BAMS Article

Enhancing Global Food Security

Opportunities for the American Meteorological Society

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ABSTRACT: Food security is a key pillar of environmental security yet remains one of the world's greatest challenges. Its obverse, food insecurity, negatively impacts health and well-being, drives mass migration, and undermines national security and global sustainable development. Ensuring food security is a delicate balance of myriad concerns within the atmospheric and Earth sciences, agronomy and agriculture engineering, social sciences, economics, monitoring, and policymaking. A Food Security Presidential Session at the American Meteorological Society's (AMS) 2022 Annual Meeting brought together experts across disciplines to tackle issues at the nexus of weather, climate, and food security. The starkest takeaway was the realization that, despite its importance and clear roles for the atmospheric and climate sciences, food security has not been a focus for the AMS community. The aim of this paper is to build on the perspectives shared by this expert panel and to identify overlapping issues and key points of intersection between the food-security community and AMS. We examine 1) the interactions between weather, climate, and the food system and how they influence food security; 2) the time and spatial scales of food security decision support that match weather and climate phenomena; 3) the role of both providers and users of information as well as decision-makers in improving research to operations for food security; and 4) the opportunities for the AMS community to address food security. We conclude that, moving forward, the AMS community is well-positioned to scale up its engagement across the global food system to address existing scientific needs and technology gaps to improve global food security.

SIGNIFICANCE STATEMENT: We examine how members of the AMS community can help ensure global food security, whether they are engaged in the physical and social sciences or the realms of policy and society. Inspired by the messages of panelists at a Presidential Forum on Food Security at the 2022 AMS Annual Meeting, we gather their perspectives and those of experts working in the various relevant fields and find that there are roles for everyone across the AMS—from providing forecasts of the hydrometeorological variables used in food security outlooks to converting data to knowledge and engaging with stakeholders and decision-makers. We make concrete suggestions to ensure the AMS and its members are fully engaged in feeding the world.

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Food security exists "when all people at all times, have the physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO et al. 2021). Shaped by ever-evolving geopolitics, socioeconomic challenges, and environmental pressures, food security lies at the heart of human well-being and prosperity and is key to achieving many of the UN Sustainable Development Goals (SDGs) and those of other global frameworks. Failure to achieve food security can exacerbate vulnerability and inequity, intensify humanitarian crises, and jeopardize international security.

The food system—including the production, distribution, and consumption of food—is highly vulnerable to extreme weather and climate events. The interactions between weather, climate, and the food system have a significant impact on food security by affecting the availability, access, utilization, and stability of food. However, the global food system is also a major driver of climate change, responsible for nearly one-third of global greenhouse gas emissions (GHG) (Crippa et al. 2021). As a result, the food system is not only vulnerable to climate change, but also drives the very shocks that threaten it. Additionally, compounding risks, such as from decreasing biodiversity—which otherwise supports diverse diets, a growing global population, and demographic transitions, and helps to absorb system shocks—are further exposing the food system to climate disruptions and cascading impacts.

Examples of the interactions between weather, climate, and food security can be traced through history. For example, during the 1780s, France suffered a series of failed harvests, a severe drought, an extreme cold snap, and severe storms, all of which resulted in food shortages that raised bread prices to 88% of the average citizen's wages; this led to riots, bloodshed and, ultimately, the French Revolution (Neely 2007). In the late 2000s, drought in Syria exacerbated poverty and social unrest in rural areas, leading to riots and mass displacement (Kelley et al. 2015). More recently, the globally networked nature of risks has become increasingly clear (UNDRR 2021). Today, devastating extreme weather events fueled by a changing climate further exacerbate global food crises that were triggered by global shocks brought on by events such as the COVID-19 pandemic and the reduction of grain and fertilizer exports from Ukraine.

However, hunger is not only an issue for countries in the Global South: an estimated 13.5 million U.S. households experienced food insecurity in 2021 (USDA 2022). In February of that year, one of the worst cold snaps in Texas state history shocked the energy system, leading to supply chain challenges and exacerbating food insecurity, particularly among vulnerable and food-insecure households. In October 2022, Hurricane Ian drove an increase in food insecurity at a time when many households were already struggling with inflation triggered by the COVID-19 pandemic and geopolitical crises across the world. According to local food banks in Florida, demand quadrupled and vulnerable migrant communities were particularly hard hit (Feito 2022).

Across the world, communities most affected by food shocks are low income, underrepresented, and disproportionately impacted by extreme weather events and climate change impacts. For those communities that are already food-insecure, climate change is a "threat multiplier," threatening crop yields and the food supply while also raising prices and reducing growers' incomes. Yet these communities are also the hardest to reach with meteorological messaging that could inform agricultural decision-making, improve food security outcomes, and save lives and livelihoods. As a result, it is crucial that decision-makers understand the important roles the meteorology and climate-science communities play and the value of weather and climate research for risk management and fostering resilience.

The science, applications, technologies, and services required to address the challenge of global food security sit at the heart of the American Meteorological Society (AMS) community. This article offers a perspective that builds on the expertise shared by the Presidential Forum panel members and others with experience at the interface of food security and climate. It discusses the crucial role AMS can play in addressing this challenge (see Motivation and drivers of this paper sidebar) starting with monitoring and forecasting of weather and climate phenomena that interact with food security, and developing and providing decision-makers the information they need to take action across scales of time, space, and production. This article also highlights the importance of engaging with users and decision-makers to enhance the exchange of knowledge and expertise and identifies some of the many opportunities for meteorology and climate science to support global food security that may be underrecognized. The article concludes with a call to action to the AMS community to scale up engagement across the food system and embrace an interdisciplinary approach to break down the silos that stand in the way of addressing global food security.

Interactions of weather, climate, and food security

Food security encompasses four dimensions, namely, the physical *availability* of food, the economic and physical *access* to food of sufficient nutritional quality, the *utilization* of food, and the *stability* of these dimensions over time (FAO et al. 2021). These dimensions are commonly referred to as "the four pillars of food security" and are impacted by the interactions between weather, climate, and the food system.

