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Climate Services Can Support African Farmers' Context-Specific Adaptation Needs at Scale

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We consider the question of what is needed for climate services to support sub-Saharan African farmers' adaptation needs at the scale of the climate challenge. Consistent with an earlier assessment that mutually reinforcing supply-side and demand-side capacity constraints impede the development of effective climate services in Africa, our discussion of strategies for scaling up practices that meet farmers' needs, and opportunities to address long-standing obstacles, is organized around: (a) meeting farmers' climate information needs; (b) supporting access, understanding and use; and (c) co-production of services. A widespread gap between available information and farmers' needs is associated with entrenched seasonal forecast convention and obstacles to using observational data. Scalable innovations for producing more locally relevant historical and forecast climate information for farm decision-making are beginning to be adopted. Structured participatory communication processes help farmers relate complex climate information to their experience, and integrate it into their management decisions. Promising efforts to deliver rural climate services strategically combine communication channels that include participatory processes embedded in existing agricultural advisory systems, and innovations in interactive broadcast media. Efforts to engage farmers in co-production of climate services improve delivery to farmers and dialogue among stakeholders, but often with little impact on the usability of available information. We discuss challenges and options for capturing farmers' evolving demands, and aggregating and incorporating this information into iterative improvements to climate services at a national scale. We find evidence that key weaknesses in the supply and the demand sides of climate services continue to reinforce each other to impede progress toward meeting farmers' needs at scale across Africa. Six recommendations target these weaknesses: (1) change the way seasonal forecasts are produced and presented regionally and nationally, (2) use merged gridded data as a foundation for national climate information products, (3) remove barriers to using historical data as a public good, (4) mobilize those who work on the demand side of climate services as an effective community of practice, (5) collectively assess and improve tools and processes for communicating climate information with rural communities, and (6) build iterative co-production processes into national climate service frameworks.

Keywords: co-production, scaling, climate risk management, climate information, agricultural extension, national meteorological services

INTRODUCTION

Climate variability is a major contributor to food insecurity and an impediment to efforts to improve the livelihoods of smallholder across most African countries; and climate change is intensifying the problem. Climate services are increasingly recognized as crucial for adaptation in the agriculture sector, by providing foundational knowledge of the local climate, informing the decisions of farmer and institutional decision-making, supporting a range of resilience-building interventions, and providing an enabling environment for adoption of climate-smart agriculture. While national meteorological services (NMS) provide climate information at a national scale, much of the research and effort toward the delivery and use of climate services for Africa's agriculture sector has remained at a pilot scale. The resulting body of experience offers a great deal of insight about the challenges that farmers face in accessing, using and benefitting from climate information; and options for addressing many of these challenges. But the urgency of adapting to climate change—highlighted recently by the release of the IPCC Special Report on Global Warming of 1.5°C (http://www.ipcc.ch/report/sr15/), and the launch of the Global Commission on Adaptation (https://gca.org/global-commission-on-adaptation)– calls for aggressive action to make climate services work for the vulnerable, including smallholder farmers, at scale.

Developing effective agricultural climate services at a national scale requires managing tradeoffs between the goals of meeting the context-specific needs of farmers and providing cost-effective services at scale. There is evidence that farmers' climate service needs and options for acting on climate information can be quite context specific. In addition to differences due to farming system, the literature identifies differing climate information needs linked to gender (Ingram et al., 2002; Archer, 2003; Ziervogel and Calder, 2003); and more recently at the intersection of gender, seniority, wealth and livelihood activities (Tall et al., 2014b; Carr and Owusu-Daaku, 2015; Carr and Onzere, 2016; Carr et al., 2016a); associated with social norms that enable or constrain particular climate-sensitive agricultural and livelihood decisions. On the other hand, resource constraints and broad, multi-sector mandates make it challenging for NMSs to provide information tailored to context-specific local demands. The challenge may be framed both as "scaling down" the information that NMS provide in order to better meet farmers' context-specific needs; and scaling up communication and engagement practices that are effective at a pilot scale, depending on whether one is starting from the supply side or the demand side of climate services.

Progress may also be hampered by challenges that span the supply and demand sides of climate services. In 2006, a multi-stakeholder, cross-sectoral assessment concluded that climate information failed to contribute meaningfully to development across Africa because of "market atrophy" associated with the long-term interaction between ineffective demand by development stakeholders and inadequate supply of actionable climate information (IRI, 2006). To the degree that this conclusion still holds, efforts to develop climate services that contribute effectively and sustainably to agricultural adaptation at scale must address persistent supply- and demand-side capacity constraints in parallel, and better bridge the demand and supply sides of the services.

In this paper, we consider the question of what is needed in order for climate services to achieve its potential contribution to sub-Saharan Africa's farmers adaptation and risk management needs, at the scale of the climate challenge. Consistent with the notion that mutually reinforcing supply-side and demand-side capacity constraints impede the development of effective agricultural climate services, the discussion is structured around (a) tailoring climate information to farmers' needs, (b) communicating information effectively with farmers, and (c) engaging farmers in co-production of services. In each of these areas, we consider what is known about farmers' information needs and how to meet them at a local scale, strategies and inherent tradeoffs in scaling up good practice nationally, and opportunities to overcoming longstanding constraints to improving the effectiveness of climate services across Africa. We draw on the climate services literature and, on our experiences developing and evaluating climate services for agriculture in sub-Saharan Africa, much in the context of the CGIAR research program on Climate Change, Agriculture and Food Security (CCAFS). Emphasis is on information at a climate variability time scale to support farm risk management decisions.

ACTIONABLE CLIMATE INFORMATION PRODUCTS

The early development of agricultural climate services has its roots both in agricultural research efforts to bring seasonal prediction into agrometeorology and agricultural systems modeling, and in climate research efforts to bring agricultural applications into the development of seasonal climate prediction. Pioneering work led by agricultural researchers concentrated in northeastern Australia in the early to mid 1990s laid a foundation for the systematic use of climate information for agricultural management. This work, led by an agricultural systems research group in partnership with agricultural industry, integrated emerging understanding of the predictability associated with the El Nino/Southern Oscillation (ENSO), with analysis of local daily meteorological data to understand and quantify risks, and agricultural systems modeling and decision support tools to translate climate information into forms that are relevant for agricultural management decisions. In Africa, the development of climate services has strong connections to the Regional Climate Outlook Forums (RCOF). A surge of investment and research on agricultural applications of seasonal prediction was prompted by the publicity surrounding the strong 1997/98 El Niño event, the coincidental launch of the RCOF process in southern, eastern and western Africa in 1997, and a paper published in Nature that showed that an ENSO index was correlated more strongly with maize yields than with rainfall in Zimbabwe (Cane et al., 1994).

