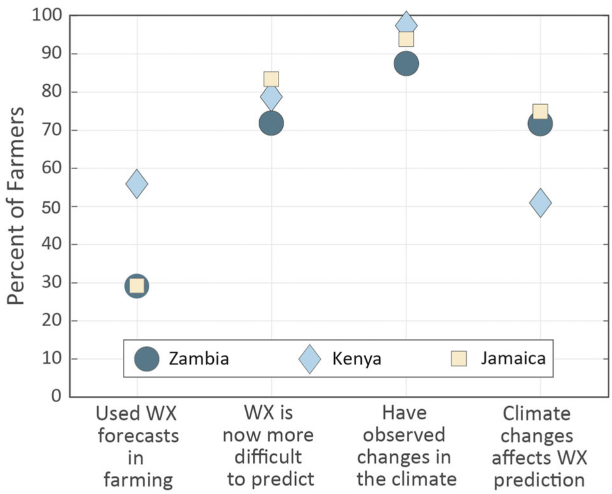

Fig. 3 Perceptions about climate and weather among smallholders in Zambia, Kenya, and Jamaica. Data collected in Jamaica and Kenya occurred in 2018–2019 and 2018, respectively. Sample sizes for the four questions for Zambia were either 1083 or 1084; for Kenya, they were between 436 and 601; and for Jamaica, they were between 227 and 293. "WX" refers to "weather."

between half and three-quarters of farmers stated that changes to the climate change have affected weather forecasts (Figure 3). As we explore in the next section using data from our more in-depth Zambian survey, the most commonly held belief among farmers was that climatic effects on weather forecasts came in the form of reduced forecast accuracy.

4.2 Links between forecast accuracy and use in Zambia

As previously described, only 29% of the Zambian farmers used weather forecasts during the 2018–2019 agricultural season (Table 1, Figure 3). Of those who did, they mainly used them to inform the timing of planting and the type and varieties of crops to sow (Suppl. Figure S1). On the other hand, among those 71% of farmers who did not use weather forecasts, their lack of usage cannot typically be attributed to a lack of awareness: approximately 72% of the 768 who did not use weather forecasts were aware that the forecasts existed. The low rates of forecast usage also did not result from the belief that it was impossible to predict the weather. This belief was held by only 16% of the non-using farmers (Table 1).

With regard to perceptions of the weather forecasts' accuracy, Zambian farmers had differing views: 39% perceived the forecasts to be mostly or always accurate, compared with 23% and 14% who perceived them to be sometimes accurate or not very accurate, respectively (Table 1). An additional quarter of the farmers indicated they could not comment on forecasts' accuracy. When grouped into two categories—those who perceived forecasts to be mostly or always accurate and those who viewed them otherwise, farmers who used the forecasts tended to perceive them to be more accurate than the farmers who did not use them ($P < .001$; Suppl. Table S4).

We explored the relationship between forecast use and perceived accuracy across a series of questions, noting two primary findings. Although weather forecasts have become more important over the past decade to a majority of farmers (52%), a sizable percentage (16%) expressed the opposite. Farmers' explanations as to why are presented in Figure 4 (more detailed statistics presented in Suppl. Table S5). Generally, farmers were likelier to attribute changes in the importance of weather forecasts to changes in weather predictability than to changes in forecasts' accuracy. However, perceptions of the direction of the changes in weather predictability and forecast accuracy varied meaningfully across groups of farmers who did and did not use weather forecasts in their agricultural decision-making. For example, those who thought that weather had become more predictable were more likely to use weather forecasts, whereas those who thought the weather had become less predictable and more variable were less likely to use forecasts. Additionally, belief in weather forecasts' improved accuracy over time was associated with higher rates of their use, consistent with the finding above that three-quarters of the farmers who used the forecasts perceived them to be either mostly or always accurate. In contrast, belief in weather forecasts' declining accuracy over time was associated with low rates of their use. These results had highly significant differences ($P < .001$) in the percent of farmers who used and did not use the forecasts for each of the accuracy-, predictability-, and variability-related drivers (Figure 4).