The complex food system—conceptualized as three simplified components including the production, distribution, and consumption of food—is highly vulnerable to weather and climate phenomena such as droughts, floods, heatwaves, cold spells, and storm events (hail, snow, ice, wind, etc.). However, it is also a major contributor to the global emissions that lead

Motivation and drivers of this paper

A Food Security Presidential Session at the 102nd AMS Annual Meeting in January 2022 (Muñoz-Arriola et al. 2022) and a Food Security Podcast started in 2021 leading up to the meeting brought together experts across disciplines to tackle issues at the nexus of weather, climate, and food security. A stark takeaway from these activities was the realization that, despite its importance and scientific relevance, food security has not been a focus for the AMS community to date. Two major themes emerged from the workshop: 1) increased recognition that standard approaches to food security were being overwhelmed by compounding risks and cascading impacts associated with a varying and changing climate and 2) the importance of engaging directly with vulnerable communities to improve their access to reliable information and technology and utilizing their experience and expertise in turn to stimulate scientific advancement.

Listen to the Food Security Podcast here: https://tinyurl.com/29ey8vdw.

to human-induced climate change—a feedback loop in which the global food system drives the very climate shocks that threaten it. As a result, monitoring, forecasting, and projecting these weather and climate phenomena is crucial to understanding how they interact with the food system and their implications for food security.

The food system. *Food production* is highly dependent on climate drivers including precipitation, temperature, evaporative demand, evapotranspiration, and atmospheric carbon dioxide (CO_2). Extreme weather events, in particular, can have devastating impacts on crops and livestock and the effects of climate change will increasingly strain food security. Rising global temperatures will shift climate zones suitable for growing crops and increase health risks to farm laborers who may have to reduce their working hours due to extreme heat and humidity. However, food production activities are also a major contributor to global GHG emissions, particularly agricultural activities and land-use change, which accounted for 71% of the GHG emissions that originated from the global food system in 2015 (Crippa et al. 2021).

Food distribution and supply networks are vulnerable to weather- and climate-driven disruptions to the supply-chain infrastructure, which can lead to food loss and waste and, consequently, higher food prices. These shocks are also deeply intertwined with global geopolitics that can further exacerbate food-distribution challenges. For example, the war in Ukraine sent shockwaves across the global food-supply chain, leading to soaring wheat prices; at the same time, India banned wheat exports following a record-breaking heatwave that devastated yields (Singh 2022). Food distribution also contributes to global GHG emissions, particularly through supply chain activities (storage, processing, transport, etc.), which account for approximately 5%–10% of the food system's total GHG emissions (IPCC 2019).

Food consumption is also affected by climate variables such as temperature and CO_2 concentrations, which influence biological processes that impact food quality and nutrition (IPCC 2019). For example, higher CO_2 levels have been shown to result in large declines in vitamin content across all rice cultivars, jeopardizing food security for hundreds of millions of people in lower-income countries (Zhu et al. 2018). Food consumption choices also influence GHG emissions, with plant-based diets associated with lower emissions than animal-based diets. Consumption patterns are also closely tied to food loss and waste, which accounted for 8%–10% of total, global anthropogenic GHG emissions in 2010–16 (IPCC 2019).

Meteorology and climatology in food systems. Food security decisions are affected by a number of physical systems, markets, natural resources conditions, and individual factors. The key phenomena that weather and climate research and applications communities seek to monitor, forecast, and project to support food security decisions are climatological suitability conditions (e.g., the expected seasonal cycle of temperature and precipitation) and meteorological and hydroclimatic extremes. These climatic impact drivers (CIDs)—physical climate conditions that directly affect society or ecosystems and influence responses of agricultural systems (IPCC 2021b; Ruane et al. 2022)—are derived from key fluxes and states, including precipitation, streamflow, soil moisture, evapotranspiration, evaporative demand, wind, temperature, relative sea level rise, coastal flooding, snowpack, and river flows.

Agroclimatic information is derived from in situ observations or remotely sensed platforms. Retrospective analyses (reanalyses), derived from assimilation of observations into modeling frameworks, produce seamless spatial and temporal datasets that fill in observational gaps. Direct application of agrometeorological and agroclimatic information derives indices representing important agricultural conditions that support food security decision-making frameworks. Additionally, weather and climate data may be indirectly used at a variety of time frames to create impacts assessment (see "Scales of action"), such as through land surface models, water-stress models, agricultural water demand models, crop water requirements models, genetic-by-environment models, or more comprehensive crop, livestock, and socioeconomic models [e.g., the Agricultural Model Intercomparison and Improvement Project (AgMIP); Rosenzweig et al. 2013; Ruane et al. 2017; and the Genomes to Fields initiative (G2F); Jarquin et al. 2021]. The data may be used in impact models (biological and socioeconomic) across all time horizons (Ruane et al. 2021; Jägermeyr et al. 2021), though this development is not yet fully implemented in practice.

The choice of states and fluxes to be observed, modeled, or forecasted must strike a balance between the competing demands of physical relevance to food security and the observability, predictability, and availability of data. While precipitation and temperature have long been the most commonly estimated quantities, other physically relevant quantities are often more useful (Ruane et al. 2022). For example, atmospheric evaporative demand represents a physical link between plant physiology, water stress and/or availability, and atmospheric conditions and is therefore central to food-security monitoring, where it is used as an input in such metrics as the water requirement satisfaction index (WRSI; Verdin and Klaver 2002) and standardized drought indices such as the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al. 2010). Hobbins et al. (2023) demonstrates the power of implementing an accurate, long-term reanalysis of evaporative demand in food-security monitoring, while both McEvoy et al. (2016b) and Shukla et al. (2017) show that evaporative demand is often forecast at the same or longer lead times with equal or better skill than precipitation, thereby permitting more accurate monitoring and more skillful predictions of the demand side of food-security water balances than of the supply side.