Although farmers' options for acting on climate information and the types and time scales of information that can inform farmers' decisions can be quite context specific, aspects of information needs such as format and spatial scale appear to be generalizable. Experience across a range of contexts that reveals widespread mismatch between farmers' needs, and the types and formats of information that are routinely available across most of sub-Saharan Africa suggests a pathway for improving the effectiveness of climate services. The resulting "usability gap" (Lemos et al., 2012) has been studied most in the context of seasonal climate forecasts.

What We Know About Farmers' Climate Information Needs

Periodic Regional Climate Outlook Forums (RCOFs) across Africa, Latin America and Asia (https://public.wmo.int/en/our-mandate/climate/regional-climate-outlook-products) and most NMS follow a convention that the first RCOFs adopted in the late 1990s, which present consensus seasonal forecasts as the probability that upcoming rainfall or temperature will fall in the "below-normal," "normal" or "above-normal" terciles of the historical distribution. Forecast probabilities are typically provided as maps of tercile probabilities that are homogeneous over large areas, without any information about the spatial and interannual variability of the underlying local climate. While NMS are charged with downscaling and tailoring the forecasts to user needs, in practice the probabilistic information is often collapsed into a deterministic forecast of the most probable 1 or 2 tercile categories (e.g., "rainfall will be normal to above-normal") before it reaches the rural population.

These forecasts are a poor match for farmer decision-making needs in a few important ways. First, they do not directly provide information about anticipated climate conditions at the local scale of farm decision-making (O'Brien et al., 2000; Jochec et al., 2001; Ingram et al., 2002; Patt and Gwata, 2002; Podestá et al., 2002; Vogel and O'Brien, 2006). Second, the forecast categories are arbitrary in terms of the thresholds they represent (i.e., 67th and 33rd percentiles of the distribution), and are often misinterpreted as something other than historic terciles (O'Brien et al., 2000; Patt and Schrag, 2003; Klopper et al., 2006; Pennesi, 2007). Furthermore, presenting both directional shifts from the "normal" category, and probability shifts from the 33% baseline probability that defines each category, introduces a level of complexity that makes the tercile format particularly prone to misinterpretation (Hansen et al., 2004; Coventry and Dalgleish, 2014). Third, acting appropriately on forecast information requires understanding uncertainty of the forecast in probabilistic terms (Childs et al., 1991; Ziervogel and Calder, 2003; Suarez and Patt, 2004). Although tercile forecasts are probabilistic, the format and the frequent translation of forecasts into deterministic statements leave ambiguity about the degree of uncertainty of the forecasts, which can in turn lead to inappropriate management responses and damage the credibility of NMS (Nicholls and Kestin, 1998; Orlove and Tosteson, 1999; Hammer et al., 2001; Changnon, 2002). Finally, farmers need information beyond average conditions during the growing season, such as timing of the season start and end, and risk of damaging dry spells or other extremes (O'Brien et al., 2000; Phillips and McIntyre, 2000, Ingram et al., 2002; Klopper et al., 2006).

The main criticisms of the tercile convention can be rectified by statistically downscaling seasonal forecasts onto local historical observations; and presenting the forecasts as full probability distributions, in probability-of-exceedance format, along with the historical climate distribution (**Table 1**). In contrast to the tercile convention, this format: (a) connects the forecast to local historic climate variability—with the added benefit of building awareness of the past behavior of the local climate—and hence to the information that decision makers would use in absence of the forecast; (b) provides probabilities associated with any threshold (e.g., minimum rainfall to meet crop demand) that might be relevant to decision options, instead of being tied to arbitrary tercile boundaries; and (c) conveys the uncertainty of forecasts in a clear, transparent manner (Hansen et al., 2004, 2011). Although the proposed changes diverge from longstanding convention across much of Africa, they reflect widespread practice in the early development of agricultural climate services particularly in Australia; and in the USA have been recommended (Barnston et al., 2000; National Academy of Sciences, 2006), and adopted alongside the tercile convention by the Climate Prediction Center (CPC) and the International Research Institute for Climate and Society (IRI) (Barnston and Tippett, 2014).

The use of historical meteorological data, directly and with the aid of simulation models, to analyze risk and support decision-making, is well-established in agricultural research and practice. But climate information providers in much of Africa have been slow to recognize the essential role of local historical data in agricultural climate services. In addition to their crucial role in producing, evaluating and communicating locally relevant seasonal forecasts, historical data are the main source of knowledge about the behavior (seasonality, variability and trends) of the local climate that is foundational to managing risk and adapting to change. Farming communities understand their local climate from experience, and nearly always use observable indictors to anticipate upcoming weather conditions. But this indigenous climate knowledge can be biased or be confounded by other drivers of change such as soil degradation, raising concerns that agricultural systems may be poorly adapted to the current climate (Meinke and Hammer, 1995; Meze-Hausken, 2004; Thomas et al., 2007; Slegers, 2008; Rao, 2011). Analyses of historical meteorological records enable farmers and other decision-makers to better understand and adapt to the variability, seasonality and any trends that characterize their local climate (e.g., Stern and Cooper, 2011). Historical data analyses can reveal whether perceived change is more likely due to anthropogenic climate change, natural multi-decadal climate variability, or another driver of change such as soil degradation (Slegers, 2008; Mubaya et al., 2012).

In principle, translating "raw" climate information into agricultural impacts and management advisories increases its relevance for farmer decision-making. Agricultural climate services employ both quantitative model-based tools, and subjective consultative processes to translate climate information into more actionable information, often highly tailored to specific crops and management decisions. The use of model-based decision support tools, such as Whopper Cropper and YieldProphet, to translate local weather data into probabilistic yield and economic outcomes, played a crucial role in the early development of agricultural climate services in Australia (Hammer, 2000; Hammer et al., 2001; Nelson et al., 2002; Hochman et al., 2009). But these tools proved to be more useful for fostering dialog and learning than for guiding farmers to make particular farm management adjustments in response to climate conditions (McCown, 2002; Hochman and Carberry, 2011).

TABLE 1 | Solutions to key gaps in the usability of the widely used tercile seasonal forecast convention for farmer decision-making.

Gap	Solution
Lack of information about local climate	Downscale forecasts
	Present forecasts with local climatology
Categories difficult to communicate and understand	Provide full forecast probability distribution
Tercile categories do not match decision-relevant thresholds	
Ambiguity about forecast uncertainty	
Limited relevance of seasonal climatic conditions alone	Expand suite of seasonal forecast variables
	Translate into impacts, management options

How Can a NMS Meet Farmers' Local Information Needs at Scale?

National Meteorological Services (NMS) have a mandate to provide a wide range of stakeholders across sectors with observed and forecast information, and warnings for pending hydroclimatic threats. The current range of climate information products available, and capacity to expand the suite of products available for agricultural decision-makers vary considerably among NMS in the Global South. In sub-Saharan Africa, most face significant challenges to providing specialized information tailored to the needs of particular sectors or decision-makers due to limited human capital, inadequate financial resources and obsolete technologies (AMCOMET, 2015); and many lack the capacity to provide even a basic level of service. While most African NMA are able to produce improved climate information products at a pilot scale through custom analyses or downscaling based on local long-term station records, replicating this process for locations across a country would overtax their human and financial resources.