4.3 Links between climate change and weather forecast use

Climate change appears to have influenced Zambian farmers' perceptions of forecast accuracy and weather predictability. Nearly all Zambian farmers we surveyed reported observing

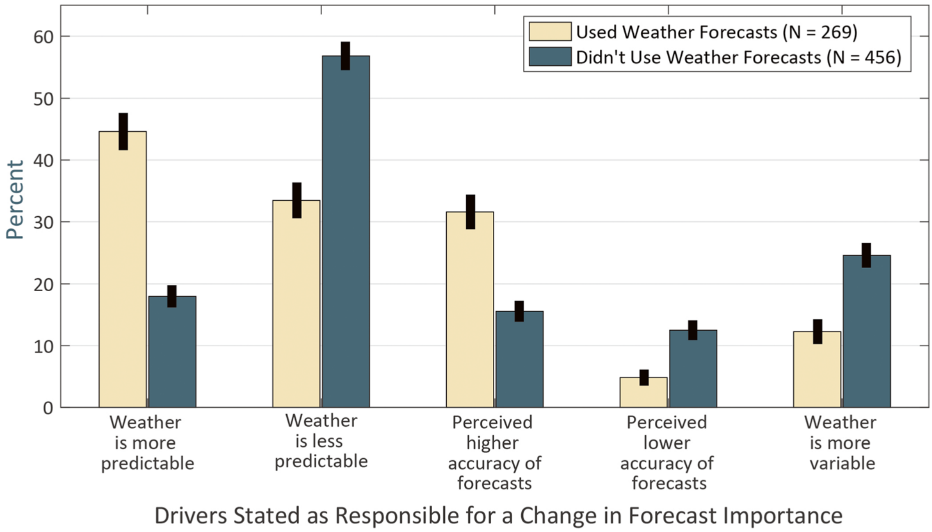

Fig. 4 Among those farmers who believed that the importance of weather forecasts had changed over time, the percent who identified a given driver as being responsible for that change; results are disaggregated by use or non-use of weather forecasts at the time of the survey. For each driver, an independent means T test showed significant differences at the $P < 0.001$ level between respondents who did and did not use weather forecasts. Vertical lines represent the standard errors of the means. The percent within each use category (denoted by color) sum to more than 100% because farmers could select multiple responses (see Suppl. Table 3).

weather and climate changes (Table 1); only 3.9% of the farmers reported not observing at least one element of climate change. The vast majority stated that they observed declines in rainfall, and a plurality stated that they observed increases in droughts and temperatures. Additionally, most farmers perceive that predicting the weather has become more difficult. About 70% of the farmers believe that predicting both the onset of rain and in-season rain—two critical aspects of the growing season that affect production decisions—is more challenging now than in the past. The farmer observations of climate dynamics strongly relate to their perceptions of the accuracy of weather forecasts. A plurality of the farmers, 43%, believe that these changes have affected weather forecast accuracy, while another 32% were unsure. Only 25% stated that climate changes did not affect the accuracy of weather forecasts (Table 1).

The explicit connection between farmers' observations of a changing climate and their perceptions of the weather forecasts' accuracy is further reflected in their use of weather forecasts. Among the full sample of Zambian respondents, Figure 5 demonstrates that the use of weather forecasts is associated with views on climate change's effect on forecast accuracy. Rates of weather forecast use are far lower among those who believe that climate change impacts forecast accuracy than among those who do not share this belief. More than half of those who used weather forecasts believed climate change did not affect forecast accuracy, compared to only a quarter who believed climate change did affect the accuracy.

We assessed the robustness of this result in two ways. First, we included in the analysis only those farmers who believed weather forecasts were "always" or "mostly" accurate. Second, we omitted from the analysis the group of farmers who believed weather forecasts were always accurate. In both cases, the rates of weather forecast use remain significantly