Scales of action

Providing hydrometeorological, climatological, and agronomic support for food-security monitoring requires data across time and space scales—from nowcasts to multidecadal predictions and from plant to global scales—to inform stakeholders across their decision time and space horizons, as shown in Fig. 1 (Ruane et al. 2015; Sarzaeim et al. 2023). While meteorological phenomena tend to have a strong relationship between temporal and spatial scales (e.g., fine-scale turbulence is fast and small, while global climate change is long and widespread), agricultural decisions typically span time and space. Farmers employing precision agriculture practices may operate on the scale of individual plants and rows within a field, with management tailored to fine-scale soil–hydrology interactions and the thermodynamics of plant canopies and shading structures (Nakabuye et al. 2022). Many of those same farmers have already seen the increasingly emerging signs of climate change across their region, challenging the long-term legacy of family farms and encouraging proactive planning to anticipate new risks and opportunities (e.g., related to greenhouse gas mitigation). The mandates and tools available for important food-system decision-makers may also point to specific spatiotemporal scales, for example, aid agencies tasked with responding to seasonal famines in a vulnerable country or water resource planners designing a long-lived reservoir or canal system to support a regional breadbasket. Insurance instruments can spread risk across time and space, and farm extension agents typically have territories of concentrated outreach. The interconnected food system can also buffer consumers and prices against regional heterogeneity and extreme event risks via diverse production regions and well-established value chains. Weather and climate services supporting food systems thus benefit from efforts to match models and information sources with the spatiotemporal requirements of specific decision processes.

At the global scale, the expansion of agriculture and consequent land-use changes have altered land surface–atmosphere interactions and local-to-regional patterns of climate variability. Changes in land use and climate affect the quantity and quality of water and

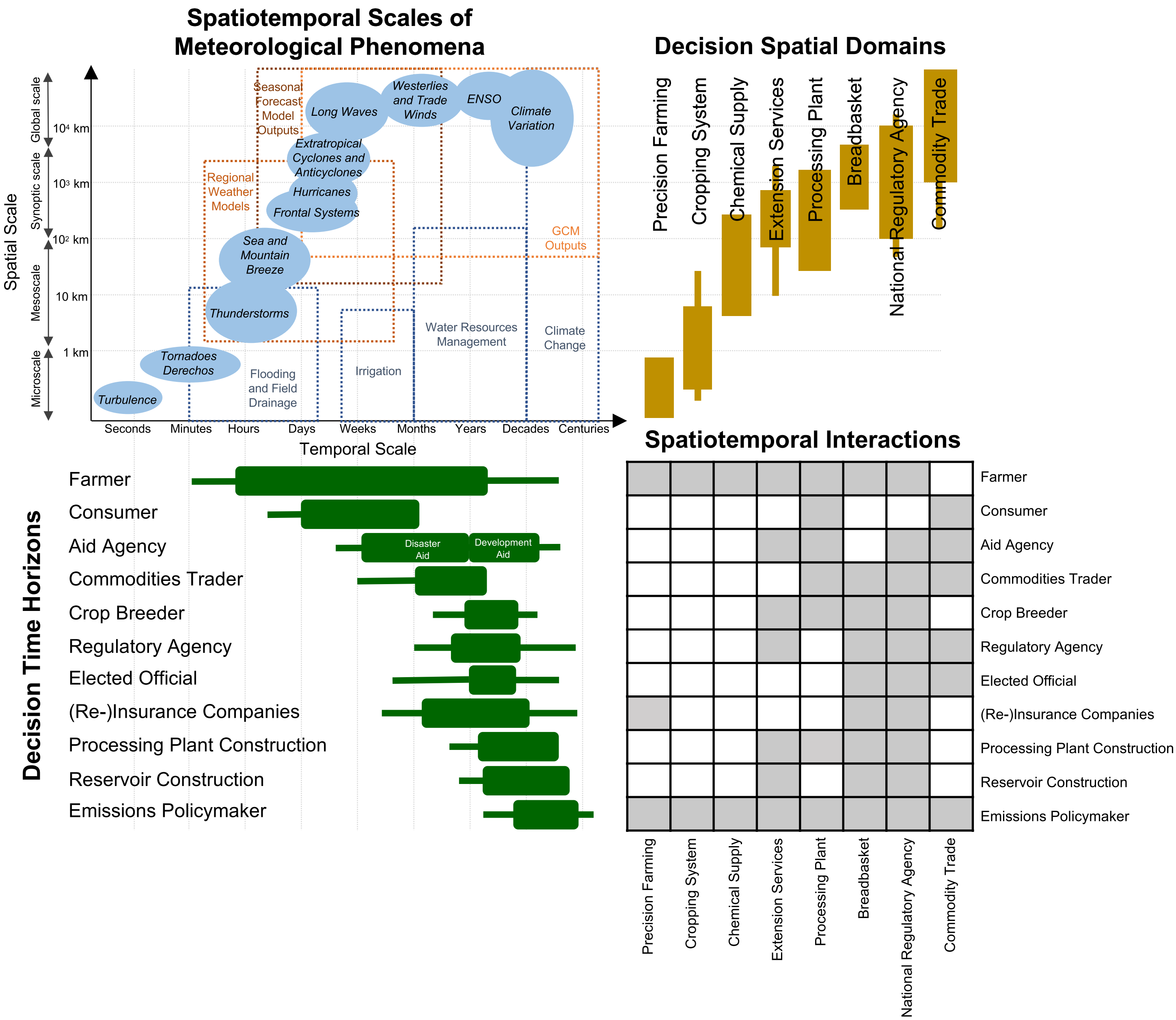

Fig. 1. Interacting spatiotemporal scales of meteorology and agricultural decisions. (top left) Spatiotemporal scales of meteorological phenomena, with domains of different modeling types shown in orange boxes and agricultural applications areas in blue [adapted from Tavakolifar et al. (2017) and Nese and Grenci (2011)]. Agricultural decision (top right) spatial domains and (bottom left) time horizons are shown in alignment with the top-right temporal and spatial scales, identifying decisions that are likely to be shaped by corresponding meteorological phenomena. Thick boxes show the main decision scales with thinner boxes extending to important but less prevalent decision scales. (bottom right) How stakeholders often weigh multiple temporal and spatial scales in decision processes.

consequent agricultural management (Kukal and Irmak 2018; Muñoz-Arriola et al. 2021; Jaimes-Correa et al. 2022). At plant-to-field scales, irrigation and plant breeding evince humanity's adaptations to climate changes (Ou et al. 2018; Evett et al. 2020; Sarzaeim et al. 2021). Across these time and spatial scales, data must be gathered that are physically and socially robust, including being timely, relevant, accessible, accurate, usable, and useful.

