Priority innovations and investment recommendations for COP28[1]

Innovation Commission Secretariat

The Innovation Commission for Climate Change, Food Security and Agriculture has prepared notes on innovations that mitigate the climate impact of agriculture and promote climate adaptation in low- and middle-income countries. The seven innovation notes linked below were produced at the request of the COP28 Presidency. For adaptation, the Commission focused on innovations that would serve those most vulnerable to climate change: smallholder farmers and landless laborers in low- and middle-income countries. For mitigation innovations, it focused on those that would deliver substantial co-benefits to low- and middle-income countries.

To identify these innovations, the Commission reviewed the literature, consulted a range of experts, and solicited inputs on innovation areas from researchers and practitioners from the government, the private sector, international organizations, and civil society. The Commission will continue to explore other promising innovation areas with guidance from an advisory group.

These innovations are categorized as ready to transition to scale or earlier-stage. The Commission adopted strict criteria for classifying innovations as ready to transition to scale, focusing on innovations with rigorous evidence of impact and value for money, not only for the innovation itself but also for policies to increase its adoption. The Commission also made judgments about whether there was a plausible pathway to scale. The second category is earlier-stage innovations, which have the potential to generate high returns and even be transformative.

[1] This is a draft document that will be updated periodically until the publication of the Innovation Commission final report

Improved Weather and Seasonal Forecasts

1. Context

Farmers in low- and middle-income countries are increasingly vulnerable to weather uncertainty due to climate change. Weather uncertainty increases farmers' production risks. Climate change will exacerbate this uncertainty, with variation in daily precipitation increasing by 4-5 percent and temperature variability increasing by 10-15 percent per degree Celsius of warming (1, 2). Climate change is also making the timing of seasons more variable. This has major implications for regions dependent on a single rainy season for most of their annual rainfall, such as India and others affected by the South Asian Monsoon.

Farmers need short, medium, and long-range forecasts to optimize their agricultural decisions. Short-range forecasts (0-3 days ahead) are the most widely available and enable farmers to make day-to-day decisions like the timing of irrigation or the application of water-soluble fertilizer. Medium-range forecasts (4-10 days ahead) and long-range forecasts (ten days to one year) are less readily available and are relevant to strategic decisions such as crop and seed choice, area planted, and planting and harvesting date. This need for improved forecasting goes beyond just the timing of rainfall: low- and middle-income countries are also extremely vulnerable to inland and coastal flooding, heat waves, and extreme weather events caused by climate change.

The forecasts to which most farmers currently have access are insufficient. Forecasts produced in many low- and middle-income countries, typically by national meteorological departments, are often inaccurate, at the wrong time scale, or cover too broad of a geographic region, to inform farmers' management decisions (1, 2, 3, 4). This is partly due to limited weather observation data–which is an input to forecasts and enables assessments of accuracy–and limited coordination and data sharing across countries. Even with current weather observation data, better forecasts can be produced.

Most farmers in low- and middle-income countries currently lack access to reliable, high-quality, local forecasts. An estimated 260-305 million farms in South Asia, sub-Saharan Africa, and Southeast Asia stand to benefit the most from improved forecasting.

2. Improved Forecasts

New technology allows more accurate and timely forecasts, with large benefits for farmers in the context of increased weather variability. For example, new forecasts allow the timing of monsoon onset to be predicted over a month in advance. New technology also allows more accurate predictions weeks or even months in advance for broad characteristics of the weather due to better observation and research on regional or global phenomena driving local weather, like the El Nino-Southern Oscillation, and more accurate day-ahead forecasts in tropical regions.

Several public research institutes and for-profit firms now offer forecasts of improved breadth and quality. For example, the Potsdam Institute for Climate Impact Research now produces improved monsoon and rainy season onset forecasts for areas either not covered by any existing forecasts or only by coarse national forecasts, and with a substantial increase in lead time of up to six weeks. The Climate Forecast Applications Network produces a variety of forecasts, at several different time ranges (1-15 days, 16-40 days, and 2-7 months), offering several different weather parameters (rainfall, temperature, wind, and prediction of extreme events like cyclones), and with a resolution of either 18km or 36km. The Climate Hazards Center at the University of California, Santa Barbara (UCSB) provides daily 5-day, 10-day, and 15-day precipitation forecasts at a resolution of 5km across the globe.

However, these improved forecasts are not readily available to smallholder farmers. Global forecasting centers and many national meteorological departments are not tasked or financed to ensure their forecasts reach users in low- and middle-income countries. Forecasts are a public good that can be shared easily between end users. Hence, the private sector has a limited profit incentive to innovate to sell forecasts directly to the millions of farmers who need them.

Current forecasts often have limited accuracy due to limited observation stations. The Systematic Observations Financing Facility (SOFF) was launched in 2021 to help the countries with the biggest shortfall in weather operations expand their networks of weather stations. Investing in weather stations through the SOFF initiative could improve forecasts by allowing better assessments of accuracy as well as increasing the amount of historical weather data available for improved forecasts in the future. During SOFF's initial three-year phase, financing is needed to install and upgrade the highest priority 200-400 weather stations across 28 countries.

Longer-term investments could help improve forecast accuracy and strengthen systems for sharing data and delivering forecasts. Areas of opportunity for improved forecasting include better observation and research on regional or global phenomena (e.g., the El Niño-Southern Oscillation) driving local weather, which could lead to more accurate predictions weeks or even months in advance.

Public investment is warranted to improve the availability of high-quality forecasts in low- and middle-income countries. Forecasts are a public good in two senses. First, improvements in forecasting in one geography can help to improve forecasts in other geographies. As a result, governments have underinvested in collecting and sharing weather data and producing accurate forecasts because they do not capture the full benefit of these investments. Second, one user can share forecasts with another at zero cost while still retaining the full benefit of the information. As a result, each farmer is unwilling to pay the full value of the information, so the private sector lacks the profit incentive to deliver forecasts directly to farmers. Procuring and delivering improved forecasts at scale would enable sustained net social benefits to farmers that greatly exceed the costs, providing a strong justification for public support.

3. Impact and cost-effectiveness

Multiple studies find that farmers adjust their behavior and investment decisions in response to accurate weather forecasts. In Ghana, farmers in communities that received forecasts via SMS altered their planting and investment behavior, including farmers who received forecasts directly and those who did not. This suggests information about the forecasts spread among farmers in the same communities. In India, farmers who were randomly assigned to receive digitally-distributed weather forecasts substantially altered their planting and investment decisions to better align with the forecasted seasonal timing: farmers who had expected a shorter season than what was forecast increased their land under cultivation, added new crops and invested 34 percent more in all pre-harvest expenditures (Burlig et al. preliminary results).

Procuring and disseminating improved forecasts would have large benefits for farmers. For forecasts of the monsoon seasonal rainfall totals in India, the benefits of improving all state-level forecasts to at least the average level of accuracy would exceed USD 3 billion[2] for farmers over five years (estimation based on Rosenzweig and Udry 2019). Similar benefits are found for short-range forecasts. In Benin, when farmers received forecasts over SMS, a randomized evaluation estimated benefits of USD 104-356 per farmer per year (estimation based on Yegbemey et al 2023). A randomized trial of disseminating weather forecasts and price information by SMS in Colombia found labor savings of USD 103-280 per farmer per

[2] All values adjusted for inflation and standardized to 2023 USD.

year–although this result is imprecisely estimated (estimation based on Camacho and Conover 2019). These studies include a wide range of different types of forecasts, agricultural decisions, geographies, crops, delivery channels, and methodologies, so significant heterogeneity is to be expected. However, all these studies show positive impacts and present a realistic range of the potential benefits of forecasts in various settings. Forecasts also have large impacts on increasing resilience to disasters and improving health (1, 2, 3, 4).

The benefits of procuring and delivering improved weather forecasts outweigh the costs by orders of magnitude. Improving monsoon onset forecasts in India has estimated benefits of USD 3 billion (estimation based on Rosenzweig and Udry 2019). The cost of procuring these weather forecasts could be as little as USD 5.6 million over five years, based on conversations with forecast providers. Activities to deliver forecasts more widely would have additional costs, but also additional benefits.

4. Potential for further improvements

Improvements in weather observation will have a greater impact if coupled with country agreements to share data generated from weather stations. As many weather systems are larger in scale than individual countries, data from one country benefits forecast accuracy in others, while limited coordination and data sharing hinder forecast system improvement. Building on the successful model of the World Meteorological Organization (WMO), investments that release data and forecasts into the public domain are likely to have spillover benefits for other forecasts, in addition to their direct benefits.

An online data-sharing platform could facilitate greater coordination and improve forecasts. The WMO's global Climate Services Information System (CSIS) is one example. Such a platform could act as a public portal for users, including forecast providers, researchers, and "boundary organizations" that bridge between forecast providers and end users. This platform could host past, present, and future weather data to allow users to produce, deliver, and validate improved forecasts.

A standardized system for evaluating forecast accuracy would improve transparency and incentives for producers and facilitate procuring better forecasts. Additional research to identify where and under which conditions existing forecasts are already performing well would build on the existing work of the International Research Institute for Climate and Society (IRI) and the European Centre for Medium-Range Weather Forecasts (ECMWF)]. The results would identify "forecasts of opportunity" where existing forecasts can be used immediately, as well as establish the standards for external validation of forecasts. This system could be housed within the WMO or another similar organization. The results of this validation and research should be made publicly available so that they can be used by governments and other stakeholders when deciding which forecasts to procure and deliver in their geographies.

5. **Potential for scale**

Two-hundred-six million smallholder farming families who would benefit most from improved forecasts live in six countries affected by the South Asian Monsoon (estimation based on Leow et al., 2023)--Bangladesh, India, Indonesia, Pakistan, Thailand, and Vietnam--and six countries affected by the East and West Africa Monsoons--the Democratic Republic of the Congo, Ethiopia, Kenya, Nigeria, Tanzania, and Uganda. Procuring improved forecasts of monsoon onset timing from the Potsdam Institute for Climate Impact Research for these 12 countries would cost USD 23 million over five years, based on consultations with several improved forecast providers. Forecasts of other weather features, like rainfall amounts or temperature, at different timescales, (from days to weeks ahead of an event), could be produced by other forecast providers at similar costs. These forecasts could be prioritized based on the identified needs of farmers and the corresponding forecast aspects that would maximize benefits. In some cases, such as for monsoon onset, scaling access to improved forecasts could be done at a very low cost. Because monsoon onset forecasts are a topic of wide public discussion, relatively light-touch dissemination approaches could allow high-quality forecast information to spread widely. In other cases, weather forecasts could be delivered at relatively low cost using digital platforms via SMS and other channels.

