7-1-2019

Evaluating Agricultural Weather and Climate Services in Africa: Evidence, Methods, and A Learning Agenda

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Received: 19 December 2017 | Revised: 7 March 2019 | Accepted: 27 March 2019

DOI: 10.1002/wcc.586

ADVANCED REVIEW

WIREs CLIMATE CHANGE WILEY

Evaluating agricultural weather and climate services in Africa: Evidence, methods, and a learning agenda

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Edited by Timothy R. Carter, Domain Editor, and Mike Hulme, Editor-in-Chief

Abstract

Weather and climate services (WCS) are expected to improve the capacity of Africa's agricultural sector to manage the risks of climate variability and change. Despite this, a lack of evidence prevents a realistic analysis of whether such services are delivering on their potential. This paper reviews 66 studies that have evaluated outcomes and/or impacts of agricultural WCS in Africa, highlighting areas that have received relatively more attention as well as persistent gaps. While the evaluation of WCS outcomes is relatively straightforward, estimates of the number of people who access and use these services are uneven (covering a small number of communities in 23 of 54 African countries) and highly variable (with access estimates ranging from ~2 to 86%, depending on the service and the population). Meanwhile, 22 documents estimate the impact of WCS with respect to yields and/or income. Developed with a variety of methods, these estimates are also wide ranging and illustrate how impact is conditioned on a number of characteristics of the service, the user, and the context in which both operate. The paper uses lessons developed through this review to develop a "learning agenda," or evidence-building roadmap, to establish priorities that can guide work to improve the design, delivery, and impact of agricultural WCS in Africa. Priority learning areas include activities that can strengthen the evidence of access, use, and impacts of WCS, along with those that can advance the use and usability of evidence so as to improve the design and targeting of WCS services.

This article is categorized under:
- Assessing Impacts of Climate Change > Evaluating Future Impacts of Climate Change
- Vulnerability and Adaptation to Climate Change > Learning from Cases and Analogies

KEYWORDS

Africa, agricultural development, agriculture, climate services, evaluation, evidence-based decision making, impact, outcome, weather services

1 | INTRODUCTION

Agriculture plays a critical role in most African economies and among the livelihood strategies of a majority of Africans (Collier & Dercon, 2014). Yet African agriculture is marked by low productivity, low levels of investment, and high levels of weather and climate-related risk (Sonwa et al., 2016). Weather and climate services (WCS), which involve the production, translation, transfer, and use of scientific information for decision-making, are expected to improve the capacity of Africa's agricultural actors to manage the risks associated with climate variability and change—and, in so doing, to transform investment in this important sector. As such, agricultural WCS stand to play a critical role in Africa's efforts to meet the Sustainable Development Goals, including those that pertain to poverty (SDG1), hunger (SDG2), health (SDG3), gender equality (SDG5), responsible consumption and production (SDG12), and climate action (SDG13) (Campbell et al., 2014).

Given the degree to which weather and climate shape agricultural production, a great deal of research has explored the relationship between weather, climate, and African agriculture (Calzadilla, Zhu, Rehdanz, Tol, & Ringler, 2013; Knox, Daccache, & Wheeler, 2012; Kotir, 2011; Schlenker & Lobell, 2010; Ziervogel et al., 2014). Research has also focused on: the kinds of weather and climate information that can inform agricultural decision making (Hansen, Mason, Sun, & Tall, 2011; Sheffield et al., 2014; Stern & Cooper, 2017); the quality of existing weather and climate information (Landman & Beraki, 2012; Landman, DeWitt, Lee, Beraki, & Lotter, 2012); and the ways in which African farmers can use such information to improve their livelihoods (Cooper et al., 2008; O'Brien, 2000). Despite this, evidence regarding the effectiveness of agricultural WCS in Africa lags these other fields.

This evidence gap can be traced in part to the unique history of the WCS communities, originally dominated by scientists with more experience evaluating the quality of weather and climate information than in understanding the impact of its use (McNie, 2013). Even as the number and diversity of actors interested in this information has grown—including through the Global Framework for Climate Services, which was formally implemented by the World Meteorological Organization in 2012—a number of challenges complicate the evaluation of WCS, thwarting the efforts of skilled evaluators and tempting information providers to defer evaluation, or to rely on more easily tracked but less meaningful metrics including web traffic, workshop participants, and peer-reviewed papers (Meadow et al., 2015) (Box 1).

This lack of objective evidence has prevented the community from developing a more complete understanding of the role that climate services can and do play in African agricultural development. How and to what extent do farmers access and use weather and climate information to inform their decisions? What impact do WCS have on farmers' livelihoods and on agricultural development goals? How do particular aspects of the design and implementation of WCS influence their effectiveness? Were they available, convincing answers to these questions could be used to improve the implementation of existing services; support adequate investment of public funds in National Meteorological Services; inform the appropriate balance of investment in the production, translation, transfer and use of climate information (World Meteorological Organization, World Bank, & United States Agency for International Development, 2015); and shape the role that WCS play in national adaptation and climate finance plans, among other things.

To guide efforts to generate the evidence that can meet these needs, our paper develops a "learning agenda" for the evaluation of agricultural WCS in Africa. We begin by defining terms and describing the state of agricultural WCS in Africa (Section 2). Section 3 details the methodology used to guide our review. Section 4 reports on (Collier & Dercon, 2014) that state of evidence regarding the access, use, and impact of WCS in Africa's agricultural sector and (Sonwa et al., 2016) the methodological approaches that have been used to develop this evidence. After considering these threads separately, the paper brings them together in Section 5, where evidence and methodological gaps are synthesized, before developing a "learning agenda" in Section 6. The learning agenda is designed as a roadmap to prioritize areas where additional work holds the most potential to advance our understanding of how WCS can and do contribute to improved agricultural outcomes in Africa.

2 | BACKGROUND

2.1 | Agricultural WCS in Africa

A number of factors have contributed to a growing interest in the development and use of weather and climate information for agricultural decision making in Africa. In 1994, a study by Cane, Eshel, and Buckland (1994) showed that maize yields in Zimbabwe were more strongly correlated with Pacific sea surface temperatures, a feature of the El Niño Southern Oscillation, than with seasonal total rainfall in Zimbabwe itself. Three years later, the public visibility of a strong El Niño event (1997/1998) prompted a surge of field research on the potential use and value of seasonal forecasting for Africa, with a

BOX 1 TERMINOLOGY

While terms can be used differently across disciplines, this paper uses the following definitions (adapted from World Meteorological Organization, World Bank, & United States Agency for International Development (2015)):

Evaluation is a structured process designed to generate information about a program, with the purpose of informing judgments about and/or improving the program.

Evaluations can be ex ante or ex post:

Ex ante evaluation (often termed *appraisal*) analyzes the anticipated impacts of the program, using models and/or stated preference methods to forecast value and/or potential impact. In full ex ante appraisal, this can be extended to consider the possible options and select the preferred design.

Ex post evaluation is conducted after a project is complete, documenting the lasting benefits associated with actual use

Evaluations can focus on outputs, outcomes, and/or impacts:

Output: the result of a project (i.e., the existence of information tools, products, or services)

Outcome: the degree to which an intervention leads to a change in knowledge or behavior (i.e., reported changes in access to or use of climate services)

Impact: the degree to which outcomes lead to changes in welfare (i.e., increased agricultural outputs, increased efficiency, reduced losses, etc.)

A variety of methods can be used to collect and analyze evaluative evidence:

Household surveys quantitatively and/or qualitatively sampling individual units of a population

Facilitated *focus groups* allow evaluators to get a sense of a range of opinions and experiences

Interviews provide an opportunity to gather in-depth evidence one-on-one with individuals

Participatory processes structure evidence gathering through group activities

Contingent valuation is a survey-based technique used to ascertain willingness to pay for services

Descriptive statistics describe or summarize data regarding access, use and/or impact

Inferential statistics allow for generalizations about the populations from which samples are drawn

Benefit transfer methods transfer estimates developed in one context to another context, as a substitute for developing entirely new estimates

WCS provide scientific information for decision making

Weather services provide weather forecasts and warnings about hazardous conditions; they may include storm warnings, daily, 3-day, and 10-day (dekadal) forecasts, and so on.

Climate services involve the provision of climate information in a way that assists decision making by individuals or organizations; they may include seasonal outlooks, drought forecasts, agroclimatic bulletins, and so on.

particular focus on smallholder agriculture. Coincidentally, Regional Climate Outlook Forums (RCOFs) were initiated in Southern, East and West Africa the same year, though planning had been initiated before the El Niño event was anticipated (Gerlak et al., 2018).

As interest in WCS has grown, so too has the capacity of African actors to provide them. Most national meteorological services in Africa now provide seasonal rainfall forecasts, monthly climate outlooks, agrometeorological bulletins, and extreme weather alerts (Kadi, Njau, Mwikya, & Kamga, 2011a, 2011b); 15 African countries regularly share agrometeorological bulletins through the World Agrometeorological Information Service (World Agrometeorological Information Service, 2019). Of the 17 sub-Saharan meteorological services that responded to an email survey in 2010, most reported adding value to RCOF forecasts by including additional information (e.g., start and duration of the rainfall season, rainfall frequency or distribution), though only two reported making historical observations freely available. Most also reported proactively serving farmers and other agricultural stakeholders, with the nature of the partnerships and the communication channels used to do so varying by country (Hansen et al., 2011).

African WCS have also benefited from support of the Global Framework for Climate Services, an outcome of the third World Climate Conference. For instance, support from the GFCS prioritized African efforts to develop national climate service policy frameworks and action plans; this has included Benin (Meteo-Benin, 2017), Chad (Ministere du Developpement aeronautique et de la Meteorologie Nationale, 2016), Cote d'Ivoire (Ministre des Transportes, Direction de la Meteorologie

Nationale, 2016), Malawi (MetMalawi, 2014), Mali (Republique du Mali, 2016), Senegal (Republique du Senegal, 2016), and South Africa (Republic of South Africa, 2016), among other countries.

Within this context, a number of development organizations have come to see climate services as a practical way to advance climate adaptation and resilient development goals in Africa. Significant recent initiatives include: ClimDev-Africa (African Development Bank, Africa Union Commission, and UN Economic Commission for Africa); the World Bank's Africa Hydromet Program; DfID's Weather and Climate Information Services for Africa program; CGIAR research program on Climate Change, Agriculture and Food Security (CCAFS); and sizeable projects implemented with support from the Green Climate Fund and bilateral donors (DfID, NORAD, SIDA, USAID, German Federal Ministry of Education and Research).

While there is no comprehensive inventory of agricultural WCS in Africa, a 2017 regional coordination event organized by GFCS (World Meteorological Organization, 2017) was a step toward capturing and sharing knowledge.

2.2 | Challenges of WCS evaluation

The evaluation of WCS should not be confused with the evaluation of weather and climate information; while the latter assesses the quality of the information itself (e.g., data quality control, forecast verification), the former is primarily concerned with (Collier & Dercon, 2014) documenting the extent to which potential users are able to access and use services (Sonwa et al., 2016) estimating the actual or potential impact and/or value services; and (Campbell et al., 2014) identifying those elements of design and implementation that lead to better outcomes with respect to Collier and Dercon (2014) and Sonwa et al. (2016).

Several characteristics of WCS impose challenges to evaluation (Tall, Coulibaly, & Diop, 2018). First, the nonrival, nonexclusionary nature of WCS means that information can easily be passed along social and family networks. At the same time, however, the information transferred through informal networks may be incomplete or distorted. This makes it difficult to distinguish between those who receive the service and those who do not, complicating efforts to identify a control sample that does not have access to the information, as required for a randomized control trial.

Second, because of the stochastic nature of the climate, the use, impact and even the mechanism of impact, can vary considerably from year to year. The number of years required to sample the range of variability, and hence provide reliable estimates of use and impact, can be expected to exceed a typical project cycle. Furthermore, climate conditions during project baseline and end-line surveys may confound cumulative indicators of impact, making it difficult to distinguish between benefits of the service, and the influence of climatic conditions in the baseline and evaluation years.