Time and space scales for analyses of the past, present, and future. There have long been efforts to incorporate climate change information into agriculture and food security, particularly climate variability at the seasonal-to-interannual range; the longest-standing may be CGIAR's Research Program on Climate Change, Agriculture, and Food Security (CGIAR 2023).

However, in this paper we advance the concept that addressing food security requires that the Earth system science community engage in food-security monitoring and outlooks at multiple time horizons and spatial scales. Observational data and monitoring tools commonly originate in conventionally gathered meteorological data observed at stations or remotely from satellite observations. In poorer, food-insecure countries, reanalyses and remotely sensed data may mitigate the effects of unreliable observational networks and limited cross-border data sharing. Data ideally belong to long (multidecadal) observed climatologies to contextualize ongoing anomalies, provide accurate statistics and initial conditions for forecasting, and establish the predictability of anomalies. On regional and global scales, model-derived outputs and global land and ocean data assimilation systems and reanalyses are widely available and commonly used for estimating variables that the food-security community has traditionally relied on (e.g., drivers such as precipitation and temperature) to derive agricultural metrics and indices.

Food security outlooks are based on the monitored and future states of key variables in the Earth system, which draw on the expert interpretation of a variety of forecasts. Here, we focus on three time horizons related to the growing seasons envisioned by the Famine Early Warning Systems Network (FEWS NET 2018), and illustrate how forecasts and interpretation are used to support food security outlooks:

1) *6–9 months before a growing season*: Although forecast skill is low for many agricultural drivers at lead times longer than 6 months, actionable information may be derived from the monitored state of the climate and from understanding climatological characteristics leading up to, and then during, the next growing season. For example, anomalously low soil moisture prior to land preparation and planting may delay planting and crop development, which can reduce yields.
2) *Within 6 months of a growing season*: The predictability of slowly varying modes of climate variability like El Niño–Southern Oscillation (ENSO; FEWS NET 2020a,b) and the Indian Ocean dipole (FEWS NET 2021) and their known effects on regional climates provide forecasts of opportunity, which are defined as “windows in time when expected skill is higher than usual at a particular place because of the presence of certain features in the Earth system” (NASEM 2016). Hence agricultural drivers are more predictable many months in advance of a growing season. For example, if an ongoing La Niña event in July is forecast to continue into the following year, then below-average precipitation is most likely during the Horn of Africa’s short-rains season.
3) *Within 3 months of and during a growing season*: Expert interpretation of monitored and forecast conditions is used to predict the most likely state of agriculture drivers, and thereby capitalize on windows of opportunity of more skillful forecasts.

There is an increasing realization that prediction skill on longer than weather time scales (>2 weeks) can leverage specific climate phenomena (e.g., the Madden–Julian oscillation, disruptions of the stratospheric polar vortex) or conditions for a predictable signal above the weather noise but that are not captured in present climate change projections. These forecasts of opportunity are intermittent in time and have spatially heterogeneous impacts on skill. Users’ expectations for prediction skill would be better informed by a more nuanced awareness of when and where to expect skill and thus if the prediction is actionable.

Converting data into knowledge. Food security–relevant data are only useful if they are converted to information and, eventually, to actionable wisdom to inform decisions across time and space scales. However, converting data into knowledge to support decision-making requires a robust forecasting infrastructure, which is often not available in countries most

FEWS NET

FEWS NET is an example of successful implementation of food security early warning with robust stakeholder engagement through institutional commitments and interagency agreements. FEWS NET, which is managed and supported by the U.S. Agency for International Development (USAID), provides early warning and analysis of acute food insecurity to inform the proactive preposition of humanitarian aid. Though many factors contribute to food security, the effect of weather and climate is consistently important, and to that end, forecasts and Earth system monitoring from NOAA, the U.S. Geological Survey (USGS), the National Aeronautics and Space Administration (NASA), the U.S. Department of Agriculture (USDA), and university collaborators play a critical role.

NOAA provides forecasts,[SB1] atmospheric forcing data, and develops the knowledge base regarding the predictability of environmental extremes that lead to food insecurity.[SB2] USGS, NASA, and the USDA provide rich Earth system monitoring tools[SB3,SB4] that allow FEWS NET to analyze current conditions and their anticipated effect on livelihoods and agriculture. The FEWS NET model has guided programmed humanitarian assistance to lessen the impacts of food insecurity since its creation in 1985.

SB1 www.cpc.ncep.noaa.gov/products/international/
SB2 https://fews.net/el-ni%C3%B1o-and-precipitation
SB3 https://earlywarning.usgs.gov/fews
SB4 https://lis.gsfc.nasa.gov/projects/fewsnet

vulnerable to food insecurity. The climate modeling community has made important strides in addressing forecasting challenges and closing the gaps to address the needs for actionable food security outlooks and decision-making. Climate forecasts are probabilistic in nature, however, and expressed with some degree of uncertainty, requiring adequate messaging for stakeholders' understanding of the forecasts and confidence in their use to make decisions.

While monitoring and forecasting the climate variables that drive food security are crucial for developing decision-support tools, these data must be integrated into the larger socioeconomic context, including market prices, consumption patterns, income, sanitation, healthcare, governance, and policy. This integration requires close interaction between not only physical and social scientists but also stakeholders to codevelop food security decision-support tools that are easy to understand, useful, usable, scalable, accurate, and timely. Engagement with stakeholders is key for converting data into knowledge and driving impact-based forecasts that address local needs and improve early action. The FEWS NET, highlighted in the "FEWS NET" sidebar, is an example of how integrated physical and socioeconomic data and robust stakeholder engagement have been used to support food security decision-making.