Farmers demand high-quality forecasts. In India, 86.5 percent of farmers who were offered an improved forecast of rain onset accepted the offer and valued forecast access at USD 1.22 on average, far more than the cost of delivering it at scale (Burlig et al. preliminary results). This valuation is likely to be an underestimate of the forecast's true value since farmers can share forecasts for free with other farmers.

With the right technical assistance, national governments can facilitate the delivery of forecasts to the hundreds of millions of people who need them. Many governments already facilitate the delivery of forecasts through various channels such as newspapers, radio, television, websites, and in-person agricultural extension. While these channels do not reach all farmers, there are potentially large benefits to delivering better forecasts through these channels. Technical assistance could focus on helping governments select the best forecasts for their settings, adapt and customize forecasts to users' needs, communicate probabilistic forecasts in a way that is easy to understand and interpret, supplement forecasts with actionable agricultural advice, optimize messages for frequency, timing, length, and complexity, and rigorously test and evaluate service delivery to inform how to scale most effectively. For example, technical assistance helped improve a governmental phone-based agricultural extension system in East Africa that has provided agricultural advice to more than 6 million farmers via interactive voice response (IVR). Changes recommended for the design of this system had substantial effects on the amount of information accessed by farmers.

6. Potential path forward

This section first discusses estimated investment costs for procuring improved forecasts for monsoon onset timing in India and procuring monsoon onset and long rains forecasts for a set of twelve countries, including India. Then, the section discusses the dissemination of improved forecasts, including opportunities with the Indian Ministry of Agriculture and Farmers' Welfare. Finally, the section discusses a set of investments to improve global forecast systems.

Donors could support procuring forecasts to benefit 100 million farmers in low- and middle-income countries in Africa and Asia. Research institutes and for-profit firms already produce shovel-ready forecasts for some states in India for parameters such as the timing and quantity of seasonal monsoon rainfall. These could be replicated for the entire South Asia region and beyond at a relatively low cost.

RFPs for the provision of these forecasts should specify that both the forecasts and information on how the forecasts were constructed would have to be put in the public domain. This would be important to help ensure that forecasts could be improved globally over time and that costs remain low.

Procuring improved forecasts for monsoon onset for all of India would cost approximately USD 5.6 million over five years. Cost estimates are based on consultations with several improved forecast providers. More extensive due diligence with a wider range of forecast providers is needed to refine this cost estimate.

Procuring higher-quality forecasts for twelve countries (South Asian Monsoon onset forecasts in Bangladesh, India, Indonesia, Pakistan, Thailand, and Vietnam, as well as long-rains onset in the Democratic Republic of the Congo, Ethiopia, Kenya, Nigeria, Tanzania, and Uganda) would cost about USD 23 million over 5 years. Cost estimates are based on consultations with several improved forecast providers. More extensive due diligence with a wider range of forecast providers would be needed to refine this cost estimate.

Existing delivery channels could be used initially for disseminating improved forecasts, with expansion into improved digital tools over time. Forecasts could be delivered at scale through mass media channels such as newspaper, radio, and TV as well as through digital channels such as voice messages, SMS, and WhatsApp. Digital delivery may not be necessary for all geographies and forecast types. However, it could provide additional value by allowing customization to individual farmers' needs and providing forecasts at greater geographic resolution and frequency, especially for forecasts that vary across small geographic distances and with shorter time horizons. See [companion case on digital agriculture] for more on the potential of digital channels to deliver weather and other information to farmers at scale.

Several complementary investments could help improve global forecast systems to facilitate the production and procurement of better forecasts in low- and middle-income countries. These investments could be implemented over the next five years but are expected to deliver impact in 5-10 years. Budget estimates are preliminary and based on published budgets from SOFF, figures from Rethink Priorities, and consultations with other implementing organizations.

An investment of USD 14 million could support installing and upgrading 200-400 weather stations through the SOFF initiative to increase the volume and quality of weather data. The SOFF Terms of Reference have identified an initial three-year phase, during which results-based financing is needed for the highest priority 200-400 weather stations to be installed and upgraded across 28 countries.

An investment of USD 7-10 million could help strengthen the global Climate Services Information System (CSIS) or another similar platform to facilitate data sharing and coordination among stakeholders. This would support a team to manage this platform, standardize data shared through this platform, make it widely accessible, and enforce WMO regulations for data sharing.

To address the limited transparency of forecast accuracy, donors could support research to benchmark forecasts and a standardized system to validate forecast quality. An investment of USD 3 million could support research to determine where and when existing forecasts are accurate in twelve low- and middle-income countries and a total of nine forecasts. Using that research, an additional investment of USD 9 million could establish a standardized, objective system for external validation of forecast accuracy (USD 9 million).

Digital Agriculture

Digitally delivered services, including weather forecasts, advice on agricultural practices, and information about new crops and technologies, could have very significant benefits for farmers in the context of climate change. These services have very low marginal costs, making them highly cost-effective. Governments are already providing digital services to farmers, but there is scope to improve and expand digital agriculture.

1. Context

Changes in temperature, precipitation, pests, and agricultural markets due to climate change can reduce the effectiveness of traditional agricultural practices. This increases farmers' need for new sources of information, for example on weather, pests, new crops, and improved farming practices. Timely and accurate information can help farmers to adopt new practices, and mitigate losses from external shocks.

Most smallholder farmers lack access to science-based agricultural information. In part due to the cost of in-person extension, farmers often outnumber extension workers by more than 1000 to 1. Many extension programs have inadequate management and limited accountability of extension workers. According to a 2017 survey conducted in India, only 6 percent of farmers reported receiving advice from an extension agent within the past year, and 70 percent of farmers expressed distrust in the recommendations provided by extension workers.

2. Digital Agriculture

Digital agriculture can inexpensively provide timely, science-based, and potentially customized information to farmers on topics such as weather forecasts, pest outbreaks and control, new seeds or other agricultural technologies, and soil chemistry. Beyond directly providing advice to farmers, digital communications could help improve the effectiveness of in-person agricultural extension workers, link farmers to others facing similar challenges, and improve the efficiency of agricultural markets by linking farmers, input markets, cooperatives, contract farming organizations, and traders.

Growing smartphone ownership can increase the effectiveness of digital agriculture. Smartphone ownership is already high in many low- and middle-income countries and is forecast to grow rapidly over the next few years. In India, around three-quarters of rural households with children aged 3-16 own a smartphone. The widespread adoption of smartphones can be leveraged to enhance digital extension, including showing video demonstrations of agricultural techniques and providing more complex services to farmers, for example, by allowing farmers to take photographs of pests and receive personalized advice on them.

Multiple organizations have experience implementing large-scale digital agriculture advisory services. Government programs that have implemented digital agricultural extension include 8028 from the Agricultural Transformation Agency in Ethiopia, mKisan in India, Agronet in Colombia, MoA-Info in Kenya, the Extension 2.0 program in Punjab, Pakistan, and the e-Extension Program for Agriculture and Fisheries in the Philippines. Telecommunication company-supported programs include Connected Farmer from Safaricom in Kenya, Connected Agriculture Program for Punjab from Telenor, Pakistan Krishi Sheba from GrameenPhone, Tigo Kilim by Tigo in Tanzania, and Farmer's Club by Vodafone in Ghana. Non-profit organizations include iCow in Kenya, Esoko in Ghana, Acceso in Colombia, the Ethiopian Soil Information System, and Digital Green and Precision Development[3], which have implemented programs in East Africa and South Asia.

Several governments have worked with technical partners to develop new digital advisory systems or improve existing ones. For example, Ethiopia worked with technical partners and discovered that streamlining the registration process for their phone-based service increased the time farmers spent listening to the agricultural content by 18 percent. The Government of Punjab, Pakistan, collaborated with NGO Precision Development to enhance farmers' understanding and adoption of soil health card recommendations. They consulted farmers and leveraged human-centered design principles to redesign soil health cards and supplement them with explanatory phone calls. Technical assistance can also help governments deploy and scale digital agriculture services. In Odisha, India, an NGO worked with the government to design a digital extension service that the government later took over and expanded with public funds. The program now reaches over 6 million farmers.

3. Impact and Cost-effectiveness

Farmers adjust their behavior and investment decisions in response to accurate digitally distributed weather and seasonal forecasts. In Telangana, India, farmers who received

[3] Michael Kremer discloses that he is a non-compensated board member of Precision Development, a nonprofit organization.

forecasts of monsoon onset via SMS updated their planting and investment decisions: farmers who had expected a shorter monsoon season than what the forecast predicted cultivated more land, added new crops, and invested 34 percent more in pre-harvest expenditures (estimation based on Burlig et al. preliminary results), while farmers who expected longer monsoon seasons than predicted adjusted toward the forecast in the opposite direction. In Ghana, farmers in communities that received weather forecasts via SMS optimized the timing of their planting and chemical application to align with forecast weather. This included both the farmers who receive forecasts directly and others in the same community, indicating that farmers who received digital forecasts shared them with others. In Pakistan, farmers who received 2-day weather forecasts via pre-recorded voice calls accurately recalled forecast information and changed their farming activities to be on days with more conducive weather.

The benefits of delivering accurate forecasts to farmers are estimated to be orders of magnitude larger than the costs. In Benin, a randomized evaluation found that SMS messages with day-ahead forecasts generated gross benefits of USD 104-356 per farmer per year in the form of increased yields and decreased labor costs (estimation based on Yegbemey et al. 2023). A randomized trial of disseminating weather forecasts and price information by SMS in Colombia found farmers saved USD 104-281 on labor costs per year, although this result is imprecisely estimated (estimation based on Camacho and Conover 2019). The cost of procuring weather forecasts varies, but at a sufficient scale could be well under $0.10 per farmer over five years.[4] The cost of designing and delivering messages could also be low. This suggests that benefits are hundreds or thousands of times larger than costs. Providing weather information with sufficient lead time for farmers to adjust their practices can reduce farmers' risks. Besides directly reducing farmer vulnerability, reducing risk for farmers also spurs investment.

Climate change influences pest and plant disease conditions, and digital agriculture advisory can provide farmers with information on new pests and diseases and improve practices around pest and disease management. Kenya's MoA-INFO system provided farmers with information on Fall Armyworm. In Gujarat, India, an automated voice message service increased the adoption of recommended practices for seeds and more effective pesticides by six percentage points among cotton farmers. In Ecuador, sending text messages summarizing Integrated Pest Management (IPM) practices increased the adoption of these practices by 7.2 percentage points among potato farmers who had attended an IPM training. Pest alerts can help farmers optimize input use. A blight alert system for potato farmers in

[4] Cost estimates are based on consultations with several improved forecast providers.