Third, the impact of climate information comes through changes in management decisions, which are also influenced by other agricultural development interventions, and by farmers' varying goals, skills and constraints. Information has no intrinsic economic value. The fact that weather and climate information is one of many interacting factors that influences decisions and determines livelihood impacts makes it difficult to isolate the relative contribution of WCS. It also means that causal pathways between access to climate information and livelihood impact can vary among farmers. While not unique to WCS, this is a particular concern when the evaluation calls for input from farmers who may not be comfortable discussing the nature of their productivity or economic performance. Even in cases in which farmers are willing to report, they may be unable to correctly estimate harvests or production costs; they might also prefer to over- or underestimate harvests, if they perceive that those estimates might lead to some potential gain (e.g., food aid).

3 | METHODS

This paper reviewed documents (the vast majority of which were in English, though some were in French; e.g., Ngana, Maina Ababa, Gapia, & Kossi, 2013) that provide evidence of access, use, and impact of agricultural WCS in Africa. Documents were identified with online searches using Web of Science and Google Scholar (see Table 1), and by requests made within the authors' professional networks, including as part of two sessions at the fifth International Conference on Climate Services, held in Cape Town, South Africa in 2017, and at the Adaptation Futures Conference held in Cape Town in 2018.

Papers were included in the study if they generated qualitative or quantitative evidence that addressed one or more of the following criteria:

1. documenting the extent to which potential users are able to access and use services;
2. estimating the actual or potential impact and/or value of services; and
3. identifying those elements of design and implementation that lead to better outcomes with respect to (1) and (2)

TABLE 1 Search terms and the number of papers reviewed; given the large number of papers returned through Google Scholar, only the first 150 papers were reviewed from each search

Search engines	Total number of papers Web of Knowledge		Google Scholar		
Search terms	**Returned, reviewed**	**Included in study**	**Returned**	**Reviewed**	**Included in study**
Agriculture/* climate services Africa	529	5	~1,220,000	150	6
Agriculture/* weather services Africa	137	9	~303,000	150	2
Evaluation climate services Africa	139	3	~1,160,000	150	6
Evaluation weather services Africa	32	0	~215,000	150	3
Climate information agriculture Africa	1,042	20	~1,954,000	150	13
Weather information agriculture Africa	235	15	~439,000	150	4

Note. Many papers turned up in more than one search.

To ensure the review was focused on issues of access, use and impact, studies that verified climate and/or production forecasts (Bezuidenhout & Schulze, 2006) without exploring the impact of actual or potential use of those forecasts, were not included. Studies that explored potential users and uses of information, whether qualitatively or quantitatively, were also not included, though they are considered in depth in a separate review paper (Carr, Goble, Rosko, Vaughan, & Hansen, 2017). Studies that focused only on the use of traditional, rather than scientific, weather or climate indicators were also not included.

Both peer-reviewed and gray-literature studies were included regardless of whether documents were originally intended as program evaluations or not.

The evaluations described in each paper were analyzed with respect to region; country; number of individuals surveyed; type of weather or climate information provided; estimates of access; estimates and descriptions of use; estimates of impact; implementation and design factors identified or surveyed; and evaluation methods. This analysis allowed the authors to describe (Collier & Dercon, 2014) the current state of evidence and (Sonwa et al., 2016) the methods used to generate that evidence, detailed and interpreted below.

4 | RESULTS

The review resulted in 66 studies, which were conducted in 23 African countries over a span of 40 years. Studies were concentrated in West (27/66), East (22/66), and Southern (22/66) Africa (note some studies include more than one location); the review found just one study in Central Africa and one in North Africa that met our criteria. Even in regions where evaluations were relatively more common, certain countries (e.g., Burkina Faso, Kenya, Tanzania, Ethiopia, Zimbabwe) turned up frequently, while other countries (e.g., Angola, Eritrea, Cote d'Ivoire, Gambia) were not represented at all. The vast majority of studies evaluate services that were built on forecast information at weather, subseasonal, or seasonal climate time scales, or were ambiguous with regards to the kind of information that was provided. Roughly 80% of the documents included in the study were published in scientific journals; only one was published as a book chapter, and 15 were project outputs or case studies. All documents are available online. Information regarding the geographical scope of these studies is presented in Figure 1. A full list of documents is found in Appendix A.

This section first presents the evidence base generated by these studies before considering the methodologies used to generate that evidence.

4.1 | Evidence

Evaluation efforts have generated evidence regarding the access, use, impact, and design of climate services; while evidence remains somewhat limited, particularly in certain regions, the evidence that does exist seems to indicate that WCS are more accessible in certain regions than in others; that when available, services are used more frequently by farmers than pastoralists; and that the impacts associated with WCS depend on a number of factors related to design, targeting, and implementation.

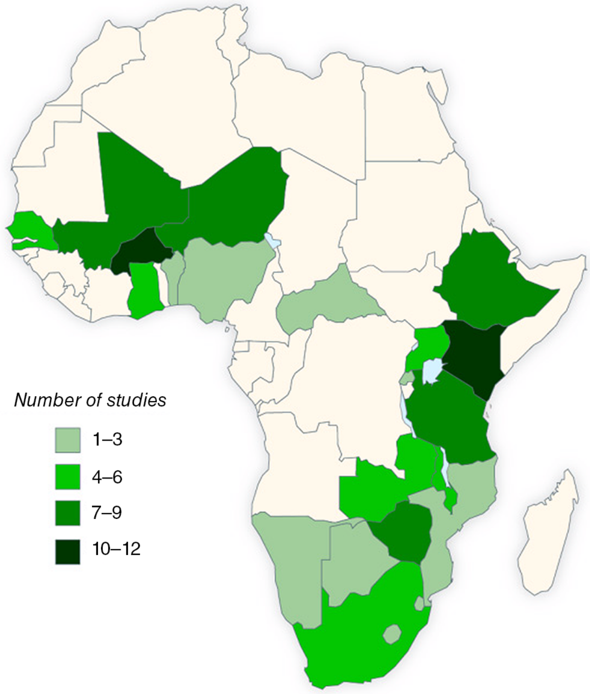

FIGURE 1 The geographical scope of the WCS evaluation studies included in the review. WCS, weather and climate services

4.1.1 | Variable access to information

The evidence indicates that Africans' access to WCS varies based on region, livelihood strategy, demographic characteristics, and information type.

In East Africa, for instance, studies in Kenya, Ethiopia, Tanzania, and Uganda estimate the number of certain populations that are able to access WCS in the range of 15–82%, with lower estimates for pastoralist versus farming communities and some indication that men are more able to access climate information than women (Daly, West, & Yanda, 2016; Lybbert, Barrett, McPeak, & Luseno, 2007; Ngugi, Mureithi, & Kamande, 2011; Oyekale, 2015). In Southern Africa, estimates in Malawi, Mozambique, Namibia and Zimbabwe range from 27 to 86%, with an indication that radio is the primary source by which farmers access weather and climate information (Coulibaly, Kundhlande, Tall, Kaur, & Hansen, 2015; Mudombi & Nhamo, 2014; Mulwa, Marenya, Bahadur, & Kassie, 2017; O'Brien, 2000; Zamasiya, Nyikahadzoi, & Mukamuri, 2017; Zuma-Netshiukhwi, Stigter, & Walker, 2013). Evidence also suggests that weather information is more accessible than seasonal forecasts in this region (Lazo, 2015).

There is some indication that WCS may be more accessible in East and Southern Africa than in West Africa, though evidence is mixed (Limantol, Keith, Azabre, & Lennartz, 2016; Oyekale, 2015; Zongo et al., 2016). One West African study comprising Mali, Burkina Faso, Niger, and Nigeria found that 70% of 566 surveyed households were aware of and able to access climate information (Tarhule & Lamb, 2003), though more recent studies have presented somewhat lower numbers. In Burkina Faso, for instance, Zongo et al. (2016) found 22% of sampled farmers ($n = 629$) had access to climate information, while Rasmussen, et al. (2014) found a minority of Burkinabe herders ($n = 61$) had access to weather forecasts (30%), flood information (6–13%), and seasonal climate forecasts (SCFs) (7%) (Rasmussen et al., 2014; Zongo et al., 2016). Oyekale (2015) sampled 701 farmers in five West African countries, finding that slightly more than half were able to access climate information.

While just one study considers access in Central Africa, it finds only 2% of farmers in the Central African Republic have access to any kind of meteorological information (Ngana et al., 2013). A summary of access estimates is found in Table 2. More detailed information regarding access estimates is found in Appendices B–D.

4.1.2 | Differing levels of use

Evidence regarding the use of agricultural WCS varies based on livelihood strategy, among other things (see Table 3). In fact, many studies find evidence that a majority of *farmers* use WCS when they are accessible. Averaging across six documents that provide sufficient information to calculate the rate of use of SCFs by farmers who report accessing such forecasts, the rate

TABLE 2 Regional summary of estimates of access to agricultural WCS found in the literature

	Countries	Samples	Estimate range (%)	Key references
Central Africa	Central African Republic	315 individuals surveyed	2	Ngana et al. (2013)
East Africa	Kenya, Tanzania, Uganda, and Ethiopia	3,088 individuals surveyed; 122 interviews; 23 focus groups	15–82	Coulibaly et al. (2015), Daly et al. (2016), Deressa, Hassan, Ringler, Alemu, and Yesuf (2009), Egeru (2016), Gebrehiwot and van der Veen (2013), Ngugi et al. (2011), and O'Brien (2000)
Southern Africa	Mozambique, Malawi, Namibia, South Africa Zimbabwe	4,144+ individuals surveyed; 46 interviews	27–86	Lazo (2015), Mudombi and Nhamo (2014), Mulwa et al. (2017), O'Brien (2000), Patt, Suarez, and Gwata (2005), Zamasiya et al. (2017), and Zuma-Netshiukhwi et al. (2013)
West Africa	Benin, Burkina Faso, Ghana, Mali, Niger, Senegal, Nigeria	2,545 individuals surveyed; 192 interviews; 144 focus groups	5.6–75	Amegnaglo, Asomanin, and Mensah-bonsu (2017), Carr et al. (2014), Limantol et al. (2016), Ouedraogo, Diouf, Ouédraogo, Ndiaye, and Zougmoré (2018), Oyekale (2015), Rasmussen et al. (2014), Roncoli et al. (2009), Roncoli, Ingram, and Kirshen (2002), Tarhule and Lamb (2003), and Zongo et al. (2016)

Abbreviation: WCS, weather and climate services.

of use is found to be 74% (Amegnaglo et al., 2017; Coulibaly, Kundhlande, et al., 2015; O'Brien, 2000; Patt et al., 2005; Roncoli et al., 2009). Aggregating across the range of information products, management response, locations and social groups in the 14 studies that provide sufficient information to calculate aggregate use rates for any type of WCS found that the majority of farmers who access WCS use the information to adjust a range of management decisions, as illustrated in Appendix E. These studies document farmers' application of weather and climate information to a range of decisions, including those regarding the choice of fields, crops, and/or crop varieties; the timing of agricultural tasks; the application of inputs, and the negotiation of annual loans (Egeru, 2016; Lo & Dieng, 2015; Mudombi & Nhamo, 2014; Patt et al., 2005; Phillips, Deane, Unganai, & Chimeli, 2002; Rao, Hansen, Njiru, Githungo, & Oyoo, 2015; Roncoli et al., 2002, 2009; Tarhule & Lamb, 2003).