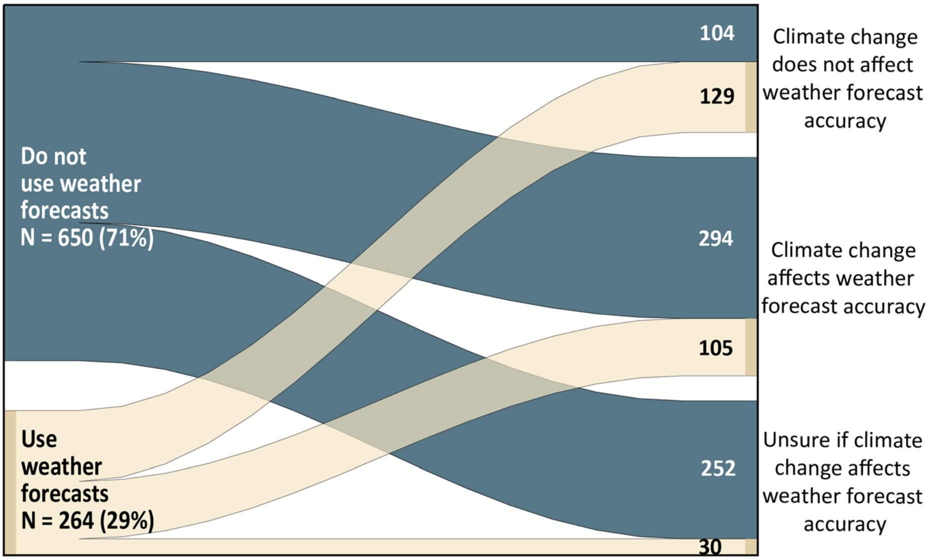

Fig. 5 The relationships between the perception of the influence of climate change on weather forecast accuracy and the use of the forecasts. The sample sizes for each weather forecast use *groups* (left side) and the *categories* of their perceptions of the effect of climate change on forecast accuracy (right side) are noted. Perceptions that climate change affects weather forecast accuracy are statistically significantly associated with use (or non-use) of the forecast (Chi square; $P < 0.001$)

lower for those who believe climate change influences the accuracy of weather forecasts as compared to those who do not ($P < 0.01$; not shown in Figure 5). Together, these results suggest that perceptions of climate change are strongly associated with forecast use.

5 Discussion

5.1 Weather forecasts and climate change

Large fractions of smallholder farmers across Kenya, Jamaica, and Zambia do not use weather forecasts, and comparably large proportions believe that climate change affects weather prediction. Among Zambian farmers, rates of weather forecast use are particularly low among those farmers who believe that climate change affects weather forecast accuracy or who are unsure about the relationship between climate change and forecast accuracy.

The finding that climate change appears to influence the use of weather forecasts suggests a simplified cognitive model whereby farmers observe changes in weather and climate that then alter their views about the accuracy and usefulness of near future predictions. Other scholars have observed a complementary manifestation of the same process, showing that climate change undermines farmers' traditional means of knowing the future (Roncoli et al. 2001; Ingram et al. 2002; Kalanda-Joshua et al. 2011; Funk et al. 2019). Taken together, these outcomes can put farmers at a double disadvantage in the face of climate change. As climate change proceeds, farmers are less able to rely upon traditional knowledge to forecast the weather, but the view that weather forecasts are becoming less accurate prevents farmers' use of weather forecasts—a potentially valuable complement to (or substitute for) farmers' traditional knowledge. If utilized and accurate, weather forecasts can help offset the impacts of climate change by making farm management decisions more efficient. For example, Wood et al. (2014) found that smallholder farmers who reported access to weather forecasts were in general more likely to make adaptive farming decisions such as adjustment to their timing of agricultural activities and modifications to their fertilizer use. Sowing ahead of a rainy period and delaying adding inputs prior to heavy rains are two examples where forecasts could save limited household resources. Instead, the existence of climate change causes some farmers to disregard this potentially valuable information.

Within our Zambia-based study group, we also associate the high rate of non-use (71%) with farmers' perceptions that weather forecasts are inaccurate. It is indeed possible that weather forecast skill in Zambia is low. Although there are no published assessments of the country's forecast skill, inaccurate forecasts may be rooted in inadequate technical capacity and surface observing networks; across Zambia, the station network is sparse, consisting of 41 official meteorological stations for 752,500 km^2 area (Venäläinen et al. 2016). Scant surface stations and poor upkeep have been common challenges for many African countries. By one estimate, as many as 54% of its surface weather stations and 71% of its upper-air weather stations do not report accurate data (World Bank 2017). The WMO estimated that Africa needs an additional 4,000–5,000 basic meteorological stations (Rogers and Tsirkunov 2013); others have estimated investments of US$1.5 billion to 2 billion initially followed by US$ 400–500 million annually in order to make substantial improvements in weather and climate scientific capacity across Africa (Rogers and Tsirkunov 2013). Recent declines in financing national meteorological services (Rogers and Tsirkunov 2013), however, do not bode well for near-term improvements.

While more investments in observations and forecasting are needed in Zambia (and many other countries), improvements in infrastructure and scientific capacity alone are unlikely to lead to widespread use, absent the development of farmer resource bases and access to resources and information (Eakin et al. 2014). After all, perceptions of accuracy relate to forecast use, and those perceptions of accuracy inform and often undermine farmers' observations of changes in the climate. What is troubling about the association between climate change and weather forecast accuracy is that climate changes are discernible in many places; in Zambia, for example, increasing temperatures, changes in the rainy season onset, the frequency of dry periods, and inter-annual rainfall variability have all been documented (Mulenga et al. 2017) (Suppl. Figure S2). Therefore, continued and intensifying climate changes may create a permanent barrier to weather forecast use.

