1-17-2022

Impact Pathways From Climate Services to SDG2 (“Zero Hunger”): A Synthesis of Evidence

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Repository Citation

Hansen, James; List, Geneva; Downs, Shauna; Carr, Edward; Diro, Rahel; Baethgen, Walter; Kruczkiewicz, Andrew; Braun, Melody; Furlow, John; Walsh, Kayla; and Magima, Nitin, "Impact Pathways From Climate Services to SDG2 (“Zero Hunger”): A Synthesis of Evidence" (2022). *International Development, Community, and Environment*. 67.
https://commons.clarku.edu/faculty_idce/67

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Climate Risk Management 35 (2022) 100399

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Impact pathways from climate services to SDG2 (“zero hunger”): A synthesis of evidence

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ARTICLE INFO

Keywords:
Climate services
Food security
SDG2
Impact evaluation
Risk
Insurance

ABSTRACT

Climate services can help address a range of climate-sensitive development challenges, including agricultural production and food security. However, generating empirical evidence of impact is challenging. In this paper, we synthesize published evidence of pathways by which climate services contribute to improved food security. A summary of key mechanisms by which climate risk drives food insecurity provides a context for understanding potential climate risk management interventions. Our review of available evaluation literature finds moderately strong evidence that climate services contribute to improvements in food security or its precursors through farmers’ risk management decisions and index-based agricultural insurance; and a weaker body of emerging evidence of impacts through timelier humanitarian and adaptive social protection interventions. There are gaps in the available evidence of anticipated food security impacts through agricultural value chain actors, government agricultural planning, nutrition interventions and policy. Attributing SDG2 impact to climate services is particularly challenging for initiatives that aim to build an enabling environment to scale and sustain impacts of climate services through capacity development and policy engagement with national institutions. In such cases, employing a theory of change approach grounded in the evolving body of evidence included in this review can provide confidence that improved production and use of climate services by actors along hypothesized impact pathways will contribute towards improved food security.

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https://doi.org/10.1016/j.crm.2022.100399
Received 22 July 2021; Received in revised form 9 January 2022; Accepted 11 January 2022

1. Introduction

The world is largely off track to achieve the second sustainable development goal (SDG2), to “end hunger, achieve food security and improved nutrition and promote sustainable agriculture,” by 2030 (UNICEF et al., 2019). Despite significant progress in many countries, approximately two billion people (~25% of global population) continue to experience moderate or severe food insecurity (FAO et al., 2020), 47 million children under 5 are wasted (i.e., acutely malnourished), 144 million are stunted (i.e., chronically malnourished), and approximately two billion people are deficient in key micronutrients (FAO et al., 2020; UNICEF et al., 2019).

The most widely accepted definition of food security, “… when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life,” recognizes four pillars: availability (i.e., sufficient quantity of food of appropriate quality), access (physical and economic), utilization (through adequate diet, clean water, sanitation and health care) and stability (FAO, 2006). This definition of food security evolved considerably from the earlier focus on the “availability at all times of adequate world food supplies of basic foodstuffs to sustain a steady expansion of food consumption and to offset fluctuations in production and prices” (United Nations, 1975). Sen’s (1983) influential work on the causes of famines, in particular, contributed to a shift in focus from the aggregate supply of food to the ability of households to access food through their assets, or “entitlements,” and in so doing, highlighted the strong link between food insecurity and poverty. Although SDG2 (“zero hunger”) interacts with other SDGs, it is therefore particularly closely linked with SDG1 (“no poverty”). While the overall goal is to end hunger, SDG2 target 2.2, to “end all forms of malnutrition” by 2030, reflects growing concern over health impacts of dimensions of nutrition beyond aggregate caloric and protein intake, including diversity, micronutrient content, and obesity. SDG2 thus reflects a recent trend toward integrating nutrition into food security concepts and interventions (Ingram, 2020).

The risk associated with climate variability been a major obstacle to past efforts to improve food security and the well-being of rural populations across the developing world. The strong link between climate risk and food security suggests that improving climate risk management must be part of the strategy for achieving SDG2. A well-functioning climate service provides the information and support that decision-makers need to understand, anticipate, and manage climate-related risks across the range of relevant time scales. While climate services can include information at the weather (e.g., daily observations, forecasts out to about 10 days), climate variability (e.g., historical analyses of seasonality, variability and trends; seasonal forecasts) and climate change time scales, long-term projections of anthropogenic climate change have little relevance to immediate food security interventions and to the 2030 SDG target date. Climate services, defined by the Climate Services Partnership as “production, translation, transfer, and use of climate knowledge and information in climate-informed decision making and climate-smart policy and planning”[1] are often described in terms of a value chain that requires a diverse set of institutions actors, and expertise from multiple disciplines (Hewitt & Stone, 2021). With the support of Regional Climate Centers, and globally from the World Meteorological Organizations, National Meteorological Services (NMS) have the primary responsibility to produce observed and forecast weather and climate information, and warnings of impending hydro-climatic threats at the country level. Climate services involve more than generating and disseminating information; and NMS are part of the larger community of public, private, academic, and development organizations that work together to translate weather and climate information into actionable forms, deliver information and advisories to decision makers across climate-sensitive sectors, and build the capacity of these decision makers to understand and act on the information.

This paper reviews published evidence of pathways by which climate services contribute to improved food security. To provide context for examining the contribution of climate services to food security, we first summarize key mechanisms by which climate risk drives food insecurity (Section 2). We then present methods (Section 3) and results (Section 4) of our review of the available evidence of pathways by which climate services contribute to improvements in food security and its precursors. In Section 5, we summarize the state of this evidence; and discuss implications for how to evaluate and strengthen the contribution of climate services to SDG2 in the context of the “Adapting Agriculture to Climate Today, for Tomorrow” (or ACToday) project[2], which seeks to transform the way that climate information is brought to bear on the challenges of hunger, food security, nutrition, and sustainable agriculture in six countries: Bangladesh, Colombia, Ethiopia, Guatemala, Senegal and Vietnam.

2. Background: climate risk is a driver of food insecurity

In this section, we summarize the main pathways by which unanticipated and unmitigated climate risk, contributes to both short-term and persistent food insecurity impacts, and hence works against SDG2. The available literature reveals that: (a) shocks associated with extreme climate events trigger acute food insecurity, (b) the uncertainty associated with climate variability suppresses agricultural production and livelihoods, (c) climate impacts on food accessibility propagate through the economy, and (d) the adverse impacts of climate risk on food security and its precursors can persist long after a period of climatic stress. While the literature supports these generalizations across a range of contexts, there is a great deal of variability in the timing and nature of climate impacts, and in the strategies that vulnerable households employ to cope with those impacts.

2.1. Climate shocks trigger acute food insecurity

A substantial body of literature, including reviews and meta-analyses (Asmall et al., 2021; Belesova et al., 2019; Brown et al., 2020;

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[1] https://climate-services.org/about-us/what-are-climate-services

[2] https://iri.columbia.edu/actoday/

Cooper et al., 2019b; Delbiso et al., 2017), documents near-term impacts of weather and seasonal climate extremes on food consumption; the prevalence of food-insecure or undernourished individuals; and health impacts expressed as wasting (i.e., low weight-for-height), stunting (i.e., low height-for-age), underweight (i.e., low weight-for-age) and mid-upper arm circumference (MUAC). While the most frequently reported climatic trigger is drought (Amare et al., 2018; Bahru et al., 2019; Bauer and Mburu, 2017; Belesova et al., 2019; Cooper et al., 2019b; Delbiso et al., 2017; Hoddinott and Kinsey, 2001), studies also document impacts of high and low temperature extremes (Asfaw and Maggio, 2018; Brown et al., 2020; Hagos et al., 2014; Randell et al., 2020), flooding (Akukwe et al., 2020; del Ninno and Lundberg, 2005; Muttarak and Dimitrova, 2019), and excess rainfall (Cooper et al., 2019a). A meta-analysis of 90 studies of factors associated with child malnutrition found evidence of statistically significant links between drought and underweight, between excess rainfall and wasting, and between extreme temperature and stunting (Brown et al., 2020). The majority of research linking climate shocks to malnutrition has focused on early childhood and pregnancy because malnutrition during this critical period – particularly the 1000 days from the time the child is conceived to their second birthday – can have long-term impacts on health, cognitive development and economic productivity (Schwarzenberg et al., 2018). A few studies assess impacts of climate shocks on nutrition among households (Akukwe et al., 2020; Amare et al., 2018; Asfaw and Maggio, 2018), adults (Hoddinott and Kinsey, 2001) and older children (Bahru et al., 2019).

Food security and associated health impacts of climate shocks are influenced by confounding factors that include the impacts of social dynamics and poverty on food production and access (Carr, 2020, 2019; Cavicchioli, 2018; Hadley et al., 2008; Hoddinott and Kinsey, 2001; Manlosa et al., 2019; Mishra et al., 2004; Muttarak and Dimitrova, 2019), the timing of the shock (Hill et al., 2019a,b), and the capacity of the government to anticipate and respond to a shock (Cooper et al., 2019b). For example, while a shock might impact an entire community, gendered patterns of cultivation might result in uneven impacts on food availability and income within households, while uneven levels of asset ownership will result in different abilities to weather the shock across households in a community (Carr and Onzere, 2018).

Most often the first and most direct impact of a climate shock is reduced crop production. For smallholder farm households, a failed harvest directly reduces the availability of food from subsistence production, or for those engaged in cash production it reduces income available to purchase food (Amare et al., 2018; Lesk et al., 2016). For rural households that routinely experience a hunger season that starts when dwindling reserves lead them to ration meals and ends at the next harvest, a climate-driven production shock causes the hunger season to start earlier and intensifies its impact on assets and health. Climate shocks can also interrupt access to safe, clean water, which can disrupt food preparation and reduce proper sanitation and hygiene practices – further impacting diets and the body's capacity to utilize food. These seasonal climate stresses also impact food access by shaping price cycles and household disposable income, and food utilization through the timing and severity of disease outbreaks such as diarrhea and malaria (Bandyopadhyay et al., 2012; Baye and Hirvonen, 2020; Chotard et al., 2010).

A climate-driven drop in staple food production can trigger cascading impacts that negatively impact economic accessibility of food. First, a climate-driven reduction in availability of a staple crop can increase its price because demand for staple foods is relatively inelastic, however integration with regional and global markets or the presence of buffer stocks within a country can greatly reduce or eliminate the price shock (Brown, 2014; Devereux, 2007; Yami et al., 2020). Although farm income from a price increase can partially compensate for the impact of a negative productivity shock on the income of farmers who are net sellers (Ahmed et al., 2009; Wineman et al., 2017), rural households who are net buyers of food face the combined impact of reduced availability through subsistence production and reduced accessibility through higher food prices. Relatively poor households typically respond to price shocks by reducing dietary diversity, and shifting towards staple cereal crops or lower quality foods that are more processed and less nutrient-rich (Brinkman et al., 2010; Carpena, 2019). Second, as farm households deplete their food stocks and savings, they increasingly turn to off-farm casual employment to meet the shortfall, which can flood a local labor market. The resulting crisis also reduces demand for casual labor by reducing the disposable incomes of relatively wealthy farmers and those in the rural non-farm economy who depend indirectly on agriculture (Carpena, 2019). Third, the value of durable assets decreases as affected households seek to exchange assets for food, through distress sales or barter, at the same time demand for these assets is decreasing in response to falling incomes and rising food costs. The impact of climate shocks on terms of trade is particularly serious for pastoralists, as shocks such as severe drought that reduce grazing resources lead both to widespread livestock mortality, and distress sales that lead to over-supply and drop in market price (Devereux, 2009; Maxwell and Fitzpatrick, 2012; Salama et al., 2012).