Bangladesh increased investment in fertilizer by 8 percent, which led to a 7 percent increase in yields.

Farmers respond to soil chemistry information disseminated through digital extension. East African farmers who received SMS messages—from One Acre Fund, Precision Development, and the Government of Kenya— were, on average, 22 percent more likely to adopt agricultural lime for acidic soils, albeit from a very low base, and were also more likely to use appropriate quantities of fertilizer. The program's estimated benefits exceeded marginal costs by 9 to 1.

Digital agriculture may also have the potential to address nitrogen fertilizer overuse. Nitrogen fertilizer overuse is common in some parts of the world, contributing to greenhouse gas emissions, reducing farmers' profits, imposing fiscal costs on governments subsidizing fertilizer, and damaging the local environment (1, 2). Governments in India and Pakistan dedicate significant resources to soil chemistry tests and disseminating findings to farmers via soil health cards. However, these cards are often difficult for farmers to understand. Digital agriculture can improve comprehension of soil health cards. In Gujarat, India, complementing soil health cards with audio messages and notes increased comprehension[5] by 37 percentage points from a base of six percent, which was equivalent to the impact of having an in-person discussion with an agronomist but much less costly.

It will be important to ensure that soil health information disseminated to farmers is accurate, and a current limitation of soil health cards is that soil chemistry information in soil health cards is often not well correlated with nutrient levels observed in third-party testing. Key steps for improving soil testing include incorporating better sampling and sample collection procedures, conducting third-party audits of a sample of soil chemistry tests, and using information based on spectroscopy.

4. Potential for Further Improvement

The user base and infrastructure of digital extension can be leveraged to provide other agricultural services digitally. Digital agriculture systems initially designed for extension could be used to deploy services that facilitate connections among farmers and extension workers or provide farmers with information on input suppliers or link farmers with each other or with cooperatives or contract farming operations.

[5] Note, however, that a different research design in another part of India did not find that automated voice calls and text messages improved comprehension of soil health cards.

Human-centered design could help ensure that content is relevant and actionable. For example, human-centered design principles were used to redesign soil health cards in Gujarat, India, and develop complementary multimedia materials to better convey information to farmers. Similarly, in Ethiopia, identifying the obstacles farmers faced when using the hotline and conducting A/B tests to refine the service led to increased user engagement for an agriculture hotline.

Machine learning tools and advances in artificial intelligence, such as large language models, could help adapt extension services. For example, an experiment in India found that personalizing the timing of digital extension based on farmers' characteristics and past engagement led to a 2.6 percentage point increase in farmers' pick-up rate (an 8 percent increase over the baseline rate of 31 percent). With sufficient information on farmers, digital advisory services could be adapted for various crop choices, soil conditions, and educational background, and deliver specific weather forecast information based on farmers' geographical location. Substantial data will be needed to achieve this. This could potentially be collected through phone surveys, extension workers, or crowdsourcing directly from farmers, but cost-effective methods would have to be developed. Satellite data could also be used to provide location-specific information. Large language models could also enable farmers to engage with digital agriculture services in a more natural chat interface.

In-person interventions based on behavioral science have shown tremendous impacts. These could potentially be adapted and delivered digitally, allowing them to reach many more people. For example, digital agriculture platforms could substantially enhance post-harvest financial management, reducing the severity of lean seasons. Lean or hungry seasons, when food security consumption dramatically drops in the period before harvest, are a common phenomenon faced by many smallholder farmers in low-income countries. In Zambia, providing maize farmers with a simple infographic tool to remind them of future expenses that occur in the lean season increased savings by 15 percent. Farmers used the increased savings to self-finance additional farm inputs— labor and fertilizers—that subsequently increased their crop revenues by 9 percent. It may be useful to explore how digital platforms could provide similar tools to help farmers plan their future expenses.

Promising tools that have demonstrated effectiveness in assisting farmers with long-term planning and investment decisions could be adapted for digital platforms. In rural Kenya, an interactive intervention designed to raise aspirations and encourage long-term planning—through videos about successful local households and goal-setting activities—increased labor supply by 5 percent and investment in inputs by 22 percent. Similar effects among households in rural Ethiopia persisted five years after a screening of documentaries about real successful stories of local role models who moved out of poverty. In Bolivia, dairy producers who participated in a similar aspirational hope training increased the use of quality-enhancing practices three months later. These tools could be adapted for digital delivery.

Digital tools can help in-person extension services reach more farmers and communicate with them more efficiently. Many extension workers already have smartphones, which they can use to share decision-support tools with farmers, show informational videos to farmers, look up information farmers need, and invite farmers to upcoming extension activities (1, 2, 3, 4). Developing a set of digital materials for extension workers could increase their effectiveness.

Mobile phones can be used to improve extension worker performance. When the Paraguayan government provided GPS-enabled cell phones to agricultural extension agents (thus allowing supervisors to monitor extension agents better), extension agent performance and farmer satisfaction improved. A rating platform for artificial insemination services provided by veterinarians in Pakistan increased provider effort and resulted in 25 percent higher insemination success for farmers without any change in prices paid. Evidence from the health sector suggests substantial gains from providing front-line workers with digital tools. For example, CommCare, an open-source mobile and web cloud product developed by Dimagi, provides near-real-time information about health worker performance. Equipping front-line health workers with CommCare improved prenatal care outcomes and reduced infant mortality, with an estimated social benefit-cost ratio exceeding 24:1.

Digital services can also improve efficiency markets, reducing price volatility. A digital platform in Uganda linking traders with each other reduced volatility in agricultural markets by facilitating spatial arbitrage within the country. This can improve food security by helping insulate consumers against local shocks.

Digital services can also improve supply chains in contract farming. In Kenya, a hotline allowing sugar cane farmers to communicate with the company management reduced late fertilizer delivery by 23 percent and non-delivery by 54 percent.

5. Potential for Scale

Digital agriculture provided by governments offers tremendous potential for scale. The public sector has historically supported in-person agriculture extension; digital extension offers an opportunity for governments to expand their reach at a low cost. Digital agriculture programs led by governments have already reached large numbers of farmers in multiple countries, including Bangladesh, Ethiopia, Ghana, India, Kenya, Pakistan, and the Philippines (1, 2, 3, 4, 5, 6, 7).

Subscription services, where farmers pay a fee to access digital extension services, reach only a small fraction of the potential market, creating a rationale for free provision by governments. There may be a significant gap between the information's value and farmers' willingness to pay for it. Information is a public good because it is nonrival and nonexcludable. Farmers who don't subscribe to digital extension services can still access the information by speaking to subscribers, and purchasers can share the information with other farmers while retaining the information's full benefit. In addition, farmers may be unable to evaluate the quality of the information. This gap undermines incentives for the private sector to provide digital extension. These factors create a rationale for free public provision.

Governments can digitally disseminate agricultural information at a low cost. Cell phone towers in rural areas are often underutilized, so the true marginal social cost of sending additional messages is close to zero. As telecom regulators, governments could mandate that telecommunications companies offer public service announcement messages, particularly those related to national emergencies, such as weather disasters or pest outbreaks, at reduced rates or free of charge.

6. Potential Path Forward

Digitally disseminating weather forecasts in India offers the opportunity to quickly reach large numbers of farmers and lay the foundation for further work in India and other countries. India has experience rolling out digital extension services and a track record of maintaining these services. Odisha state worked with NGO Precision Development to build Ama Krushi, a digital extension program, which has now transitioned to state government operation. The government's mKisan platform, which was used to offer agro-meteorological data to farmers, has the potential to be expanded significantly using its database of over 100 million farmers. Digital weather forecast provision could also be an entry point to providing a wider set of digital agriculture services.

Providing technical assistance to deploy digital agriculture services in six countries over five years is estimated to cost USD 13-20 million[6,7]. Technical assistance would include the following activities: i) identifying which forecasts to disseminate , ii) identifying additional digital agriculture services that could be provided alongside, iii) interviewing farmers and conducting focus group discussions to identify the most effective approach for conveying weather and agronomic information, and iv) supporting the government with dissemination, which would include identifying opportunities to refine the program, conduct A/B testing, and improve monitoring. These budgets cover the approximate cost of technical assistance needed to design, deploy, and refine these services in each country for five years. These estimates do not include dissemination costs, such as telecommunications fees[8]. Costs could be covered by donors, and potentially national governments, especially in the case of some middle-income countries. Across Bangladesh, India, Ethiopia, Kenya, Nigeria, Pakistan, Tanzania, Vietnam, and Uganda, 383 million farmers could potentially benefit from digital agricultural services.[9] The next steps would be to understand where governments are interested in pursuing digital agriculture, where systems are in place to obtain lists of farmers' phone numbers, and where it otherwise makes sense to move forward.

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6 These estimates are based on budget projections from Precision Development.

7 This budget does not include the costs of procuring regional weather forecasts from global providers.. Weather forecasts are global public goods, and the Commission recommends that donors procure them and make them available to governments.

8 The estimated telecommunication costs associated with sending 15 SMS messages per farmer per year for five years are USD 11.3M for India, USD 406M for Vietnam, USD 179.2M for Ethiopia, USD 117M for Pakistan, USD 84.2M for Bangladesh, USD 70.5M for Nigeria, USD 94.4M for Tanzania, USD 68.7M for Kenya, and USD 51.4M for Uganda.

9 Cost estimates assume reaching 50 percent of farmers in each country.

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interested in pursuing digital agriculture, where systems are in place to obtain lists of farmers' phone numbers, and where it otherwise makes sense to move forward.

In countries that depend on a rainy reason for most of their annual rainfall, digital agriculture services could begin with the dissemination of high-quality seasonal forecasts. Farmers in regions affected by the Asian Monsoon, such as Bangladesh, Cambodia, India, Pakistan, and Vietnam, as well as farmers in regions affected by the long rains in East and West Africa, including Ethiopia, Ghana, Kenya, Nigeria, Tanzania, and Uganda could benefit significantly from forecasts of rainy season onset. Digital delivery would be particularly valuable for forecasts that vary across small geographic distances and require frequent real-time messages.

The provision of weather forecasts can be an entry point for digital agriculture; this infrastructure can be leveraged to offer more complex digital agriculture services more broadly over time. Disseminating weather forecasts is a promising entry point for digital agriculture at scale because of the large expected benefits for farmers. The infrastructure to support weather forecast dissemination (or other agricultural advisory services) could then be leveraged to provide more services to farmers, such as those described in Section 4.