Long-term historical data are the foundation of information at a climate time scale. The kinds of actionable climate information products discussed in Section What We Know About Farmers' Climate Information Needs can only be generated for locations where long-term, quality controlled, digitized local meteorological records are available. Unfortunately, the meteorological observation network in much of the Global South is seriously inadequate and often in decline (Malhi and Wright, 2004; Washington et al., 2006; Parker et al., 2012; Dinku et al., 2014a, 2018). Because the distribution of existing stations is uneven and concentrated in cities and towns along major roads, coverage tends to be worse in rural areas.

TABLE 2 | Suitability of different communication channels for climate service communication functions (***, well suited; **, moderately suitable; *, less suitable), based on the authors' subjective preliminary assessment.

Function	Communication channel			
	Group meeting	Mass media (radio, TV)	Mobile phone (basic)	Internet via computer, smart phone
Awareness of services	**	***	*	*
Learning concepts, interpretation of climate information	***	**		**
Evaluating suitability of current management to local climate	***	*		**
Forecast-based seasonal planning	***	*		**
Weather monitoring and forecasts		***	***	*
Extreme weather alerts		**	***	*
Customized information and advisories	*	*	***	***
Facilitating collaboration, farmer feedback	***	*	**	***
Information access, support for agricultural advisors				***

Addressing Data Gaps

Although a long-term solution to data availability must include investment in observing infrastructure, and in NMS capacity to collect and process those data, it will take new stations decades to accumulate records that are long enough to meet climate information needs. In the near term, viable methods for reconstructing historical records now make it feasible for a NMS to derive historical and forecast climate information at a spatial resolution that is useful for farm-level decision-making. The oldest and simplest method, spatial interpolation, is the basis for several global gridded rainfall data sets (e.g., Mitchell and Jones, 2005; Becker et al., 2013; Harris et al., 2014). But the quality of interpolated data is quite sensitive to the density and spatial distribution of the observations used, and hence susceptible to the sparse and deteriorating observing network that exists across much of the Global South. Better quality can be obtained by combining available station observations with satellite or other proxy estimates. Satellite rainfall estimates offer near-global coverage, moderately high temporal and spatial resolution, and free availability in near real time. While several products use the small set of data that countries make freely available through the World Meteorological Organization's Global Telecommunication System (GTS), some such as Climate Hazards group InfraRed Precipitation with Stations (CHIRPS) improve quality by incorporating additional station data (Funk et al., 2014, 2015).

The ENACTS Approach to Enhancing NMS Capacity

The ENACTS (Enhancing National Climate Services) initiative, led by the IRI (Dinku et al., 2014a, 2018), demonstrates several innovations to overcome data and human capacity constraints to providing climate information that is relevant to farmers' local needs, at a national scale. This is accomplished by providing collaborating NMS with methods, tools and training to: (a) develop high-resolution spatially and temporally complete gridded historical meteorological data sets; (b) generate suites of derived climate information products; and (c) disseminate them through online "Maprooms." Data gaps are addressed by combining quality-controlled station records with proxies (satellite data for precipitation and climate model reanalysis data for temperature) that are freely available from global sources. The approach produces long-term (>35 years for rainfall, >55 years for temperature) daily or 10-daily gridded time series data, at a nominal 4 km grid. Because NMS in developing countries are stewards of much more data than are available to external organizations, the resulting national data sets are expected to be of higher quality than similar global products from advanced institutions in the Global North (Dinku et al., 2014b, 2018). An array of derived historical, monitored and forecast information products and analyses is made available through an interactive online "Maproom" portal that allows users to view statistics spatially, and access location-specific graphical and tabular information products for any selected grid cell or administrative boundary. At the time of writing, 10 African countries (Ethiopia, Ghana, Kenya, Madagascar, Mali, Rwanda, Senegal, Tanzania, Uganda, Zambia) have implemented at least a basic set of Maproom tools based on merged gridded data.

Several countries (Rwanda, Senegal, Ethiopia, Mali, Madagascar) and two regional climate centers (ICPAC, AGRHYMET) have extended their Maprooms to include agriculture-relevant products such as rain day frequency, mean rainfall intensity, wet and dry spell frequency, and onset of the rainfed growing season. With added requirements for soil and temperature data, soil water balance Maproom tools translate daily rainfall data into soil water content and water balance-based agricultural drought indicators such as the Water Requirements Satisfaction Index (WRSI) (Verdin and Klaver, 2002). An improved approach to presenting seasonal forecasts has recently been incorporated into several Maprooms, with the goal of improving how seasonal forecasts are communicated and used for local agricultural decision-making. The map view goes beyond the conventional tercile format by providing probabilities of exceeding a user-selected rainfall amount or climatological percentile. Users can also access downscaled forecasts for any selected grid cell, in the probability-of-exceedance format discussed in Section What We Know About Farmers' Climate Information Needs.

Priority Challenges and Opportunities

Positive examples of innovative efforts by African NMS and Regional Climate Centers (RCCs) to reduce the usability gap with respect to farmer needs, seem to be exceptions to a widespread inertia. In addition to the resource and political constraints that NMS across the Global South face, key obstacles to meeting farmers' climate information needs at scale across Africa include entrenched conventions that have been formalized by the RCOFs, gaps in historical observations, and NMS policies and business models that treat observational data as a source of revenue.

The RCOFs continue to play a crucial role in supporting and sustaining national climate services in Africa. However, the conventions that they adopted and perpetuate are a disincentive for NMS to produce more actionable seasonal forecast and climatology information. In principle, the RCOFs develop regional forecasts at a coarse scale, and NMS have the responsibility to downscale the forecasts and translating it into actionable information for decision-makers. But the RCOF processes tends to work against this, first by modeling and implicitly endorsing the tercile format and subjective consensus process as standard practice, with the backing of regional and global climate centers. Second, the regional tercile probabilities and subjective consensus forecast process cannot be used directly as input to the best statistical methods for downscaling forecasts in the form and spatial resolution that is needed.

In the late 1980s and 1990s, NMS in Africa and globally began shifting away from sharing meteorological data as a public-good resource for development, toward restricting access in order to sell it as a source of revenue. This shift was influenced by donor-driven structural reform policies that reduced public investment in NMS and other government services, and reflected in World Meteorological Organization (WMO) Resolution 40 in 1995, which sought a compromise between open and restrictive data policies by defining a small subset of meteorological data that should be shared globally. Although NMS across sub-Saharan Africa provide seasonal forecasts freely, and most are proactive about reaching out to the agricultural sector, few make historical observations freely available, and as far as we know, none make them accessible through a public repository (Hansen et al., 2011).