2.2. *Climatic uncertainty suppresses agricultural production and livelihoods*

While the impacts of extreme climate events on food insecurity are more visible, the uncertainty due to climate variability also contributes to chronic food insecurity by reducing the efficiency of input use, and by acting as a disincentive to adopting improved agricultural practices and investing in agriculture. The uncertainty associated with climate variability creates a moving target for management that reduces efficiency of land and production inputs and hence profitability, as management that is optimal for average climatic conditions can be far from optimal for growing season weather in most years (Hansen et al., 2009; Jones et al., 2000). Furthermore, in the face of climate variability and in the absence of risk transfer instruments (e.g., insurance), farmers tend to employ precautionary strategies to protect against the possibility of catastrophic loss in the event of a climatic shock and thus do not optimize management for average conditions, but for adverse conditions. Farmers' *ex-ante*, precautionary strategies include: selecting less risky but less profitable crops and cultivars (Dercon, 1996; Sesmero et al., 2018), generally avoiding investment in production assets (Barrett et al., 2007; Fafchamps, 2003; Newman and Tarp, 2020) and technologies (Barrett et al., 2004; Kebede, 1992; Marra et al., 2003; Sesmero et al., 2018), under-use of fertilizers (Dercon and Christiaensen, 2011; Morris et al., 2007; Ogada et al., 2010; Simtowe, 2006), using livestock for precautionary savings rather than income, (Abay and Jensen, 2020), distributing farm plots across different topographies (Carr 2011), and shifting household labor to less profitable off-farm activities (Rose, 2001; Rosenzweig and Stark, 1989). Although the greatest setbacks to the welfare of rural populations can often be linked to the most damaging climatic extremes, the opportunity costs of farmers' *ex-ante* response to climate risks are substantial – perhaps greater than the ex-post cost of shocks (Carr, 2011; Elbers et al., 2007) – as farmers experience these opportunity costs in favorable and near-normal seasons far more frequently.

2.3. *Climate impacts on food accessibility propagate through the economy*

The cascade of impacts that farm households experience also manifest at an aggregate level through economic general equilibrium effects. Studies employing statistical analyses of panel data or economic equilibrium modeling have demonstrated adverse macroeconomic impacts of climate shocks on Gross Domestic Product (GDP) across sectors and within the agriculture sector (Brown et al., 2013, 2011; Damania et al., 2020; Loayza et al., 2012; Montaud, 2019), per capita income beyond the farming sector (Montaud, 2019; Wineman et al., 2017), poverty rates (Ahmed et al., 2009; Brown et al., 2013, 2011; Pauw and Thurlow, 2011) and per capita food consumption (Ahmed et al., 2009; Montaud, 2019). Temperature extremes have been linked to changes in GDP growth across more- and less-developed countries (Burke et al., 2015; Dell et al., 2012). Although analyses have not detected significant association between macroeconomic conditions and rainfall averaged at a national scale (e.g., Burke et al., 2015; Dell et al., 2012), significant negative impacts of drought or excess rainfall are apparent in many developing countries when analyses account for the spatial heterogeneity of rainfall within the country (Brown et al., 2013, 2011; Damania et al., 2020).

A climate-driven production shock can propagate through the economy through several pathways (Al-Riffai et al., 2012; Devereux, 2007; Pauw and Thurlow, 2011). For example, reduced supply and increased price of crops can increase costs of livestock, and other production and food processing activities that use crop commodities as inputs. Increased food costs increase the proportion of household incomes used for food, thereby reducing demand for other goods and services, which in turn reduces employment opportunities particularly for casual labor across sectors. Although the impacts of climate shocks tend to be greatest within the agriculture sector, the combination of reduced income and increased food prices reduces food consumption of non-farm households, particularly those who depend on casual labor (Borgomeo et al., 2018).

2.4. *Climate impacts are persistent*

The food security impacts of a climate shock often persist long after climate conditions return to normal. This is due both to long-term consequences of early childhood health impacts, and to household coping strategies that deplete productive assets.

A severe or prolonged crisis that leads to malnutrition *in utero* or during the critical first 1000 days of life can adversely impact the individual's health and livelihood long after the crisis is over through several physiological mechanisms (Stephenson et al., 2018; Wells et al., 2020). Long-term studies link nutrition status early in life, to health, educational achievement and income into adulthood (Alderman et al., 2006; Currie and Vogl, 2013; Maluccio et al., 2009; Victora et al., 2008). For example, Galasso and Wagstaff (2018) estimated that early childhood stunting reduces income later in life by 5–7%, averaged across 34 developing countries that account for 90% of the world's stunted children. Similar long-term impacts on physical and mental health, amount of education completed, income and wealth are evident for individuals who experience drought (Abiona, 2017; Dercon and Porter, 2014; Dinkelman, 2017; Maccini and Yang, 2009) or temperature shocks in early childhood (Randell and Gray, 2019, 2016). A study of 106,330 women in 19 sub-Saharan African countries showed that drought experienced during early childhood reduced educational attainment and wealth as adults, adversely affected empowerment, and increased the likelihood that their children would have low birth weight – for rural but not for urban populations (Hyland and Russ, 2019).

When a severe climate shock, such as a drought, flood or heat wave, reduces the availability and accessibility of food, vulnerable households typically employ a sequence of coping strategies to endure the immediate crisis. While the type, sequence and timing of responses can vary considerably among households and contexts, initial coping responses typically include consuming less preferred food (often lower in nutritional quality), working off farm, consuming savings, borrowing, and rationing meals among adult members – particularly women (Clarke and Hill, 2013; Farzana et al., 2017; Hill et al., 2019a,b; Weldearegay and Tedla, 2018). If the crisis persists or if a subsequent shock leads to a compound shock (Kruczkiewicz et al., 2021) after these initial coping strategies are exhausted, households then may implement more drastic coping strategies; for example defaulting on loans, liquidating productive assets, withdrawing children from school and over-exploiting natural resources; that increasingly erode their capacity to secure livelihoods and sustenance in the future (Barrett and Carter, 2001; Carter et al., 2007; Carter and Barrett, 2006; Dercon and Hoddinott, 2003; Hoddinott, 2006; McPeak and Barrett, 2001; Mottaleb et al., 2013; Wood, 2003). The duration of a crisis, co-occurring shocks, and the timeliness of any intervention are therefore crucial for determining whether affected households fully recover once climatic conditions return to normal.

Given the strong connection between food insecurity and poverty, the literature on poverty traps provides a useful lens for understanding the role that climate plays in persistent food insecurity. A dynamic poverty trap occurs when a critical threshold of household assets exists, below which individuals are unable to accumulate the necessary resources to escape poverty (Barrett, 2005; Carter and Barrett, 2006). It can be understood as a low-level equilibrium characterized at the rural household level by dominance of subsistence staple crop production, poor adoption of innovation, persistent food and livelihood insecurity; and at an aggregate scale by economic stagnation and sometimes chronic dependence on humanitarian assistance (Barrett, 2005; Barrett et al., 2007). Climate-related risk contributes to such poverty traps through several mechanisms (Hansen et al., 2019a,b,c). First, climate shocks erode the productive assets and human capital of affected households. Second, the precautionary risk management strategies of risk-averse farmers reduce the productivity and profitability of their land (i.e., through mining soil nutrients without replenishing with fertilizers) and other assets, and discourages productive asset accumulation. The impact is greater on relatively poor households because individuals with less wealth tend to be more risk averse and hence less able to invest their scares resources in profitable but risky options (Rosenzweig and Binswanger, 1993; Sesmero et al., 2018; Zimmerman and Carter, 2003; Carter and Barrett, 2006). Third, rural households and communities often respond to stress by adopting increasingly rigid roles, responsibilities and practices that constrain innovation and erode resilience over time (Carr, 2020).

Rural households experiencing acute food insecurity often face a tradeoff between protecting productive assets at the expense of food consumption, or protecting consumption at the expense of assets. Although rural households typically prioritize maintaining a minimum level of consumption when they face a crisis, in the presence of a poverty trap a growing body of research shows that households close to the poverty trap threshold are inclined to sacrifice consumption, and hence the nutrition and health of family members, to protect their assets (Carter and Lybbert, 2012). However, prioritizing assets can still trap families in long-term poverty and food insecurity if reduced food consumption permanently impairs the future productivity and livelihood potential of young children.

2.5. *Climate impact pathways and potential interventions*

Our preceding summary expands on existing reviews (e.g., Belesova et al., 2019; Brown et al., 2020; Hansen et al., 2019a,b,c; Ngcamu & Chari, 2020) by highlighting the main pathways by which unanticipated and unmitigated climate risk contributes to food insecurity impacts and hence works against SDG2 (Fig. 1). Our understanding of these pathways suggests potential opportunities for improved climate risk management, informed by climate services, to contribute towards SDG2. For example, forecasts that reduce uncertainty about seasonal climate conditions can enable farmers to adopt technologies that increase their productivity in years with favorable conditions, and protect their investments in years with adverse conditions. In the face of a climate shock, insurance payouts or social protection interventions can enable vulnerable households to avoid harmful coping strategies and hence protect their productive assets. At an aggregate scale, governments can mitigate the impacts of anticipated climate-driven food production shortfalls through trade and other market interventions, and humanitarian organizations can use early warnings to direct assistance to populations that are most severely impacted by resulting income and price shocks. Our understanding of these potential interventions informed our review of climate service contributions to food security (Sections 3 and 4).

3. Methods

Advances in climate service investment and practice, and innovation in a range of climate-informed agricultural, development, nutritional and humanitarian interventions, is generating a growing body of knowledge and evidence of ways that climate services and climate-informed interventions can contribute towards food security. Our review of evidence of climate service contributions to food security considered studies published in English in the peer-reviewed literature or credible institutional reports, in the past ten years, that provide quantitative evidence linking the use of weather and climate information to food security impacts in developing countries relative to a defined counterfactual (Table 1). We include evaluations of interventions that would clearly require the use of climate-related information, even if such information is not explicitly referenced. We exclude studies of impacts that are purely subjective, including contingent valuation based on willingness-to-pay. We did not consider studies of the use of long-term climate change projections, as they are not relevant to the 2030 SDG target date and their impact cannot be compared empirically to a counterfactual.

Impacts included in our analysis include those that map onto SDG2 targets, and intermediary impacts towards food security (Table 2). SDG2 defines five targets, each with proposed metrics: (2.1) universal access to safe and nutritious food; (2.2) ending all forms of malnutrition; (2.3) doubling the productivity and incomes of small-scale food producers; (2.4) sustainable food production and resilient agricultural practices; and (2.5) maintaining genetic diversity in food production. Climate risk, and hence the potential contribution of improved climate risk management, are associated with the first four SDG2 targets. Climate risk also influences factors such as food price and household incomes, that impact food security but are not included as SDG2 targets. The list of SDG2 and intermediary impacts in Table 2 served as a basis for searching and organizing evidence of the contributions of climate services to SDG2 in Section 3. We include benefit-cost ratio (BCR) as an intermediate impact on the assumption that improving the BCR would increase the number of people that scarce humanitarian resources could assist in an emerging food crisis.

Based on the authors' collective understanding, our search considered eight hypothesized pathways for using climate services to support SDG2: (a) use of climate services by farmers and pastoralists, (b) index-based agricultural insurance, (c) de-risking agriculture value chain investment, (d) government agricultural planning, (e) nutrition interventions identified in the literature (Bhutta et al., 2013) (e.g., treatment of severe acute and moderate acute malnutrition, macro- and micronutrient supplementation), (f) food security humanitarian interventions, (g) adaptive social protection programs, and (h) enabling policy. We used a combination of methods to identify publications that meet these criteria, including (a) authors' familiarity with the subject matter, (b) Google Scholar searches, (c) existing review papers with overlapping scope, and (d) forward searches of papers that cite accepted studies.

The search identified 56 studies (summarized in Appendix A) that meet the inclusion criteria, covering: farmers' use of climate services, index-based agricultural insurance, and humanitarian and social protection interventions (Fig. 2, Table 2). Our review combines humanitarian and social protection interventions because the anticipatory pilot projects that have generated most of the

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[3] Includes World Bank low-income, lower-middle-income and upper-middle-income economies (https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups).