Engaging with users and decision-makers

Engaging with decision-makers, farmers, fishermen, and other stakeholders results in substantial improvements in our understanding of atmospheric and climatic drivers. For example, a careful examination of variability in salmon fisheries in the North Pacific Ocean and the U.S. Pacific Northwest paved the way for discoveries in fundamental aspects of the Pacific decadal oscillation (PDO; Mantua et al. 1997). While numerous papers highlight the importance of improving the transition of research to operations (R2O) to overcome the research "valley of death" (when research developments do not effectively reach operations), its sister process, the translation of user expertise to the research community [operations to research (O2R)], is underprioritized. O2R enables the research agenda to include user needs and research interoperability with operational environments and helps align priorities for research and development (R&D) with those most important for decision-makers (Merceret et al. 2013; Steenburgh et al. 2013).

Although it could be greatly expanded, several food security organizations already prioritize and capitalize on the extensive knowledge of decision-makers to stimulate robust scientific advancement and prioritize development. For example, AgMIP (Rosenzweig et al. 2013) includes decision-makers as active participants from the outset by listening to stakeholder questions before bringing modelers together. Another example is the NOAA Regional Integrated Sciences and Assessments Program (RISA; recently renamed Climate Adaptation

Partnerships), which was developed to present climate data at decision-making scales across the United States with a strong emphasis on dialogue between users and researchers to establish priorities and ensure that research is focused on addressing decision-maker's challenges (Pulwarty et al. 2009).

Challenges in engaging with users and decision-makers. Although beneficial to the research community, multiple challenges limit the efficacy of O2R and R2O. A significant challenge is often ineffective communication, which can prevent practitioners from being aware of available datasets or how to effectively use them. On the other hand, researchers may not know the nuances of the decision-making process, limiting their ability to connect users with the correct products. Such disconnects have been documented since the early days of ENSO forecast applications with attendant recommendations (NRC 1999) that have yet to be sustained beyond the project level and at the needed scales of action. One recent Harvard Business Review study highlights the broader nature of this challenge, finding only a 50% correlation between managers' assumptions and clients' actual needs (Kenny 2021), suggesting a simple remedy: engage users in conversations and ask their priorities instead of using standardized surveys or raw data science. This process has increasingly been recognized as key and commonly referred to as "coproduction" and is expanding within the humanitarian world and in sustainability research. For example, the oceanic portion of the UN Sustainable Development Goals were developed through discussions between scientific and business experts (Norström et al. 2020; Lokot and Wake 2023). Additionally, communication between operationalists and researchers is often limited during extreme events, when operational demands take priority. Knowledge exchange and effective communication is critical before, during, and after extreme events to foster an understanding of the lessons, norms, and practices that both researchers and practitioners are embedded in and that have become socialized over time. Much of this knowledge needs to be collaboratively derived and iterated between events.

The exchange of knowledge must also be sustainable, equitable, and consistent—a challenging prospect. The processes for engagement for O2R and R2O should represent a seamless continuum where assumptions can be queried and responded to (see Fig. 2). However, this is in contrast to current research and funding practices, which often embrace a unidirectional approach of identifying what users want and how researchers can provide (Stokes 1997). Instead, a broader scientific agenda is needed that requires a user-inspired framing that advances both research and practices. Such framing is exemplified in the development of the evaporative demand drought index (EDDI; Hobbins et al. 2016; McEvoy et al. 2016a): users from regional and national drought-monitoring communities were engaged at the beginning of the development of EDDI and during subsequent iterations of the process. This codevelopment across the continental United States allowed for an easier development of EDDI as a new tool to support food-security monitoring in data-sparse regions by both FEWS NET and the U.S. Department of Agriculture's Foreign Agricultural Service.

Facing the challenges in O2R–R2O: The role of prototypes and testbeds. Although there are many challenges across the O2R and R2O nexus, prototypes and testbeds are important tools to support effective communication and knowledge transfer. Prototypes offer a strategic perspective of systems (organizational, socioenvironmental connections), people (skills, values, and perspectives), and joint visioning, which together allow for the design and development of effective testing (Lasswell 2005). Since they are crafted as learning-by-doing enterprises, prototypes are also reversible if participation or outcome trajectories are not developing as intended.