We see three priority opportunities for African NMS and the Regional Climate Centers (ICPAC in eastern Africa, AGRHYMET in West Africa, and the SADC Climate Services Center in southern Africa) that support them, to improve their responsiveness of their services to the needs of their agriculture sector. The first is to move beyond the tercile seasonal forecast convention, and present forecasts as a full forecast distribution, statistically downscaled onto and presented with the corresponding local climatological distribution. The second priority is to expand the use of data merging to fill gaps in historical records, and use the resulting gridded data sets as a foundation for localized historical, monitored and forecast climate information products tailored to the needs of agricultural decision-makers. Two regional climate centers and a growing number of have already begun to adopt these technical innovations. A third priority, making meteorological data freely available as a public good and resource for development, is likely the most challenging as it will require changes in long-standing data policy and potentially adjustments to the allocation of public funds to the NMS.

EFFECTIVE CLIMATE COMMUNICATION PROCESSES

Weather is a relatively simple concept to understand and factor into decision-making, as people experience weather daily. In contrast, climate—the statistics of weather—is an abstract statistical concept and climate information is inherently probabilistic. Climate information is therefore more challenging than weather information to understand, and requires different communication processes and more support to use it appropriately. In this section we discuss how structured participatory communication processes support farmers' understanding and use of climate information, and the opportunities and challenges in scaling and combining effective climate information communication processes.

Communication Processes That Support Farm Decision-Making

Building on the insights from pilot-scale participatory action research with farming communities, several research and development organizations have developed participatory communication processes into structured group communication and training protocols, a few of which have been used widely and documented. For example, the Participatory Scenario Planning (PSP) process developed by CARE, which involves multi-stakeholder dialog and planning around each of the seasonal forecast tercile categories, has been piloted in several countries in Africa and Southeast Asia, and adopted for county-level climate services across all of Kenya (Ambani et al., 2018). Participatory Integrated Climate Services for Agriculture (PICSA); developed by University of Reading, piloted in several countries in Africa and Latin America, and adopted for national agricultural climate services in Rwanda; emphasizes the use of historical climate data in combination with participatory activities to support participants' farming and livelihood decisions (Dorward et al., 2015). A workshop-based process developed by the IRI, designed to help farmers relate downscaled seasonal forecasts in probability-of-exceedance format to their own memory of historic climate variability (Hansen et al., 2004, 2007), is being adapted and integrated with PICSA for Rwanda. Programs in Indonesia (Siregar and Crane, 2011) and The Philippines (Chandra et al., 2017), adapted the Farmer Field School model, lead participants through a series of modules through the agricultural season on climate-smart agricultural practices and climate risk management. From the literature, two knowledge exchange workshops (May et al., 2013; Krupnik et al., 2018) and personal discussion with developers, it is apparent that most participatory communication processes have been developed independently, with little or no apparent cross learning. The one exception we are aware of is the Climate-Resiliency Field Schools, which built on Indonesia's Climate Field Schools.

Participatory communication processes can be effective at increasing farmers' understanding and willingness to act on complex climate information, as evidenced by controlled studies in Zimbabwe (Patt et al., 2005) and Burkina Faso (Roncoli et al., 2008), and high rates of climate information use and positive subjective assessment of benefits of the PICSA process (Clarkson et al., 2017; Stats4SD, 2017). They are effective in part because they provide opportunity for formal training and social learning, and because they help overcome cognitive challenges to processing and using uncertain information. The human mind uses different modes for processing decisions under uncertainty, depending on whether the information is obtained through statistical description ("analytical processing") or through repeated experience ("experiential processing"). Experiential processing tends to take precedence over analytical processing in decision-making because of its connection to strong emotion. Research pioneered by Kahneman and Tversky (Kahneman et al., 1974; Kahneman and Tversky, 1982) showed that people tend to make several common errors when making decisions based on probabilistic information; some of which work against effective use of climate information (Nicholls, 1999; Stern and Easterling, 1999). But other research shows that those difficulties are reduced when analytical and experiential processing modes are combined (Epstein, 1994; Marx et al., 2007). Climate communication processes often incorporate group activities that, intentionally or unintentionally, foster understanding and use by relating statistical climate information to personal or vicarious experience. These include games that provide accelerated experience with simulated decisions (Hayman, 2000; Suarez and Patt, 2004; Roudier et al., 2014; Suarez et al., 2014); activities that relate climate information graphs to farmers' collective memory of recent agricultural seasons (Hansen et al., 2004, 2007); and group discussions of hazards, opportunities and decision options associated with above- and below-normal seasonal climate scenarios.

Scaling Up Effective Communication

The tension between tailoring and scaling climate services is particularly apparent when it comes to the choice of communication channels for delivering services. The face-to-face participatory communication processes that are effective at a pilot scale are challenging to implement at an aggregate scale. Broadcast media can reach many farmers at relatively low cost – although broadcasts do not necessarily reach all targeted users (Archer, 2003; Peterson et al., 2010)—but providing context-relevant content that farmers can understand and act on through conventional programming is challenging. We consider options for scaling up participatory communication processes, for making broadcast media more responsive to context-specific user needs, and for combining complementary communication channels for delivering climate services to rural populations.

Scaling Up Participatory Communication Processes

Government agricultural extension services, development NGOs and agribusiness enterprises already play an active role in translating climate information into advisories, and communicating information and advisories to farming communities in many African countries. Where participatory communication processes and associated training materials are sufficiently developed, training agricultural extension services or other intermediary institutions that farming communities already know and trust offers a potential avenue for scaling up. In Rwanda, the USAID-funded Rwanda Climate Services for Agriculture project is working with the country's national agricultural extension service to scale up the delivery of climate services using the PICSA approach. Rwanda's hierarchical, decentralized *Twigire Muhinzi* extension service combines agricultural professionals with volunteer Farmer Promoters who are trusted members of the communities they serve. The project's training-of-trainers approach provides advanced training to equip professionals to train and mentor local extension staff and volunteer farmers, who in turn train and facilitate farmer groups to understand climate information and incorporate it into their planning. As scaling out to new locations accelerated, four local faith-based NGOs were contracted to facilitate the training and support implementation in farming communities in their respective provinces. As of September 2018, roughly three-fourths through the project, 1612 government staff and volunteer Farmer Promoters were trained, who in-turn trained and facilitated more than 105,000 farmers in the PICSA process. Preliminary evidence suggests that farmer-to-farmer sharing may extend the reach by roughly an order of magnitude (Clarkson et al., 2017). We expect that improving training and self-learning materials, and using ICT-equipped local government offices as resource centers for extension staff and farmer volunteers will help accelerate and sustain the scaling process.