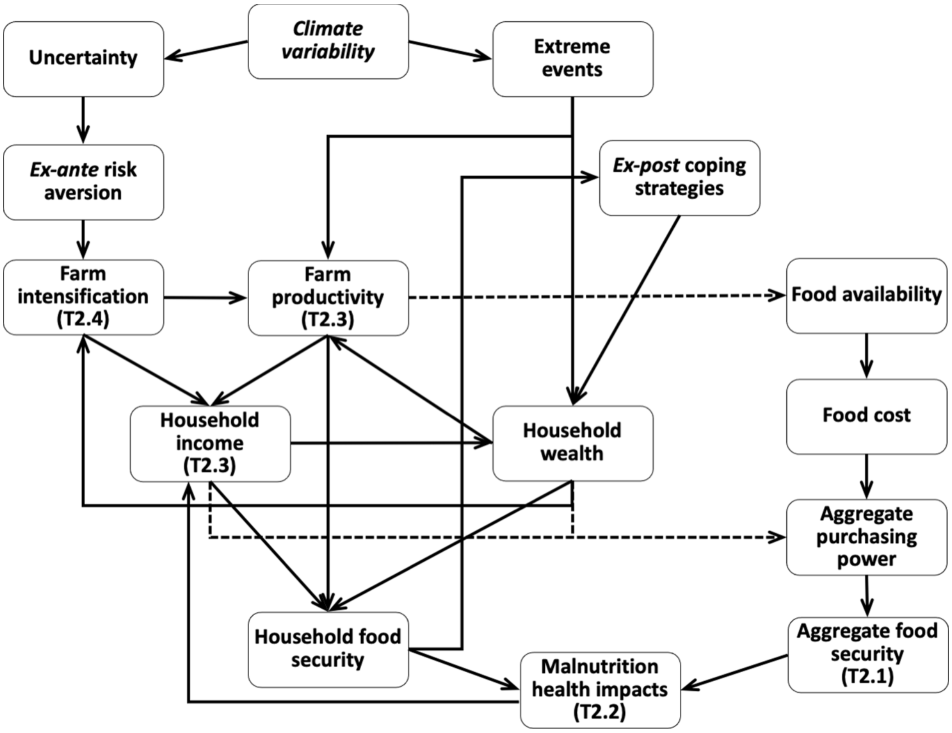

Fig. 1. Main pathways by which climate risk contributes to food insecurity, reviewed in Sections 2.1 to 2.4. Dashed arrows represent links between household and aggregate scale (right column) impacts. Numbers in parentheses are SDG2 targets (https://sdgs.un.org/goals/goal2).

Table 1
Inclusion criteria for evidence of climate-informed risk management contributions to SDG2.

	Included	Excluded
Scope	● Evaluation studies linking weather or climate information use to food security or intermediate impacts.	
Pathways	● Farmers' use of climate services to manage risk ● Index-based agricultural insurance ● De-risking agriculture value chain investment ● Government agricultural input and market planning ● Nutrition interventions ● Humanitarian and social protection anticipatory action ● Enabling policy and institutional environment	
Climate information	● Historical, monitored or forecast information at weather to climate variability time scales ● Climate-related remote sensing information ● Climate information translated into impact prediction, advisories or decision support ● Early warning systems that include a climate component. ● Interventions that depend on climate information, even if the information is not described	● Change projections ● Indigenous climate indicators
Impacts	● SDG2 targets and intermediate impacts (Table 2)	
Nature of evidence	● Ex-post and ex-ante evaluations that provide quantitative evidence of impact relative to a defined counterfactual	● Willingness-to-pay studies ● Purely subjective assessments of benefit
Type of publication	● Peer-reviewed academic publications ● Publicly available grey literature from academia, or other institutions with known evaluation expertise	
Geographic scope	● Developing countries[3]	
Period	● Published in 2011 to present (early 2021)	
Language	● Text in English	

Table 2
Numbers of included studies, by pathway and impact.

Impact	Examples	Pathways			Total
		Farmer risk management	Index-based insurance	Anticipatory action	
Intensification (T2.3/T2.4)	Credit access Technology adoption Investment in inputs	5	18	0	23
Productivity (T2.3/T2.4)	Crop yield increase Cultivated area increase Animal productivity increase	7	5	6	18
Income (T2.3)	Harvest value increase Production cost decrease Gross margin increase Household income increase	8	5	1	14
Wealth (a determinant of food access)	Assets protected Assets accumulated Escape from poverty Escape from poverty trap	2	6	6	14
Food security (T2.1/T2.2)	Food consumption Food expenditure Dietary diversity	3	3	6	12
Health status (T2.2)	Weight-for-height (wasting) Height-for-age (stunting) Mid-upper arm circumference	0	1	0	1
Aggregate economic impact (a determinant of food access)	Gross domestic product (GDP) Consumer + producer surplus	2	0	0	2
Benefit-cost ratio		1	0	9	10
Included Studies		*18*	*25*	*13*	*56*

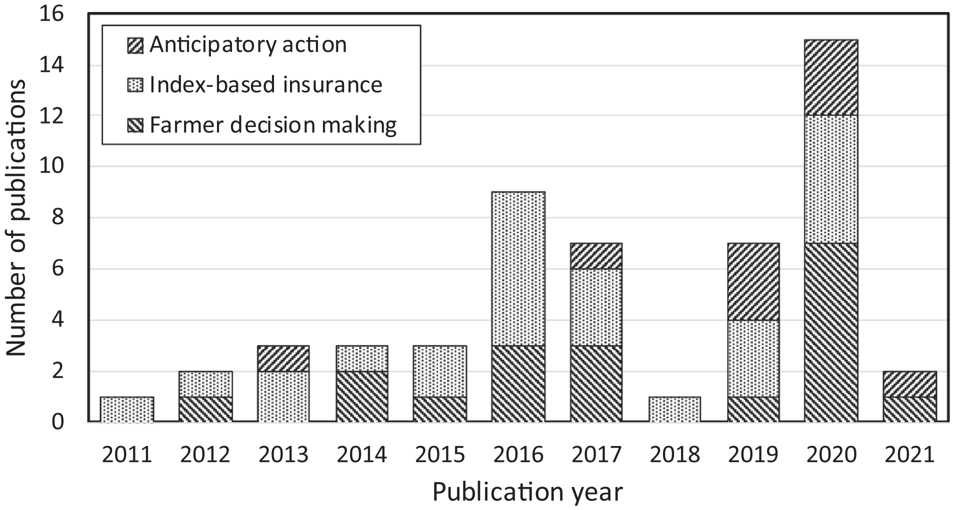

Fig. 2. Annual numbers of included evaluations.

relevant evidence fall outside of established social protection and humanitarian response processes, and incorporate elements of both. We did not find any evaluations of climate service use for agricultural value chains, government planning, nutrition interventions or enabling policy that met the inclusion criteria. The number of relevant evaluations published has generally increased during the recent decade (Fig. 1). They employ a wide range of evaluation methods (Table 3).

Table 3
Methods commonly employed in included evaluation studies.

Method	Summary	Strengths	Limitations	Key examples
Simple comparison (SC)	Impact estimated as difference in metrics between treatment and control groups.	Simplicity of design and analysis.	Selection, self-selection bias.	Birachi et al., 2020; Pople et al., 2021
Randomized control trial (RCT)	Random sampling of participant and control individuals or locations. Impact estimated as difference in metrics between treatment and control groups.	Straightforward estimation. Randomization controls for selection bias.	Potential self-selection bias. Random exclusion of control group is sometimes impossible or unethical.	Rao et al., 2015; Karlan et al., 2014
Difference-in-differences (DID)	Impact estimated as difference in change of metrics between treatment and control groups during intervention period, based on panel data.	Accounts for unobservable differences between participant and control groups. Reduces self-selection bias in RCTs.	Requires baseline data. Depends on assumption that differences between treatment and control groups are constant over time.	Gebrekidan et al., 2019; Wong et al., 2020
Instrumental variable (IV)	Participation in intervention is predicted by an “instrumental variable” that is uncorrelated with the outcome (other than by predicting participation).	Exploits external source of variation to estimate treatment status when participation is voluntary.	Depends on assumption that the instrument affects the impact metric only indirectly by influencing participation.	Diouf et al., 2020; Jensen et al., 2017
Propensity score matching (PSM)	Selects treatment and control sub-samples with similar observable characteristics that are correlated with participation. Impact estimated as difference in metrics between similar treatment and control subsamples.	Reduces (self-)selection bias. Can exploit secondary demographic data for matching variables.	Can require large samples since it excludes a portion of available data.	Gitonga et al., 2020; Gros et al., 2020
Regression discontinuity (RD)	Uses an eligibility cutoff based on a continuous variable (e.g., age, income). Impact estimated as difference in metric regression estimates between eligible and ineligible samples at eligibility cutoff.	Exploits eligibility cutoff to reduce selection bias	Limited to programs with eligibility thresholds. Depends on assumption that treatment and control groups are similar at cutoff.	de Janvry et al., 2016
Framed field experiments (FFE)	“Experimental games” aim to capture influence of interventions on decision making in controlled setting. Impact estimated as difference in behavior outcomes among simulated treatments.	Control of treatments and potential confounding factors.	Assumes decisions are consistent between experimental and real-world context. Demanding of participants.	Cole et al., 2017; Karlan et al., 2014
Field trials (FT)	Farmer-managed or experiment station agronomic trials. Impact estimated as difference in metrics (e.g., crop yields, gross margin) between climate-informed and control plots.	Control of treatments and counterfactual. Not dependent on farmer recall.	Design often confounds influence of climate information with differing farmer vs. researcher decision criteria.	Tarchiani et al., 2017
Scenario simulation (SS)	Multi-year simulation of intervention and control scenarios informed by combination of data and expert opinion. Impact estimated as difference in simulated metrics between treatment and control scenarios, averaged among years.	Can sample many years of climate information and observations. Flexible model specification provides control of treatments and counterfactual. Can test aspects of intervention that are not yet implemented.	Limited by ability to model decisions and their consequences. Subjective definition of Intervention and/or control scenarios.	Cabot Venton & Majumder, 2013; Coulter et al., 2013
Bioeconomic modeling (BEM)	Simulate decisions and their agricultural and economic consequences. Impact estimated as difference in simulated metrics between treatment and control scenarios, averaged among years.		Limited by ability to model decisions and their consequences.	Chantarat et al., 2017; Giuffrida, 2017
Computable general equilibrium modeling (CGE)	Simulate economic equilibrium, aggregates micro-economic impact estimated by other evaluation methods. Aggregate economic and welfare impact estimated as difference between intervention and control scenarios.	Captures aggregate scale market and welfare impacts of intervention or adoption at scale.	Tools limit range of aggregate impacts that can be modeled. Dependent on quality of micro-economic impact estimates.	Rodrigues et al., 2016
Qualitative methods	Uses focus groups, key informant interviews, ethnographic methods to understand casual pathways of impacts estimated by quantitative evaluation.	Insights about mechanisms and pathways that produce observed impacts.	Depending on the scale of analysis, limited external validity.	

4. Results: contributions of climate services to food security

4.1. Farmers' use of climate services

Smallholder farmers and pastoralists are a major focus of efforts to reduce hunger and achieve SDG2, because they are responsible for the food supply in the developing world, and because chronic malnutrition, manifest as child stunting, is most prevalent in rural populations that are dependent on agricultural livelihoods (Roser and Ritchie, 2019). Because agricultural production – particularly smallholder rainfed crop farming and pastoralism in the sub-humid, semi-arid and arid regions – is so dependent on climate and vulnerable to climate-related risks, it has also long been a major driver and target of the development of climate services.

The 18 evaluations of farmers' use of climate services to manage risk that met our selection criteria provide moderately strong evidence that farmers who use weather and climate information experience productivity and income benefits, and more limited evidence that this translates into food security benefits for the farm households and economy-wide benefits. The majority of these involved management of rainfed annual crops, while four cited livestock management (Gitonga et al., 2020; Machado et al., 2020; Mapanje et al., 2020; Birachi et al., 2020). Most of the evaluations included in our analysis (16 out of 18) focused on Africa. Our analysis overlaps Africa-focused reviews of access, use and impacts of climate services for farmers by Vaughan et al. (2019), Tall et al. (2018) and Mwangi et al. (2019).

Three studies link farmers' use of weather and climate information with measures of improved household food security. In Namibia, access to information significantly increased average household spending on food (33–41%) and dietary diversity score (13–14%, depending on propensity matching method) after accounting for confounding factors (Gitonga et al., 2020). In Rwanda, participation in improved climate services in the form of a participatory communication and planning process, and weekly radio listening clubs, was associated with a similar improvement (15%) in household dietary diversity score, and extended the average period that harvested crops could meet household subsistence needed by 0.5 to 1.5 months depending on crop and intervention (Birachi et al., 2020). In Uganda, participation in a drought early warning program, which provided drought information, training and seed, reduced likelihood of food insecurity (24%) and average household food insecurity access scale (15%), and increased dietary diversity score 36% relative to non-participant households during a drought year (Akwango et al., 2017).

The majority of included studies on farmers' use of climate services assessed impacts related to productivity or income. Seven of these showed crop productivity increases associated with use of climate information (Anuga and Gordon, 2016; Birachi et al., 2020; Chiputwa et al., 2021; Diouf et al., 2020; Maini and Rathore, 2011a; Rao et al., 2015; Tarchiani et al., 2017). Eight studies show increases in farm income (Barrett et al., 2020; Gunda et al., 2017; Mapanje et al., 2020) or its components: gross margins (Tarchiani et al., 2017), income from crops (Birachi et al., 2020; Diouf et al., 2020; Roudier et al., 2016), and reduced production costs (Maini and Rathore, 2011a). While studies (reviewed by Born et al., 2021; Vaughan et al., 2019) report a wide range of farm management responses to weather and climate information, we took a narrow interpretation of SDG2 target 2.4, "sustainable food production and resilient agricultural practices," and limited our analysis to studies that link climate services with adoption of more productive or more profitable agricultural practices. The limited available evidence shows that climate services that provide more than dissemination of information have led to increased adoption of intensified production practices including shifts to more profitable crops, and investing in improved crop varieties, soil fertility management and land management (Chiputwa et al., 2020; Gunda et al., 2017; Maggio and Sitko, 2019; Rao et al., 2015; Wood et al., 2014).