USD 10 million could create an open, tiered, evidence-based fund for innovations including digital agriculture. This would fund experimentation and innovation in digital agriculture–such as the potential improvements discussed in Section 4. The fund would be open to proposals from any entity, such as governments, NGOs, private companies, or researchers. The fund would be tiered to discipline spending decisions, with small grants to pilot early-stage ideas, medium-sized grants to test the most promising ideas, and large grants for scaling up only for innovations that have been rigorously tested and shown to be highly cost-effective. Development Innovation Ventures,[13] a social innovation fund at USAID, has a similarly open, tiered, evidence-based structure, and has yielded a high rate of returns.

[13] Michael Kremer discloses that he is the Scientific Director of Development Innovation Ventures.

Climate-Resilient Social Protection

Climate change is expected to drive 35-122 million people into extreme poverty by 2030, not only by adversely affecting food security and agricultural productivity but also through more frequent and intense weather events. Innovations in social protection can support households in moving out of extreme poverty and coping with the risks of extreme weather events: (i) climate-resilient graduation programs persistently move households out of extreme poverty, generating benefits over three times their cost; (ii) weather-responsive cash transfers in advance of predictable disasters, such as floods, can address food security and boost resilience.

1. Climate-resilient graduation programs for households living in extreme poverty

1.1 Context

Climate change increases the vulnerability of people in extreme poverty. Nearly 700 million people live in extreme poverty. Climate change is expected to drive 35-122 million people into extreme poverty by 2030. Most of the poorest households in low- and middle-income countries are smallholder farmers—among the most vulnerable to disruptions caused by climate change, such as extreme weather events.

1.2 Climate-resilient graduation programs

Graduation programs are a multifaceted innovation designed to help poor households move persistently out of extreme poverty. They typically include 1) a one-off grant or interest-free asset transfer (typically livestock) to start small businesses 2) a regular food or cash transfer during the first year of the program 3) enterprise development training (typically in livestock, agriculture, but sometimes in non-farm activities); 4) hands-on coaching through high-frequency visits by program staff; 5) access to a savings account; 6) preventive healthcare services; and 7) community mobilization committees. In contrast to standard social protection programs that provide supplemental income to ensure minimum consumption levels, the graduation approach is designed to equip households with the skills and productive assets to increase earnings and start a virtuous cycle of savings and investment. Households graduate from the program by achieving economic and social advancement measured by predetermined graduation criteria over the 24 months of the program cycle. BRAC developed the approach in Bangladesh, and it has since been implemented in several other countries.

1.3 Impact and cost-effectiveness

Graduation programs have persistent positive impacts on consumption, assets, and earnings. BRAC's graduation program in Bangladesh increased earnings by 21 percent and per-capita consumption by 11 percent four years after the asset transfer. Among villages that had been hit by a sustained drought, the graduation program protected households from incurring a 30 percent reduction in their assets, such as livestock.[14] After eleven years, for households above an initial wealth threshold, the program increased total productive assets by USD 542 and net earnings by USD 72, enough for these households to exit extreme poverty. Furthermore, the program significantly diversified income streams for ultra-poor households, transitioning from paid domestic work and agricultural labor to livestock rearing and land cultivation. Similar positive effects persisted ten years after a similar program implemented by Bandhan in India.

Graduation programs generate persistent benefits over three times their cost, but their cost-effectiveness can vary across settings. BRAC's graduation program in Bangladesh costs approximately 750 USD per household but generates benefits more than three times the cost.[15] Similar graduation programs implemented by other NGOs in Ethiopia, Ghana, Honduras, India, Pakistan, and Peru had benefits greater than their costs—with estimated benefit-to-cost ratios ranging from 1.3 in Ghana to 4.3 in India three years after the transfer—except in Honduras.[16] In Bangladesh and India, consumption gains persisted in measurements conducted seven and ten years after the asset transfer, respectively (1, 2). In Ethiopia, the benefits were approximately equal to the cost of the program, as the consumption gains attenuated seven years after the transfer, unlike in Bangladesh.

While eliminating some components from graduation programs would reduce costs, there is reason to believe this may also reduce program effectiveness. For example, providing only the asset transfer or access to a savings account was not cost-effective in Ghana. The relatively large size of the asset transfer may also be important for program effectiveness. Balboni et al. (2022) have argued that the program may enable beneficiaries to

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[14] Oriana Bandiera, email message to author, October 19, 2023.
[15] Benefits are measured in terms of consumption gains observed at the last round of data collection and assumed to persist for 20 years.
[16] The benefit-to-cost ratio is calculated as the net present value of the benefits over the net present value of the program costs, discounted at a 5 percent annual rate. In Honduras, the program did not have apositive effect due to a disease killing the chickens transferred.

move out of a poverty trap—a situation where households whose wealth is below a threshold would not have the means to make the investments needed to pursue more productive occupations, such as animal husbandry, to move persistently permanently out of poverty.

1.4 Potential for further improvement

Impact evaluations could be conducted for new components added to graduation programs to increase climate resilience amongst ultra-poor households. BRAC designed new components such as coaching for climate-resilient asset development and diversification (through, for example, alternative fodder production and management, infectious disease prevention in livestock, multilayer vegetable production, and alternate wetting and drying for rice production). Additionally, to protect against climate-driven risk, BRAC is adding an insurance component in which participants receive conditional loans or grants in response to climate disasters such as floods. It would be useful to test these additional components to assess their incremental impact.

1.5 Potential for scale

Climate-resilient graduation programs could be further scaled up in Bangladesh, as well as in other contexts with climate challenges where they have been found to be successful. BRAC has already scaled up the graduation program to reach over 2.1 million households in Bangladesh, as well as an additional 1.1 million households in 14 other countries. BRAC is partnering with governments to scale the graduation approach and aims to reach 4.6 million more households by 2026. To date, BRAC has worked with government partners to adapt the graduation program to the local context and integrate it into national social protection programs, including in Bangladesh, India, Kenya, Lesotho, Pakistan, The Philippines, Rwanda, Tunisia, South Africa, and Zambia. In India, the Bihar government has implemented the largest government-led graduation program, with technical support provided by Bandhan, aiming to reach approximately 200,000 households by 2024.

1.6 Potential path forward

Additional funds could scale up climate-resilient graduation programs in countries where they have been most cost-effective, like Bangladesh and India, and expand them to other climate-vulnerable countries with high poverty rates. In new settings, it would be advantageous to start at a modest scale, and rigorously evaluate the program's impact to inform how to allocate additional resources. In Bangladesh, a program cycle lasts 24 months and costs approximately USD 750 per household, for an implementer like BRAC, whereas elsewhere, the program cycle could last up to 30 months and would cost more (USD 1200-1800 per household) to adapt the program to different contexts.[17] On average, the direct transfers (assets and cash) account for about a third of the program costs, whereas the other components (such as training, coaching, and financial inclusion) account for about half of the program costs, with the remainder accounted for by indirect operational and initial setup costs.

USD 41-289 million over seven years could support BRAC's climate-resilient graduation program to reach 36,000-300,000 households in five countries; with several options to reallocate resources across countries. An initial investment of USD 14-102 million could reach a cohort of 12,000 to 100,000 households in five countries over two to three years (Bangladesh, Liberia, Sierra Leone, Tanzania, and Uganda) highly vulnerable to extreme weather events and where the graduation model can be replicated. In Bangladesh, USD 4-56 million could provide the graduation program to 5,000-75,000 new households. An additional 10 percent of this component of the investment could fund the costs of testing the effectiveness of the novel climate-resilient components in Bangladesh. USD 9 to 37 million could reach a cohort of 1,750 to 5,000 households per country in Liberia, Sierra Leone, and Tanzania, as well as 1,750 to 10,000 households in Uganda. An additional 10 percent of this component of the investment per country could be used to evaluate impacts to inform further scale-up decisions.[18] Investing more would enable the enrollment of more households in the same countries, costing an additional USD 13 to 93 million per cohort of 12,000 to 100,000 households across five countries (as described in Table 1).

2. Anticipatory cash transfers ahead of extreme weather events

2.1 Context

Climate change is accelerating the frequency and intensity of floods and other natural disasters, disproportionately affecting the most vulnerable. The frequency of natural disasters has increased fivefold in the past 50 years, causing losses of USD 3.6 trillion globally.

[17] A program cycle includes: in a first phase, a three-month inception period during which geographical selection, office setup, finalizing participant selection guidelines, staffing, and staff training take place; in the second phase, activities such as targeting, cash and asset transfer and enterprise development training, are generally completed within the first six to eight months of the cycle (depending on the needs, cash transfers are extended over a year or more); in a third phase, all activities related to financial inclusion and hands-on coaching run simultaneously until the end of the program cycle.

[18] These estimates are from BRAC, but a funder could solicit proposals from multiple potential implementers.

Floods are the most frequent type of natural disaster, and their frequency and intensity are expected to increase with climate change. Of the 1.8 billion people living in areas at risk of extreme flooding, approximately 90 percent are in low- and middle-income countries; four out of ten people exposed to flood risk live in extreme-to-moderate poverty.

2.2. Weather-responsive anticipatory cash transfers

Weather-responsive anticipatory cash transfers leverage forecasting models, remote sensing, and mobile banking to deliver cash to households ahead of climate-related disasters, such as floods. This allows households to respond to disasters in advance (for example, by moving themselves and movable assets to safety), rather than relying on ex-post humanitarian assistance. Several organizations have piloted flood-responsive anticipatory cash transfers, such as the World Food Program in Bangladesh or GiveDirectly in Mozambique and Nigeria.

2.3 Impact and cost-effectiveness

Weather-responsive anticipatory cash transfers can support households preparing for and adapting to floods, increasing their resilience. Cash transfers are a cost-effective intervention to improve food security and enhance livelihood resilience in humanitarian settings, though traditional ex-post-disaster responses tend to be slow at reaching households in a crisis. Growing evidence suggests that anticipatory cash transfers ahead of floods are faster and can boost food security and resilience more cost-effectively than ex-post assistance. Households in Nigeria that received transfers from the International Rescue Committee before a flood were less likely to resort to harmful coping strategies, such as missing meals, compared to similar households that received the transfer after a flood. In Bangladesh, the World Food Program used data-driven forecasting to send cash transfers to households about to experience severe flooding. A non-experimental study estimated that households that received the transfer before a flood hit were 36 percent less likely to go a day without eating and more likely to evacuate household members and livestock than comparable households who did not receive the cash transfer.[19]

[19]Households were sampled from a list of past WFP recipients. Sampled households received the transfer if they had active mobile money accounts with a specific provider during a verification call a few days before the flood peaked and compared to households which had inaccurate or inactive accounts with the same provider.