TABLE 3 Summary of work evaluating the use of WCS, including the information and decisions most commonly explored, as well as the sample and key references by group and region

	Information type	Key decisions	West Africa	East Africa	Southern Africa
Farmers	Daily weather info; seasonal forecasts; drought; rainfall onset; pests	Choice of field; crop selection; crop variety; timing of farm activities; water conservation; stocking decisions;	3,201 individuals surveyed; 134 focus groups; 159 interviews; 32 test plots; 3 workshops (Carr et al., 2014; Ouedraogo et al., 2018; Zongo et al., 2016)	3,468 individuals surveyed; 73 interviews, 4 focus groups (Oyekale, 2015; Stats4SD, 2017)	3,186+ individuals surveyed; 46 interviews (Klopper, 1999; Mudombi & Nhamo, 2014; Mulwa et al., 2017)
Pastoralists	Flood forecasts; grazing; rainfall onset; sub-seasonal forecast; extreme events;	Stocking; shifting livestock; selling firewood; seeking military escort to grazing areas; purchasing veterinary drugs;	61 individuals surveyed; 8 focus groups; 15 interviews (Rasmussen et al., 2014; Roncoli et al., 2002)	1,023 individuals surveyed, 79 interviews (Egeru, 2016; Lybbert et al., 2007; Ngugi et al., 2011)	—
Organizations	SCFs	Food security planning	22 individuals surveyed (Tarhule & Lamb, 2003)	33+ interviews (Broad & Agrawala, 2000)	—

Abbreviations: WCS, weather and climate services; SCF, seasonal climate forecast.

Working with Malian farmers, Carr et al. (2014) and Carr and Onzere (2017) found that farmers' use of climate information was dependent on the roles and responsibilities associated with particular identities, primarily seniority and gender. Contrary evidence was found in Malawi, where a roughly equal number of male and female farmers ($n = 320$) report having access to climate information, but not using it—relying instead on indigenous knowledge and personal experience, which they perceive as more reliable and more relevant to local decision making (Coulibaly, Kundhlande, et al., 2015). The current review found no evidence that farmers use climate information to make costly investments (e.g., irrigation or agroforestry), a finding that is supported by work in Ethiopia and South Africa (Bryan, Deressa, Gbetibouo, & Ringler, 2009).

While evidence indicates that farmers use WCS in a variety of circumstances, *pastoralists'* use of WCS appears more limited. In documenting the use of forecasts among herders of southern Ethiopia, for instance, a 2016 study found that most (96%, $n = 200$) rely on traditional, rather than scientific, forecast information (Egeru, 2016). An earlier study found that a majority of Kenyan and Ethiopian pastoralists ($n = 323$) did not use SCFs—a finding the authors attributed to the relatively large number of mid-season decisions that allowed herders to cope with unfavorable conditions as they developed, rather than in advance (Luseno, Mcpeak, & Barrett, 2002).

This is corroborated by studies that show that fewer types of information are useful to pastoralists, who face a very different suite of decisions than farmers. A 2014 study found that Burkinabe pastoralists ($n = 61$) were inclined to make changes to herd management based on information regarding the availability of grazing (75%); onset date (6–53%); and rainfall during the first 2 weeks of the rainy season (17%)—though they did not adjust herding practices in response to seasonal forecasts (Rasmussen et al., 2014). In Uganda, pastoralists ($n = 198$) reported using information on onset and drought to make decisions regarding shifting livestock to new grazing areas; seeking military escorts to those areas; selling firewood and charcoal; and purchasing veterinary drugs (Egeru, 2016).

More detail regarding access and use estimates is found in Appendices B–E.

4.1.3 | Context-dependent impacts

Evidence regarding the impact and potential impact of agricultural WCS on yields and/or incomes is generally positive—though also relatively varied, depending on the context, climate, and crop, as well as the type and accuracy of the information in question (see Table 4).

In Burkina Faso, for instance, evidence indicates that on-farm gains associated with the use of seasonal forecasts increased monthly cereal production (Zongo et al., 2016)**.** Similarly, Ouédraogo et al. (2015) report that Burkinabé cowpea farmers ($n = 170$) with climate information showed higher yields than those without information (an average of 847 kg/ha compared to 685 kg/ha); information recipients were shown to have made decisions that resulted in savings in seed and pesticides, resulting in gross margin gains of 66% above the control group. The same study found that sesame farmers provided with climate information had slightly lower yields (550 kg/ha compared to 605 kg for the control group) and lower margins, as the information prompted an increased investment in fertilizer that did not lead to significant returns (Ouédraogo et al., 2015).

Also in West Africa, Roudier et al. (2014) modeled (ex ante) the introduction of seasonal and 10-day forecasts in Senegal: their modeling findings indicate farmers who used both types of information were likely to experience yield gains in roughly one-third of the cases; this study also estimated that impacts vary according to the nature of rainy season, the accuracy of the forecast, and the type of response.

Reporting on the results of a multi-year project in Southern Africa, Patt et al. (2005) found that Zimbabwean farmers ($n = 578$) who used seasonal forecasts showed a small, insignificant difference in yields in the first year, and a larger and marginally significant difference in the second year.

In 2004, Thornton et al used a bio-economic modeling approach to show that commercial ranchers who consistently used seasonal forecasts over 25 years were likely to experience considerable benefits (~$85,000, adjusted to 2018 USD), though at the cost of increased variability in year-to-year income (Thornton et al., 2004). A modeling study of the potential impact of SCFs in Lesotho found that while the use of forecast information had the potential to improve outcomes for marginal households, forecasts with poor skill were more likely to be associated with negative impacts (Ziervogel et al., 2005); a companion study found that the timescale of adoption for seasonal forecasts is likely to be very long (Bharwani et al., 2005).

In East Africa, Anuga and Gordon looked at the relationship between agricultural outcomes and the employment of "climate resilient" strategies in Ethiopia; they found that receiving training in the use of weather information had the greatest influence on yield (17% increase) (Anuga & Gordon, 2016). Barrett and Ndegwa (2016), working in Kenya, found that farming households with access to local advisories and seasonal forecasts had consistently higher income levels. Also in Kenya, an ex ante modeling study conducted by Hansen et al. (2009) found that that seasonal forecasts based on a general circulation

TABLE 4 Ex post and ex ante estimate of impact of agricultural WCS as found in the literature

Country	Impact estimate	Information type	Approach	References
Burkina Faso	Cowpea farmers, gross margin is greater (66%) for climate-aware farmers	SCF	Ex post	Ouédraogo, Zougmoré, Barry, Somé, and Grégoire (2015)
Ghana	Farmers trained to access info increased yam yield by 17%. 21% of variation on maize yield caused by use of weather info	weather forecasts	Ex post	Anuga and Gordon (2016)
Kenya	Perfect knowledge of daily weather worth ~24–69% of avg gross margin, GCM predictions based on ob SST increased avg gross margins 9–24%	SCF	Ex ante	Hansen et al. (2009)
Kenya, Malawi, Mozambique, Tanzania, Zambia	Adopted by all farmers, SCF generates avg regional income gains of US$113 million/year (US$317 million/year perfect info)	SCF	Ex ante	Rodrigues et al. (2016)
Malawi, Tanzania	Evaluation of climate service intervention in the GFCS Adaptation Programme for Africa	Weather forecasts, participatory tools, agroadvisories	Ex post	Stats4SD (2017)
Mali	Maize yields experienced by farmers using agromet information vary from control group by −9 to +105%, depending on location	weather forecasts; SCF; 10-day agromet bulletin	Ex post	Hellmuth, Diarra, Vaughan, and Cousin (2011)
Mauritania	Sorghum yields increased by 64%; increased benefit of ~ $260 (USD) per season	weather forecasts; SCF; 10-day agromet forecast	Ex post	Tarchiani, Camacho, Coulibaly, Rossi, and Stefanski (2018)
Niger	10-days forecasts alone, or with SCFs, beneficial for all types of farmers; those w more land and fertilizer benefit more.	10-day forecasts, SCF	Ex ante	Roudier, Alhassane, Baron, Louvet, and Sultan (2016)
Niger	Yield increase is lowest imperfect tercile forecasts (+6.9%), higher (+11%) with perfect tercile forecasts, and highest (+31%) when adaptation strategies and additional climatic indices are available	SCFs, advice, climate indices	Ex ante	Roudier et al. (2011)
Senegal	Forecast use associated with gains in crop yields in 62 of the 177 cases, with losses in 22 cases	10-day forecasts, SCF	Ex ante	Roudier et al. (2014)
Senegal	When a dryer-than-average rainy season is predicted, forecasts yield an increase of the farmers' income—13.8% for statistical model and 9.6% for DEMETER ensemble mean	SCF	Ex ante	Sultan et al. (2010)
Senegal	Test farm led to increase in yield by roughly 15–50%	SCF; 10-day; daily forecasts;	Ex post	Lo and Dieng (2015)
South Africa	Over 25 years, the accumulated impact of livestock stocking was estimated at 500,000 (2001 Rand)/~ $85,000 (2018 USD)	SCF	Ex ante	Thornton et al. (2004)
South Africa	Unless forecasts are accurate 60–70% of the time, positive benefits are unlikely	SCF	Ex ante	Ziervogel, Bithell, Washington, and Downing (2005)
South Africa	Over 99 years, and when SCF are 65% accurate, well-off farmers experience cumulative annual household income of ~$11,000 (2018 USD); poor farmers who use the forecast go bankrupt after 15 years	SCF	Ex ante	Bharwani et al. (2005)
Zimbabwe	Farmers who used SCF significantly improved harvests over baseline amounts	SCF	Ex post	Patt et al. (2005)
Zimbabwe	Long-term mean production could increase in the presence of forecasts, production volatility also shown to increase	SCF	Ex post, ex ante	Phillips et al. (2002)

Abbreviations: SCF, seasonal climate forecast; WCS, weather and climate services.

TABLE 5 Willingness to pay (WTP) for seasonal climate forecasts (SCF), adjusted to 2017 USD, from studies included in the review

Country	Sample size	Average WTP for SCFs (2017 USD)	References
Benin	354 farmers, 18 villages	$13.52	Amegnaglo et al. (2017)
Burkina Faso	629 farmers, 11 villages	$1.19	Zongo et al. (2016)
Burkina Faso	170 farmers, 11 villages	$15.36	Ouédraogo et al. (2015)
Kenya	120 farmers, 12 villages	$3.35	Rao et al. (2015)
Zimbabwe	1,125 farmers, 9 districts	$5.69	Makaudze (2005)

Note: Most studies offer more detail, breaking down averages by gender or location.

model led to gross margin increases of 9–24%, averaged across years, while perfect knowledge of daily weather was worth an estimated 24–69%.

At a regional level, Rodrigues et al. (2016) modeled economy-wide impacts of national seasonal forecast systems in Kenya, Malawi, Mozambique, Tanzania, and Zambia. The study estimated that perfect information adopted by all farmers would generate regional GDP gains averaging $113 million USD per year ($3 USD per hectare) relative to a no forecast baseline. The study estimated benefits are higher for poorer households as they are more likely to be engaged in farming (Rodrigues et al., 2016).

4.1.4 | Perception of value

While the impact estimates described above are developed using surveys or modeled analysis, other studies solicit the "value" of WCS from potential users directly. These studies ask or elicit what users would be willing to pay for WCS information or services in the future, and thus the benefit farmers would expect to receive from the use of such services. Adjusted to 2017 rates (USD), these estimates have ranged from $1.19 (Zongo et al., 2016) to $15.36 (Ouédraogo et al., 2015) for improved seasonal forecasts (see Table 5).

Individual studies elaborate on this range: Ouédraogo et al. (2015) for instance, found that seasonal information ($15.36) is much more highly valued than decadal information ($3.55) or even contextualized agrometeorological advisories ($5.77) in Burkina Faso. Rao et al. (2015) found men and women valued different services (e.g., training, advisories, etc.) differently, and Zongo et al. (2016) showed variations in willingness to pay for seasonal information depending on agroecological zone. In addition to the willingness-to-pay estimates, Amegnaglo et al. (2017) used a ranking system to identify which information is perceived to be more valuable to farmers.

4.1.5 | Design and targeting

As earlier sections make clear, many studies have generated evidence regarding the degree that elements of design, implementation, and targeting affect access, use, and/or impact; evidence regarding several of these factors are discussed below and presented in Table 6.

User characteristics

A number of studies have focused on the role that user characteristics have played in conditioning the access, use, and impact of WCS. These studies have primarily focused on livelihood strategy and identity, including for instance, gender, education, and socioeconomic status (Carr & Owusu-Daaku, 2016; Gebrehiwot & van der Veen, 2013; Ngugi et al., 2011; Oyekale, 2015). Several studies have also explored understanding of climate forecasts, showing that users are able to recognize and adapt to the uncertainty implicit in such forecasts (Luseno et al., 2003; Lybbert et al., 2007).