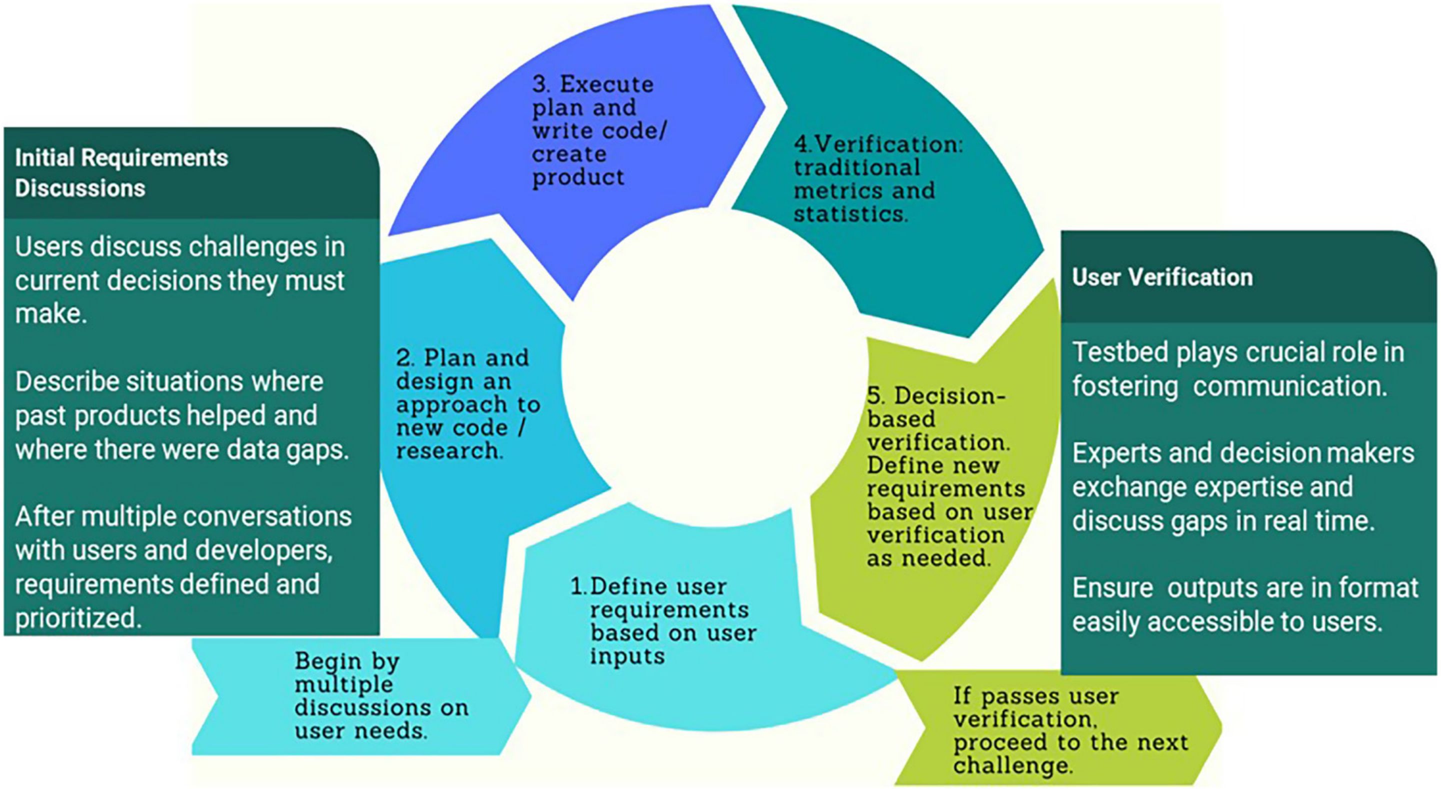

Fig. 2. A cyclical or iterative prototype framework for jointly advancing O2R and R2O inspired by Agile project management principles (Agile Alliance 2001).

A testbed offers the operational component of a prototype in a controlled but dynamic environment where both failure or success of information application is acceptable since joint learning between researchers and practitioners is the goal (e.g., CGIAR 2023). By definition, testbeds are entities that foster collaboration "to accelerate the translation of R&D results into better operations, services and decision-making" (TBPGCC 2020). Additionally, testbeds address the challenge of sustainable knowledge transfer by establishing a framework to support both O2R and R2O on a consistent and regular basis.

While many testbeds have already been established, there is great potential to extend the concept to facilitate the transfer of expertise between researchers and humanitarian decision-makers before, during, and after extreme events (Steenburgh et al. 2013). During extreme weather events, the product of O2R–R2O knowledge transfer is most essential, yet operationalists are the most taxed. Much needs to be in place before such events. While many organizations provide open-source data to humanitarian decision-makers during such events, they are often run on a voluntary basis with limited funding. As a result, data may not always be available or produced in a way that is accessible to users (Schumann et al. 2018; Niebuhr and Schreck 2021). Establishing a humanitarian prototype for knowledge exchange within the food-security space could help ensure the operability of decision-support products, their verification and visualization, and the accessibility of data to users. Additionally, such a testbed would build the capacity of partners, particularly in lower-income countries, thereby ensuring that the expertise of humanitarian actors directly reaches scientists while simultaneously increasing knowledge and accessibility to scientific tools. This two-way knowledge transfer will ensure sustainability for humanitarian efforts.

Applications of meteorology and climate science to support global food security

Supporting global food security will require a multidisciplinary approach that brings together scientists, policymakers, humanitarians, and other communities across the science–policy–society interface (UNIGSSG 2023). This section highlights opportunities for the AMS community to engage across this science–policy–society interface to address food security. The opportunities highlighted in this section are in no way comprehensive, but represent some of the many applications for meteorology and climate science to support global food security that may be underrecognized.

Modeling, and attribution of meteorological and climate impacts for food security applications. Models—including weather, climate, and agricultural models—are crucial for food security applications. While models have improved significantly over the years, predictability of precipitation at S2S time scales is generally low and there remains a need for improved process understanding and process representation that could uncover additional sources of predictability. Models should also be better connected to food-security applications, e.g., better linking dynamic agricultural conditions, farm management, and information on responsive interventions into land surface models and biogeochemical and Earth system models (MacBean et al. 2021; McDermid et al. 2017). Meteorological information provided for process-based and data-driven crop models is needed to capture more complex responses given the dynamic nature of plant and animal systems and their responses to CIDs under different management conditions (Jarquín et al. 2014; Wang et al. 2017; Raymond et al. 2020; Montesinos-Lopez et al. 2022; Sarzaeim et al. 2021). Development of these models must be scientifically rigorous and anticipated applications must be socially robust. The expansion of applications must include the diversity of social and cultural aspects of human activities and their connection with the physical parameterizations or data-driven analytics to benefit a better understanding of Earth living support system's complexity, the interplay between uncertainty and unintended consequences, and the relevance of deliverables to changing communities (Saltelli et al. 2020; UNIGSSG 2023).

Additionally, recent methodological advancements have dramatically improved the ability to detect and attribute the signature of anthropogenic climate change in extreme climate events (IPCC 2021a). There is tremendous potential in extending this approach into agricultural impacts using combinations of crop models, land surface schemes, hydrologic parameterizations, data-driven models, and historical bias-adjusted climate datasets (Livneh et al. 2015; Ou et al. 2018; Amaranto et al. 2018, 2020). Recent work has shown our ability to identify the proportion of production anomalies attributable to climate conditions (Ray et al. 2015) and long-term climate changes (Lobell et al. 2011). Ruane et al. (2021) demonstrated the use of crop models to capture agroclimatic vulnerability with variations by country and system, while also showing a strong dependence on the choice of a driving historical climate datasets and of the specific vegetation dynamics employed. The development of historical counterfactual climate datasets (representing recent climate without human climate changes) that are suitable for agricultural modeling and analysis is a prerequisite for the direct detection and attribution of human influences on the food system (Mengel et al. 2021).