2.4 Potential for further improvement

Recent advances in technology can be deployed to rapidly scale up weather-responsive anticipatory cash transfers and reach the households most likely to benefit. New technologies can produce higher-accuracy forecasts—such as where and when floods would occur, better target beneficiaries using remote sensing, and send transfers more rapidly through mobile money. Further investments are needed to adapt these technologies to different contexts.

Improvements in physical and institutional infrastructure could enable further expansion of anticipatory weather-responsive cash transfers. Donors could set up a flexible pre-financed payment system to guarantee financing ahead of extreme weather events. Data-sharing partnerships with telecom operators and/or integration with government social registries could increase the speed up and reduce the costs of targeting and of transfer delivery. In some places, expanding mobile access and connectivity may be needed. One strategy for developing this infrastructure would be for the early phase of the scale-up process, including creating and testing the necessary infrastructure for large-scale anticipatory cash transfers to be led by an organization with experience in targeting and enrollment technology, remote sensing, and data science, as well as the ability to establish partnerships, such as data use agreements with telecom companies and government regulators. These novel delivery systems could eventually be integrated into existing safety net programming.

2.5 Potential for scale

Several organizations that plan to scale up anticipatory responses to extreme weather events could be scaling partners. Many international organizations (such as the UN Office for the Coordination of Humanitarian Affairs, World Food Programme, and other NGOs like GiveDirectly) plan to expand weather-responsive anticipatory assistance programs that include cash transfers. Pilots of weather-responsive anticipatory programs have been implemented in over 60 countries since 2014 but have yet to reach large scale (beyond 30,000 recipients at once), partly due to lack of sufficient funding.

2.6 Potential path forward

USD 39-190 million over five years could reach up to 100,000-500,000 people at risk of floods and improve the technologies to further scale up weather-responsive anticipatory cash transfers. This investment aims to reach up to 100,000 to 500,000 recipients in up to four countries (Bangladesh, Malawi, Mozambique, and Nigeria) that have the highest exposure to flood risks and the highest share of the population living in extreme poverty.[20] USD 1 million could be used in the first year to analyze existing data and assess the potential of emerging technologies. Concurrently partnerships and data-sharing agreements could be formed with telecom companies and governments, research conducted to operationalize improved targeting systems, and context-specific flood risk models enhanced (costing on average USD 0.4-2 million per country). In the subsequent two to three years, USD 40-160 million would fund weather-responsive anticipatory cash transfers for 100,000 to 500,000 recipients across the four countries, depending on the realizations of extreme weather events. Countries could be phased in gradually, starting from those with the largest population exposed to flood risk (Bangladesh and Nigeria), and implementation in subsequent countries could be adapted based on lessons learned from previous implementations. The geographical distribution of recipients across those four countries would depend on where extreme weather events occurred in practice, so the investment could remain adaptable based on forecasting, rolling out transfers in countries where severe floods are expected to occur first. About 75 percent of this component of the investment would fund direct transfers of USD 250 per person; an additional USD 83 per person (approximately a quarter of the value of the transfer) would cover operational costs for targeting and delivery. Concurrently, approximately USD 2 million per country would fund country-specific monitoring and impact evaluations, and an additional USD 0.25-1.2 million per country on average would fund training for local stakeholders on implementing weather-responsive anticipatory transfers. Additional funding (approximately USD 1 million) could establish a global scaling strategy and knowledge-sharing.[21]

[20] The investment focuses on sudden-onset disasters such as floods, but it could apply to other climate-related extreme events, such as droughts.
[21] These estimates are from GiveDirectly, but a funder could solicit proposals from multiple potential implementers.

Table 1. Estimated range of costs for climate-resilient graduation programs

Lower range

	Cohort 1 (# of households)	Cohort 2 (# of households)	Cohort 3 (# of households)	Cost per household (USD)	Cohort 1 Cost (million USD)	Cohort 2 Cost (million USD)	Cohort 3 Cost (million USD)	Evaluation costs (million USD)	Total (million USD)
Bangladesh	5,000	5,000	5,000	750	3.8	3.8	3.8	0.4	12.0
Liberia	1,750	1,750	1,750	1,800	3.2	3.2	3.2	0.3	9.8
Sierra Leone	1,750	1,750	1,750	1,700	2.0	2.0	2.0	0.2	6.0
Tanzania	1,750	1,750	1,750	1,500	2.0	2.0	2.0	0.2	7.0
Uganda	1,750	1,750	1,750	1,200	2.1	2.1	2.1	0.2	7.0
Total	**12,000**	**12,000**	**12,000**		**13.0**	**13.0**	**13.0**	**1.3**	**41.8**

Upper range

	Cohort 1 (# of households)	Cohort 2 (# of households)	Cohort 3 (# of households)	Cost per household (USD)	Cohort 1 Cost (million USD)	Cohort 2 Cost (million USD)	Cohort 3 Cost (million USD)	Evaluation costs (million USD)	Total (million USD)
Bangladesh	75,000	75,000	75,000	750	56.3	56.3	56.3	5.6	174.4
Liberia	5,000	5,000	5,000	1,800	9.0	9.0	9.0	0.9	27.9
Sierra Leone	5,000	5,000	5,000	1,700	8.5	8.5	8.5	0.9	26.4
Tanzania	5,000	5,000	5,000	1,500	7.5	7.5	7.5	0.8	23.3
Uganda	10,000	10,000	10,000	1,200	12.0	12.0	12.0	1.2	37.2
Total	**100,000**	**100,000**	**100,000**		**93.3**	**93.3**	**93.3**	**9.3**	**289.1**

Table 2. Estimated costs of an investment in anticipatory weather-responsive cash transfers.

Lower range

	Recipients reached	Transfer sent to recipient (USD)	Operational costs per transfer (USD)	Transfer costs, (million USD)	Program setup (million USD)	Research and evaluation costs (million USD)	Coordination and training of local stakeholders (million USD)	Total (million USD)
Landscaping and initial R&D								1
Bangladesh	40,000	250	83	13.3	0.7	0.7	0.4	15.1
Nigeria	40,000	250	83	13.3	0.7	0.7	0.4	15.1
Malawi	10,000	250	83	3.3	0.2	0.2	0.1	3.8
Mozambique	10,000	250	83	3.3	0.2	0.2	0.1	3.8
Knoweldge sharing for further scaling								1
Total	100,000			33.3	1.7	1.7	1.0	**39.6**

Upper range

	Recipients reached	Transfer sent to recipient (USD)	Operational costs per transfer (USD)	Transfer costs, (million USD)	Program setup (million USD)	Research and evaluation costs (million USD)	Coordination and training of local stakeholders (million USD)	Total (million USD)
Landscaping and initial R&D								1
Bangladesh	200,000	250	83	66.6	3.3	3.3	2.0	75.3
Nigeria	200,000	250	83	66.6	3.3	3.3	2.0	75.3
Malawi	50,000	250	83	16.7	0.8	0.8	0.5	18.8
Mozambique	50,000	250	83	16.7	0.8	0.8	0.5	18.8
Knoweldge sharing for further scaling								1
Total	500,000			166.5	8.3	8.3	5.0	**190.1**

Training for Rainwater Harvesting

1. Context

Land degradation and water stress are significant threats to agricultural productivity and food security in the context of climate change, especially in arid regions like the Sahel. In sub-Saharan Africa, growth in agricultural output has relied on increased land use on increasingly marginal soils and shorter fallow periods (1, 2, 3, 4, 5, 6). This approach will be hard to sustain, especially in a context with more frequent climate shocks (1, 2, 3).

The lives and livelihoods of the estimated 135 million people of the Sahel–eighty percent of whom depend upon agriculture for their income–are affected by drought, land degradation and desertification (1, 2). Drought affects up to 50 percent of arable land in any given year in the Sahel. Approximately 80 percent of agricultural land in the Sahel suffers from nutrient depletion and poor soil fertility (1, 2). Severe degradation of land can contribute to desertification and land erosion, leaving land unsuitable for agriculture, and increasing pressure on natural vegetation. Desertification and other sources of land degradation affect 494 million hectares of land in Africa–approximately 17 percent of the continent's total land area (estimation based on UNEP 2015). In addition to effects on incomes, food security, and health, climate change can increase the risk of conflict (1, 2).

2. Training for Rainwater harvesting

On-farm rainwater harvesting techniques reverse land degradation, increase agricultural yields and revenues, sequester carbon in the soil, and combat desertification. Agronomic trials demonstrate that rainwater harvesting can help to retain soil moisture and replenish soil nutrients while reducing the risk of crop failure. It is particularly useful where irrigation is unfeasible and chemical input use is limited.

Micro-catchments, including demi-lunes (half-circular bunds) and zai or tassa (soil pits), are often a particularly appropriate type of on-farm rainwater harvesting for smallholder farmers because they do not require specialized equipment and can be implemented after harvest when the opportunity costs of family labor and local wages for paid labor are lower. Demi-lunes are suited to the sloped land with severely degraded soil, known as glacis, that is estimated to cover 40 percent of degraded land in the agro-pastoral zone of Niger.[22]

Despite the effectiveness of rainwater harvesting and substantial investment in promoting demi-lunes in Niger, adoption remains low. Only around 10 percent of farmers in Niger adopt demi-lunes on any part of their private land. Simple awareness of techniques may be insufficient to achieve widespread adoption, requiring more nuanced and detailed training than existing government extension agents may typically provide.

3. Impact and cost-effectiveness

Simple training sessions cost-effectively increase the adoption of on-farm rainwater harvesting techniques, which would benefit farmers across severely degraded areas of the Sahel and in other arid and semi-arid farming regions. In Niger, the Ministry of Environment tested strategies to increase the adoption of demi-lunes and found that a simple training increased adoption by over 90 percentage points and increased field coverage by 20 demi-lunes per hectare, despite a majority of farmers already being familiar with the technology (estimation based on Aker and Jack 2023). The training provided instructions on constructing demi-lunes without special tools, encouraged adoption on private as well as communal land, and distributed instructional reference booklets for farmers to reference at home. The training increased specific technical knowledge about how to construct demi-lunes, such as the recommended depth or number to construct per hectare, by 8 to 21 percentage points. Demi-lune adoption in Niger increased per-farmer agricultural revenue by USD 34-37 per year and improved soil quality and land usage over multiple years while increasing farmers' costs by USD 30 in the first year and USD 4 in subsequent years. Financial incentives did not lead to increased adoption of demi-lunes after three years relative to farmers who only received training. Farmers who adopted demi-lunes were also able to bring previously unproductive land into cultivation—on average, an additional 0.3 hectares. The training was cost-effective, with an average cost of USD 9 per participant. There is some evidence that demi-lunes continue to provide benefits at least five years after construction. Another example of on-farm rainwater harvesting is pit planting, which involves planting seeds in a shallow pit to help retain moisture. In Malawi, randomized trials found that pit planting adoption increased agricultural yields by 19 to 44 percent (1, 2) and reduced labor costs relative to traditional ridge planting methods.