Service design

With respect to the service itself, studies have considered the role of information type (e.g., weather-scale information, flood forecasts, grazing forecasts, onset date, seasonal forecasts) and dissemination channel (e.g., radio, TV, internet, SMS, and in participatory workshops) in influencing access and use (Anuga & Gordon, 2016; Coulibaly, Kundhlande, et al., 2015; Coulibaly, Mango, et al., 2015; Lo & Dieng, 2015; Mudombi & Nhamo, 2014; Roudier et al., 2016; Zongo et al., 2016). Forecast accuracy has also been shown to be a determinant in the potential impact of WCS (Hansen et al., 2009; Patt et al., 2005; Roudier et al., 2014).

TABLE 6 Frequency with which the relative effectiveness of implementation and/or design factors have been explored in the literature

	Factor type	Access	Use	Impact	WTP	References
Accuracy for forecasts	S			4	1	Amegnaglo et al. (2017), Hansen et al. (2009), Hulme et al. (1992), Roudier et al. (2011), and Sultan et al. (2010)
Additional resources or information for decision making	U		3		1	Luseno, McPeak, Barrett, Little, and Gebru (2003), Mudombi and Nhamo (2014), Ngugi et al. (2011), Oladele et al. (2018), Rasmussen et al. (2014), Roncoli et al. (2002), and Thornton et al. (2004)
Climate conditions	C	1	1	3	1	Ngugi et al. (2011), Oyekale (2015), Rodrigues et al. (2016), Roudier et al. (2014), Ziervogel et al. (2005), and Zongo et al. (2016)
Costs/prices	C			2		Hansen et al. (2009), Rodrigues et al. (2016)
Dissemination (channel, workshop, presentation, timing)	S	9	6	1	3	Amegnaglo et al. (2017), Anuga and Gordon (2016), Coulibaly, Kundhlande, et al. (2015), Coulibaly, Mango, et al. (2015), Daly et al. (2016), Egeru (2016), Luseno et al. (2003), Mudombi and Nhamo (2014), Ngugi et al. (2011), Oladele et al. (2018), Patt et al. (2005), Rao et al. (2015), Rasmussen et al. (2014), Roncoli et al. (2002), Roncoli et al. (2009), and Zongo et al. (2016)
Gender	U, C	4	4		2	Amegnaglo et al. (2017), Carr et al. (2014), Carr and Onzere (2017), Carr and Owusu-Daaku (2016), Coulibaly, Kundhlande, et al. (2015), Coulibaly, Mango, et al. (2015), Jost et al. (2016), Luseno et al. (2003), and Rao et al. (2015)
Information type	S	4	4	4	4	Amegnaglo et al. (2017), Coulibaly, Kundhlande, et al. (2015), Daly et al. (2016), Hulme et al. (1992), Luseno et al. (2003), Ngugi et al. (2011), Ouédraogo et al. (2015), Oyekale (2015), Rodrigues et al. (2016), Roncoli et al. (2002), Roudier et al. (2011), Roudier et al. (2016), Sultan et al. (2010), and Zare et al. (2017)
Institutional capacity	U, C	1	1		2	Broad and Agrawala (2000), Glantz (1977), Hulme et al. (1992), and Suarez, Ribot, and Patt (2004)
Livelihood strategy	U		2	6	2	Carr et al. (2014), Carr and Onzere (2017), Hellmuth et al. (2011), Hulme et al. (1992), Luseno et al. (2003), Ouédraogo et al. (2015), Oyekale (2015), Roudier et al. (2011), Roudier et al. (2014), Roudier et al. (2016), Ziervogel et al. (2005)
Location/agroecological zone	C	6	1	1	3	Amegnaglo et al. (2017), Carr et al. (2014), Carr and Onzere (2017), Coulibaly, Kundhlande, et al. (2015), Daly et al. (2016), Hellmuth et al. (2011), Makaudze (2014), Oyekale (2015), Roncoli et al. (2002), Tarhule and Lamb (2003), and Zare et al. (2017)
Socioeconomic status	U, C	2	1	1	1	Amegnaglo et al. (2017), Carr et al. (2014), Carr and Onzere (2017), Daly et al. (2016), Luseno et al. (2003), Makaudze (2014), Roncoli et al. (2009), and Ziervogel et al. (2005)
Risk aversion	U			2		Hansen et al. (2009) and Roudier et al. (2016)
Trust/credibility	U, S, C	1	1		1	Daly et al. (2016), Egeru (2016), and Luseno et al. (2003)
Understanding	U	2				Luseno et al. (2003) and Lybbert et al. (2007)

Note: Factors are assigned to the following categories: C, context; S, service; U, user.
Abbreviation: WTP, willingness to pay.

Context

With respect to broader context, several authors have shown that information is more impactful under certain conditions (i.e., drier than normal, wetter-than-normal) and in certain agroecozones (Carr et al., 2014; Makaudze, 2014). Relatively few studies have considered how broad issues related to supply, institutions, and/or context influence access and use of weather and climate information in African agriculture—though Ngugi et al. (2011) and Suarez et al. (2004) are notable exceptions, exploring the influence of the 1997–1998 El Niño on forecast use and the various factors that may motivate providers to develop conservative forecasts (i.e., for the middle tercile), respectively.

4.2 | Evaluation methodologies

The evidence presented above was generated using a variety of methods; here we consider these methods more directly, paying attention to how current approaches have been able to deliver useful information regarding agricultural WCS and to the extent to which they are suited to address the unique challenges of WCS evaluation.

4.2.1 | Outcome evaluation

Studies regarding the access and use of WCS fall under the heading of outcome evaluation, since they take stock of changes in the behaviors and practices that result from an intervention. Table 7 summarizes the frequency of use of particular methods to evaluate access and use of WCS in Africa.

To date, most of what is known about access to WCS in Africa's agricultural sector has been gathered through household surveys and analyzed using descriptive statistics. This includes studies that use panel survey methods to collect data over several years and others that have sampled progressively (e.g., surveying the population before, during, and after the agricultural season) to document changes over time, or differences between farmers' expectations regarding access and reality once the season had begun (Egeru, 2016; Mudombi & Nhamo, 2014).

Surveys are well suited to capturing the number of individuals who access particular information products. Since access reflects both availability and demand for particular information products, its evaluation may seek evidence of either or both. Surveys can be expanded to answer questions such as: What is the reach of particular communication channels? What is the demand for a particular information product, or relative demand among different information products? What are the most effective communication channels? How do farmer characteristics (e.g., gender, age, farming system) influence access to particular information products and use of particular communication channels?

Studies that explore the use of WCS employ similar, though a wider variety of, methods to those that engage issues of access: Data on use is gathered through focus groups, workshops, interviews, and/or household surveys, and results are reported using statistics (Bryan et al., 2009, 2013; Deressa et al., 2009; Klopper & Bartman, 2003) and/or qualitative methods

TABLE 7 Frequency with which methods have been used regarding access and use of WCS in Africa's agricultural sector

	Data collection				Data analysis			
	Surveys	Interviews	Focus groups	Workshops	Qualitative analysis	Descriptive statistics	Econometrics	References
West Africa	8	6	3	2	6	9	2	Amegnaglo et al. (2017), Carr et al. (2014), Limantol et al. (2016), Oyekale (2015), Rasmussen et al. (2014), Roncoli et al. (2002), Roncoli et al. (2009), Tarhule and Lamb (2003), Zongo et al. (2016)
East Africa	12	5	2	1	4	8	6	Broad and Agrawala (2000), Bryan et al. (2013), Coulibaly, Kundhlande, et al. (2015), Coulibaly, Mango, et al. (2015), Daly et al. (2016), Deressa et al. (2009), Egeru (2016), Gebrehiwot and van der Veen (2013), Luseno et al. (2003), Lybbert et al. (2007), Ngugi et al. (2011), O'Brien (2000), Oyekale (2015)
Southern Africa	7	5	1	2	3	6	2	Coulibaly, Kundhlande, et al. (2015), Lazo (2015), Mudombi and Nhamo (2014), Mulwa et al. (2017), O'Brien (2000), Patt et al. (2005), Zamasiya et al. (2017), and Zuma-Netshiukhwi et al. (2013)
Central Africa	1	—	—	—	—	1	—	Ngana et al. (2013)

Abbreviation: WCS, weather and climate services.

(Carr et al., 2014; Patt & Dessai, 2005; Patt et al., 2005; Roncoli et al., 2009; Tarhule & Lamb, 2003; Zongo et al., 2016). This wider variety of methods reflects the fact that studies of use require the establishment of some kind of counterfactual, that is, what the decision would have been without the information.

Indeed, eliciting how individuals use WCS depends on the ability of those individuals to attribute changes in particular management decisions to the information they contain. Since many conscious and sub-conscious factors can influence decisions, this may be a strong assumption. Obtaining management plans from individuals before and after they have been exposed to predictive information (e.g., seasonal forecasts) increases confidence by providing a reasonable counterfactual. The nonexcludability of information makes it difficult to compare management decisions between samples of farmers with and without access. Since management can vary as a function of forecast conditions—which are stochastic—many seasons may be required to provide a complete understanding of use of predictive information.

4.2.2 | Impact evaluation

Impact evaluations are designed to generate evidence regarding the ultimate impacts of an intervention, whether those impacts are direct or indirect, intended or unintended. While this type of evidence is critical for understanding the role that agricultural WCS can play in building the resilience of Africa's agricultural sector, there is far less evidence regarding impact than access and use: 17 out of the 66 documents reviewed for this study used this approach and many of these involve modeled estimates. While there is a broader range of methods used than in evaluations of access and use, each of these methods has significant limitations, and provides rather indirect evidence of the actual benefit of use of climate information.

Methods to evaluate the impact of WCS can be classified into two distinct categories: ex-post empirical studies of the benefits of WCS-informed decisions (i.e., investigating existing WCS); and ex-ante methods that model or estimate how potential uses of information could improve production, livelihoods or other impacts of interest. A summary of the frequency with which different methods have been used to evaluate the impact of agricultural WCS in Africa is found in Table 8.

Ex post studies

Eight studies have used ex post analysis to evaluate the impact of WCS on African agriculture (Anuga & Gordon, 2016; Lo & Dieng, 2015; Ouédraogo et al., 2015; Patt et al., 2005; Phillips et al., 2002; Stats4SD, 2017); those that have are generally based on household surveys and/or interviews, and focused on yields and/or marginal income (Anuga & Gordon, 2016; Ouédraogo et al., 2015). While these methods are time and resource intensive, they have been used in a variety of contexts, allowing for the development of a relatively large literature that explores the difficulties of survey-based ex post evaluation, including the attendant strengths and weaknesses of experimental and quasi-experimental design (Baker, 2000; Bamberger, Rugh, Church, & Fort, 2004).

Another method that has been used to generate evidence regarding the impact of WCS involves test plots. In this case, WCS are used to make decisions regarding a specific plot of land throughout the season, after which yields from the test plot are compared to those of plots where more traditional practices were employed (Lo & Dieng, 2015; Tarchiani et al., 2018). If well designed, test plots have the advantages of providing a counterfactual, capturing farmer decision-making, and potentially overcoming challenges of farmer recall and the elicitation of sensitive economic information.

The test plot studies reviewed as part of this work were limited to the management of individual crops, and therefore missed potentially important resource allocation decisions made in response to WCS. They also focused on yield—but since many uses of WCS involve saving the costs of inputs, gross margin (i.e., market price of harvest minus costs of production, per unit area) may be a useful metric. It is important to note as well that test plots are only useful when they compare farmers' management based on WCS to farmers' management without WCS; trials that compare climate-based expert recommendations with farmers' normal practice, the difference between the experts' and the farmers' decision criteria confound the influence of WCS. Because of the stochasticity challenge, it is generally not feasible to run a test plot for enough years to provide stable estimates of the value of the information.