While most of the evaluations of farmers' use of climate services focused on the farm or household level, two estimated aggregate impacts of widespread adoption. In an ex-ante computable general equilibrium modeling analysis, Rodrigues et al. (2016) estimated the potential economy-wide benefits of seasonal climate forecasts in Kenya, Malawi, Mozambique, Tanzania, and Zambia at USD 113 million per year, if all farmers were to use the information to adjust their management. Based on an ex-post econometric analysis of household survey data, Barrett et al. (2020) estimated that, by increasing farmer income, improved decentralized seasonal forecasts and advisories contributed USD 3.25 M annually to the economy of a county in Kenya relative to the more general climate forecast information that is available nationally.

Among the three pathways for which we found empirical evidence, farmers' risk management involves the broadest range of types of climate information, and is hence most dependent on a strong national meteorological service (NMS). Although a wide range of information products was involved, seasonal forecasts were most common, followed by weather forecasts. The few studies that evaluated improvements to climate services against the status quo, rather than non-use, as a counterfactual (Barrett et al., 2020; Birachi et al., 2020; Chiputwa et al., 2022, Chiputwa et al., 2020) add to the evidence that the benefits from farmers' use of climate services are dependent on demand-side interventions including group participatory processes that build farmers' capacity to understand and act on climate information, and institutional arrangements that engage farmer representatives and other local stakeholders in co-production of services (Carr et al., 2019; Hansen et al., 2019b).

Evaluations of impacts of farmers' use of climate services have employed a wide range of methods, including quantitative studies based on survey data, qualitative studies (e.g., focus groups, key informant interviews, ethnographic methods) – sometimes in combination with quantitative surveys, agronomic field trials; and *ex-ante* analyses employing empirically grounded bioeconomic models, and economy-wide equilibrium models. Although climate services for farmers have been a focus of substantial research and investment for more than three decades, rigorous *ex-post* evaluations that use appropriate randomized designs or econometric methods to account for confounding factors and potential biases are a relatively recent development.

4.2. Index-based agricultural insurance

Index-based agricultural insurance (IBAI) triggers payouts based on an index (e.g., rainfall, vegetation remote sensing, area-average yield) that is correlated with agricultural losses, rather than actual losses. Basing payouts on an index instead of verified losses largely overcomes the problems of moral hazard, adverse selection, high transaction costs and payout delays that made traditional loss-based crop insurance infeasible for smallholder farmers. However, it introduces basis risk – resulting from the imperfect relationship between farmers' losses, and the index that triggers payouts – as a new challenge. Climate services play at least a nominal role when the insured index is based on meteorological data, and when historical climate data are used to estimate risks and design and price contracts. Index insurance initiatives often seek to validate meteorological indexes with farmers' experience and historical production statistics. IBAI can play both livelihood protection (i.e., preserving productive assets and hastening recovery after shocks) and livelihood promotion (i.e., supporting access to credit, and adoption of improved farm technologies and practices) roles. Insurance for crop-based or mixed farming systems often aims to promote farmers' livelihoods by overcoming risk as a barrier to adopting improved practices, or accessing credit and market opportunities – even in years when payouts are not triggered. On the other hand, index-based livestock insurance (IBLI) programs are designed primarily to protect herders' main productive asset in the event of major shocks, such as drought impacts on forage availability, by providing payouts to reduce animal mortality (e.g., by purchasing fodder) or replenish their herds after the shock.

Our analysis overlaps Hansen et al. (2019), who reviewed contributions of insurance and three other climate risk management strategies to rural poverty reduction. We found 25 evaluations of index-based agricultural insurance that met our selection criteria. The majority (18 out of 25) targeted crop production. Several of these provide evidence that index-based crop insurance contributes to improvements in household food security or livelihoods (Ashimwe, 2016; de Janvry et al., 2016; de Nicola, 2015; Isaboke et al., 2016; Madajewicz et al., 2013). The most direct evidence we found of index-based crop insurance impacting food security comes from Isaboke et al. (2016), who showed adoption significantly improved dietary diversity and perceived food security of farm households in eastern Kenya. An evaluation of the R4 Rural Resilience Initiative in Ethiopia showed positive impacts of insurance on wealth, contributing to nearly 300% increase in household savings and 25% increase in the number of households who owned oxen (Madajewicz et al., 2013). In Rwanda, adoption of commercial index-based crop insurance was associated with an estimated USD 100 increase in mean annual household income (Ashimwe, 2016). In Mexico, De Janvry et al. (2016) estimated that index insurance payouts led to a 38% increase in average farm household income and 27% increase in average expenditure. Association between insurance and intensified production, through increased adoption of improved production technologies or shifts to higher-valued crops, was demonstrated in evaluations of operational insurance programs in Ethiopia (Haile et al., 2020; Madajewicz et al., 2013), Kenya (Sibiko and Qaim, 2020), Senegal (WFP, Oxfam, 2016) and Mexico (de Janvry et al., 2016; Fuchs and Wolff, 2016); and in experimental studies (Bulte et al., 2020; Cole et al., 2017; Delavallade et al., 2015; Hill et al., 2017; Karlan et al., 2014; Mishra et al., 2021b; Miura and Sakurai, 2015; Mobarak and Rosenzweig, 2012). Intensified production practices were associated with increased use of credit in two studies (Mishra et al., 2021a; Madajewicz et al., 2013). The influence of insurance on crop management translated into increased yields in operational insurance programs in Mexico (Fuchs and Wolff, 2016) and Kenya (Sibiko and Qaim, 2020), and in experimental conditions in Senegal and Burkina Faso (Delavallade et al., 2015). Although most of the crop insurance evaluation studies included in our analyses show positive influence on intensification, Carter et al. (2016) argues on theoretical grounds that index-based insurance can be expected to significantly stimulate adoption of technology only in environments where risk is high and farmers lack collateral to secure loans. Experimental studies suggested that insurance stimulated investment in improved technology primarily for relatively wealthy farmers in Cambodia (Falco et al., 2016), and for forward looking farmers in Ethiopia (Wong et al., 2020).

Index-based livestock insurance (IBLI) is designed primarily to protect against loss of herds to drought or extreme weather events. The six index-based livestock insurance (IBLI) evaluations included in our analyses come from just two neighboring countries: Kenya and Ethiopia. They use indexes based on satellite remote sensing products, primarily NDVI, are included in our analysis because such indexes are strongly related to climate conditions (i.e., recent precipitation, potential evapotranspiration) and are used in a manner similar to crop insurance indexes based on monitored precipitation. IBLI programs have also been implemented and evaluated in Central Asia, but are not included in our review because they are based on aggregate animal mortality statistics and are hence not linked to climate services. Insurance payouts reduced distress sales of livestock in Ethiopia (Gebrekidan et al., 2019) and Kenya (Noritomo and Takahashi, 2020). However, research in northern Kenya suggests that the impact of insurance depends on whether herd size is above or below a poverty trap threshold estimated at 15–16 TLU[4]. Insurance reduced the likelihood of distress animal sales by 96% for pastoralists above a threshold estimated at 10 TLU, and by 54% for those below the threshold (Janzen and Carter, 2019). Insurance increased the probability of maintaining herd size above 16 TLU in drought and non-drought years (Cissé and Ikegami, 2016), and increases projected future herd size (Chantarat et al., 2017) only for relatively well-off pastoralists with herd sizes above this threshold. For relatively poor pastoralists, with herd sizes below an estimated poverty trap threshold, Janzen and Carter (2019) estimated that insurance reduces rationing meals as a coping strategy by 49% during a drought. Using a stochastic model parameterized with household survey and experimental data, Chantarat et al. (2017) estimated that an optimal index-based livestock insurance scheme would reduce poverty rate among pastoralists in northern Kenya, projected 15 years into the future, from 55% to 42%. Also using a dynamic stochastic model parameterized with experimental data, Cissé & Ikegami (2016) showed that adoption would decrease the probability of severe child malnutrition during drought years.

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[4] A tropical livestock unit (TLU) is a conversion from number of animals to 250 kg live weight. Conversion factors are: cattle = 0.7, sheep = 0.1, goats = 0.1, pigs = 0.2, chicken = 0.01.

The use of rigorous evaluation methods is more mature for index-based agricultural insurance than for the other pathways covered in this review. This likely reflects the strong evaluation culture and expertise that exists within the economic research community that has been at the forefront of much of the development of IBAI. Several of the evaluations occurred under experimental rather than operational settings, and controlled aspects of the implementation to answer specific research questions. Uptake and impacts are likely overestimated where experimental design included incentives (e.g., complete or partial insurance subsidies) to increase adoption or measure demand. On the other hand, experiments that aim to isolate insurance from its intended impact pathway (e.g., guaranteeing access to credit) arguably have underestimated demand and expected impacts. The majority of these studies assessed influence of insurance on management decisions. A smaller but growing set of studies provide evidence insurance improves measures (health, food security, wealth, income, productivity) of the well-being of rural households, through a combination of ex-post impacts of payouts and ex-ante influence on management. For crop farmers, there is strong evidence that IBAI increases adoption of improved production practices and access to credit, and moderate evidence that these changes improve farm productivity, income and wealth. These benefits occur even in years with no insurance payout. For pastoralists, there is moderate evidence that IBLI protects and promotes the productivity of their main productive asset, their herds. Research also reveals rather complex interactions between IBLI, drought risk and poverty dynamics among pastoralists in the presence of poverty traps.

Climate services play a crucial but relatively minor role in index-based insurance. In many cases, index-based agricultural insurance initiatives are not linked to NMS, but use either proprietary station networks, or proxy meteorological data based on remote sensing. This is due in part to gaps in NMS weather station networks, and fees and long bureaucratic approval processes that are often required to access their data. However, bypassing NMS raises concerns about the quality and transparency of the data and the sustainability of index insurance programs. Furthermore, weather index insurance initiatives also tend to use rainfall statistics, rather than exploiting existing agrometeorological knowledge and tools that likely better capture impacts of weather on crop losses. This implies that there is opportunity to improve the quality of insurance, and likely reduce basis risk, through stronger collaboration with NMS and national agricultural research systems.

4.3. Humanitarian and social protection anticipatory action

Social protection programs and humanitarian actions (*ex post* and *ex ante*) can have in common the use of cash or in-kind transfers to support the most vulnerable members of a population in the face of shocks and stresses, but historically they have started at opposite ends of the spectrum: social protection programs provide reliable assistance on an ongoing basis, whereas humanitarian response is triggered when a shock leads to a humanitarian crisis (Stephens et al., 2015; Willitts-King et al., 2020).

The humanitarian community has long used early warning systems (EWS) to anticipate crises and target interventions, recognizing that the welfare impacts of a shortfall in consumption are sensitive to the duration of the stress, and that intervening before damaging coping strategies are implemented and communities exhaust their coping capacity is crucial to avoiding long-term food and livelihood security impacts of an emerging crisis. Food security EWS that combine climate, remote sensing and market information can indicate likelihood of a production shortfall well before harvest. Yet the conventional process of monitoring, emergency assessment, appeal, resource mobilization, and delivery of assistance often delays intervention by several months, even when effective EWS are used and each step is managed efficiently (Haile, 2005). Several highly visible failures to avert humanitarian crises despite ample warning (Broad and Agrawala, 2000; Devereux, 2009; Hillbruner and Moloney, 2012; Lautze et al., 2012), and early Red Cross experience with mobilizing funds and prepositioning supplies based on a seasonal forecast of increased rainfall in West Africa in 2008 (Braman et al., 2013; Tall et al., 2012) prompted innovative efforts to improve the timeliness and effectiveness of humanitarian intervention by combining early warnings with earlier anticipatory action. Most of these anticipatory action initiatives include: EWS, trigger thresholds of observed or forecast indicators, pre-defined emergency contingency plans, and rapid finance through contingency funds or insurance. Anticipatory action initiatives are dependent on climate services when climate information is a component of their EWS and triggers. Social protection programs, typically operated through national governments, aim to protect the livelihoods of chronically poor households through a combination of cash or in-kind transfers, labor market and risk mitigation interventions. Adaptive social protection (ASP) refers to a range of innovations that aim to support adaptation and foster resilience in the face of a changing climate (Arnall et al., 2010; Davies et al., 2013, 2009). ASP also aims to respond to emerging shocks by incorporating financial mechanisms and triggers that scale up (through increased benefits per participant) and out (to an expanded set of beneficiaries) support in the face of emerging shocks (Costella et al., 2017; Davies et al., 2009; Drechsler and Soer, 2016). We address anticipatory action for humanitarian response and for social protection together because these innovations are blurring the historical distinctions between humanitarian and development interventions (Béné et al., 2018; Davies et al., 2009), and because similar approaches to foster anticipatory response to climate shocks are being applied to both purposes – often in pilot projects that fall outside of established social protection programs and humanitarian response processes.