The AMS plays a crucial role in supporting the modeling and attribution of meteorological and climate impacts by creating a space for discussion at conferences and engaging with committees that address existing challenges. However, the AMS should better link these discussions to food security applications and encourage greater collaboration across the weather, water, climate, and agriculture sectors to ensure these advancements in science are suitable for agricultural decision-making.

Addressing systemic risks and cascading crises. Systemic risks are interdependent failures across a system that might lead to cascading events or a breakdown of the entire system. Failure can arise through one or several external shocks or be embedded in the system itself

Systemic risks associated with droughts

The characteristics of systemic risks are clear during droughts, which can act as a trigger for cascading events and feedback loops that further exacerbate the initial hazard. The interdependence among compounding hazards, such as heatwaves and prolonged droughts, can generate different event chains that, exacerbated by system vulnerabilities, can cause damage to different exposed elements such as agricultural production, critical infrastructure, or service networks. For example, because the globalized world consists of highly interdependent social, economic, environmental, and technical systems, drought-induced crop losses in one region may lead to ripple effects, such as food spikes across the world. Additionally, droughts can have highly nonlinear effects and, despite often developing gradually, they may act as a sudden, dramatic tipping point that triggers high food insecurity and famine, which may then lead to social unrest. Source: UNDRR (2021).

and have cumulative risk potential when characteristics of a system change. The management and reduction of systemic risks is fundamental in moving from food security risk to resilience (UNDRR 2021, 2022).

Cascading climate-related events, poverty, rapid urbanization, weak governance, and the decline of ecosystems are threatening food security, increasing disaster risk, and, at times, introducing new threats. As climate extremes often affect large areas, sometimes over several years, these cascading impacts can affect large parts of society, even those distant from the initial event. However, the spatial or temporal correlation among these extreme events remains poorly understood (USGCRP 2017). The "Systemic risks associated with droughts" sidebar highlights the cascading impacts that can result from drought- and heat-related extremes, key factors that can result in agricultural production losses, human health stresses, or damage to infrastructure.

In the manifestation of risk, the level of societal vulnerability is unequal, with a disproportionate impact on the poor and marginalized where the cost of the resulting food insecurity is measured in terms of lives, livelihoods, and impoverishment. Systemic risk characteristics further influence cascading events such as price volatility, food insecurity, and food-related conflict. Related indirect and cascading impacts can affect employment rates, food prices, and international trade, for example. As a result, cascading and systemic risks must be integrated into local, national, and international dialogues on sustainable development, security, and political stability.

Many food systems are currently in a transitional phase in which the former dominant reliance on natural systems is being replaced by anthropogenic inputs and drivers drawn from across the globe (Rist et al. 2014). Moving forward, there is a need to analyze the dynamics and frequency of compound events occurring together in a region, such as droughts, wildfires, and heatwaves (Mallapaty 2022), as well as the likelihood of failures occurring simultaneously in different regions—so-called multibreadbasket failures. Additionally, foresight scenarios and early warnings will be increasingly important as changes in climate and socioeconomic systems may result in surprises and rapid transitions (Pulwarty and Sivakumar 2014). As risks evolve, the AMS is well poised to inform impact assessments of climate model limitations, contribute to approaches to quantify and manage the risk of multibreadbasket failures, and enhance early warning systems that are multisectoral, interdisciplinary, and informed by local communities and that are essential in data gathering and surveillance.

Enabling humanitarian action and supporting sustainable development. The impacts of extreme weather and climate change on the food system interact with geopolitical and socioeconomic challenges, potentially leading to humanitarian crises that require urgent global action to save lives and reduce human suffering. According to the UN World Food Programme (WFP 2022), 828 million people across the world are hungry, of whom an estimated

FbF for droughts

Across Africa, forecast-based financing (FbF) has been used in practice to anticipate potentially catastrophic drought and support resilience in the food system. Tailored climate forecasts and vulnerability analyses triggered anticipatory actions, such as creating soil and water conservation structures, introducing drought-resistant seeds and training smallholder farmers on climate-smart agricultural practices. As a slow-onset event, droughts manifest over time, which is both a challenge and opportunity for FbF. On one hand, it is challenging to produce accurate long-range forecasts that enable early action months before a potential drought. However, the slow-onset nature of most droughts also provides a longer time frame for action and a stronger focus on resilience and adaptation versus saving lives and reducing losses, which are the primary objectives in rapid-onset events. Source: World Food Programme (WFP 2019).

49 million are on the brink of famine due to ongoing conflict, economic consequences of the COVID-19 pandemic, and weather and climate shocks.

Effective early warning enables early action and weather and climate information play crucial roles in supporting anticipatory humanitarian action that saves lives and livelihoods, reduces losses and damages, and enhances food security. For example, forecast-based financing is a form of humanitarian action that uses weather and climate forecasts and detailed risk analyses to release financial resources ahead of a disaster in order to enable early action (IFRC 2019). This approach, summarized in the FbF for droughts sidebar, has successfully been used in various contexts across the world to not only save lives and livelihoods, but also reduce losses and damages and support the resilience of local communities.

The SDGs, an initiative spearheaded by the UN, includes 17 interconnected goals intended to achieve global sustainable development by 2030. One of these goals, SDG 2—Zero Hunger, is centered around food security and strives to eliminate hunger and malnutrition. Food security is deeply intertwined with many other SDGs, such as SDG 1—No Poverty, SDG 3—Good Health and Well-Being, SDG 11—Sustainable Cities and Communities, and more indirectly, SDG 4—Quality Education. Without improvements in food security, many SDGs will not be achieved.