Ex ante studies

Twelve studies have attempted to characterize the potential impact of agricultural WCS in Africa using ex ante methods. These include appraisal studies (undertaken as part of design or in advance of WCS implementation) but also the use of ex ante methods, such as models, to estimate the potential impact of existing WCS. These studies have employed a range of approaches—including experimental economics, models, and surveys—as a means to estimate, rather than analyze ex post, the possible benefits of planned or existing services.

TABLE 8 Methods used to evaluate the impact of WCS on African agriculture

Ex post/Ex ante	Methodology	Data needs	Question addressed	Possible uses of evidence	Strengths of methodology	Weakness of methodology	References
Ex post	Survey methods and descriptive/inferential statistics	Household surveys	What impacts were experienced by intended targets of an actual WCS?	Describing return on investment; identifying factors that condition impact; deciding whether a similar service will provide benefit	May allow for evidence to be gleaned through information collected for other purposes	May not capture impacts over time, since cost constraints may not allow for data collection across many years	Anuga and Gordon (2016) and Ouédraogo et al. (2015)
Ex post	Test plots	Harvest data	To what extent could WCS improve yields?	Design of WCS	Provides first-hand experience of impacts of use of SCF; allows for testing different use strategies	Often compares decisions made by resource-constrained small-scale farmers with those made by well-resourced agronomists	Ouedraogo et al. (2018) and Rodrigues et al. (2016)
Ex ante	Experimental economics	Workshops, surveys	How do target individuals perceive potential impacts?	Design of WCS; identifying and accounting for multiple uses of information	Existing groups may provide opportunities for low-cost data collection	Requires good facilitation and an understanding of the community; participant fatigue	Jost et al. (2016), Patt et al. (2005), and Roudier et al. (2014)
Ex ante	Crop simulation/economic models	Weather, crop, economic data	To what extent might individual farmers stand to benefit from WCS?	Design of WCS; estimating impact over many years; estimating impact when difficult to establish counterfactual	Can sample many years of climate information and weather observations. Flexible model specification	Limited by ability to capture decisions and economic impacts; ignores market impacts of adoption at scale	Hansen et al. (2009), Roudier et al. (2011), Roudier et al. (2016), Sultan et al. (2010) and Thornton et al. (2004)
Ex ante	Agent-based modeling	Weather, crop, ethnographic data	How might impacts evolve overtime and/or for different types of actors?	Identifying whether services are likely to benefit certain actors; estimating impact when difficult to establish counterfactual	Captures competition or coordination among decision-makers	Limited by ability to capture decisions and economic impacts	Bharwani et al. (2005) and Ziervogel et al. (2005)
Ex ante	Computable General Equilibrium models	Weather, crop, economic data	How might the impact of WCS be felt at national or regional scale?	Justifying investment; exploring how services will impact scale	Captures market impacts of adoption at scale and wider economy effects	Limited by ability to capture decisions and economic impacts	Anuga and Gordon (2016)
Ex ante/ex post	Contingent valuation	Household surveys	What value might individuals assign to WCS?	Justifying/planning investment and design of WCS; exploring fee-for-service or other business models	Simple data requirements; CV methods could be combined with experimental economics	Difficult to estimate value of new products. WTP expected to be lower than average economic benefit	Amegnaglo et al. (2017), Makaudze (2005), Ouédraogo et al. (2015), Rao et al. (2015), and Zongo et al. (2016)

Abbreviations: CV, contingent valuation; SCF, seasonal climate forecast; WCS, weather and climate service; WTP, willingness to pay.

Sometimes described as participatory methods or "serious games," experimental economics approaches provide farmers with an opportunity to simulate how they might use WCS, were they to be provided, and to report their perception of potential results. While recent work has shown that these methods can be very useful in helping to estimate the impact of WCS, several challenges have been noted: In order for these methods to work, for instance, they must be run by skill facilitators who can ensure that all participants feel they can share and explore—and issues of power, gender, and hierarchy may distort the results if facilitators are not aware. In addition, participatory methods are time consuming; they may lead to fatigue among participants, and potentially expose them to uncomfortable or challenging situations (Jost et al., 2016; Suarez, Mendler de Suarez, Koelle, & Boykoff, 2014).

Several modeling approaches have also been used to estimate the potential value of agricultural WCS in Africa. For instance, crop simulation and economic models have been useful in helping evaluators to estimate the value of WCS. Biophysical models may be used on their own to estimate yield changes, or linked directly with economic models (e.g., bioeconomic models) so as to characterize the impacts of different decisions informed by WCS. Simple field- and farm-level bio-economic models have been used to estimate potential impacts of weather and climate information in Kenya, Niger, and Senegal; these models have also allowed researchers to explore the range of possible outcomes associated with different contexts and/or the design and implementation of the services themselves (Hansen et al., 2009; Roudier et al., 2011; Sultan et al., 2010; Thornton et al., 2004).

Agent-based models have also been used to reveal how agents interact with other agents and the environment—allowing for the exploration of the impact of WCS in complex systems, as well as the how interactions producing emergent effects may differ from effects of individual agents. These analyses have helped to characterize which types of actors are likely to be impacted, and in what capacity, by the use of climate information (Bharwani et al., 2005; Ziervogel et al., 2005).

A limitation of farm-level and agent-based modeling approaches is that they ignore the potential impact that the collective action of many farmers can have on market prices or on other sectors of the economy. One study in Africa undertook such an economic analysis, using computable general equilibrium modeling to estimate the potential economy-wide impacts of large-scale farmer adoption of SCFs across several countries (Rodrigues et al., 2016).

Where long-term records are available, bioeconomic modeling approaches can sample many years of weather observations and climate information, and can provide insight that may address the stochasticity challenge. The main weakness of model-based impact estimates, however, is that their realism can be limited by the ability of the models to capture farmer decisions and resulting economic impacts, particularly when weakly grounded in empirical data. In most instances, globally and in Africa, these modeling approaches have been applied in a stylized manner to hypothetical uses of information; realistic evaluation was often not the objective (Meza, Hansen, & Osgood, 2008). However, this is not an intrinsic limitation of the approach—and though bio-economic modeling tools tend to have demanding data requirements, it is feasible for analyses to be well grounded in empirical data, as is often the case for ex-ante evaluation of agricultural production technologies.

Finally, contingent valuation is a survey-based econometric technique that elicits the amount that potential users would be willing to pay for specific services, and thus implicitly their benefit (to these users). The contingent valuation, or "willingness-to-pay," approach, estimates the maximum price that a user will pay for the information or service directly, whereas the other ex ante approaches estimate value through the expected economic benefits of the use of the new information. Nonetheless, all these techniques seek to derive the (economic) value of information (Hilton, 1981).

Contingent valuation assumes the potential user can adequately estimate the expected economic gain, averaged across years, from using the new information; as such, it avoids the need for an explicit counterfactual. It is simpler for the analyst, but has significant limitations, especially for new or planned information products. Farmers cannot assess, and typically underestimate, the value of information that they do not have a lot of experience with. For a stylized seasonal forecast system, Pope et al. (2017) estimated that users would have to experience at least 30 forecasts in order to provide a realistic estimate of the value of the information (Pope, Buontempo, & Economou, 2017). However, training or accelerated experience through participatory processes can help to reduce this bias.

5 | DISCUSSION

5.1 | Strengthening evidence of access and use

Evidence regarding the access and use of agricultural WCS in Africa is more plentiful and more homogenous than evidence regarding the impact of those services, making it relatively more straightforward to compare estimates of access and use across regions and/or populations. Our analysis has pointed to several evidence key gaps, however.

It is clear, for instance, that estimates regarding access to weather and climate information vary considerably—and while there has been some effort to understand the factors that cause this disparity, *a more complete mapping* of who has access to what kind of information, as well as the factors that enable or constrain access, would help to inform the investment and design of WCS. As Table 2 makes clear, evidence regarding access to agricultural WCS is particularly lacking in Central and North Africa—though no region boasts a preponderance of evidence, particularly given the diversity of actors that contribute to Africa's agricultural sector.

The review also highlights the uneven nature of evidence regarding the use of agricultural WCS. As seen in Figure 1, our analysis includes data from just 23 of Africa's 54 countries—and even within these countries, certain populations are relatively more studied than others (e.g., farmers vs. pastoralists). Moreover, with a few exceptions (Daly et al., 2016; Glantz, 1977; Hulme et al., 1992), the literature rarely explores the extent to which WCS are used by government and nongovernment agencies—and it makes almost no mention of how/whether private organizations (e.g., input suppliers, wholesalers, etc.) use such information.

With regards to methodology, two gaps stand out as well. The first is linked to the fact that many of the studies included in our analysis were performed without baseline analysis, making it difficult to identify changes in access and use over time, or as a result of a particular intervention. Fortunately, the kind of baseline survey that can help to build this sort of evidence is becoming more common in Africa and elsewhere (Coulibaly, Birachi, Kagabo, & Mutua, 2017; Coulibaly, Kundhlande, et al., 2015; Coulibaly, Mango, et al., 2015; Daly et al., 2016) and will likely improve the evaluation of agricultural WCS in the future. Methods to *attribute changes in access and use* of climate services to changes in the service and/or context will also need to be improved.

Finally, while the literature has begun to *explore the barriers and enablers* to the use of climate information, new qualitative and quantitative approaches are needed to continue to flesh out the role that these factors play in influencing access and use. This includes expanding consideration of the role of communication strategies (e.g., messaging, visualization, etc.) and dissemination mechanisms (e.g., radio, SMS, etc., see Jost et al. 2016), and exploring the study of new factors. For instance, the business models that sustain WCS have rarely been evaluated, despite the important role that they play in conditioning access, use, and impact on both short and long timeframes (Jost et al., 2016).

5.2 | Strengthening evidence of the impact of WCS

The landscape of evidence regarding the impact of WCS is both scarcer and more complicated than that regarding access and use, displaying a wide array of ex post and ex ante methodologies that rely on a range of different assumptions to help characterize the contribution of the services in question. These methodologies respond to the various challenges associated with the evaluation of WCS, though they also generate evidence that is somewhat more indirect than the evidence regarding access and use.

Several evidence gaps call particular attention—especially regarding the extent to which different groups benefit differently from WCS. It is also important to note that the studies included in this review have defined impact almost entirely with regards to yields and/or incomes, despite the fact that WCS can be expected to have a host of impacts (e.g., improved decision processes, time saved, more efficient allocation of resources, changes in social organization, etc.), and that these impacts can be expected to accrue at different levels. To date, no studies have explored the impact of agricultural WCS on African societies (e.g., does the promotion of scientific information isolate young, educated cohorts from traditional knowledge?) or the environment (e.g., do WCS facilitate more intensive farming practices? Could they lead to increased greenhouse gas emissions?). Exploring this *broader range of impacts* will be important to strengthening the evidence base.

Improving the evaluation of the impact of WCS will also require more attention to generating evidence in the face of a stochastic climate. Given the interaction between impact and stochastic climate variability, future studies should develop a better sense of the *relationship between confidence/stability of impact estimates and the number of years sampled.* It will also be important to explore the available options for capturing variability and increasing confidence during limited number of years of any particular project.

In improving methodology, the key issue will be to develop approaches that allow evaluators to *compare the consistency of methods.* This will require applying different methods in the same contexts in order to help estimate biases and identify methods that may be better suited to particular cases. This approach can also expose weaknesses in methods—allowing methods to be improved and better tailored to the climate service context or helping inform recommendations regarding the triangulation of methods in certain cases.

Combining methods provides promising opportunities to triangulate estimates of the impact of WCS, take advantage of complementary strengths, and overcome some of the most problematic limitations. For example, if bioeconomic modeling were combined with participatory approaches and/or survey-based data, the empirical results could be used to validate and, if needed, drive modeled farmer management response to climate information, while the models could then sample more of the range of variability of observed weather and climate information (Jochec, Mjelde, Lee, & Conner, 2001). A related issue will be to validate models to make it easier to assess the robustness of their results.

5.3 | Improving usability of evaluative evidence of WCS

Improving evidence regarding access, use, and impact is essential toward improving our understanding of the relative contribution of WCS. Another important component here is to improve the usability of such information, so that national governments, development agencies, program managers, and private companies can make informed decisions regarding their own climate service investments. Improving the usability of this information will require focusing on three key issues.