Thirteen studies that quantify the benefits of anticipatory action in the context of humanitarian intervention or social protection meet our inclusion criteria. Critical summaries of the available evidence by Weingärtner et al. (2020) and Levine et al. (2020) cover most of these studies. Cost-effectiveness, particularly benefit-cost ratio (BCR), was the most frequently estimated impact metric (9 out of 13 studies). Comparable numbers of studies (6 each) present food security, productivity and asset protection benefits, often expressed as avoided losses during extreme events.

We found three *ex-post* evaluations of household-level impacts that employed rigorous methods to test and control for potential selection bias, two published in the peer-reviewed literature in the context of forecast-based finance projects. In Bangladesh, Gros et al. (2019) used surveys, qualitative methods and propensity score matching to show that that forecast-based finance grants to rural households triggered by a cyclone forecast reduced food rationing and high-interest borrowing relative to a comparable sample of non-participant communities. In Mongolia, Gros et al. (2020) applied similar methods to show that grants and animal care kits, triggered by an extreme winter weather forecast, reduced livestock mortality and improved survival rates of offspring relative to non-participant households. In Bangladesh, a survey-based evaluation of a World Food Program pilot project, which exploited unplanned exogenous barriers to participation of some eligible households and tested consistency between participant and control sample, found that early cash transfers triggered by a flood protected household food security and economic wellbeing immediately after the flood and three months later relative to non-participants (Pople et al., 2021).

African Risk Capacity (ARC) is a sovereign catastrophe risk pool that offers member states index-based insurance that provides timely payouts that are triggered by rainfall data linked to a simple soil water balance model and historical disaster response data, primarily to finance humanitarian response to climate-driven disasters. Evaluations of ARC that compared model results for scenarios assumed with and without sovereign insurance, showed substantial potential to reduce welfare losses through earlier intervention and expanded numbers of beneficiaries (Clarke and Hill, 2013; Kramer et al., 2020).

The remaining evaluations included in our review were conducted as part of pilot projects, and commissioned by the sponsoring organizations. The U.K. Department for International Development (DfID) commissioned a set of ex-ante studies that modeled 20-year early action scenarios to estimate the potential reduction of losses and BCR of early humanitarian interventions in Bangladesh, Mozambique, Kenya and Ethiopia, although only the Bangladesh (Cabot Venton and Majumder, 2013) and Mozambique (Coulter et al., 2013) studies described the role of climate and climate-related information sufficiently to include in our review. A set of evaluations associated with FAO's Early Warning Early Action (EWEA) system in the Greater Horn of Africa, Madagascar, Mongolia, The Philippines and Colombia, compare indicators derived from surveys of participant and non-participant households to assess benefits of anticipatory interventions to participating households and calculate benefit-cost ratios (FAO, 2020, 2019a, 2019b, 2018a, 2018b). These reports do not provide information about the sampling strategy, or evidence of the comparability of intervention and control samples. In each of these cases, combinations of climate and food security indicators triggered interventions identified with national and local stakeholders that emphasized production inputs (e.g., seed, irrigation equipment, animals) and community support to bolster food production and incomes to mitigate the anticipated crisis. While these evaluations provide evidence of specific productivity, livelihood and food security benefits from the interventions, they do not provide sufficient evidence to attribute the benefits to the early warning information, nor do they estimate how the benefits of the interventions are influenced by climatic conditions.

Early warning systems are a key feature of anticipatory action initiatives, yet the conceptual and empirical literature on anticipatory action often refers to early warning information in vague terms. Although climate information is usually a component of established EWS and the *ad hoc* information used to trigger action in some pilot projects, these EWS often fall outside of national meteorological services (NMS) and mainstream climate service initiatives, and sometimes use remote sensing climate proxy data instead of higher quality NMS observational or merged data. This may be out of necessity in fragile contexts where NMS lack capacity or restrict access to relevant data.

There is evidence that early action interventions, informed by forecast or monitored climate-related information alone or in combination with other early warning indicators, have aggregate benefits that exceed their costs, and limited evidence that this results in avoided losses of productivity, wealth and food security for participant households. However, the strength of the evidence is weaker than for the use of climate information for farm decision making or index-based agricultural insurance, and interpreting the impacts and the contribution of climate services is challenging. First, the majority of included evaluations have had weak counterfactuals. With a few recent exceptions (Gros et al., 2020, 2019; Pople et al., 2021), ex-post evaluations do not appear to test or control for selection bias when comparing participant and control samples of households. The counterfactual scenarios used in *ex-ante* studies depend on assumptions that have little empirical evidence about the timing and impact of interventions in the absence of early action. Second, most empirical *ex-post* evaluation reports do not provide evidence that the reported benefits from the interventions interact with climate conditions or with the timing of intervention, making it difficult to attribute benefits to the use of climate-related early warning triggers. Third, while the early interventions included in this body of evidence arguably require climate-related information, several of the studies do not explicitly identify or address the role of climate information. Anticipatory action is a relatively recent emerging innovation, and has not yet had time to develop a culture of evaluation or body of evidence.

5. Discussion

5.1. State of evidence for climate service role in ending hunger

In the 56 studies that met our inclusion criteria, we found moderately strong evidence that climate services contribute to improvements in food security, or to intermediate impacts that are precursors of improved food security, through farmers' use to manage risk and index-based agricultural insurance; and a weaker body of emerging evidence of impacts through timelier humanitarian and adaptive social protection interventions. In our subjective assessment of the relative strength of the evidence among the three pathways, we considered the numbers of studies that met our inclusion criteria, the numbers of studies that employed sampling and analytical methods that control for potential biases, the balance between estimates of food security impacts and estimates of its precursors (i.e., intensification, productivity, income, wealth), and the diversity of contexts of the interventions. The evidence of food security benefits is weaker for social protection and humanitarian anticipatory action for the reasons discussed in Section 4.3. This is likely because anticipatory action innovations are quite nascent, and have not yet had time to develop a mature culture of evaluation or body of evidence. There is more evidence of intermediate impacts on precursors of food security, particularly farm intensification, productivity and income, than of improvements in food security or nutrition impacts. This likely reflects the goals of agricultural climate service and index-based insurance projects, which are more often expressed in terms of agricultural production or livelihoods than food security or nutrition.

Despite interest in using climate information for government agricultural planning, risk management by agriculture value chain actors, and nutrition interventions, we did not find any evaluations for these pathways that met our criteria. Our review highlights a critical gap in the literature examining the impacts of climate services on diets and nutrition outcomes. While there is a recognition within the nutrition community that climate risk has important implications for undernutrition, in the absence of coordination structures between the climate and nutrition communities, climate considerations are largely missing from routine nutrition programming and policies, and hence their evaluation (Singh et al., 2020). The lack of empirical evidence for these hypothesized climate-informed interventions is not necessarily evidence of lack of impact, but may reflect other constraints to evaluation. For example, agricultural planning by governments (ministries of agriculture) and risk management within agricultural value chains generally involve too few actors – and often only a single actor – to establish a counterfactual by comparing participant and control samples. On the other hand, the pathways that are supported by empirical evidence involve many individuals, and therefore can, in principle, be evaluated by comparing participants with a control sample. Furthermore, in the case of farmer-focused climate service projects, index-based agricultural insurance programs and anticipatory action pilot projects, the requirements of development funders for public goods and evidence of development impact, and the evaluation capacity within the research and development organizations that participate in project implementation favor publication of evaluations. Government agencies and private sector value chain actors, on the other hand, often lack the incentive and capacity to produce and publish comparable evidence of impact.

5.2. Priorities for mobilizing and aligning climate services for SDG2

Although we found substantial evidence that climate services contribute to food security, widespread weaknesses in existing climate services relative to agricultural needs constrain that contribution. While some of the evaluations of farmers' use of climate services consider how they are implemented, most consider only whether weather or climate information was used, and not the quality of the information or effectiveness of the services. Uncritical evaluation of poorly designed services can underestimate the potential benefits of climate services (Hansen et al., 2011; Vaughan et al., 2019). There is a growing consensus about some aspects of good practice needed to overcome those weaknesses. Several recommendations are relevant to mobilizing and aligning climate services to better contribute to national food security goals:

- Develop institutional and policy arrangements that formalize and strengthen the role of relevant institutions in climate-sensitive sectors, including agriculture and food systems, in the co-production, delivery and evaluation of climate services while removing barriers to interaction (Hansen et al., 2019a, 2019b; Sivakumar et al., 2014; Tall et al., 2014; WMO, 2019).
- Understand the needs, and invest in the capacity of farmers and other food system decision makers to use climate services to manage risk, and to drive the co-production of improved services (Carr et al., 2019; Hansen et al., 2019a; Sivakumar et al., 2014; Tall et al., 2014; WMO, 2019).
- Strengthen the delivery of climate services to farming and pastoralist populations through a strategic combination of face-to-face (e.g., public- and private-sector advisory services) and ICT (e.g., mobile phone, broadcast media) channels (Gumucio et al., 2020; Hansen et al., 2019b; Tall et al., 2014).
- Address the challenges of women and other under-served groups, for example by tailoring information and communication processes to their needs, integrating services with rural development efforts that target women, and partnering civil society to address constraining socio-cultural norms (Gumucio et al., 2020; Tall et al., 2014).
- Improve the usability of national climate information by (a) changing the way seasonal forecasts are produced and presented, (b) filling observational data gaps (e.g., through merging station and proxy data, historical data rescue, upgrading observation infrastructure), (c) removing barriers to using historical climate data as a public good, and (d) engaging decision makers and sector experts in co-design (Hansen et al., 2019a, 2019b; WMO, 2019).
- Integrate monitoring, evaluation and learning into climate services governance to continuously improve the impact of services (Tall et al., 2014; WMO, 2019).

Efforts to evaluate climate services could contribute more to evidence-based good practice guidance by giving more attention to the different elements of the design and implementation of climate services.

Our review also highlights fragmentation and redundancies in the climate information that supports food security interventions. The use of climate services for farmer decision-making, insurance, food crisis humanitarian response and social protection can contribute toward national food security goals, yet there is often a lack of coordination and policy coherence among these interventions. Efforts to support farmers with climate services tend to be integrated with NMS and with national climate service investment and policy. Humanitarian and social protection anticipatory action and index-based agricultural insurance programs, on the other hand, use meteorological data but are often disconnected from NMS, and from climate service initiatives and policy frameworks. Index-based agricultural insurance programs typically use proprietary indexes that incorporate meteorological data from either their own observational networks or from global remote sensing products. Many of the food security EWS used to trigger action also use climate products based on remote sensing. While global climate proxy data based on remote sensing are typically easier to access than data from NMS, their quality is a concern. A growing number of NMS have filled gaps in their climate observations by merging quality-controlled station data with satellite remote sensing (for precipitation) or climate model reanalysis (for temperature) proxies. Since the quality of merged gridded climate data is determined by the amount of observational data used, and NMS typically steward one to two orders of magnitude more data than are available to global data producers, the quality of resulting national products is expected to be higher than the best available global products (Dinku et al., 2018b, Dinku et al., 2018a, Dinku et al., 2014). This suggests there is a need both to strengthen the capacity of NMS in countries where they are weak, and to develop more integrated national climate service strategies and coherent policy frameworks that ensure, for example, that EWS for social protection and humanitarian action, and index-based agricultural insurance, use the best available climate information, and that this information is made accessible and available in a timely manner. This suggests there is a need to develop more integrated national climate service strategies and policy frameworks that ensure, for example, that EWS for social protection and humanitarian action, and index-based agricultural insurance, use the best available climate information, and that this information is made accessible and available in a timely manner.