While the Rwanda experience demonstrates the feasibility of scaling up the delivery of rural climate services through participatory processes, it has benefitted from factors that are not necessarily present across sub-Saharan Africa including: a strong national agricultural extension system; effective partnerships among the government's agricultural extension system, local partner NGOs and international research organizations; integration of partner NGOs' activities into local government planning and accountability processes; and a high degree of trust between the local NGO partners and farmers.

Making Communication Through Broadcast Media More User Responsive

Broadcast media (radio, and in some regions television) is well-suited for building awareness, reinforcing concepts and opportunities around the use of climate information to manage risk, and providing regular access to information at a weather time scale. Although broadcast media is largely a one-way communication channel, several innovations can make communication more interactive, and hence better able to respond to context-specific farmer needs. Featuring farmers in creative programming such as village dialogs, radio drama and the *Shamba Shape-Up* farmer reality television show popular in East Africa (Clarkson et al., 2018) help connect abstract climate-related information and concepts to vicarious experience, and hence facilitate understanding and motivate action (Section Communication Processes that Support Farm Decision-Making). Community listening groups, which have their roots in programs in Canada and Australia as early as the 1940s (Goodman, 2016), combine the reach of radio with the benefits of group interaction and social learning. They have been part of several efforts to support rural climate services through radio in Africa, and can be effective at fostering change in farm practices (Hudson et al., 2017).

Innovative broadcast programing that exploits the rapid expansion of mobile phone use in rural areas is making communication more interactive (Perkins et al., 2015; Hudson et al., 2017). For example, to capture listeners' response to simple questions in real time during a radio program, Farm Radio International's "Beep-2-Vote" approach, which allows listeners to submit their answers to simple questions based on which phone number they dial, without answering and charging for the call, as a low-cost way to capture the response of many listeners in real time. The "Beep-2-Vote" model has been extended to use radio stations as call centers, registering farmers' requests for a call from an expert to address, e.g., a weather-related question ("Beep-4-Weather," piloted in Tanzania and Malawi) without charging the farmer to place the call (Hampson et al., 2015; Perkins et al., 2015).

Combining Communication Channels

NMS typically use a range of communication channels to disseminate weather and climate information, including websites, broadcast media (television, radio), agrometeorological bulletins, mobile phones, and various forms of face-to-face communication—often in partnership with agricultural extension services and other intermediary organizations. Although there has been little published research on the suitability of particular communication channels for particular types and time scales of information or climate service functions, our experience and intuition suggest that these channels are not substitutes, but play different and complementary roles in agricultural climate services (**Table 2**). For example, face-to-face participatory processes are effective for initial learning and seasonal planning around complex information at a climate time scale, and provide an opportunity for the learning and feedback that are needed to design effective services. Radio and television are well-suited to building awareness, reinforcing concepts introduced through participatory processes, and delivering frequent forecasts and advisories at a weather time scale. Mobile phones can push location-specific weather forecasts and alerts of extreme events as SMS or voice messages; and provide targeted information on demand through call centers, menus and interactive voice response. Increasing rural penetration of smart phones and data service is expanding possibilities for accessing location-specific graphic climate information and advisories, for expanding training and reinforcing concepts through video, and for decision-support tools to translate location-specific climate information into management advisories. This suggests that the delivery of climate services for farmers at scale is best supported by a combination of innovative participatory, media- and ICT-based communication processes. However, there is still a gap in evidence-based guidance about how they can best be combined, and the associated tradeoffs between meeting context-specific needs and cost-effective scaling.

Efforts by CCAFS and partners to improve communication of climate information for agriculture in Senegal and Rwanda involved both participatory workshops and interactive radio programming, but with contrasting roles in the two countries. In Senegal, a collaborative effort by CCAFS and the NMS [*Agence Nationale de l'Aviation Civile et de la Météorologie* (ANACIM)] evolved from participatory communication and training workshops at pilot site in Kaffrine in 2011, toward using community radio as a mechanism to scale up delivery of climate services. Pilot workshop participants, concerned about sustaining access, asked ANACIM to provide climate information through rural radio and local agricultural extension agents once (Ndiaye et al., 2013). In response, CCAFS supported ANACIM to enlist Multidisciplinary Working Groups (*Groupe de Travail Pluridisciplinaire* (GTP), in French) to translate seasonal and 10-day forecasts into advisories for farmers, and trained the *Union des Radios Associatives et Communautaires du Sénégal* (URAC)—an association of 83 community-based radio stations across the country—to incorporate climate information into its programming. As of 2015, climate information communicated through radio and SMS reached an estimated 740,000 rural households across Senegal's 14 administrative regions (CCAFS, 2015). In contrast, interactive radio programming in Rwanda is used as a parallel communication channel that complements the PICSA face-to-face process being integrated into agricultural extension activities nationally. The initiative works with the *Radio Huguka* community radio network to produce bi-weekly climate service programming. The two communication channels are now being further integrated through radio listening clubs led by Farmer Promoters who already facilitate the PICSA communication and planning process. Listening clubs participate in call-in shows and live debates with experts, via mobile phone, on a rotating basis, to ensure equitable participation among the roughly 5,000 farmers involved in the initial pilot. Survey-based evaluation studies, planned in both countries for 2019, are expected to provide empirical evidence of the reach and impact of the two contrasting strategies for combining communication channels to scale up climate service delivery.

Priority Challenges and Opportunities

A vital but often overlooked subset of the climate services research and practitioner community comes from the climate-sensitive sectors (e.g., agriculture, health, water resources, humanitarian response), and works on demand-side issues such as the translation, communication and use of climate information, and partnerships and mechanisms to engage their sectors in the co-design and co-production of more useful climate services. Where climate services for farmers are effective, they are generally supported by demand-side researchers and organizations (e.g., international agricultural research-for-development organizations, National Agricultural Research and Extension Systems (NARES), rural development NGOs) who work beyond the NMS to improve the delivery and support to rural communities of locally relevant climate information and advisories.

A few weaknesses within this demand-side climate services community constrain its impact. The first is its limited capacity to effectively articulate the demand of the users it serves, and influence climate information providers to respond. Although the efforts of researchers and development organizations from the agriculture sector have advanced processes for communicating climate information with rural communities, much of this effort has focused more on tailoring communication processes to the information products that NMS routinely provide, than on working with NMS to tailor the information they provide to the known needs of farmers. This gap in effective demand capacity is reflected, for example, in communication and planning processes designed around rainfall tercile categories scenarios, and the stated rationale for efforts to combine conventional NMS seasonal forecasts with communities' indigenous climate indicators, to compensate for the weaknesses of climate information products from NMS discussed in section Actionable Climate Information Products (e.g., Ambani et al., 2018)

Second, as new organizations are moving into rural climate services, attracted and supported by increasing donor funding, they typically design new and sometimes innovative processes for identifying farmer needs, communicating climate information and supporting its use, rather than building on existing knowledge and experience. This failure to build on or share these innovations leads to redundant efforts, but also represents a missed opportunity for innovations developed by one organization to address gaps in the approaches of others. We therefore expect that a modest effort to share, compare and critically assess the strengths and limitations of existing participatory processes, and use the resulting learning to strengthen processes and their associate training materials, would have a big impact on the farmers who use climate services.