First, it will be important to *expand evidence regarding a wider variety of users and uses.* For instance, there is more evidence regarding access and use by farmers than by pastoralists, much more for small-scale farmers than commercial farmers, and for staple rather than cash crops. There is very little information regarding government and/or nonprofit organizations and none regarding the private sector. Addressing these gaps should be a priority, especially with regards to disaggregating populations by the identities that shape their roles and responsibilities and exploring access and use for a wider range of actors (e.g., input suppliers, insurance companies, wholesalers, extension services, etc.) (see for instance Table 3).

It is also important for evaluators to take into account the fact that many WCS in Africa's agriculture sector are operating suboptimally; evidence of the relative contribution of these services limits the understanding of what constitutes good practice. There is currently no guidance on how this existing information could be used to improve outcomes and impacts; developing this guidance will help advance the field. Given the variability in the design of climate information that has been evaluated, future work can help *identify how the quality of services can best be factored into the body of evaluation results.*

This will help to improve knowledge of how to generate and use impact information to improve the design and/or implementation of agricultural WCS. Documenting how services are able to deliver outcomes and impacts, and good practice, will be critical to improving design and delivery, providing insights. With the exception of a 2015 study in Kenya (Rao et al., 2015), there is little robust analysis regarding how different strategies (e.g., user engagement, coproduction, dissemination, capacity building, use) lead to different outcomes or impacts. Developing a broader suite of methods to generate this kind of information—and use this in design—has huge potential to improve future WCS.

A final issue will be to *standardize the evidence* generated by evaluations of WCS so as to allow for comparison of interventions. This includes expanding the use of economic approaches to appraise (ex ante) the socioeconomic benefits of WCS, to help better design new services, to justify prior and existing investments, and to help develop the case to continue (or increase) allocation of resources for WCS into the future. This will also require additional methodological development for costs as well as benefits (Lazo, Raucher, Teisberg, Wagner, & Weiher, 2009; World Meteorological Organization et al., 2015). Ensuring that methods capture the full range of costs and benefits require new techniques and will require guidance and support, but further development in this area has a key role to play in the scale-up of WCS in Africa.

6 | CONCLUSION: A LEARNING AGENDA FOR THE EVALUATION OF AGRICULTURAL WCS IN AFRICA

This review has characterized the state of evidence and methods regarding the evaluation of agricultural WCS in Africa. It has identified where our knowledge of access, use and impacts of WCS is relatively strong, but also where there are persistent gaps. Building on this analysis, we have developed a "learning agenda," or evidence-building roadmap, to establish priorities that can guide future work to generate evidence that can improve the design, delivery, and impact of agricultural WCS in Africa. Priority learning areas include activities that can strengthen the evidence of access, use, and impacts of WCS, along with those that can advance the use and usability of evidence so as to improve the design and targeting of WCS services; they are summarized below:

1. Strengthening evidence regarding the access and use of WCS
   1.1. Broaden evidence regarding access and use of different kinds of information, in different agricultural systems, across countries and contexts.
   1.2. Deepen understanding of the role that barriers and enablers play in conditioning access and use of WCS.
   1.3. Attribute changes in access and use to changes in evolving service delivery and/or context over time.

2. Strengthening evidence regarding the impact of WCS
   2.1. Explore a broader range of impacts, including those that might accrue to the environment and/or society.
   2.2. Articulate a clearer view of the relationship between the stability of impact estimates and the number of years sampled, given a stochastic climate.
   2.3. Develop robust guidance regarding the suitability of specific methods to address particular evaluation questions, including the extent to which certain methods show biases in particular contexts.
3. Improving the use and usability of evidence regarding WCS
   3.1. Ensuring evidence explores a range of users and uses.
   3.2. Interpret information in the context of the quality of the service.
   3.3. Standardize output so as to allow for comparison of interventions.

ACKNOWLEDGMENTS

We thank Sarah Henly-Shephard, Kristin Lambert, Eliot Levine, and Alison Rose for comments that improved the paper; the contributions of Elisabeth Gawthrop and Francesco Fiondella in developing the graphic are also appreciated. Thanks are due as well to the participants of the February 2017 workshop on climate services evaluation, held in conjunction with the fifth International Conference on Climate Services, who reviewed an initial draft, and to those who participated in a June 2018 session at the Adaptation Futures conference.

C.V. and E.C. were funded by the Climate Information Services Research Initiative, made possible by the generous support of the American people through the United States Agency for International Development, Agreement Num AID-OAA-A-16-00072ber. J.H. was supported in part by the CGIAR Research 918 Program on Climate Change, Agriculture and Food Security (CCAFS), which is carried out with support from the CGIAR Trust Fund and through bilateral funding agreements. Details are available here: https://ccafs.cgiar.org/donors. The opinions expressed are those of the authors and do not necessarily reflect the views of USAID, the United States Government, or CCAFS or its cosponsoring or supporting organizations.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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How to cite this article: Vaughan C, Hansen J, Roudier P, Watkiss P, Carr E. Evaluating agricultural weather and climate services in Africa: Evidence, methods, and a learning agenda. *WIREs Clim Change*. 2019;10:e586. https://doi.org/10.1002/wcc.586

APPENDIX A: FULL LIST OF DOCUMENTS IN THE STUDY

Authors	Title	Year	Type	Country
Amegnaglo, C. J., Anaman, K. A., Mensah-Bonsu, A., Onumha, E. E., |& Gero, F.A.	Contingent valuation study of the benefits of seasonal climate forecasts for maize farmers in the Republic of Benin, West Africa	2017	Journal article	Benin
Anuga, S.W., & C. Gordon	Adoption of climate-smart weather practices among smallholder food crop farmers in the Techiman municipal: Implication for crop yield	2016	Journal article	Ghana
Barrett, S., & Ndegwa, W.	An economic valuation of the Kenya Meteorological Department's Decentralized Provision	2016	Project report	Kenya
Bharwani, S., Bithell, M., Downing, T. E., New, M., Washington, R. , & Ziervogel, G.	Multi-agent modeling of climate outlooks and food security on a community garden scheme in Limpopo, South Africa	2005	Journal article	South Africa
Broad, K., & Agrawala, S.	The Ethiopia food crisis—Uses and limits of climate forecasts	2000	Journal article	Ethiopia
Bryan, E., Ringler, C., Okoba, B., Roncoli, C., Silvestri, S., & Herrero, M.	Adapting agriculture to climate change in Kenya: Household strategies and determinants	2013	Journal article	Kenya
Carr, E. R. (Ed.)	Assessing Mali's Direction Nationale de la Meteorologie Agrometeorological Advisory Program	2014	Project report	Mali
Carr, E. R., & Onzere, S.N.	Really effective (for 15% of the men): Lessons in Understanding and Addressing User Needs in Climate Services from Mali	2017	Journal article	Mali
Carr, E. R., & Owusu-Daaku, K. N.	The shifting epistemologies of vulnerability in climate services for development: The case of Mali's Agrometeorological Advisory Programme	2016	Journal article	Mali
Chemura, A., Kutywayo, D., Chidoko, P., & Majoya, C.	Bioclimatic modeling of current and projected suitabiltiy of coffee (*Coffee arabaica*) production in Zimbabwe	2016	Journal article	Zimbabwe
Clarkson, G., Dorward, P. Kagabo, D., & Nsengiyumva, G.	Climate services for agriculture in Rwanda: Initial findings from PICSA monitoring and evaluation	2017	CCAFS Info Note	Rwanda
Coulibaly, J. Y., Mango, J., Swamila, M., Tall, A., Kaur, H., & Hansen, J.	Which climate services do farmers and pastoralists need in Malawi?	2015	CCAFS working paper	Malawi
Coulibaly, J. Y., Mango, J., Swamila, M., Tall, A., Kaur, H., & Hansen, J.	What climate services do farmers and pastoralists need in Tanzania? Baseline study for the GFCS Adaptation Program in Africa.	2015	CCAFS working paper	Tanzania
Coulibaly, J. Y., Birachi, E. A., Kagabo, D. M., & Motua, M.	Climate services for agriculture in Rwanda	2017	CCAFS working paper	Rwanda
Dabire, W. P. I., Barbier, B., & Andrieu, N.	Evaluation ex ante de la prévision saisonnière climatique en petit paysannat burkinabé. Revue d'élevage et de médecine vétérinaire des pays tropicaux	2011	Journal article	Burkina Faso
Daly, M. E., West, J. J., & Yanda, P. Z.	Establishing a baseline for monitoring and evaluating user satisfaction with climate services in Tanzania	2016	CICERO/GFCS Report	Tanzania

(Continues)

APPENDIX A (Continued)

Authors	Title	Year	Type	Country
Deressa, T. T., Hassan, R. M., Ringler, C., Alemu, T., & Yesuf, M.	Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia	2009	Journal article	Ethiopia
Egeru, A.	Climate risk management information, sources and responses in a pastoral region in East Africa	2016	Journal article	Uganda
Gebrehiwot, T., & van der Veen, A.	Farm level adaptation to climate change: The case of farmers in the Ethiopian Highlands	2013	Journal article	Ethiopia
Glantz, M. H.	The value of a long-range weather forecast for the West African Sahel	1977	Journal article	Sahelian states
Hansen, J. W., Mishra, A., Rao, K. P. C., Indeje, M., & Ngugi, R. K.	Potential value of GCM-based seasonal rainfall forecasts for maize management in semi-arid Kenya	2009	Journal article	Kenya
Hellmuth, M.E., Diarra, D.Z., Vaughan, C., & Cousin, R.	Increasing food security with agrometeorological information: Mali's national meteorological service helps farmers manage climate risk	2011	WRI case study	Mali
Hulme, M., Biot, Y., Borton, J., Buchanan-Smith, M., Davies, S., Folland, C., Nicholds, N., Seddon, D., & Ward, N.	Seasonal rainfall forecasting for Africa. Part II—Application and impact assessment.	1992	Journal article	Sahel
Jiri, O., Mafongoya, P. L., Mubaya, C., & Mafongoya, O.	Seasonal climate prediction and adaptation using indigenous knowledge systems in agriculture systems in Southern Africa: A review	2016	Journal article	Botswana, Malawi, South Africa, Swaziland, Zimbabwe, Zambia
Jost, C., Kyazze, F., Naab, J., Neelormi, S., Kinyangi, J., Zougmoure, R., Aggarwal, P., Bhatta, G., Chaudhury, M., Tapio-Bistrom, M.-L., Nelson, S., & Kristjanson, P.	Understanding gender dimensions of agriculture and climate change in smallholder farming communities	2016	Journal article	Uganda, Ghana
Klopper, E., & Bartman, A.	Forecasts and commercial agriculture: A survey of user needs in South Africa	2003	Book chapter	South Africa
Lazo, J.	Survey of Mozambique public on weather, water and climate information	2015	NCAR technical report	Mozambique
Limantol, A. M., Keith, B. E., Azabre, B. A. & Lennartz, B.	Farmers' perception and adaptation practice to climate variability and change: A case study of the Vea catchment in Ghana	2016	Journal article	Ghana
Lo, M., & Dieng, M.	Impact assessment of communicating seasonal climate forecasts in Kaffrine, Diourbel, Louga, Theis and Fatick regions in Senegal	2015	CCAFS working paper	Senegal
Luseno, W. K., McPeak, J. G., Barrett, C. B., Gebru, G., & Little, P. D.	Assessing the value of climate forecast information for pastoralists: Evidence from southern Ethiopia and northern Kenya	2003	Journal article	Ethiopia, Kenya
Lybbert, T. J., Barrett, C., McPeak, J. G. & Luseno, W. K.	Bayesian herders: Asymmetric updating of rainfall beliefs in response to external forecasts	2007	Journal article	Ethiopia, Kenya
Makaudze, E. M.	Assessing the economic value of seasonal climate forecasts for smallholder farmers in Zimbabwe: Using contingency valuation approach	2014	Journal article	Zimbabwe