[22]Glacis lands are impermeable soils, whereby rainwater runs off or evaporates, further depleting the soil biome. Moreover, this type of degraded soil is frequently too dry to absorb the rainfall: as a result, destructive river floods and numerous flooding episodes have been observed.

Knowledge from training on rainwater harvesting diffuses among farmers and also benefits farmers who have not received the training. In Niger, households in villages where others received training on demi-lunes were 18 percentage points more likely to have constructed demi-lunes three years after the training. In Malawi, incentives for farmers to train others on pit planting increased adoption by about 7-14 percentage points. Targeting farmers who are better connected in social networks increased the diffusion of pit planting techniques, possibly because farmers need to learn from multiple people before adopting themselves. Extension agents could achieve most of the potential gains in diffusion by asking a few farmers in each village with whom they talk about agriculture most frequently to identify and target well-connected farmers for training.

A one-time training is sufficient for years of sustained adoption of rainwater harvesting techniques, suggesting a path to long-run sustainability with relatively small ongoing costs. The training in Niger cost USD 9 per participant and had lasting impacts of a similar magnitude at least three years later, suggesting a high social cost-benefit ratio and that ongoing training need not happen frequently to sustain benefits.

Rainwater harvesting techniques, including demi-lunes and *zai* or *tassa* soil pits, increase carbon sequestration in soils. The FAO estimates that demi-lunes in Niger could sequester 0.32 tons of CO2e per hectare per year, and that *zai* or *tassa* soil pits could sequester 0.19 tons of CO2e per hectare per year.

4. Potential for further improvement

Transitioning this innovation to scale could involve adaptation to new contexts, including identifying appropriate rainwater harvesting techniques and updating training content to match local languages, crops, and existing practices. Implementers could investigate the possibility of providing training materials digitally and training a cadre of extension workers and local trainers. A staged scaling process, starting at a moderate scale while monitoring and potentially rigorously measuring impact, could include A/B testing to identify whether one rainwater harvesting technique achieves similar benefits at lower costs, or performs better than another on particular types of soil, in particular agro-climatic conditions, or for particular crops.

Integrating remote sensing techniques could help detect the adoption of rainwater harvesting techniques, which can be used to reward extension agents and lead farmers. Monitoring tools and performance incentives for extension agents and farmers could play important roles in ensuring the effective diffusion of information (1, 2). Innovations in remote sensing and other technological tools, such as drones or automated processing of geo-referenced photos from smartphones, could facilitate implementing such monitoring and incentives at scale. Remote sensing could also facilitate monitoring the persistence of adoption for quantifying carbon sequestration benefits.

5. Potential for scale

Training for rainwater harvesting techniques can be scaled through government delivery channels. The Ministry of the Environment in Niger partnered with researchers to conduct trainings on demi-lune adoption. The Ministry has now begun scaling the innovation, with plans to train more than 10,000 farmers in 400 villages by the end of 2023.

Many international organizations also have experience in training farmers on rainwater harvesting and could be useful scaling partners, especially in areas where government extension services are severely under-resourced. Organizations including ActionAid, Catholic Relief Services, Concern Worldwide, Islamic Relief, ICRISAT, Justdiggit, Save the Children, and the World Food Program have trained farmers in on-farm rainwater harvesting techniques in countries including Burkina Faso, Burundi, Ethiopia, The Gambia, Kenya, Niger, Senegal, Tanzania, and Uganda. These organizations could potentially implement the innovative training from the Ministry of Environment in Niger to improve the cost-effectiveness of their programming.

6. Potential path forward

Funding of USD 6 million could enable this innovation to reach about 75,000 households (or about 580,000 individuals) in Niger. In addition to reaching more farmers, this funding would support the addition of remote sensing to monitor innovation adoption and trainer performance. This estimate is based on inputs from the current implementers and accounts for the costs of training participants, training trainers, and new monitoring efforts. This would be expected to generate at least USD 8.3 million in increased income for participants over five years, and likely much greater benefits over time due to improvements in soil health and resilience. Based on estimates of knowledge transfers to neighbors of trained farmers, this investment could also generate at least USD 1,000,000 in additional benefits over five years for other farmers. This funding could also potentially generate substantial climate mitigation benefits by sequestering carbon in rehabilitated soil. The FAO estimates that demi-lunes sequester 0.32 tons of CO_2e per hectare per year, although more due diligence would be needed to understand the magnitude and permanence of sequestration in this context. Assuming a social cost of carbon of USD 190 per ton, the estimated annual social value of carbon sequestered by this funding in Niger is USD 2.3-8.6 million. Scaling this intervention in Niger has an estimated social benefit-cost ratio between 4 and 9:1, accounting for the marginal costs of training farmers, the costs to farmers to construct demi-lunes, the costs of monitoring and evaluation, and the suggested further improvements discussed above in Section 4.

A larger grant of funding could bring this innovation to farmers in more countries. Expanding to new countries could involve additional work to adapt training materials, identify target regions with highly degraded soils, and build in impact evaluation and A/B testing to confirm the techniques and training materials that are most appropriate and cost-effective for each context. Funding of about USD 21 million could enable this innovation to reach 225,000 households (or about 1.8 million individuals) in Burkina Faso, Mali, and Chad. This funding would be expected to generate at least USD 24.9 million in direct benefits for participants over six years, and potentially greater benefits over time due to improvements in soil health and resilience. Based on estimates of knowledge transfers to neighbors of trained farmers, this funding could also generate at least USD 3 million in additional benefits over five years for other farmers. Assuming again carbon sequestration of 0.32 tons CO2e per hectare, and a social cost of carbon of USD 190 per ton, the estimated annual social value of carbon sequestered by this investment is USD 6.8-22.8 million. More due diligence would be needed to understand the magnitude and permanence of sequestration in each country's context. Scaling this innovation to three additional countries has an estimated social cost-benefit ratio between 3 and 6:1, accounting for the marginal costs of training farmers, the costs to farmers to construct demi-lunes, the costs of monitoring and evaluation, and the suggested further improvements discussed above in Section 4.

Alternative proteins

Alternative protein innovation has the potential to contribute to climate mitigation, relieve food insecurity, and help address malnutrition.

1. Context

The livestock sector is a key driver of climate change. It accounts for two-thirds of annual greenhouse gas emissions from agriculture, and meat products are typically the most emissions-intensive. The largest share of livestock-related emissions today comes from production in upper-middle-income economies, while some high-income countries are large contributors in terms of per capita consumption. While reducing the emissions intensity of the livestock sector is part of the answer, alternative proteins can help by providing a low-emissions substitute for meat.

Climate change threatens agricultural productivity and food security. Crop yields in Africa have stagnated over the last 60 years (1, 2, 3). Climate change is expected to reduce global crop yields for key crops (except rice), even after accounting for adaptation. Climate change may lead to food price increases and food insecurity. Alternative proteins can help relieve food insecurity by reducing the risk of food price spikes from animal feed demands - 37.5 percent of the world's cereals supply was allocated to animal feed in 2020 (1, 2).

Under pessimistic climate-change scenarios, impacts on food production could be severe, creating a high option value of investing now in approaches that could address food security needs if necessary. For example, end-of-century losses for maize yields are 26.1 percent under a high emissions scenario (RCP 8.5, a representative greenhouse gas concentration trajectory adopted by the IPCC) compared to 9.8 percent under a moderate emissions scenario (RCP 4.5). The large costs heavily influence the expected costs of climate change in high-impact but lower-probability scenarios (1, 2). Investing in alternative proteins could help insure against worst-case scenarios by reducing emissions and by providing a climate-resilient source of proteins.

Investing in alternative proteins now could help address malnutrition, a key driver of which is a lack of access to affordable, high-quality proteins. Approximately one billion people, mainly in low- and middle-income countries, have inadequate protein intake. A lack of dietary utilizable protein ("protein quality") and the greater dietary needs resulting from poor living conditions in low- and middle-income countries exacerbate the problem. Insufficient protein intake among children is associated with stunting (1, 2). Increased temperatures are associated with increases in acute childhood malnutrition - projecting forward, global warming would be associated with a 37 percent increase in the prevalence of wasting by 2100 in Western Africa.

2. **Alternative proteins**

Alternative proteins, which do not rely on conventional animal agriculture, could help address these issues by potentially providing low-cost, reliable sources of high-quality protein. Alternative protein categories include:

- Classic plant-based foods: Examples include legumes and tofu.
- Novel plant-based foods: Examples include "biomimicry" burger products. These plant-based foods aim to be indistinguishable from conventional meat and are often developed using plant protein concentrates.
- Biomass fermentation: Examples include meat substitutes made from mycoprotein (fungal protein). Biomass fermentation uses the high-protein content and rapid growth of microorganisms to make large amounts of protein-rich food efficiently.
- Precision fermentation: Examples include the heme protein that gives a "meat" taste. Precision fermentation uses microorganisms to produce specific functional ingredients. Precision fermentation enables alternative protein producers to efficiently make specific proteins, enzymes, flavor molecules, vitamins, pigments, and fats.
- Cultivated meat: Examples include chicken nuggets in Singapore, though the technology is at an early stage with few commercial products currently available. Cultivated meat involves growing animal cells in a nutrient-rich environment to build muscle and fat.

In low- and middle-income countries, alternative protein technologies have the potential to be a source of low-cost, high-quality proteins. In the near term, plant-based foods could be adapted to meet local tastes and nutritional needs. In the medium term, biomass fermentation has the potential to generate high-quality proteins at a large scale and low cost. It is a flexible process that allows microorganisms to convert agricultural (waste) streams into food-grade proteins in bioreactors in a manufacturing-like setup. Such a setup could also continue manufacturing proteins regardless of climatic conditions.

Specific innovation priorities for advancing biomass fermentation for low- and middle-income country contexts include:

- Feedstock identification and optimization: This includes investigating and developing the potential of different raw materials, including local agricultural side (waste) streams as inputs for fermentation.

- Microbe identification: This includes screening known microbes for their use in fermentation and bioprospecting for new microbes that may be more suited to local food stocks.

Low-cost alternative proteins could help address malnutrition. They could potentially be incorporated into foods to treat severe wasting (ready-to-use therapeutic food) and moderate acute malnutrition (ready-to-use supplementary food).