These weaknesses in effective demand capacity and knowledge sharing within the climate services community are symptomatic of fragmentation in the research, implementation and donor community that works on the demand side of climate services. This fragmentation is in part as a result of organizations and researchers being embedded primarily in communities of practice within the sectors that they serve. The problem is compounded by the growing number of development organizations that are moving into climate services, and perceived incentive to compete for funds at the expense of sharing knowledge and coordinating action with other actors in the climate services community (Jones et al., 2016; Webber and Donner, 2017). Development and adaptation donors, many of whom are also relatively new to climate services, have limited capacity to require and assess implementation of good practice, or knowledge sharing and coordination with other funders and implementers that are working toward shared goals. The substantial body of knowledge that is relevant to the expanding community of agricultural climate service implementers and funders, is scattered within the academic and gray literature.

In light of evidence of the impacts of fragmentation on the demand side of climate services, a high priority is to incentivize and facilitate actors working in this space to organize as a community of practice. Climate information providers are supported globally by WMO, in Africa by the African Ministerial Conference on Meteorology (AMCOMET) and by the Climate Research for Development (CR4D) pan-Africa climate research strategy, and by meteorology professional societies in many countries. Comparable structures do not yet exist for those working on climate services outside of the meteorological and climate science community, but the Climate Services Partnership (CSP) is a promising entry point at a global scale. The CSP, launched in 2011 as an outcome of the inaugural International Climate Services Conference and in response to fragmentation in the climate services community, has made progress in convening a diverse community of researchers and practitioners to share knowledge through its series of International Climate Service Conferences, and advance the agenda on climate service issues such as economic valuation and ethical standards (Hansen et al., 2014). A better community of practice could address current gaps in knowledge exchange, quality and ethical standards, and professional development for those working on the demand side of climate services. It would also be in a position to strengthen communication processes targeting rural communities, and more effectively support NMS to understand and respond to farmers' information needs. While competition for climate service funds has contributed to this fragmentation, donors who invest in user-focused climate services are in a position to use their influence to incentivize knowledge sharing and other collaborative actions that would enhance their impact.

BRIDGING THE DEMAND AND SUPPLY SIDES OF CLIMATE SERVICES

In principle, one way to ensure that climate services meet the needs of individual farmers is to involve farmers or their representatives in developing them. Co-production has been a major focus of agricultural climate services research and practice, even before use of the term became widespread. A recent review of 131 academic publications that discuss "co-production" and "climate" identified eight distinct ways that the term "co-production" is used, with substantially different goals and criteria for success (Bremer and Meisch, 2017). The largest portion of this literature, and our own perspective, views co-production through what they describe as the "iterative interaction lens," which aims to enhance usability by better aligning information supply with demand. But the co-production concept is also seen as a means to advance goals that may not align with enhancing usability, such as preserving and empowering traditional climate knowledge systems (the "empowerment lens"), and placing other forms of knowledge on equal footing with scientific knowledge (the "extended science lens").

Engaging Farmers in the Co-production of Services

At a pilot scale, participatory communication processes provide a forum for communication and co-learning among farmers, researchers and climate information providers, and hence a conducive environment for co-production of climate services. But co-production is not an assured result of dialog. Obstacles on either the supply (e.g., inflexibility, non-responsiveness, capacity constraints) or the demand side (e.g., limited knowledge of what can feasibly be provided, limited influence on information providers) prevent co-production from influencing the production of climate information. Therefore, while the limited available evidence shows that participatory communication processes are effective at improving farmers' understanding and use of available climate information, they do not necessarily reduce the gap between available information and farmers' needs.

Co-production of Services at Scale

In addition to the requirement of effective demand capacity on the part of farmers and responsiveness on the part of NMS, co-production at a national scale also requires methods to quickly and effectively understand farmers' needs, a process for aggregating and prioritizing user needs, and institutional arrangements and processes that incorporate this feedback into the design or improvement of services.

Understanding Farmers' Climate Service Needs at Scale

Climate service projects that involve significant investment and aim for significant scale often begin with a needs assessment—sometimes as a donor requirement. But efforts to understand farmer needs at scale face significant methodological challenges and potential for biases arising either from the designers of the services or from the users. An assessment of current practices in the identification of climate service users and needs (Carr et al., 2017) noted that service provider assumptions about who the users of information should be, and what they should need, can bias the questions that are asked and limit opportunity for users to articulate their actual preferences. Efforts to identify users and their needs must deal with differing ability of individuals within communities and households to participate in such assessment processes (Archer, 2003; Peterson et al., 2010; Roncoli et al., 2010), and assess who is included and whose voice might be excluded.

Even when assessments avoid bias from the service provider, efforts to identify user needs are hampered by effective demand constraints which emerge when farmers and other users of climate services cannot articulate demand for potentially useful products or services that they have had limited experience with, or have not yet been exposed to (IRI, 2006; Pope et al., 2017; Christel et al., 2018). As a result, feedback tends to be biased—either favorably or unfavorably—toward the status quo. When such constraints limit farmers' ability to articulate demand, useful and nuanced understanding of potential users and potential demands can be obtained by focusing on understanding climate-sensitive livelihood decisions and the factors that determine them (Ziervogel, 2004; Carr et al., 2016b), but these methods currently require substantial time and resources, and are challenged by questions of external validity.

The learning process during engagement with climate information can increase farmers' understanding and capacity to express their needs. The use of such information can change practices and outcomes, which can in turn further shift climate service needs. Therefore, the assessment of who users of information are, and what they need, can be expected to be more reliable as an ongoing, iterative process than as a single event. The process can be streamlined if it builds on existing knowledge about those aspects of climate information needs, such as spatial scale, graphical formats, transparency about uncertainty and processes that facilitate understanding, that appear to be consistent across contexts (Section What We Know About Farmers' Climate Information Needs).