5.3. Lessons for evaluating development-focused climate service programs

Impact evaluation is less mature for climate services than for many other development interventions – a weakness highlighted in the inaugural 2019 State of Climate Services Report on Agriculture and Food Security (WMO, 2019). This is due in part to characteristics of climate information that makes evaluation particularly challenging (Tall et al., 2018; Vaughan et al., 2019). First, the influence of individual characteristics (e.g., wealth, education, gender, age, risk tolerance) on decisions such as purchasing index-based insurance or using climate information for farm management leads to differences between adopter and non-adopter populations that can influence measured impacts and hence bias estimated impacts of these decisions. The resulting self-selection bias is a widespread challenge for evaluating development interventions that involve individual adoption or participation decisions. Second, when evaluating climate service impacts for individual decision makers such as farmers, it is difficult to identify a control sample without access to information because climate information is shared readily and rapidly along social and institutional networks. The difficulty in isolating a control sample without access to information imposes a particular challenge to evaluating climate services for individual decision makers such as farmers. Third, using a control sample as a counterfactual is not possible in cases where a single actor, such as a national government ministry or agency, acts on climate information. This challenge likely contributed to the gap in relevant evaluations of climate-informed government planning and enabling policy. Fourth, the stochastic nature of climate and its impacts means that the benefits of climate services vary from year to year, and that many years of measurement may be needed to provide robust estimates of average benefits. Furthermore, because climate conditions can impact national food security metrics, any before-after comparisons of SDG2 indicators are likely to be confounded by climate conditions in the baseline and endline years, complicating attribution of change to climate-related interventions. Fifth, and perhaps most important, because climate services represent a very small portion of the effort in any country towards SDG2, and their impacts come largely through making other interventions more effective, it is challenging to attribute any changes in national development indicators to climate services.

Several evaluation methods are available that address some of these challenges and avoid or reduce the resulting biases (Table 3); and employing them more widely would strengthen the credibility of evidence of the development impacts climate service interventions. For example, propensity score matching controls for self-selection bias by using measurable characteristics that may

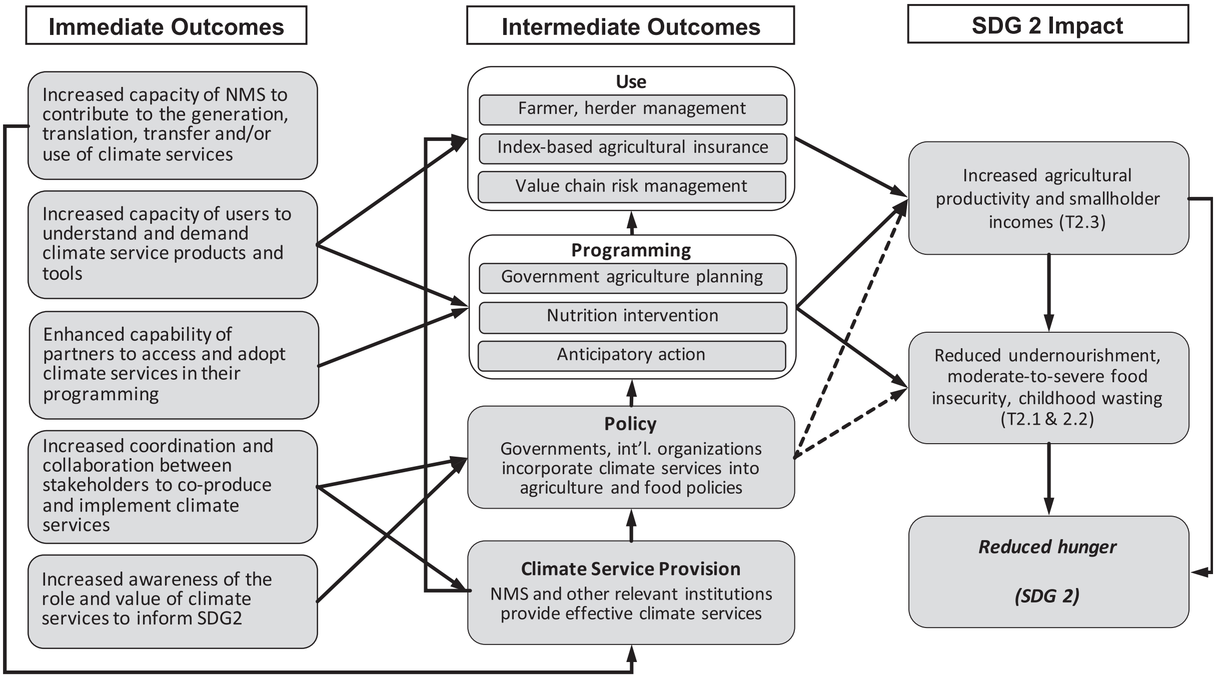

Fig. 3. Impact pathways within the ACToday theory of change. Intermediate outcomes are disaggregated to include pathways included in our literature search.

influence the measured impact to select treatment and control samples with similar characteristics. Spillover effects from informal information sharing can be reduced through a combination of random assignment of interventions to locations, and measuring differences in change from a baseline and endline (i.e., a difference-in-difference analysis) instead of absolute differences between treatment and control samples. For programs such as social protection or insurance, in which when eligibility to participate is based on a continuous measurable variable such as age or income, regression discontinuity analysis uses the difference in regression estimates just above and just below the eligibility cutoff to control for any systematic differences between eligible and ineligible populations. Rigorous evaluation methods that control for common biases have been used fairly widely for index-based agricultural insurance. However, they have been adopted only in recent years in evaluations of climate services for farmers, and are largely missing from evaluations of anticipatory action. While these improved sampling and evaluation methodologies can reduce common sources of bias, they do not address the challenge caused by the interaction between interventions and stochastic climate fluctuations. Because the magnitude and even the mechanism of impact of climate services can vary considerably from year to year, obtaining robust impact estimates requires either repeating empirical evaluations over many years; or complementing ex-post evaluation with empirically grounded bioeconomic modeling, which can easily sample many years of historical data.

While the recent proliferation of climate service evaluation studies that are relevant to food security is encouraging, their scope is limited to downstream decisions and impacts, particularly at the level of farm households, and often in the context of pilot projects. There is a tradeoff between up-stream capacity building and enabling environment with a view to scale and sustainability; and piloting interventions with farmers and other grassroots stakeholders, which is easier to evaluate but challenging to scale and sustain. The ACToday initiative has focused the majority of its effort on upstream interventions, e.g., fostering an enabling policy and institutional environment, and building the capacity of NMS, agricultural research and extension institutions and other government ministries and agencies within the food system, on the understanding that this strategy has the potential to achieve a larger and more sustainable impact (Goddard et al., 2014). However, these upstream interventions do not lend themselves to empirical ex-post evaluation because they often involve a single actor; and because there is a long time period between the development of an enabling environment, and when the actions of downstream actors lead to measurable impact. Given these constraints, the strategy for assessing the contribution of ACToday to SDG2 starts with a theory of change that captures our hypotheses, assumptions and causal pathways by which the project's climate service interventions are expected to contribute to impacts related to SDG2 (Fig. 3). A set of outcomes, defined as particular changes in the capacity or behavior (e.g., investment, policy, programs, practice) of particular actors, are the bridge between project interventions and the intended food security impacts. While measuring and attributing food security impacts to project interventions is challenging, measuring outcomes is more feasible. The majority of effort within ACToday targets improved climate service provision and enabling policy environment – outcomes that do not impact food security directly, but enable more downstream outcomes by actors such as government institutions and farmers whose climate-informed actions can improve food security. For the subset of pathways covered in our review, the growing body of empirical evidence provides a basis for expecting that food security will be enhanced if actors within the impact pathway change their behaviors in a manner that is consistent with the theory of change. The goal of this evaluation strategy is to provide evidence of contribution to SDG2, and not attribution of food security and nutrition improvements to project interventions.

6. Conclusions

Unanticipated and unmitigated climate risk is a driver of food insecurity and impediment to achieving the "zero hunger" Sustainable Development Goal (SDG2). We summarize existing knowledge of how cascading impacts of a climate shock trigger acute food insecurity, mechanisms that cause impacts to persist long after climate conditions return to normal, the impact of climatic uncertainty on agricultural production and livelihoods, and the propagation of climate impacts on food accessibility through the economy.

Our review of evidence of the contribution of climate services to SDG2 showed moderately strong evidence that climate services contribute to improvements in food security, or to intermediate impacts that are precursors of improved food security, through farmers' use to manage risk and index-based agricultural insurance; and a weaker body of emerging evidence of impacts through timelier humanitarian and adaptive social protection interventions.

While the recent proliferation of climate service evaluation studies that are relevant to food security and SDG2 is encouraging, the resulting evidence is largely confined to decisions and interventions at a grassroots level, particularly involving rural households. There is a gap in empirical evaluation of anticipated contributions food security through agricultural value chain actors, government agricultural planning, nutrition interventions and policy.

While the emerging body of evidence justifies strengthening climate services for agriculture and food systems as an essential part of national strategies to achieve SDG2, it provides only limited guidance about how to mobilize and align climate services to food security goals. The way climate services are implemented can enhance or constrain their contribution to food security. Our review highlights fragmentation in the climate information that supports some promising food security interventions, and suggests the need for an integrated strategy and coherent policy framework to ensure, for example, that index-based agricultural insurance, and EWS for social protection and humanitarian action, use the best available climate information and engage stakeholders in co-production. Other than highlighting a few general consensus recommendations, good practice for climate services in support of agriculture and food security are beyond the scope of this paper. Evaluation studies could be more useful for guiding implementation and investment if they were to give more attention to the different elements and options for the design of climate services.

Demonstrating development impact on the ground is particularly challenging for initiatives, such as ACToday, that aim to build an enabling environment to scale and sustain impacts of climate services primarily through upstream capacity development and policy engagement with national institutions. A theory of change that captures hypotheses and assumptions about causal pathways from project interventions to development impacts, combined with the broader evolving body of evidence included in our review, provides a basis for expecting that outcomes along the impact pathways, if demonstrated, will contribute towards improved food security.

Declaration of Competing Interest

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

Acknowledgements

The authors are grateful to the ACToday leadership team: Lisa Goddard, Tufa Dinku, Angel Muñoz, Ashley Curtis, Dannie Dinh, Amanda Grossi, Carmen Gonzalez Romero and Pamela Jordan. We also thank Cathy Vaughan for initial contributions to the ACToday theory of change, and Tatiana Gumucio who contributed to the initial design of this paper. Thoughtful comments of two anonymous reviewers improved the clarity of the paper. This work is undertaken as part of the Columbia World Project, ACToday, Columbia University in the City of New York.

Appendix A. Summary of Evaluation References

No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
Farmers' use of climate services							
1	Akwango et al., 2017	Uganda	Drought early warning system	Production diversification	Participation, including drought warning, training and inputs (seed, watering cans) reduced likelihood of food insecurity (24%) and average household food insecurity access scale (15%), and increased dietary diversity score (36%).	SC-liner regression, multistage purposeful sampling of drought early warning on household food security n=305	T= Participant farmer C= Non-participant farmer
2	Anuga and Gordon, 2016	Ghana	Weather forecasts	Not specified	Combination of information and insurance explained 24% (yams) and 21% (maize) of yield variability. Information access and training in its use significantly increased yam (14-17%) and maize (13-16%) yields.	SC-linear regression of adoption of climate smart practice on maize and yam yield n=320	T= Adopter of climate smart practices (including weather information) C= Non-adopter of climate smart practices (including weather information)
3	Barrett et al., 2020	Kenya	SCF, advisories	Crop, livestock and fodder management decisions	County-level SCF and advisories increased farmer income relative to Kenya Meteorological Department (KMD) national forecasts. The marginal impact of the local SCF is KSH 26,121 ($253). The county-wide economic value is KSH 335 M ($3.2 M). BCR = 15	SC-linear regression, stratified random sampling of access to KMD's local SCF and advisory products on productive income n=250	T= Access local SCF, local advisory C= Access national SCF only C2= No access to national SCF, local SCF, or local advisory
4	Birachi et al., 2020	Rwanda	SCF, historical data, weather forecasts	Land management, crop and varietal selection, timing,	Participatory communication (PICSA) increased the value of crop	SC-means, stratified random sampling of participation in PICSA,	T= Participant of PICSA only T2= Participant of LC only