Low-cost alternative proteins could also be sold commercially. This market route is important because most underweight and malnourished children in sub-Saharan Africa fall outside the bottom 20 percent of wealth and consumption distributions. Alternative protein products could supplement meals (e.g., bouillons, porridge, or noodles) or be incorporated into prepackaged foods. Consumer demand could emerge if firms develop nutritious products that appeal to local tastes.

In high- and upper-middle-income countries, alternative proteins could reduce greenhouse gas emissions by substituting for conventional meat products if they can compete on taste and price. In the medium term, this would involve further development of novel plant-based foods and fermentation technologies. Specific innovation priorities include optimizing crops and post-harvest ingredients for use in plant-based meats. In the longer term, cultivated meat may offer the potential to replicate conventional meat at a cellular level, which may appeal to consumers with a stronger preference for conventional meat. However, whether this technology will be economically viable at scale is debated. (1, 2). Potential innovation priorities for cultivated meat include:

- Developing new cell lines (stem cells grown to produce cultivated meat) that can be put in the public domain and used commercially. These are essential building blocks for cultivated meat. The lack of availability of cell lines is constraining commercial production and holding back innovation in media, scaffolding, and bioreactors.

- Developing cell culture media (nutrients and growth factors that cells need to grow outside of the body). Research on cell culture media is central to reducing the costs of cultivated meat (1, 2).

3. Potential impact and cost-effectiveness

Alternative proteins could contribute to climate mitigation in high- and upper-middle-income countries by reducing demand for animal proteins that drive greenhouse gas emissions. One life-cycle assessment suggests a commercially available plant-based burger generates 90 percent fewer emissions than a beef patty (1, 2). Another life-cycle assessment suggests cultivated meat sold in 2030 will have a lower carbon footprint (when using renewable energy) than ambitious carbon footprint targets set for beef and pork, and will be comparable to the targets set for chicken (1, 2). Quorn, a fermented meat substitute in the market today, has lower emissions intensity than typical animal products (1, 2). These emission profiles suggest alternative proteins could make a large contribution to climate mitigation if costs fall and consumers switch to them from emissions-intensive animal proteins.

R&D investments in alternative proteins offer option value under the worst climate change and food security scenarios. Early investments in this area would not be expensive and would accelerate the development of a technology that may be needed in the future. Further investments could be conditional on earlier investments yielding results. Such an approach may offer large benefits if the worst future climate change and food security scenarios materialize: by providing a substitute for animal proteins, alternative proteins decrease demand for animal feed and can reduce the risk of surges in food prices. Lobell et al (2011) found that climate trends between 1980 and 2008 led to a 3% loss in calories, which led to roughly 20% higher commodity prices relative to a counterfactual scenario without warming (1, 2). Price increases would clearly be much greater under the 9 percent (by 2050) and 25 percent (by 2098) yield losses projected in a high emissions scenario (RCP 8.5). Baldi et al 2021 estimate a 4 percent shift to plant-based meats would result in crop prices being 13 to 23 percent lower on average relative to a counterfactual with no plant-based meat.

By providing a substitute for milk proteins, low-cost alternative proteins could potentially reduce the costs of providing therapeutic food to malnourished populations. Milk powder is a key cost driver for ready-to-use therapeutic food (RUTF). UNICEF purchased 50,000 MT of RUTF per year on average between 2019 and 2022, accounting for 75-80 percent of global demand (with much higher purchases in 2022 and 2023). Assuming a price of USD 44 per carton of RUTF, this suggests that UNICEF spent approximately USD 160 million per year on RUTF.[23] Lower cost formulations would allow humanitarian spending to reach more people - UNICEF estimates that 50-75 percent of children suffering from severe wasting do not have access to treatment. Several studies have assessed the cost-effectiveness of changing the RUTF formulation using existing locally sourced or alternative ingredients, with mixed results

[23] UNICEF indicates 1MT = 72 cartons and an overall price per carton of USD 44.4 in 2022

across different settings (Sierra Leone; Malawi; Malawi; Zambia; Bangladesh). Alternative formulations with (novel) alternative proteins may deliver more promising results as they may have better protein quality and density.

4. Potential pathways to scale

Public and philanthropic money could accelerate the development of low-cost alternative proteins for consumers in low- and middle-income countries. Existing technologies were developed largely to mimic meat for consumers in high-income countries and will need to be adapted to provide low-cost proteins for low- and middle-income markets. In addition, incorporating low-cost alternative proteins into therapeutic foods would require regulatory approval and therefore large-scale trials.

Public and philanthropic investment in basic research could accelerate innovation in alternative proteins for climate mitigation in high and upper-middle-income countries. Firms will not capture the climate mitigation benefits of such innovations. Some fundamental innovations in this space may be hard to protect with intellectual property or first-mover advantages, which will weaken incentives to innovate. Such market failures justify public and philanthropic funding for basic research such as lab science. Given the likely demand for alternative proteins among high-income consumers, public and philanthropic investments in downstream (product) research should prioritize the needs of low- and middle-income countries.

5. Potential path forward

Greater public and philanthropic R&D funding can fill the gap left by commercial markets. Livestock-related emissions amounted to 3.5 billion CO2 equivalent tons in 2018. A one percent reduction in annual livestock emissions would have a social value of approximately USD 6.65 billion using an assigned 2020 social cost of carbon of USD 190. Public funding for R&D in alternative proteins amounted to USD 180 million in 2022, with USD 290 million on commercialization, and USD 165 million on initiatives that mixed elements of both R&D and commercialization. Current public investments in R&D for alternative proteins fall short of their potential social value - larger investments by high-income countries in basic R&D would be justified on climate mitigation grounds alone.

Alternative protein innovation focused on the needs of low- and middle-income countries is a neglected area that would benefit from more funding. A USD 10 to 30 million research program could cover biomass fermentation priorities such as feedstock identification and optimization as well as microbe identification in a range of countries.

Donors may wish to consider committing to helping to cover the cost of purchasing low-cost alternative formulations of therapeutic foods (such as ready-to-use therapeutic food and ready-to-use supplementary food) as a way to accelerate innovations in the formulation of therapeutic foods. Donor commitments to subsidize the purchase of low-cost formulations that achieve regulatory approval would help address unpredictable financing and provide incentives for firms to innovate and seek regulatory approval. While alternative proteins are a promising technology for the formulation of therapeutic foods, the commitment should encourage innovation more broadly, and so should be technology-agnostic and open to formulations that do not involve alternative proteins. Given existing levels of expenditure on RUTF, such a commitment could potentially be in the hundreds of millions (see above, UNICEF). [24]

[24] This note draws on contributions from Essential, the Good Food Institute, and the Breakthrough Institute.

Innovations to Reduce Livestock Methane Emissions

Several innovations in development have the potential to significantly reduce methane emissions from livestock, which accounts for one-third of human-induced methane emissions and nearly 15 percent of all anthropogenic greenhouse gas emissions.

1. Context

The livestock sector is a key driver of climate change. It accounts for two-thirds of annual greenhouse gas emissions from agriculture. The largest share of livestock-related emissions today comes from production in upper-middle-income economies, while some high-income countries are large contributors in terms of per capita consumption (1, 2).

Demand for products from livestock is expected to grow. Consumer demand for beef is projected to increase by 80 percent by 2050. By the end of the decade, milk output is anticipated to grow by 9 percent in high-income countries and 33 percent in low- and middle-income countries.

Reducing methane emissions is an important component of the global response to climate change. Reducing methane emissions by 45 percent from 2010 levels by 2030 could prevent nearly 0.3 degrees Celsius of temperature rise by the 2040s.

Farmers currently lack sufficient incentives to invest in technologies to reduce their emissions as animal agriculture systems do not price greenhouse gas emissions in final products. As a result, commercial incentives for R&D on methane reduction and elimination technologies fall far short of the social value of these innovations.

2. Innovations to Reduce Livestock Methane Emissions

Several innovations have the potential to significantly reduce methane emissions from livestock. Some of these innovations could also provide co-benefits to farmers by increasing productivity.

- **Feed additives that reduce methane emissions from livestock digestive systems.** These additives modify the rumen environment or interfere with methane generation and include algae, lipids, tannins, and other synthetic compounds, like 3-Nitrooxypropanol

(3-NOP) and the synthetic bromoform-containing compound Rumin8. When dissolved in animal feed, these additives can alter the chemical reactions that generate methane emissions in the animal's digestive process.

- **Gene editing techniques to curb methane emissions and increase productivity.** These techniques could be used to improve breeding strategies or to edit the genes of livestock or of the microorganisms in their digestive systems that are responsible for generating methane emissions.
- **Approaches that improve the efficiency of meat and milk production in low-yield settings.** Existing technologies for animal management can be adapted to increase production efficiency in new settings. For example, advanced feeding software that computes the optimal diet for livestock is widely used in higher-income countries and could be adapted for producers in low- and middle-income contexts.

3. Potential impact and cost-effectiveness

Innovative feed additives could reduce methane emissions by up to 26-98 percent. Methane production consumes up to 12 percent of ruminants' gross energy intake, so reducing methane emissions via feed additives like 3-NOP could also increase productivity or milk quality by sparing energy in the digestive process and redirecting it towards animal growth and milk production (1, 2, 3, 4). Some feed additives may be challenging to produce at scale or may pose a toxicity risk that would call for further research before widespread use. Others, like 3-NOP, are becoming increasingly available in higher-income countries but have not yet sought regulatory approval in lower-income countries.

Selective breeding and gene editing could also substantially reduce emissions. These innovations could be used by producers who do not regularly use feed systems, such as pastoralists or extensive-system producers. Compared to nutritional strategies, genetic solutions result in long-term progress and therefore tend to be more cost-effective over time. Selective breeding for low-methane emission is in the early stages of development but could potentially reduce between 11 and 26 percent of emissions (based on preliminary consultations with experts). Gene-editing technology such as CRISPR-Cas DNA editing and genome-resolved metagenomics could be another tool to reduce methane emissions, allowing for precise changes in ruminant gut microbiomes. Further research on these gene editing techniques could evaluate their potential to reduce methane emissions and assess their effects on human and animal health.

Advanced farm-management practices, such as improved feeding software, could reduce methane emissions intensity in low-income countries by improving the efficiency of production. Innovations like ration formulation software that integrates local resources and is adapted for local livestock varieties could help farmers adopt these feeding practices. In high-income countries, animal diets are often formulated to optimize productivity, which reduces the emissions intensity per unit of output. For example, cattle farmers in California reduced emissions intensity of production by 45 percent relative to 1964, due in part to improvements in genetics and feed efficiency.