(Continues)

APPENDIX A (Continued)

Authors	Title	Year	Type	Country
Mertz, O., Rasmussen, K., & Rasmussen, L. V.	Weather and resource information as tools for dealing with farmer-pastoralist conflicts in the Sahel	2016	Journal article	Burkina Faso, Mali, Niger
Mudombi, S., & Nhamo, G.	Access to weather forecasting and early warning information by communal farmers in Seke and Murewa districts, Zimbabwe	2014	Journal article	Zimbabwe
Mulwa, C., Marenya, P., Rahut, D. B., & Kassie, M.	Response to climate risks among smallholder farmers in Malawi: A multi-variate probit assessment of the role of information, household demographics, and farm characteristics	2017	Journal article	Malawi
Ngana, F., Maina Ababa, A., Gapia, M., & Kossi, L. K.	Traditional meteorology and rural activities by the Mandja of Sibut, Central African Republic	2013	Journal article	Central African Republic
Ngugi, R. K., Mureithi, S. M., & Kamande, P. N.	Climate forecast information: The status, needs, and expectations among smallholder agro-pastoralists in Machakos District, Kenya	2011	Journal article	Kenya
Nhemachena, C. & Hassan, R. M.	Micro-level analysis of farmers' adaptation to climate change in Southern Africa	2007	IFPRI report	South Africa, Zambia, Zimbabwe
O'Brien, K., Sygna, L., Otto Naess, L., Kingamkono, R., & Hochobeb, B.	Is information enough? User responses to seasonal climate forecasts in Southern Africa	2000	Cicero report	Namibia, Tanzania
Ouedraogo, M., Barry, S., Zougmoré, RB., Somé, L., & Bake, G.	Farmers' Willingness to Pay for Climate Information Services: Evidence from Cowpea and Sesame Producers in Northern Burkina Faso	2018	Journal article	Burkina Faso
Ouedragogo, I., Diouf, N.S., Ouedraogo, M., Ndiaye, O., & Zougmoré, R.	Closing the gap between climate information producers and users: Assessment of needs and uptake in Senegal	2018	Journal article	Senegal
Oyekale, A. S.	Access to risk mitigating weather forecasts and changes in farming operations in East and West Africa: Evidence from a baseline survey	2015	Journal article	Ethiopia, Kenya, Tanzania, Uganda, Burkina Faso, Ghana, Mali, Niger, and Senegal
Patt, A., Suarez, P., & Gwata, C.	Effects of seasonal climate forecasts and participatory workshops among subsistence farmers in Zimbabwe	2005	Journal article	Zimbabwe
Phillips, J. G., Dean, D. Unganai, L., & Chimeli, A.	Implications of farm-level response to seasonal climate forecasts for aggregate grain production in Zimbabwe	2002	Journal article	Zimbabwe
Rao, K. P. C., Hansen, J., Njiru, E., Githungo, W. N., & Oyoo, A.	Impacts of seasonal climate communication strategies on farm management and livelihoods in Wote, Kenya	2015	CCAFS working paper	Kenya
Rasmussen, L. V., Mertz, O., Rasmussen, K., & Nieto, H.	Improving how meteorological information is used by pastoralists through adequate communication tools	2015	Journal article	Burkina Faso
Rasmussen, L. V., Mertz, O., Rasmussen, K., Nieto Solana, H., Ali, A., & Maiga, I.	Weather, climate, and resource Information should meet the needs of Sahelian pastoralists	2014	Journal article	Burkina Faso
Rodrigues, J., Thurlow, J., Landman, W., Ringler, C., Robertson, R., & Zhu, T.	The economic value of seasonal forecasts stochastic economy-wide analysis for East Africa.	2016	IFPRI report	Kenya, Malawi, Mozambique, Tanzania, Zambia

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Authors	Title	Year	Type	Country
Roncoli, C., Ingram, K.T., Jost, C.C., Kirshen, P.H., & Yaka, P.	Farmers' behavioral responses to seasonal rainfall forecasts in the Sahel-Sudan	2002	Journal article	Burkina Faso
Roncoli, C., Jost, C., Kirshen, P., Sanon, M., Ingram, K.T., Woodin, M., Somé, L., Outtara, F., Sanfo, B.J., Sia, C., Yaka, P., & Hoogenboom, G.	From accessing to assessing forecasts: An end-to-end study of participatory climate forecast dissemination in Burkina Faso	2009	Journal article	Burkina Faso
Roncoli, C., Orlove, B. S., Kabugo, M. R., & Waiswa, M. M.	Cultural styles of participation in farmers' discussions of seasonal climate forecasts in Uganda	2010	Journal article	Uganda
Roudier, P., Alhassane, A., Baron, C., Louvet, S., & Sultan, B.	Assessing the benefits of weather and seasonal forecasts to millet growers in Niger	2016	Journal article	Niger
Roudier, P., Muller, B., d'Aquino, P., Roncoli, C., Soumaré, M. A., Batté, L., & Sultan, B.	The role of climate forecasts in smallholder agriculture: Lessons from participatory research in two communities in Senegal	2014	Journal article	Senegal
Roudier, P., Sultan, B., Quirion, P., Baron, C., Alhassane, A., Traoré, S. B., & Muller, B.	An ex-ante evaluation of the use of seasonal climate forecasts for millet growers in SW Niger	2012	Journal article	Niger
Stats4SD	Evaluation of Climate Services Interventions in the GFCS Adaptation Programme for Africa	2017	Project report	Malawi, Tanzania
Suarez, P.	Caution, cognition, and credibility: The risks of climate forecast application	2004	Journal article	Zimbabwe
Sultan, B., Barbier, B., Fortilus, J., Mbaye, S. M., & Leclerc, G.	Estimating the potential economic value of seasonal forecasts in West Africa: A long-term ex-ante assessment in Senegal	2010	Journal article	Senegal
Tarhule, A. & Lamb, P. J.	Climate research and seasonal forecasting for West Africans: Perceptions, dissemination and use?	2003	Journal article	Mali, Burkina Faso, Niger, Nigeria
Tarchiani, V., Camacho J., Coulibaly H., Rossi, F., & R. Stefanski	Agrometeorological services for smallholder farmers in West Africa	2018	Journal article	Mauritania
Thornton, P. K., Fawcett, R. H., Galvin, K. A., Boone, R. B., Hudson, J. W., & Vogel, C.H.	Evaluating management options that use climate forecasts: Modeling livestock production systems in the semi-arid zone of South Africa	2004	Journal article	South Africa
Wood, S. A., Jina, A. S., Jain, M., Kristjanson, P., & DeFries, R. S.	Smallholder farmer cropping decisions related to climate variability across multiple regions	2014	Journal article	Burkina Faso, Ghana, Mali, Niger, Senegal, Ethiopia, Uganda, Kenya, Tanzania
Zamasiya, B., Nyikahadzoi, K., & Mukamuri, B.B.	Factors influencing smallholder farmers' behavioral intention toward adaptation to climate change in transitional climatic zones: A case study of Hwedza District in Zimbabwe	2017	Journal article	Zimbabwe
Zare, A., Barbier, B., Bolongo-Traore, M., Diarra, A., Mahe, G., & Paturel, J. E.	Climate forecast perception and needs in wetlands: A case study in the Inner Niger Delta in Malian Wetlands	2017	Journal article	Niger, Mali
Ziervogel, G., M. Bithell, R. Washington, & Downing, T.	Agent-based social simulation: A method for assessing the impact of seasonal climate forecast applications among smallholder farmers	2005	Journal article	Lesotho

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APPENDIX A (Continued)

Authors	Title	Year	Type	Country
Zongo, B., Diarra, A., Barbier, B., Zorom, M., Yacouba, H., & Dogot, T.	Farmers' perceptions and willingness to pay for climate information in Burkina Faso	2016	Journal article	Burkina Faso
Zuma-Netshiukhwi, G. H., & Stigter C. J.	An extension approach to close the gap between suppliers and users of agrometeorological services in the south-western free state of South Africa	2016	Journal article	South Africa

APPENDIX B: WEST AND NORTH AFRICA ACCESS AND USE ESTIMATES

	Access estimates	Use estimates	Information type	Target population	Data collection, sample size	References
West Africa						
Burkina Faso	21.78% of farmers have access to climate info	—	Seasonal forecast	Farmers	629 surveys, 4 districts	Zongo et al. (2016)
	2/3 of farmers that did not participate in workshop received forecasts from participants, less in areas of social strife	Workshop participants were more likely to use SCFs for farm-level management	Seasonal forecast	Farmers	159 interviews	Roncoli et al. (2009)
	7% (seasonal); 30% (2–3 day); 6–13% (flooding)	Flooding (100%); availability of grazing (75%); onset date (6–53%); subseasonal forecast (17%), seasonal forecast (0%)	Various	Pastoralists	61 surveys, 2 sites; 8 focus groups, 2 sites	Rasmussen et al. (2014)
	—	Farmers use SCF for choice of field, crop varieties, timing of tasks, and so on, constrained by presentation and resources; pastoralists do not use forecasts	Seasonal forecast	Farmers, pastoralists	5–15 interviews/ focus groups in each of three sites	Roncoli et al. (2002)
	62.7% of farmers have access to forecasts on rainfall onset; 39.3% had access to forecasts on outbreak of pests/disease	24% used info on timing farming activities	Onset	Farmers	140 surveys	Oyekale (2015)
	18.6% aware of SCF; drought info received from media, NGOs and the gov; farmers were more likely to seek SCF from NGOs than gov	—	Seasonal forecast, drought info	Farmers	130 surveys, 3 communities	Tarhule and Lamb (2003)
Benin	Farmers receive SCF through radio (75.1%), elders (50.3%), meetings (26.3%), extension agents (24.3%), mobile phone (18.2%), friends (16.8%), research institutes (12.7%)	95% of farmers report that they would change at least one strategy in response to SCFs	Seasonal forecast, rainfall distribution, onset, amount	Farmers	354 surveys	Amegnaglo et al. (2017)

(Continues)

APPENDIX B (Continued)

	Access estimates	Use estimates	Information type	Target population	Data collection, sample size	References
Ghana	Farmers occasionally receive daily rainfall and temp forecasts from the radio; no access to seasonal forecasts; prefer the radio, in their local dialect	Men use weather info regarding varieties and cropping area; women use it for planning household chores	Daily weather and SCFs	Farmers	4 focus groups, 15–20 people each	Jost et al. (2016)
	56.4% of farmers from West Africa had access to info on rainfall onset; 18.2% access to pest/disease forecast	17.6% (rainfall onset) and 4.3% (prevalence of disease) of West African farmers report changes in practice because of forecasts	Rainfall onset outbreak of pests	Farmers	140 surveys	Oyekale (2015)
	34.5% of farmers receive weather information from extension services; 62.3% from radio; 23.5% from neighbors	—	Weather	Farmers	466 surveys	Limantol et al. (2016)
Mali	2,500 trained/had access as part of the project	—	Seasonal forecast	Farmers	—	Hellmuth et al. (2011)
	62.4% aware of SCFs; 62% of West African orgs do not think their understanding of SCF to have improved	82% of West African orgs have not found any published climate info useful to their user groups	Seasonal forecast, drought info	Farmers; intermediary orgs	160 surveys, 3 communities	Tarhule and Lamb (2003)
	—	Use estimates ranged for 8% to 24% across communities; use varies by agroecological zone and by social position (e.g., for senior men)	Seasonal forecast info; onset date	Farmers	132 focus groups, 660 interviews, 36 communities	Carr et al. (2014) and Carr and Onzere (2017)
Niger	29.2% (outbreak of pests) and 56.4% (rainfall onset) of farmers in East Africa received info; roughly 25% reported men and women having equal access to forecasts	17.6% (start of rainfall) and 4.3% (prevalence of disease) of East African farmers report changes in practice because of forecasts	Start of rainfall, prevalence of disease	Farmers	140 surveys	Oyekale (2015)
	5.6% aware of SCFs; 62% of West African orgs do not think their understanding of SCF improved	82% of West African orgs have not found any published climate info useful to their user groups	Seasonal forecast, drought info	Farmers; intermediary orgs	151 surveys in 3 communities; 18 intermediary orgs	Tarhule and Lamb (2003)
Nigeria	62% of West African orgs do not think their understanding of SCF to have improved	82% of West African orgs have not found any published climate info useful to their user groups	Seasonal forecast, drought info	Farmers; intermediary orgs	109 surveys in 4 communities; 4 orgs	Tarhule and Lamb (2003)

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APPENDIX B (Continued)

	Access estimates	Use estimates	Information type	Target population	Data collection, sample size	References
Senegal	56.4% of farmers from West Africa had access to info on start of rainfall; 18.2% access to pest/disease forecast	17.6% (start of rainfall) and 4.3% (prevalence of disease) of West African farmers report changes in practice because of forecasts	Start of rainfall, prevalence of disease	Farmers	140 surveys	Oyekale (2015)
	962 lead-farmers receive climate info through SMS; 5,323 farmers received info from lead farmers; 308 individuals receive info through email	78% ($n = 289$) use climate information; 43% make decisions related to plowing; 34% sowing; 10% planted different varieties	SCF	Farmers	Interviews; evaluation workshops	Ouedraogo et al. (2018)
North Africa						
Mauritania	—	Can use information for land preparation, crop variety, sowing, weeding	Info on weather, seasonal climate, climate change	Farmers	32 farmers	Tarchiani et al. (2018)

Abbreviations: NGO, nongovernmental organization; SCF, seasonal climate forecast.