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No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
				livestock management	production by 24%, and income from crops by 30%. Combined PICSA and radio listener club (LC) participation increased crop value and income by 47% & 56% respectively. Increased dietary diversity score (15%) and the number of months that harvest meets family subsistence needs.	LC on crop income n=1525	T3= PICSA + LC C= Non-participant of PICSA, LC
5	Chiputwa et al., 2020	Senegal	SCF, weather forecasts, advisories through MWGs	Adoption of improved seed, soil fertility management, number of crops, crop diversification	Improved climate services supported by Multidisciplinary Working Groups (MWG) were associated with increased adoption of improved seed (22%, 23%), manure (11%, 16%) and chemical fertilizers (9%, 24%), in response to SCF or seasonal and weather forecasts respectively.	IV, stratified random sampling of MWG, WCIS use on farm management decisions n=795	T= MWG, adopter of WCIS C= No MWG, non-adopter of WCIS
6	Chiputwa et al., 2022	Senegal	SCF, weather forecasts, advisories through MWGs	Agronomic planning (species, varieties, land allocation, input) and investment decisions	Use of weather and climate information increased the value of crop produced by between 10-25% for farmers with access to an MWG.	SC-linear panel data estimation approach, two locations with/ without functioning MWP on value of crop production n=795 (initial) 596 (follow-up)	T= Adopter of WCIS in a location with an MWG C= Non-adopter of WCIS, no MWG
7	Diouf et al., 2020	Senegal	SCF	Variety and crop choice, timing	SCF use increased agricultural income an average of $41/ ha, or 16%, with greater income benefit for men than women. Forecast use increased millet (158 kg/ha), sorghum 878 kg/ha) and rice (140 kg/ha) yields; but decreased maize (-55 kg/ha) and groundnut (-37 kg/ha) yields.	SC-linear regression, IV stratified two-stage sampling of use of SCF on agricultural yield and income n=1481	T= Adopter access/ take at least one decision from SCF C= Non-adopter, do not access/ take decisions from SCF
8	Gitonga et al., 2020	Namibia	SCF	Cropping (planting date, cultivar selection) and livestock (sales, restocking, feed, watering) management, food storage	Information access significantly increased average household spending on food (33-41%) and dietary diversity score (13-14%).	PSM, multistage random sampling, access to climate information on food security and adaptation practices n=653	T= Access to climate information C= No access to climate information
9	Gunda et al., 2017	Sri Lanka	SCF	Crop selection and diversification	Use of SCF increases simulated mean and variability of net income. Forecast drier conditions lead	BEM, EG, empirical survey of use of SCF on agricultural income n=800	T= Adopter of SCF C= Non-adopter of SCF (uses current climate) C= Non-adopter (uses

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No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
					to greater income benefit associated with switch to higher-value crop (onions).		historic planting practice)
10	Machado et al., 2020	Ethiopia, Tanzania	NDVI maps	Herd migration	Map usage associated with improved animal condition and herd size in Tanzania, but no statistical difference in herd size in Ethiopia.	RCT, IV (Ethiopia); SC-linear regression (Tanzania) of map use on livestock decisions n=1733 (Baseline, Ethiopia) n=734 (Baseline, Tanzania)	T= Map project recipient participant (Ethiopia) C= Non-participant in map project (Ethiopia) T= Map adopters (Tanzania) C= Map non-adopters (Tanzania)
11	Maggio and Sitko, 2019	Zambia	Seasonal drought forecast	Adoption of hybrid maize seed	Drought forecast access increased likelihood of adopting hybrid maize seed and doubled average quantity of improved seeds used.	PSM, nearest neighbor, non-random treatment of receiving drought forecast on agricultural decisions n=1311	T= Households exposed to 2015/16 drought C= Households potentially not exposed to drought
12	Maini and Rathore, 2011b	India	Weather forecasts, advice	Adoption of improved production technologies and practices (right selection of fertilizers, seeds, spraying appropriate pesticide)	Farmers from participating villages had significantly higher yields (10–15%), lower production costs (2-5%).	SC-means, random sampling, use of agrometeorological advisory on crop yield and benefit to cost ratio n=80	T= Participant in Agrometeorological Advisory Services C= Non-participant
13	Mapanje et al., 2020	Zimbabwe	10-day weather forecasts, advisories	Unspecified crop, livestock and livelihood decisions	Information access significantly increased household income (64-79%) and livestock value (27-39%). No significant impact on pearl millet yield.	PSM, multistage random sampling of CIS on yield and income n=90	T= Participant farmer C= Non-participant farmer
14	Rao et al., 2015	Kenya	SCF, training, advice	Crop and cultivar selection, land allocation, production input use	Maize yields were higher in training (19%), advisory (24%) and combined (30%) villages than control villages. Increase in expenditure on agricultural production. Yield response to interventions varied among other crops, no statistical analysis of differences among treatment means.	RCT, factorial design of CIS on agricultural practices and yield n=117	T1= SCF with training T2= SCF with agro-advisory T3= Training + Advisory C= No climate information
15	Rodrigues et al., 2016	Kenya, Malawi, Mozambique, Tanzania, Zambia	SCF	Allocation of productive resources (land, labor, and capital), reallocating labor from farm to off-farm activities	If adopted by all farmers, SCF would generate average regional GDP gains of $113 million/year for realistic forecasts, $317 million/year for perfect forecasts, with a disproportionate	CGE	C= Non-adoption scenario (no forecast)

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No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
					benefit going to poorer households		
16	Roudier et al., 2016	Niger	Weather forecasts, SCF	Cultivar, fertilizer decisions, sowing date, adapting crop location on sandy/clayey soil	10-days forecasts alone, or with SCFs, increased median simulated income from crops 2-13%, depending on farmer type and scenario.	BEM, observed rainfall data, sort term and SCF, crop model	T= Probabilistic SCF T2= Deterministic 10-day forecast T3= SCF + !0-day forecast C= Non-adoption scenario (no forecast)
17	Tarchiani et al., 2017	Mauritania, Niger, Côte d'Ivoire, Ghana	Weather forecasts, SCF, advice	Choice of variety, sowing date, land management, timing of cropping cycle	Use of information and advisories associated with higher sorghum yield (64%) and gross margin ($260/ha) in Mauritania. Not significant in Niger, Côte d'Ivoire or Ghana.	FT, SC- means, randomly selected, agromet training, information, and advice on agricultural management, crop productivity and costs n=16	T= Participant farmer C= Non-participant farmer
18	Wood et al., 2014	Bangladesh, Burkina Faso, Ethiopia, Ghana, India, Kenya, Mali, Nepal, Niger, Senegal, Tanzania, Uganda	Weather forecasts	Improved varieties, fertilization, land management, timing of agricultural activities	Information access positively associated with adoption of improved crop varieties and improved land management in India; and with adoption of improved varieties, land management and fertilizer use in East Africa (Ethiopia, Kenya, Uganda, Tanzania); but was not significantly related to management changes in West Africa.	SC- linear regression, access to weather information on changing farming practices n=4000	T= Access to weather information C= No access to weather information
Index-based agricultural insurance							
19	Ashimwe, 2016	Rwanda	Rainfall index	Weather-based crop insurance	Increased average annual household income by ~$100.	PSM, multi-stage random sampling survey of farmer participation in crop insurance on household income n=246 (T=123, C=123)	T= Participant farmer C= Non-participant farmer
20	Bulte et al., 2020	Kenya	Rainfall index	Weather index + multi-peril insurance conditioned on certified seed purchase	Free insurance conditioned on certified seed increased likelihood of purchasing certified seed by 15%; increased total area cultivated (12%), area under certified seed (60%); and fertilizer (13%), farm labor (11%), machine rental (26%) and total non-seed investment (13%) relative to control.	RCT, random lottery assigning free insurance voucher conditioned on purchase of certified seed (treatment) n=780 (T=351, C=429)	T= Free insurance voucher C= No insurance voucher
21	Chantarat et al., 2017	Kenya	NDVI index	Index-based livestock insurance (IBLI)	IBLI increases future herd size when initial size > 15 TLU poverty trap	BEM, simulated herd growth with stochastic model parameterized from household panel	C= Scenarios simulated for matched pastoralist households

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No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
					threshold; either improves or impedes accumulation when initial herd size = threshold; has no effect when initial herd size < threshold; Optimal scheme reduces 15-year projected poverty rate from 55% to 42%.	and experimental data n=500	assuming no insurance access
22	Cissé and Ikegami, 2016	Kenya	NDVI index	Index-based livestock insurance (IBLI)	Increased probability of next season herd size > 15 TLU, in drought and non-drought years.	IV, panel data, random lottery assignment of premium discount coupon (discount also randomized) to assess impact of IBLI on herd size and child health n=924	T= IBLI premium discount C= No premium discount
23	Cole et al., 2017	India	Rainfall index (station)	Rainfall index insurance policy	Farmers increase agricultural investments in higher-return but rainfall-sensitive cash crops. Increased fertilizer use, area cultivated but not statistically significant unless controlling for cash crop investments.	RCT, scratch lottery assignment of rainfall insurance policy on production and investment decisions n=1,479	T= Farmers receive insurance C= Farmers receive fixed payout equal to actuarially fair value of insurance (redeemable during insurance payout period).
24	de Janvry et al., 2016	Mexico	Drought index	Weather index insurance program	Payouts led to increased area cultivated the year following a weather shock, increased per capita household expenditure (27%) and income (38%).	RD, municipality level, effects of insurance payment on ex-post investment decisions and coping mechanisms n=976 municipalities, 5879 obs	T= % of hectares receiving payout C= Municipality without payout
25	de Nicola, 2015	Malawi	Weather shock (CWSA, rainfall data)	Weather index insurance (drought and flood)	Actuarially fair weather insurance, free from basis risk, can provide a permanent increase in consumption of almost 17%, diminishing over time. Adopting riskier (more sensitive to weather variation) but more productive seeds, equivalent to a permanent increase in consumption by 23.4%.	BEM, dynamic stochastic model, cross-sectional household survey data of weather insurance on investment, consumption, and welfare n=770	T= Adoption of weather index insurance C= Non-adoption scenario (no insurance)
26	Delavallade et al., 2015	Senegal, Burkina Faso	Rainfall (Senegal) and NDVI (Burkina Faso) index	Index insurance	Insurance increased spending on input and fertilizer purchase. As a result, yields were higher for those who bought more insurance. Stronger demand for insurance by men, saving by women.	RCT, random allocation via public lottery and endowment to one of four insurance and savings treatments on agricultural investment and yields n=806	T= Index insurance T2= Low-commitment agricultural investment savings T3= High-commitment agricultural investment savings T4= High-commitment emergency savings
27		Mexico					

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No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
	Fuchs and Wolff, 2016		Rainfall index (station)	Weather index insurance	Insurance presence at the municipality increased maize yield average of 6% and is associated with a significantly higher real per capita household expenditure (and income) of 6 to 7% with respect to counties without coverage.	RCT, pipeline randomization, panel data at municipality and household level on productivity, risk management, and income n=2,316 (counties) n=34,440 (households)	T= Municipality with index insurance C= Staggered entry, counties with index insurance in future years C2= Counties with no index insurance
28	Gebrekidan et al., 2019	Ethiopia	NDVI index	Index-based livestock insurance (IBLI)	Reduced likelihood of distress livestock sale 14% during drought.	DID, randomized incentives, household panel survey of IBLI on herd offtake (n=465)	T= Adopter of insurance C= Non-adopters of insurance
29	Haile et al., 2020	Ethiopia	Rainfall index	Weather index-based crop insurance	Increased adoption of fertilizers by 60% for insurance users, by 46% if all farmers were to purchase insurance.	IV, multistage random sampling of insurance on risk taking behavior and investment n=240 (T=120 + C=120)	T= Adopter of insurance C= Non-adopters of insurance
30	Hill et al., 2019	Bangladesh	Rainfall dry spell index	Hybrid rainfall and area yield insurance	For rice in monsoon season, insurance adoption increased cultivated area by 19%; and irrigation (39%), pesticide (29%), fertilizer (27%), hired labor (24%) and total input investment (26%). In subsequent dry season adoption increased production (14%), yield (6%), and cultivated area (14%); and irrigation (11%), pesticide (13%), fertilizer (17%), hired labor (21%) and total input investment (16%).	RCT, IV, random assignment of incentive treatments and control among villages n=1983 (T=1004, C=979)	T= Insurance offered with discount or rebate C= Households villages not offered insurance
31	Isaboke et al., 2016	Kenya	Rainfall (drought, excess) index	Index insurance	Adopters of index insurance had a higher dietary diversity score of 1.21 and a higher food security perception score of 5.769 compared to farmers that did not adopt the index insurance.	PSM, stratification matching approach, multi stage sampling cross-sectional survey of adoption of index insurance adoption on food security n=401 (T=251, C=150)	T= Adopter of weather index insurance C= Non-adopter of weather index insurance
32	Janzen and Carter, 2019	Kenya	NDVI index	Index-based livestock insurance (IBLI)	Wealthier households with insurance are 96% less likely to sell assets following a shock and poorer households with insurance reduce the coping strategy of cutting food	RCT, IV (discount coupons receipt, value) household panel data of index insurance impact on coping strategies n=673 (T=161, C=514)	T= Adopters of index insurance C= Non-adopters of index insurance