The impacts of weather and climate on the food system not only jeopardize food security, but also threaten to reverse sustainable development gains. These impacts are most prominent in vulnerable communities, which are disproportionately affected and often rely on rainfed agriculture for food and livelihoods. Additionally, these populations lack the resources to respond, recover, and adapt in a rapidly changing climate—sinking them further into poverty and food insecurity. However, weather, climate and water-related science and services can play a crucial role in achieving the SDGs by 2030 (WMO 2023).

The AMS community, in particular, can strengthen humanitarian response and sustainable development through fostering and showing the cobenefits of improved early warning of extreme events that have the potential to impact food security. In the context of sustainable development, a robust understanding of climate risk and uncertainty, integrated with local, traditional, and Indigenous knowledge, is key to successful food security interventions. Greater engagement between the AMS and sustainable development communities will promote food security interventions that are grounded in science and sustainable not only today, but also in the future under changing climatic conditions.

Supporting global frameworks for risk reduction and sustainability. Food security is a common theme across many global frameworks aimed at achieving a sustainable world for all. While we identify its cross-SDG nature above, food security is also crucial to the Paris Agreement, the Sendai Framework for Disaster Risk Reduction, and the Convention on Biological Diversity.

The United Nations Framework Convention on Climate Change (UNFCCC) is responsible for overseeing the implementation of the Paris Agreement, which explicitly mentions the "priority of safeguarding food security and ending hunger" (UNFCCC 2015). Limiting global temperature rise in line with the goals of the Paris Agreement will require urgent and ambitious action to mitigate emissions, including across the food system. Additionally, as the impacts of climate change continue to affect global food security, adaptation across the food system will be crucial to reduce vulnerabilities and increase resilience.

The Sendai Framework aims to reduce disaster risk and losses in lives, livelihoods, and health by taking a holistic approach to early warning and disaster management. The framework considers natural hazards, including hydrometeorological and geological hazards, for example, as well as human-made hazards, such as environmental degradation and technological hazards (UNDRR 2015). The framework also includes consideration of the accumulated risks of recurring small-scale and slow-evolving disasters, only more recently including drought, which constitute a high percentage of all losses and lock vulnerable communities into poverty, including through the slow erosion of food security (UNDRR 2015; FAO 2017; UNDRR 2021).

The Convention on Biological Diversity (CBD) seeks to support sustainable development in ways that protects global biodiversity, which is crucial to food security because biodiverse ecosystems provide food for humans, animals, and all life forms (Muluneh 2021). The UN Convention to Combat Desertification, under the CBD, has identified global agricultural production systems as a primary cause of land and soil degradation, biodiversity loss, and climate change (Benton et al. 2021; CBD 2022).

Moving forward, there is an opportunity to continue improving collaboration between the AMS community and policymakers to provide this best available science and ensure it is being used effectively to support the implementation of these global frameworks that will contribute to global food security and to sustainability.

Food security: Opportunities for research and action in the AMS community

The global food system is deeply intertwined with weather and climate phenomena in diverse and complex ways, demanding action across scales to effectively monitor, forecast, and communicate data and information, in partnership with farmers, decision-makers, and other stakeholders. As human-induced emissions continue to rise, climate change will lead to potentially unprecedented impacts on the global food system, jeopardizing food security and disproportionately affecting vulnerable communities.

Many scientific challenges remain. Actionable early warnings depend on reliable forecasts, yet predictability of precipitation, in particular, is low and there is a crucial need for further model development and research. Additionally, the most food insecure regions of the world are also often the most data sparse, which presents a significant challenge in monitoring, forecasting, and food system vulnerability mapping to inform decision-making. Improving observational networks, reanalyses, and remotely sensed data can enhance forecasting and foresight capabilities in these vulnerable regions (Zurek et al. 2022).

However, improving weather and climate science will not be enough. It will be necessary to take a systems-thinking approach that recognizes the risks to global food security are not independent, but are instead indivisible from socioeconomic and geopolitical challenges, often leading to cascading crises. Integration of the physical, economic, and behavioral sciences is crucial because no one discipline can address global food security alone; indeed, better linking meteorologists, climatologists, and agronomists with sustainable development practitioners, policymakers, and other users is essential to improve communication and knowledge exchanges.

The AMS has great potential to contribute its expertise and the expertise of its members to advancing global food security. This framing was first introduced formally through the 102nd AMS Annual Meeting theme of "Environmental Security: Weather, Water, and Climate for a more Secure World" and the establishment of a regular Environmental Security Symposium. However, this is only the start. The issue of food security must be elevated across the AMS in ways that meet the scale and urgency of the global challenge.

To do this, the AMS could promote sustained coordination across its committees, boards, and external partners to bring together interdisciplinary experts from the AMS and from other professional societies, users at multiple levels, industry, and decision-makers to facilitate new ideas, develop solutions, and identify where critical gaps remain and craft pathways and partnerships toward achieving global food security. Building on its history of innovation, the AMS can play an important role as a forum for advancing effective knowledge transfer to support food security and creating a professional culture that integrates food security users and decision-makers. Additionally, AMS members are encouraged to engage in the opportunities identified in this paper and pursue other opportunities that promote integration between the physical and social sciences and to further engagement. In particular, students and early career professionals are encouraged to pursue interdisciplinary education and careers that address food security. Silos between academic disciplines must be broken down to foster an interdisciplinary learning environment that will equip students with the tools, resources, and mentorship needed to address global challenges such as food security.

Achieving global food security will only become more challenging as emissions continue to rise and the impacts of climate change escalate. We have demonstrated ample opportunities for the AMS community to take an active role in addressing this challenge and, ultimately, improving the lives and livelihoods of the world's most vulnerable communities. In an increasingly complex world, global food security will not be achieved overnight: it will take a new generation and cadre of scientists, practitioners, program directors, policymakers, and decision-makers who are educated and trained across disciplines to shatter the silos that are preventing progress in addressing this complex challenge.

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