Institutional Arrangements and Processes for Co-production at Scale

Most efforts to bring climate services for the agricultural sector sustainably beyond a pilot scale have involved fostering new institutional arrangements—typically between NMS and various institutions (e.g., government agencies, research, farmer, organizations)—and new collaborative processes for translating, communicating and using climate information for agricultural decision-making. The earliest formal international mechanism to foster sustained interaction between climate information producers and potential users was Regional Outlook Forums (RCOFs), initiated in 1997–98 in Southern, Eastern and West Africa, and currently operational in about 20 regions globally. The initial motivation was to enhance credibility in the face of multiple and sometimes conflicting information sources, by engaging NMS to produce authoritative consensus seasonal forecasts (Dilley, 2001; Patt et al., 2007; Daly and Dessai, 2018). Engagement of user communities through the RCOFs in Africa and most other regions emphasizes downstream transfer of knowledge, and in some cases (e.g., East Africa) co-development of sector-specific outlooks and advisories. Although interest in engaging users in the co-production of services has become widespread since the RCOFs were initiated, this is not apparent in the objectives of most RCOFs, according to a recent analysis (Daly and Dessai, 2018). Consistent with earlier concerns (Basher et al., 2001; Cash and Buizer, 2005; Cash, 2006; Vogel and O'Brien, 2006; Hansen et al., 2007), this analysis of RCOF literature and interviews with participants in the WMO Global RCOF Review workshop (Guayaquil, Ecuador, 5–7 September 2017), concluded that "user engagement within the RCOFs is currently framed quite narrowly, and, in practice, the role of users is often constrained to downstream involvement (i.e., after the forecast has been produced)."

In several countries, national or sub-national working groups composed of representatives of NMS and various user groups, aim to play an intermediary role between national ministry and agencies (including the NMS), and between national information providers and local communities. In response to devastating drought in the West African Sahel in the early 1980s, AGRHYMET initiated *Groupe de Travail Pluridisciplinaire* (GTP), or Multidisciplinary Working Groups, across CILSS member countries as a mechanism to engage meteorologists and agricultural and water resource stakeholders to develop early warning information. Their role of the GTP was extended to produce weather- and climate-based management advisories for farmers, most notably in Mali's Agrometeorological Advisory program (Carr and Onzere, 2016). Other relevant variations include Local Technical Agro-climatic Committees (LTACs) in Colombia and Central America, adapted from the GTP model following South-South exchange visits with Senegal, (Loboguerrero et al., 2018); and multi-stakeholder seasonal planning across Kenya's counties using CARE's PSP process (Ambani et al., 2018).

In principle such working groups could play a valuable "upstream" co-production role by translating farmers' voice into the design of improved climate information products; but in practice they often play the narrower role of engaging agricultural experts to translate NMS products into management advisories for farmers. Exceptions are led or co-led by agriculture sector institutions instead of NMS (Vaughan et al., 2017; Loboguerrero et al., 2018; Ouedraogo et al., 2018) While a few comparative studies attempt to distill generalizable lessons (Orlove and Tosteson, 1999; Tall et al., 2014a; e.g., Kruczkiewicz et al., 2018), their influence on the use of climate information and resulting benefit has not been assessed systematically.

At an international level, the Global Framework for Climate Services (GFCS) supports national governments to develop "national frameworks for climate services" (NFCS): national multi-sector policy frameworks, inter-ministerial and inter-agency institutional arrangements, and processes to support climate services. The GFCS was established as a UN intergovernmental process in 2009, at the Third World Climate Conference, to develop climate services that support climate risk management and adaptation decision-making in the priority areas of agriculture and food security, disaster risk reduction, energy, health and water resources management. With guidance and technical support coordinated by the WMO, the ongoing and expanding development of these national frameworks is a promising entry point for helping countries remove institutional barriers, and formalize co-production processes that bring users' needs and voice into improvements to climate service implementation at a national scale.

Boundary Spanning

Evidence has shown that regular and sustained boundary spanning, by institutions or networks that work at the interface of supply and demand of information to facilitate the exchange of knowledge, can help increase the efficiency by which scientific research is tailored for use for decision-making (Kirchhoff et al., 2015; Buizer et al., 2016; Bednarek et al., 2018). It has also shown to increase the potential for durable decision processes and policy. Boundary spanning can increase the legitimacy (Cash et al., 2003) and social robustness of science, or the degree to which science is accepted among a diverse set of actors and is relevant for societal challenges.

In climate services, boundary spanning is often facilitated by an institution ("boundary organization") or network ("boundary chain") that has expertise and connections with both the climate and sector user communities (McNie, 2012; Scavia et al., 2014; Buizer et al., 2016). Having a broad understanding of the climate service needs of agriculture, and of relevant innovations in communication and climate science (discussed in sections Actionable Climate Information Products to Bridging the Demand and Supply Sides of Climate Services), can position a boundary organization or network to negotiate solutions to constraints on both sides, and hopefully identify and foster communication among the key stakeholders within a country. For example, CCAFS access to both relevant agricultural and climate expertise enabled the Rwanda initiative discussed earlier (Sections Effective Climate Communication Processes and Bridging the Demand and Supply Sides of Climate Services) to engage, and develop capacity for climate services, in both the agriculture sector and the NMS in a balanced and coordinated manner. In Senegal, CCAFS played a brokering role between local agricultural stakeholders and the NMS that led to the development of an expanded suite of climate information products in response to agricultural user needs (Ouedraogo et al., 2018). As relatively neutral actors, external boundary organizations are sometimes able to catalyze communication across institutional silos within a country (Buizer et al., 2016).

Priority Challenges and Opportunities

The growing attention to engaging users in co-production climate services is a positive development for the climate services community. In the context of sub-Saharan Africa, we see signs that co-production efforts have contributed to improved dialog between climate provider and agricultural user communities and improved processes for communicating climate information to communication processes with farmers and other local agricultural decision-makers. In a few cases, including work in Senegal and Rwanda that CCAFS contributes to, the NMS have introduced new climate information products in response. But these are exceptions to the generalization that co-production efforts in Africa have not significantly narrowed the gap between known farmer needs and the information that is routinely available from NMSs.

Co-production has been an integral part of the development of agricultural climate services since long before the term became popular. But a relatively recent effort to develop general principles and guidelines for co-production of climate services is apparent in several recent publications (Wall et al., 2017; Daly and Dessai, 2018; Mamnun et al., 2018; Vincent et al., 2018; Bremer et al., 2019) and projects. With a gap in empirical evidence of the effectiveness and scalability of co-production strategies, these efforts draw heavily on case studies and on co-production experience in other domains.

Despite the increasing research on co-production of climate services, the goal is still often framed narrowly as bilateral relationship between climate science and end-users—farmers in the case of this paper—ignoring the sector-specific research, institutional and policy environments in which those end-users are embedded. In most African countries, the agricultural research community, the agricultural sector ministry and its agencies responsible for research and extension, and a range of other private sector, non-governmental and civil society actors that provide information and services to farming communities are better positioned than the NMS to provide the translation and communication functions of agricultural climate services. Co-production practice cannot be expected to strengthen climate services if it excludes actors who are crucial for the translation, communication and use of those services.