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No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
					consumption by 49%.		
33	Jensen et al., 2017	Kenya	NDVI index	Index-based livestock insurance (IBLI).	Households with IBLI coverage make productivity increasing investments, reduce distress sales of livestock during droughts and increase livestock offtake during seasons with low livestock mortality rates, when livestock prices peak. IBLI coverage has a large, positive, and statistically significant impact on income per adult equivalent	IV (randomized discount coupons value), panel survey data, stratified random sampling, of IBLI on behavior and welfare of pastoralists n=924	T= Adopter of IBLI C= Non-adopters of IBLI
34	Karlan et al., 2014	Ghana	Rainfall index	Subsidized and market insurance, cash grants	Insurance at any price, increased area cultivated, investment in certified seed, fertilizer, irrigation, pesticide; but not net farm income.	Multiple RCT experiments, treatments randomly assigned to communities: Year 1: 2×2 factorial (n=502), free insurance (135), cash grant (117), both (95), control (155); Year 2: 4 insurance price treatments, control (n=1,406); Year 3: 3 insurance price treatments (n=655)	T= Non-participants or non-adopters. C= Non-participants or non-adopters.
35	Madajewicz et al., 2013	Ethiopia	Rainfall index	Weather index insurance	Increased investment in draught animals, credit, fertilizers, improved seeds. Insured farmers tripled savings, increased oxen ownership 25%.	DID, random sampling of household panel data of index insurance on agricultural decisions n=379 households (T=202, C=82, C2=95)	T= Adopter of insurance C= Non-adopter of insurance C2= Non-adopters of insurance in Tabia without insurance program
36	Mishra et al., 2021a	Ghana	Rainfall index	Micro- and meso-insured production loan	Insured loans increase farmers' likelihood of receiving credit by between 15 and 21%. No impact on the likelihood that farmers apply for credit, increase in the likelihood of loan approvals of between 17 and 25%.	RCT, two fully subsidized insurance-credit bundle treatments on adoption of improved technologies n=258 maize farmer groups	T= Production loan + index insurance contract, payout to farmer (micro-insurance) T2= Loan + insurance, payout to lender to retire farmer's debt (meso-insurance) C= Loan (no insurance)
37	Mishra et al., 2021b	Ghana	Rainfall index	Micro- and meso-insured production loan	Increased fertilizer (10%) and herbicide adoption (41%) when farmers own insurance, but not when lenders own insurance. Insurance did not significantly impact yields or area cultivated.	RCT, two fully subsidized insurance-credit bundle treatments on adoption of improved technologies. n=258 maize farmer groups	T= Production loan + index insurance contract, payout to farmer (micro-insurance) T2= Loan + insurance, payout to lender to retire farmer's debt (meso-insurance)

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No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
							C= Loan (no insurance)
38	Miura and Sakurai, 2015	Zambia	Rainfall index	Index-based insurance	Insured farmers increased area cultivated, use of fertilizer and family labor, and sowed maize earlier.	IV, randomized selection to participate in insurance, randomized treatment of additional free insurance on agricultural practices. n=444 census (n=154 randomized to buy insurance, follow-up, C=55)	T= Purchased insurance plus additional free insurance (three treatments of different amounts) C= Purchased insurance only C2= No insurance
39	Mobarak and Rosenzweig, 2012	India (Tamil Nadu)	Delayed rainfall onset index	Index-based crop insurance	Shift to higher-yielding, less drought-resistant rice cultivar mix. Insurance improved average income where basis risk was low or informal risk sharing was high.	RCT, insurance marketing and subsidy treatments assigned randomly to villages n=63 villages (T=42, C=21; T=4,667 households)	T= Farmers in villages offered insurance C = Farmers in villages not offered insurance
40	Noritomo and Takahashi, 2020	Kenya	NDVI index	Index-based livestock insurance	Payouts reduce likelihood of distress sales and slaughter of livestock during drought, but do not significantly increase herd size. Owning insurance without payouts reduces distress sales on average, but not for poorer households.	IV, randomized incentive experiment with discount coupons randomized at individual level, survey panel data n=924	T= IBLI discount coupon C= Non-adopters of IBLI (ex-ante impacts of insurance) C2= adopters who did not receive payouts (ex-post impacts of payouts)
42	Sibiko and Qaim, 2020	Kenya	Rainfall (drought, excess) index	Weather index insurance	Insurance uptake is associated with a 51% higher fertilizer quantity used, 65% higher investment in maize seeds, and 62% higher maize yields, although when controlling for chemical fertilizer and improved seeds insurance uptake is statistically insignificant on yield.	IV, multi-stage random stratified sampling, of index insurance on quantity of inputs n=386 (T=87, C=299)	T= Adopter of index insurance C= Non-adopter of index insurance
41	WFP and Oxfam, 2016	Senegal	Rainfall index	Weather index insurance	Households with insurance spent more on average on agriculture inputs than those without insurance amounting to an average monthly investment (including farm inputs and equipment) of 5,000 CFA francs compared to 3,000 CFA francs for households without insurance.	DID, random sampling across program subgroups and control in three locations for the R4 program evaluation n=1,618	T1= Food for Assets (FFA) T2= FFA + Savings (SFC) T3= FFA + SFC + insurance C= Non-participant
43	Wong et al., 2020	Ethiopia	Rainfall index	Subsidized rainfall index insurance,	Insurance bundled with input vouchers	RCT, DID, subsidized insurance and input	T= Input vouchers T2= Input voucher

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No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
				input voucher bundle	increased average investment in seed by ETB 57, less than equivalently valued voucher alone. Insurance bundle increased average total investment in agricultural inputs by ETB 350 for forward-looking farmers with lower than median time discounting.	voucher treatment, household surveys n=>1100	and insurance grant C= No vouchers or insurance-voucher bundle
Humanitarian and social protection anticipatory action							
44	Cabot Venton and Majumder, 2013	Bangladesh	Cyclone and flood forecasts	Early flood intervention (aid procurement, evacuation, shelter, malnutrition treatment)	Early intervention, based on flood early warning and Cyclone Preparedness Program (CPP), reduces annual cost of intervention plus losses $3.4 to 4.4 billion (-40% change) over 20 years relative to late intervention scenario. BCR between 5.0 and 6.4.	SS, modeled 20-year early action scenario grounded in historical flood hazard, humanitarian loss and cost data.	C=Intervention timing scenario assuming absence of flood EWS and CPP
45	Clarke and Hill, 2013	Africa	Rainfall index	Sovereign insurance for pre-approved contingency plans	BCR from 1.28 to 1.90 due to improved targeting and earlier assistance. Number of beneficiary households increased > 4-fold. Earlier delivery of assistance reduces welfare loss from reduced consumption, losses of productive assets (as a result of direct losses or distress sales), and forgone investment opportunities.	ROI of ARC assessed against household response mechanisms to drought and long-term costs to determine benefits of early intervention and improved targeting. Benefits are discussed through four contingency- planning scenarios.	T= Contribution to ARC, four scenarios C= Donor contribution to annual budget support C2= Donor contribution to emergency food aid distribution, nine months after failed harvest
46	Coulter et al., 2013	Mozambique	Drought early warning	Early drought and flood food and non-food humanitarian aid	Early intervention reduces annual cost of intervention plus losses between $837 (-53% change, conservative “top-down” model) and 1,959 billion (-93% change, “bottom-up” model) over 20 years. BCR between 2.6 and 56.	SS, modeled 20-year early action scenarios: (a) “bottom-up” based on Household Economy Model; (b) “top-down” based on historical humanitarian loss and cost data and expert estimates.	C= Late intervention scenario, defined by coping responses rather than timing
47	FAO, 2018a	Kenya, Somalia, Ethiopia	Rainfall forecast (Kenya)	Supplementary feed and care for livestock	In Somalia and Kenya, increased milk production, reduced average mortality of small ruminant livestock. 3.5 BCR in Kenya. BCR in Ethiopia 1.7.	Empirical ROI. Methodology not specified.	T = Participant pastoralist C= Non-participant pastoralist (Kenya)
48	FAO, 2018b	Mongolia					

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No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
			IRI Forecast heavy snow, *dzud*	Reducing herds in return for cash and distributing feed early	7.1 BCR from value of animals saved, extra milk production and avoided drop in livestock value	Empirical ROI. Methodology not specified.	T= Participant herders C= Non-participant herders
49	FAO, 2019b	Colombia	IRI SCF	Community production centers, seed distribution (short cycle, drought resistant), animal health support, water supply rehabilitation, online training	Average benefit of $1,351 per household from increased crop production, improved productivity and reduced mortality of livestock. BCR of 2.6. Child average daily milk consumption increased by 0.5 L.	Empirical ROI. Methodology not specified.	T= Participant farmers C= Non-participant farmers
50	FAO, 2019a	Madagascar	SCF with IPC food security projections	Provision of seeds (vegetable, short duration and staple crops), micro-irrigation equipment, agricultural training	Average benefit of $78 per household from increased vegetable production and avoided loss. BCR of 2.5. Reduced rate of inadequate staple and vegetable consumption from 40% (non-participant) to 16% (participant).	Empirical ROI. Methodology not specified.	T= Participant farmers C= Non-participant farmers
51	FAO, 2020	Philippines	ENSO forecast, SCF, remote sensing vegetation data	Provision of small livestock, drought-tolerant vegetable seeds, garden tools, fertilizer, micro-irrigation equipment, cash for work programs, awareness campaign	Average benefit of $538 per household from increased income from vegetable and egg production and avoided losses. BCR of 4.4.	Empirical ROI. Methodology not specified.	T= Participant farmers C= Non-participant farmers
52	Giuffrida, 2017	Zimbabwe	El Niño, SCF	Promotion and input provision for drought tolerant small grains	FoodSECuRE activities increased crop production value by an estimated 11%. For the population benefiting from FoodSECuRE, food insecurity increased less than the national average by only 32% compared to 86%.	BEM of production and price shock on household economic behavior and food security n=374	T= Drought tolerant small grain and maize cultivation C= Maize monoculture
53	Gros et al., 2019	Bangladesh	Hydrological model for fluvial inundation	FbF unconditional cash grant	FbF reduced household food rationing, maintained more nutritious diet, reduced high-interest borrowing as a coping strategy, relative to control group during month following flood.	PSM of forecast-based cash distribution on preparatory early action and household socio- economic and food security outcomes n=390 (T=174, C=216) n=348 matching units	T= Participant household C= Non-participant household, similarly vulnerable and flood-affected
54	Gros et al., 2020	Mongolia	Extreme winter		FbF reduced mortality of horses	PSM, nearest neighbor of forecast-based cash	T = Participant household

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No.	Study	Country	Climate information	Climate-informed action	Impact key finding	Method	Counterfactual
			forecast (Dzud)	FbF unconditional cash grants, animal care kits	by ~50%, increased survival rates of goat and sheep offspring relative to control. Benefits varied with timing of assistance, diminishing when delivered late. FbF did not significantly impact expenditure on basic necessities or overall food consumption.	distribution on livestock mortality and household socio-economic outcomes n=446 (T=223, C=223)	C= Non-participant household, similarly vulnerable and flood-affected
55	Kramer et al., 2020	Burkina Faso, The Gambia, Kenya, Malawi, Mali, Mauritania, Niger, Senegal	Rainfall index	Sovereign insurance for pre-approved contingency plans	BCR from 3.00 to 4.16 if recommended improvements are implemented on speed, cost and targeting.	ROI of ARC from Clarke and Hill (2013) methodology with updated assumptions and costs	T= Contribution to ARC, four scenarios C= Stylized emergency assistance
56	Pople et al., 2021	Bangladesh	Streamflow forecast from weather forecast and hydrological modeling	Anticipatory cash transfer	Early transfer reduced likelihood of missing meals for $\geq$ 1 day by 36%, increased likelihood of evacuating household members (12%) and livestock (17%), reduced likelihood of small livestock (8%) and poultry (5%) loss relative to control. Each additional day of lead time showed significant incremental benefit to adult food consumption. Benefits 3 months after the flood include significantly higher child and adult food consumption, higher employment and reduced borrowing.	SC- linear regression, natural experiment, non-randomized sample of anticipatory cash distribution on food security and socio-economic outcomes n=8,954 (T=6,566, C=2,388)	T= Participant households C= Non-participant eligible households

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