5.2 Weather and climate confusion

Farmers appear to perceive that climate changes influence weather forecasts. From a technical forecasting perspective, weather and climate are distinct and independent concepts. That is, the processes that lead to long-term changes in climate—changes in the energy balance—do not necessarily make forecasting weather less accurate. In the last 40 years, the skill of weather forecasting has continually improved despite a nonstationary climate (Hoskins 2013; Magnusson and Källén 2013; Bauer et al. 2015; Rose and Floehr 2017). The forecast improvements have been driven by higher spatial coverage and quality of observational networks in many locations, better data assimilation techniques, more computing power, and a greater understanding of the dynamics governing the earth system (Magnusson and Källén 2013). The effect of warming on weather forecasting, however, remains an open question. While an analysis showed that some aspects of the atmosphere change in predictability by the end of the twenty-first century under the highest greenhouse gas emissions scenario (RCP 8.5) (Scher and Messori 2019), there is also indirect evidence that weather predictability should not change in the near future (Jensen et al. 2018). At the least, given that forecast skill has been increasing in recent decades, the loss of skill due to a nonstationary climate has been outpaced by skill gains elsewhere.

Smallholder farmers in our study sites may be rightfully justified in their beliefs that weather forecasts are inaccurate. Our contention, however, is that the association of the inaccuracy is likely not due to changes in the long-term climate conditions. This suggests that the strong associations that farmers identify between climate trends and weather forecast accuracy reflect a deeper confusion about the nature of weather and climate as they are understood by western scientific approaches. The blurring of the different time scales of weather and climate has been documented elsewhere (Moser 2010), as has the confusion around forecasts operating on different time scales. In Argentina, for example, farmers often spoke about short-term weather forecasts and seasonal climate forecasts as if they were the same (Letson et al. 2001). In our study sites, farmers in all three countries appear to misconstrue how climate and weather are associated, and Zambian farmers see changing climate as the cause of decreases in the accuracy of weather forecasts. Consequently, we posit that this view presents a largely unrecognized feedback between the affirmation of a changing climate and decisions to avoid using tools to manage climate risk.

5.3 Practical steps to increase the use of weather forecasts

Although weather forecasts have great potential to improve the livelihoods of smallholding farmers (Khatri-Chhetri et al. 2017; Alley et al. 2019), new and different activities are needed to help make forecasts more useful. A recent Perspective in *science*, for example, highlighted the need for continued progress in technological and analytical aspects of weather forecasting (Alley et al. 2019). While the scale of the investment needed for infrastructure is large, it would be a mistake to overlook activities that build weather and climate literacy and tailor forecasts. Specifically, climate and weather service programs should pursue activities that reveal how individuals perceive the forecasts and help demystify the forecasts to users. Indeed, with national and international programs, as well as multilateral donors, making sizable and growing investments in weather and climate services, there is ample opportunity to do this work. In 2014 and 2015 alone, global expenditures on weather and climate services were $US56 billion (Georgeson et al. 2017).

Perceptions of accuracy and reliability are important enablers and barriers to the use of climate and weather information. While behavioral and psychosocial elements of information use in climate applications are well chronicled, our research points to a new connection within this class that merits further discussion. The confusion between changing climate and less accurate weather forecasts may be due to the "black-boxing" of weather forecasts and other tools of climate science. Even in developed societies where weather forecasts have been commonplace for more than 50 years (Benjamin et al. 2018), many individuals are unaware of how they work or what the forecasts mean (Zabini et al. 2015). The complexity and technical nature of these tools create a communication challenge that can be mitigated with a trusting public, if not one that is scientifically literate. Here, perceptions of the information credibility and legitimacy depend on the source. Barr and Woodley (2019, p. 119) argued this point for climate science, stating that ideas around climate change are contested, and what is deemed valid scientific knowledge "has less to do with what constitutes fact or opinion but rather the processes through which science becomes knowable and the ways in which this is negotiated and scaled." In fact, across 56 countries, climate change beliefs were most strongly associated with values, ideologies, worldviews, and political orientation (Hornsey et al. 2016). Perceptions of weather forecasts may therefore be influenced by beliefs about politics. Where public trust in state agencies is low or in decline, the use of weather forecasts may face even greater hurdles in the future.