The challenge seems to go beyond choosing the right needs assessment methods, institutional arrangement and processes to support co-production. For co-production to bridge the climate information usability gap, institutions that work with farmers on the communication and use of climate services must have the capacity to effectively and legitimately represent their evolving demand, and climate information providers must be responsive and accountable to those needs. From the literature and shared experience, we see evidence that these two prerequisites are seldom met; that interaction between supply-side and demand-side capacity constraints identified 13 years ago (IRI, 2006) continues to impede the development of effective agricultural climate services in Africa. Addressing these supply- and demand-side capacity challenges (sections Priority Challenges and Opportunities and Priority Challenges and Opportunities) is therefore priority for effective co-production of services that meet African farmers' needs at scale.

At a national level, the GFCS is supporting and guiding governments to develop multi-sector climate service policy and governance frameworks. With technical support from the GFCS Secretariat at WMO and its network of partners, this national climate service framework process offers a window of opportunity and entry point to foster the development of the institutional collaboration; and iterative and accountable feedback, prioritization and planning processes that are needed to sustainably bring farmers' needs and voice into incremental co-production of improved climate services.

DISCUSSION AND CONCLUSION

Given the foundational role that climate information plays in informing any adaptation intervention, efforts to accelerate adaptation to meet the scale of the challenge rightly look to climate services as one part of the solution. Most sub-Saharan African countries benefit from more than two decades of concerted research and investment in climate services. Yet investment and innovation in the production, translation and communication of climate information, and growing attention to co-production of services, have not narrowed the gap between farmer needs and the information that is routinely available from most NMS in sub-Saharan Africa to the extent that the climate challenge requires. We find evidence that the main conclusion of an assessment of the state of climate services in Africa 13 years ago (IRI, 2006) still holds: A few key weaknesses in the provision of climate information, and in efforts to deliver climate services to farming populations, continue to reinforce each other and impede progress toward meeting farmers' climate service needs at scale.

Our current understanding of agricultural climate service good practice, and key impediments to implementing good practice at scale, suggest that a few priority actions would go far in overcoming persistent obstacles, and help position climate services to support the adaptation of smallholder agriculture to a variable and changing climate at scale across sub-Saharan Africa. The first three focus on the responsiveness of climate information providers to the needs of smallholder agriculture.

First, to move beyond the constraints of the tercile convention, we recommend that NMS and the RCOFs transition to providing seasonal forecasts as full forecast distributions, statistically downscaled onto and presented with the corresponding local climatological distributions. The RCOFs and the Regional Climate Centers that support them are positioned to take the lead in demonstrating, evaluating and supporting countries to implement these improvements. ICPAC, AGRHYMET and the NMS of Rwanda and Ethiopia have introduced new online seasonal forecasts in this form, alongside their conventional tercile forecasts.

Second, we recommend expanding the use of data merging to fill gaps in historical meteorological records, and use of the resulting high-resolution merged data sets as a foundation for the generation of expanded suites of localized historical, monitored, forecast, and value-added climate information products that meet recognized needs of agricultural decision-makers. The ten African NMS that have already developed high-resolution gridded climatological datasets and at least basic online Maproom products, at the time of writing, demonstrate the feasibility of providing locally relevant climate services at scale despite gaps in the historical record.

Third, we recommend strengthening efforts to promote national data policy to make meteorological data freely available and accessible as a public good and a resource for development. Awareness of the growing climate threat, and efforts to incorporate climate adaptation and resilience into national sector policies, might provide an opportunity to reframe the NMS funding question from the cost of investing in data to the opportunity cost of failing to use data to support adaptation priorities, particularly if supported by credible economic analyses of the tradeoffs between the revenue value vs. the development and adaptation value of data. A more incremental solution might be for a ministry of agriculture or of another climate-sensitive sector to fund the NMS to provide data as a public good component of climate services.

Fostering NMS to adopt practices that reduce the usability gap for farmers requires a combination of increased "push" from WMO and the climate research community, and increased "pull" in the form of more effective expressions of demand from Africa's agriculture sector. The next two priorities focus on those development organizations, researchers, and national communication intermediaries that work on the demand side of agricultural climate services.

Fourth, we recommend that researchers and organizations who work on the demand side of climate services organize as a community of practice to more effectively share knowledge, coordinate action, develop quality standards, mobilize resources and influence the supply side of climate services. While we are not aware of any international or national professional society or organization that has this aim, the Climate Services Partnership (CSP), which convenes and supports the climate services community through its International Conferences on Climate Services, is a potential entry point at a global level. But an intentional effort is needed to articulate a strategy, convene the major institutional actors and researchers, and champion and coordinate action around these objectives.

Fifth, we recommend a collaborative initiative, among those organizations and researchers who are working to improve the communication of climate information to farmers, to compare and assess the strengths and limitations of existing communication processes and associated training materials; and use the resulting learning to strengthen these processes and materials. Objectives would include increasing the accessibility of the various communications approaches and materials e.g., through an online compendium, identify innovations in some approaches that would address weaknesses in others, and reorient communication processes to the types and formats of information products that would best meet farmers' needs. The process could be initiated at a future International Conference on Climate Services, and facilitated by the Climate Services Partnership.

Our sixth recommendation is to use the national climate services framework process, facilitated by the GFCS through WMO, to promote and guide the development of institutional arrangements and governance processes that bring farmers' evolving understanding of their needs into iterative, accountable co-production of improved climate services. With its role in supporting and guiding national governments to develop multi-sector, inter-agency climate service policy and governance frameworks, the GFCS is positioned to help advance institutional structures to support the co-production of climate services at a national scale.

Addressing a few key gaps in knowledge and evidence would support widespread adoption of improved agricultural climate services in Africa and elsewhere, although the recommended actions do not depend on new research. Key questions include: How can farmers' evolving information needs best be identified, aggregated, and prioritized to inform incremental improvements to climate services? What is the added value of improved improving climate information products for agriculture and the opportunity cost of restrictive meteorological data, to the agricultural sector and farmer livelihoods? How can communication channels best be combined to support climate services for farmers at a national scale, and what are the tradeoffs between reach and impact?

Growing recognition of the urgency of the climate challenge calls for a fresh look at the current state of climate services in Africa relative to what we know about farmers' needs, and opportunities internationally and at a national level to address longstanding obstacles to better aligning climate services with the needs of farmers and the institutions that support them. We have aimed to contribute to this discussion, by addressing the scalability of what we understand to be good practice for meeting farmers' needs, and by highlighting the need to address longstanding and interacting constraints on the supply and demand sides of agricultural climates services in a balanced and coordinated manner.

AUTHOR CONTRIBUTIONS

JH led development of the paper and overall framing, and coordinated and integrated coauthor input. Coauthors contributed specific topics and case studies. TD on building NMS capacity through the ENACTS approach, DK on scaling in Rwanda, RZ on scaling in Senegal, EC on understanding farmers' needs and constraints, CV on co-production processes. CV, EC, and JK provided input on the structure, framing, and context within the literature throughout the manuscript.

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