APPENDIX C: EAST AFRICA ACCESS AND USE ESTIMATES

	Access estimates	Use estimates	Information type	Target population	Data collection, sample size	References
East Africa						
Kenya	—	Significant change in planning and mgmt re: land prep, seed selection, fertilizer, harvesting, planting, livestock mgmt	Seasonal forecast	Farmers	120 surveys	Rao et al. (2015)
	62.7% (pests) and 48.4% (rainfall onset rainfall) of East African farmers received info; roughly 25% reported men and women having equal access	24% (rainfall onset) and 5.3% (disease) of East African farmers report changes in practice	Start of rainfall, outbreak of pests	Farmers	280 surveys	Oyekale (2015)
	82% of farmers have access to weather or climate info; main access point is through the radio (84%)	Majority who received info apply it in farm mgmt; use of info influenced by tercile; main decisions crop selection, water storage, food storage, early planting, hire more labor, etc.	Seasonal forecast	Agropastoralists	240 surveys, 40 interviews	Ngugi et al. (2011)
	49% of respondents had access to forecasts in first survey; only 4% had access in second survey	73% of farmers who received SCF used them to prepare for emergencies; 41% changed in planting date; 14% changed crop location; 9% crop type	Seasonal forecast	Farmers	198 pilot survey, 299 second survey; 3 sites	O'Brien (2000)

(Continues)

APPENDIX C (Continued)

	Access estimates	Use estimates	Information type	Target population	Data collection, sample size	References
	Awareness of forecasts: start date (48%); end date (42%); rainfall volume in own location (48%); rainfall volume in other location (45%)	Start date (24%); end date (3%); rainfall volume in own location (15%); rainfall volume in other locations (3%)	Start date; end date; rainfall volume	Pastoralists	293 households, 6 sites in Kenya; 4 in Ethiopia	Luseno et al. (2003)
Tanzania	At local level: access to climate info is highly variable; generally <50%; women have less access than men; At national and district level, all respondents had access	—	Climate advisories, climate services	Varied	33 semi-structured interviews at district level; range of data collection methods at local level	Daly et al. (2016)
	>50% of farmers have access to weather forecasts; slightly less access to seasonal forecasts; info regarding pests/diseases least accessible	38% of farmers use info on extreme events; 62% onset forecast; 22% SCF; 38% pest forecast; 0% weather forecasts	Extremes; onset; weather; SCF; pests/diseases	Farmers, agropastoralists	340 households, 17 villages (9 experimental, 8 control), 2 sites; 39 interviews	Coulibaly, Mango, et al. (2015)
	62.7% (outbreak of pests) and 48.4% (start of rainfall) of the farmers from East Africa received info; 25% reported men and women having equal access	24% (rainfall onset) and 5.3% (disease) of East African farmers report changes in practice bc of forecasts	Start of rainfall, outbreak of pests	Farmers	280 surveys	Oyekale (2015)
Uganda	Farmers report receiving weather info on radio and SMS; most do not understand it, or find it salient or credible	—	Weather, climate info	Farmers	4 focus groups, 15–20 people each	Jost et al. (2016)
	Info received from sources including; radio, diviners, community meetings, elders, humanitarian agencies, and Uganda Defense Force	info used to for shifting livestock; selling firewood and charcoal; seeking military escort to grazing areas; purchasing veterinary drugs;	Flood, drought, pest and disease forecast, onset	Pastoralists	198 multistage surveys; 10 interviews; 29 focus groups	Egeru (2016)
Ethiopia	39% have access to info on climate	Info on temp and rainfall used to choose crop varieties (18.5), soil conservation (9.5), changing planting dates (5.1%), and irrigation measures (5.4%).	Temperature, rainfall	Farmers	400 surveys, 3 districts	Gebrehiwot and van der Veen (2013)
	15% of households had access to seasonal forecasts; language and access to media are limitations	Recipients update beliefs based on below-normal, but not above-normal rainfall forecasts	Seasonal forecast	Pastoralists	Surveys, 245 households	Lybbert et al. (2007)

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APPENDIX C (Continued)

	Access estimates	Use estimates	Information type	Target population	Data collection, sample size	References
	62.7% (outbreak of pests) and 48.4% (rainfall onset) of the farmers from East Africa received info; roughly one-quarter reported men and women having equal access to forecasts	24% (rainfall onset) and 5.3% (disease) of East African farmers report changes in practice bc of forecasts	Start of rainfall, outbreak of pests	Farmers	280 surveys	Oyekale (2015)
	Gov and non-gov agencies access seasonal forecast	Gov and donor decisions not based on seasonal forecasts, but lagging indicators of crisis	Seasonal forecast	Gov and NGOs	Interviews, narrative	Broad and Agrawala (2000)
	37% have access to climate info	Info on temp and rainfall increases the likelihood of changing crop varieties by 17.6%	Temperature, rainfall	Farmers	1,000 surveys, 4 regions	Deressa et al. (2009)
Rwanda	2,600 farmers trained in Participatory Integrated Climate Services in Agriculture	93% of farmers made changes	Climate and weather information in "accessible forms"	Farmers	214 sampled farmers	Clarkson, Dorward, Kagobo, and Nsengiyumva (2017)

Abbreviation: NGO, nongovernmental organization; SCF, seasonal climate forecast.

APPENDIX D: SOUTHERN AND CENTRAL AFRICAN ACCESS AND USE ESTIMATES

	Access estimates	Use estimates	Information type	Target population	Data collection, sample size	References
Southern Africa						
Mozambique	86% have access, primarily through TV or radio	Respondents use forecasts, on average 780 times per year	Weather, SCF	General public	576 surveys	Lazo (2015)
Namibia	35% of farmers access pre-season forecasts; 85% access info through radio	60% of farmers who accessed forecasts reported using it; common action was to change planting dates (40%); substitution (35%)	SCF	Farmers	90 pilot survey, 112 second survey	O'Brien (2000)
Zimbabwe	65% access to seasonal forecasts	57% of those with access reported changing decisions based on forecasts	SCF	Farmers	4 villages, 578 surveys	Patt et al. (2005)
	59% of farmers access to rainfall info; 48% access drought info; 33% access storm info	Choice of planting dates (37%) and choice of crop varieties (37%) were most common	Rainfall forecasts; drought info; storm warnings	Farmers	300 surveys	Mudombi and Nhamo (2014)
	37.25 of farmers have access	—	Not specified	Farmers	400 surveys	Zamasiya et al. (2017)

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APPENDIX D (Continued)

	Access estimates	Use estimates	Information type	Target population	Data collection, sample size	References
Malawi	27% of farmers access to climate info	Access to climate info positively correlated to climate change adaptation	Seasonal and long-term info	Farmers	Survey, 1,786 farmers, 3 districts	Mulwa et al. (2017)
	> 80% of farmers access to 2–3 day forecasts, onset of rains, extreme events; slightly less access to disease info	69% report using onset info on onset; 49% on seasonal forecast; 48% on extremes; 38% on weather; 34% on pests/disease forecasts	Onset, SCF, weather, extremes, pests	Farmers	320 surveys, 20 villages (12 exp, 8 cont); 46 interviews	Coulibaly, Kundhlande, et al. (2015)
South Africa	--	Planting; water conservation; fertilizer application; stocking decisions;	SCF	General public	Not specified	Klopper (1999)
Central Africa						
Central African Republic	only 2% of farmers report access to scientific climate or meteorological information; 98% rely on traditional weather and climate indicators	—	Weather, seasonal	Farmers	315 surveys	Ngana et al. (2013)

Abbreviation: SCF, seasonal climate forecast.

APPENDIX E: RATES OF USE OF SEASONAL FORECASTS AND AGGREGATED ACROSS WEATHER AND CLIMATE INFORMATION PRODUCTS, AS PERCENT OF ACCESS RATE, WITH INFORMATION PRODUCTS AND MOST COMMON DECISION RESPONSES

		Use as % of access				
Country	**System**	**Seasonal forecast**	**WCS**	**Products**[a]	**Decisions**	**References**
Benin	Farming	95% (expressed intent)		SRF	Sowing date, area cultivated, cultivar and crop selection, fertilizer use	Amegnaglo et al. (2017)
Burkina Faso	Farming	76%		SRF	Location and area cultivated, cultivar selection, sowing date	Zongo et al. (2016)
Burkina Faso	Farming and pastoralism	89% (workshop participants); 76% (nonparticipants)		SRF	Location and area cultivated, crop and cultivar selection, livestock health management	Roncoli et al. (2009)
Ethiopia	Pastoralism	24%		SRF	Whether to plant, sowing date, cultivar selection	Luseno et al. (2003)
Kenya	Farming	98% (short rains); 81% (long rains); 91% (all seasons)		SRF	Cultivar and crop selection, fodder planting and management, sowing date, manure use, herd destocking	Ngugi et al. (2011)
Malawi	Farming		97%	HRD, SRF (in a participatory planning process)	Cultivar selection, agronomic practices, crop selection, herd size, new livelihood enterprise, input use	Stats4SD (2017)

(Continues)

APPENDIX E (Continued)

Country	System	Use as % of access		Products[a]	Decisions	References
		Seasonal forecast	WCS			
Mali	Farming		13%	MA, village rain gauges	Planting date	Carr and Owusu-Daaku (2016)
Namibia	Farming	60%		SRF	Sowing date, area cultivated, crop selection, livestock sales	O'Brien (2000)
Rwanda	Farming		93%	HRD, SRF (in a participatory planning process)	Unspecified crop, livestock and livelihood management	Clarkson et al. (2017)
Senegal	Farming, fisheries		78%	SRF, MA (sowing date), rainfall nowcast, wind forecast, rain cessation date;	Date of field preparation and sowing, cultivar selection	Ouedraogo et al. (2018)
Tanzania	Farming	73%		SRF	Sowing date, location cultivated, crop selection, intercropping, area cultivated	O'Brien (2000)
Tanzania	Farming, pastoralism		52%	HRD (in a participatory planning process), SRF, WF	Cultivar selection, agronomic practices, input use, livestock management, herd size cultivated, new livelihood enterprise	Stats4SD (2017)
Uganda	Pastoralism		48%	EW (drought)	Herd migration, waterhole management	Egeru (2016)
Zimbabwe	Farming	57%		SRF	Sowing date, cultivar selection	Patt et al. (2005)
Zimbabwe	Farming		96%	WF; EW (drought, storms, floods)	Sowing date, cultivar selection, land preparation, fertilizer use	Mudombi and Nhamo (2014)

[a]EW, early warning; HRD, historical rainfall data; MA, management advisory; SRF, seasonal rainfall forecasts; WF, weather forecasts.