Further development of these innovations could improve their cost-effectiveness and affordability for wider use. Existing feed additives, like Bovaer®, have to be administered daily, making them impractical for many farmers, especially those whose animals graze in pastures. At USD 85-95 per cow per year, Bovaer® is also prohibitively expensive for many farmers in the absence of incentives that would reflect the environmental benefits. More research on these additives can also inform how long their effectiveness lasts over time.

These innovations could also increase productivity, especially for dairy products, which could in turn reduce emissions by reducing the number of cows. Dairy production in sub-Saharan Africa is more than five times as emissions-intensive per liter than production in North America or Europe, and cows in the region are only 5-7 percent as productive as their counterparts in North America or Europe. Increasing milk productivity per animal would reduce the number of cows kept for dairy production under plausible assumptions on price elasticities.

4. Potential pathways to scale

Governments and philanthropists could incentivize R&D through a range of instruments. Public support could expedite the development and testing phases of these innovations, through either up-front funding or through "pull mechanisms" that signal to private investors that there will be a future market for technologies that reduce livestock emissions. Pull mechanisms, such as prizes or Advanced Market Commitments, harness the energy and creativity of the private sector to address social priorities by committing to reward the development and take-up of new technologies.

Private actors could be incentivized to support methane emissions reductions from livestock with additional policy tools. Technologies to reduce methane emissions could generate social value far in excess of their commercial value, but farmers' private incentives to reduce methane lag far behind the social value of methane reductions, creating a role for policy tools, such as incentives, regulations, and tax measures to stimulate adoption.

By announcing in advance that they would adopt a package of incentives, taxes, and regulatory actions to encourage the use of cost-effective technologies to reduce emissions, high-income countries could incentivize innovation by signaling there will be demand for such products when developed. Such a package of policies could kick in when a pre-specified cost-effectiveness threshold—linked to the social value of averted emissions—is reached. Such regulations would presumably first apply to larger producers that are responsible for most emissions.

In principle, a cap-and-trade system for methane could be a complementary policy innovation to reduce emissions. In principle, "technology-agnostic" cap and trade systems for methane emissions could allow farmers to choose efficiently among methane reduction approaches and would create strong incentives for innovators to develop methane reduction technologies. However, a cap-and-trade system would require monitoring systems. Any such methane cap and trade program would presumably be introduced first in high-income countries. Cap and trade systems would typically be structured so that farmers would be allocated permits in proportion to current livestock holdings or emissions.

If a high-income country established a cap-and-trade program for methane, lower-income countries would have considerable incentives to establish their own monitoring systems and enter into agreements with high-income countries to sell emission permits. Assuming that permits were allocated based on the initial number of livestock, such trade could result in substantial financial flows to lower-income countries, as producers in high-income countries would have incentives to purchase permits from those in lower-income countries where production is typically more methane intensive per quantity of output, reducing herd sizes in lower-income countries. This, in turn, could potentially reduce over-grazing pressure and farmer-herder conflict.

5. Potential path forward

Governments and philanthropists should both make direct investments in R&D and consider other policy tools to accelerate innovation, including market shaping instruments and a cap-and-trade system.

Direct investments should be considered for R&D activities including:

- **Expanding testing of new feed additives.** Donors could fund on-farm testing across new settings of additives that have promising potential from laboratory results.

- **Test and expand selective breeding and approaches to edit the genes of the microbes that drive enteric methane emissions from livestock digestive systems**. Further research on animal genetics can improve our understanding of which traits in existing breeds are more effective for higher yields and/or lower emissions. Advancing our knowledge of microbiome genetic mapping in ruminant digestion could involve laboratory demonstrations to reduce methane in rumen cultures via microbiome community editing, followed by live animal trials.
- **Test methods to improve the production efficiency of existing technologies.** Testing the cost-effectiveness and take-up of improved farm-management practices and feed software to account for local feed availability and costs and local breeds.

In addition to funding for R&D, it would be beneficial to explore policies to harness the energy and creativity of the private sector in developing innovations to reduce methane emissions. This includes market shaping instruments, such as Advance Market Commitments and advance regulatory commitments. Governments could also explore the possibility of creating cap and trade systems for methane**.** These policy tools could allow farmers to choose efficiently among various methane reduction approaches, which in turn would incentivize innovators to develop methane-reduction technologies that farmers and consumers would accept.

Microbial Fertilizer

Microbial fertilizers use bacteria to facilitate crops' absorption of nutrients, improving yields and reducing the need for synthetic fertilizers. Further testing and adaptation of microbial fertilizers to new agroecological contexts is needed to transition these technologies to scale in low- and middle-income countries.

1. Context

Nitrogen fertilizer is key to increasing yields in some regions, but synthetic fertilizer is a major source of emissions and environmental degradation. Globally, the production and use of synthetic fertilizer generate between 1 and 5 percent of global carbon dioxide emissions. Fertilizer use varies significantly across regions. The fertilizer application rate in sub-Saharan Africa is one-seventh of that in East and South Asia. Fertilizer underuse in Africa limits productivity, while heavy use of synthetic fertilizers in Asia leads to adverse environmental effects, in addition to high fiscal costs from subsidies.

2. Microbial Fertilizers

Microbial fertilizers use bacteria to facilitate the absorption of nutrients necessary for plant and soil health. Different types of microbial fertilizers are tailored to specific crops and nutrients. Some formulations use a single bacterium, such as Rhizobium or Azospirillum, while others combine two or more bacteria. Most microbial fertilizers target biological nitrogen fixation, though new formulations also facilitate phosphorus and potassium absorption.

3. Potential impact and cost-effectiveness

Microbial fertilizers could reduce emissions from synthetic fertilizers, generating billions in social benefits. Microbial fertilizers could reduce emissions from fertilizer production by 98 percent, relative to synthetic fertilizers. Using USD 190 as the social cost of carbon, each ton of synthetic fertilizer replaced by microbial fertilizers would be worth between USD 1,820 and USD 2,530.[25]

[25] Calculations based on EPA 2022, Yüzbaşıoğlu et al. 2021, and Zhang et al. 2013.

Rhizobium is an effective fertilizer for legumes and is widely adopted in some regions. In the 1990s, the Brazilian Agricultural Research Corporation (Embrapa) developed a microbial fertilizer using Rhizobium to enhance biological nitrogen fixation in soybeans. To date, around 100 million acres of soybean in Brazil use Rhizobium, which can increase yields by 10 to 30 percent in chickpeas, common beans, cowpeas, fava beans, peanuts, and soybeans, (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15). However, soil conditions influence its effectiveness. For example, Rhizobium may have limited or no effects in acutely degraded soils. Rhizobium provides proof of concept that microbial fertilizers can reach scale in middle-income countries.

New technologies have the potential to reduce the need for synthetic fertilizer in other staple crops. In the United States, PivotBio reprograms microbes to reduce or replace the need for fertilizer.[26]. Their main product, Proven40, combines 40 microbes to enhance biological nitrogen fixation in maize. Proven40 is being used on about 10 million acres of corn in the United States. At an earlier stage of development and not yet on the market, Kula Bio is working on a technique that allows the bacterium Xanthobacter autotrophicus to facilitate nitrogen fixation in any crop. This technique uses bioreactors to increase the microbial density of X. autotrophicus, which would allow bacteria to survive for longer periods in the soil–which can be a challenge with microbial fertilizers.

4. Potential pathways for scale

Greater funding could support the testing and adaptation of microbial fertilizers for low- and middle-income countries. Microbial fertilizers have been developed and adopted at scale in the United States and Brazil and are being adopted commercially in other upper-middle and high-income countries. However, given significant upfront costs and potentially lower expected returns, the private sector is likely to underinvest in adapting microbial fertilizers for use in many low- and middle-income contexts. As a first step, donors could support the testing and adaptation of microbial fertilizers that have a proven record. If testing yields successful results and microbial fertilizer is adopted by a substantial number of farmers in some countries, testing could be expanded to other countries and complemented with sequenced investments to transition the technology to scale.

5. Potential path forward

Funding for microbial fertilizers should be sequenced and tracked based on the initial success of local trials. As an initial step, donors could support the testing and adaptation of microbial fertilizers in low- and lower-middle-income countries. Initial tests for microbial fertilizers

[26] The microbes are gene-edited but do not contain foreign DNA.

targeting maize in Kenya offer promising early results. PivotBio has completed a set of research station trials in Kenya in collaboration with the Kenya Agricultural Livestock Research Organization (KALRO). These trials have shown that microbes work as well as synthetic fertilizers under local conditions, and PivotBio expects the technology to be marketable in Kenya in 2024 or 2025.

Testing microbial fertilizers in low- and middle-income countries would cost USD 250,000 to USD 3.5 million per country. The testing process used for PivotBio in Kenya could potentially be replicated in Angola, Ethiopia, Ghana, Kenya, Malawi, Mali, Nigeria, South Africa, Tanzania, and Zambia, which collectively produce almost 80 percent of maize in the region**.** Donors could consider partially or fully supporting:

- **Research station trials, at a cost of USD 250,000 to USD 500,000 each, to test the technology under local conditions.**
- **Farm trials, at a cost of USD 2 million each.** If research trials are successful, they could be followed by farm trials covering a substantial geographical area. Farm trials would ensure representative biological data on plants and microbes and would enable measuring the stability and persistence of microbial fertilizers in the soil across space and over time.
- **Incorporating local strains of bacteria from each country to optimize microbial fertilizers for the local context, at a cost of USD 1 million per type of fertilizer per country.** Even if research station trials and farmer trials demonstrate that the technology works well, incorporating local strains of bacteria from the country could further enhance its performance. PivotBio has already developed a second generation of its technology for Kenya following this tailoring process.

Public sector support for farmers to purchase microbial fertilizers, once they have been successfully tested and adapted, could reduce the use of synthetic fertilizer, reducing emissions and environmental degradation. Subsidizing microbial fertilizers could reduce the use of synthetic fertilizers, which have negative environmental externalities. Currently, many governments subsidize synthetic fertilizers creating further incentives for farmers to over-apply synthetic fertilizers without substantial yield gains. This imposes significant environmental and fiscal costs. While rolling back subsidies can be politically challenging, replacing subsidies for synthetic fertilizers with locally appropriate microbial varieties could be a more palatable measure while reducing environmental and fiscal costs. Subsidies would have to follow the successful testing and adapting of the technology.

Finally, establishing a fund to solicit proposals to develop, test, and adapt innovations for climate change, food security, and agriculture could support the development of cost-effective innovations to encourage the adoption of microbial fertilizers among smallholder farmers in low- and middle-income countries.