The link between the use of weather and climate observations and behaviors also has been well-documented in studies on traditional or local knowledge. In many cultures, agricultural practices have long been influenced by environmental cues, like cloud patterns and plant and animal behaviors (e.g., Orlove et al. 2000; Roncoli et al. 2002). Indeed, around two-thirds of surveyed farmers who did not use weather forecasts said it was because they "prefer own observations," although we did not inquire about the types of observations made. This also indicates that among this group, personal observations and predictions have remained preferable, despite nearly 88% of Zambian farmers reporting that they had observed changes to the climate firsthand. The presentation of technical scientific information therefore needs to be offered as a potential supplement to existing ways of knowing (Roncoli et al. 2001; Ingram et al. 2002; Kalanda-Joshua et al. 2011; Funk et al. 2019). This is especially important where the skill of weather forecasts is unknown.

Weather and climate service programs have grappled for decades with efforts to build trust in and understanding of information and systems of knowledge creation. At first, it was recognized that more public engagement was needed to compensate for the technical nature of the information, such as its uncertainly and mathematical language (Stern and Easterling 1999). More recently, evidence for the benefits of closer engagement between users and producers of climate information (Dilling and Lemos 2011; Lemos et al. 2012) have caused a movement towards a more deliberate process of information and knowledge "co-production" (Meadow et al. 2015). In a co-production mode, both the use and production of science emerge from iterative learning that transpires among routinely interacting parties. An equality of ideas and values is sought, and this can help place forecasts in proper nuanced decision-making context. In this way, co-production, as well as other forms of engagement and participatory capacity building, can be useful approaches to bring to light the tools of weather and climate and to clarify similarities and differences between concepts of climate change and weather variability (Dayamba et al. 2018). Indeed, with many programs now focused on climate-smart agriculture and climate resilience, there is ample opportunity to do this work.

6 Conclusion

Based on our surveys of smallholding farmers in Kenya, Jamaica, and Zambia, we emphasize the following findings. The use of weather forecasts in all three countries was low, the vast majority of farmers stated weather is becoming more difficult for them to predict, and farmers in each country associated climate change and the accuracy of weather forecasts. Our analysis of the Zambian farmers revealed two additional insights. First, perceptions of forecast accuracy were positively associated with forecast use. Second, farmers believed that climate change influenced the accuracy of weather forecasts, which, in turn, influenced—an often impeded—the forecasts' use. This latter result implies that perceptions of climate change can undermine the use of weather forecasts. It also implies that farmers confuse the influence of climate on weather forecasts, a result that we also found in smallholder farming systems in Kenya and Jamaica. To our knowledge, this is the first study to make explicit and statistically robust links between perceptions of climate changes and weather forecast use. Additional research will be needed across diverse contexts to see how widespread these linkages are.

Our results raise important questions for efforts that connect weather forecasts to climate resilience, poverty reduction, food security, and climate-smart agriculture. Perceptions of weather variability appear to both reinforce and undermine the importance of forecasts. They become more important as "normal" weather patterns in space and time are altered but are undermined by perceptions that what is driving the change also affects forecast accuracy. Thus, whereas recent studies have called attention to the importance of increasing the accuracy and availability of weather information (Singh et al. 2020), our work suggests a need to disentangle forecast users' preconceived ideas about weather and climate.

We conclude with several suggestions regarding the improved provision of weather services. First, media, extension services, and programs that promote the use of forecast tools need to pay careful attention to distinguishing weather and climate. Similarly, the promotion of forecast tools ought to consider the psychological factors that inform weather risk perception and behaviors (van der Linden 2015). Additionally, weather services should begin with an awareness that preconceived notions about the relationships between weather and climate are determinants of weather forecast use. As weather forecasts are highly technical outputs, they are black boxes to untrained meteorologists. This subjects the tools to misunderstanding or dismissal if public trust in them is low. It is therefore important to unpack these tools and to separate concepts of weather and climate by acknowledging their similarities and differences. With the growing calls for the "co-production" of weather and climate services (Stone et al. 2006; Webber 2019), there are opportunities to be more nuanced with direct engagement between agricultural and scientific communities.

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Data availability Data will be made available upon request to the lead author.

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Declarations

Ethics approval All procedures performed in studies involving humans were in accordance with the ethical standards of the University of Arizona (UA), and approval was obtained from the UA Institutional Review Board.

Consent to participate All the farmers surveyed were provided information about the project goals and survey, and they were allowed to freely consent or withdraw.

Consent for publication We give consent for publication.

Conflict of interest The authors declare no competing interests.

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