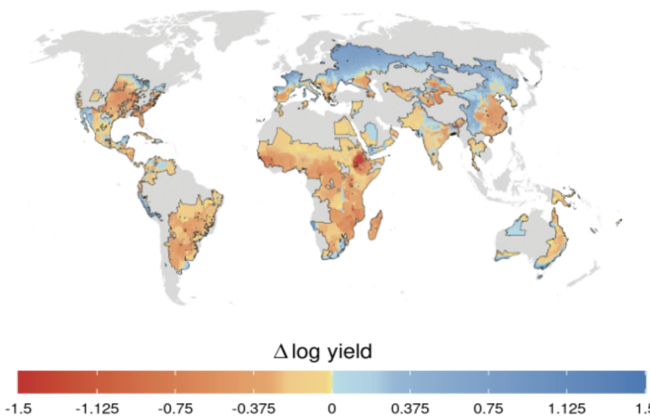
The Return to Investing in Climate-Resilient Crops[1]

Executive Summary

The increase in high-heat days, droughts, and floods resulting from climate change will cause a reduction in yields for crops critical to the livelihoods of hundreds of millions of people in sub-Saharan Africa. Developing and widely adopting climate-resilient crop varieties would mitigate billions of dollars of agricultural production losses. However, climate-resilient crop traits are not immediately valued by farmers, who may only trust these traits after experiencing severe climate impacts, limiting innovators' ability to charge higher prices. An advance market commitment that pays innovators if they successfully develop and distribute heat-tolerant varieties of staple crops could generate over $24 in economic benefits for every $1 spent.

Figure ES - 1: Change in log sorghum yields from climate change by 2100 (Hultgren et al., 2022)



We identify crops in sub-Saharan Africa with high social returns from heat resilience that are neglected by crop variety innovation markets. We calculate the net social return by combining future climate projections with data on crop yields in relation to temperature changes, prices, variety releases, and innovation costs. We model crop variety innovation through two channels: conventional breeding and advanced technologies that leverage recent scientific advances such as CRISPR and RNA methylation.

Our results show that increasing crops' heat resilience has large economic benefits (see Table ES - 1). We model heat resilience by reducing the negative impact of high temperatures between 29 and 40 degrees Celsius on crop yields. Heat-resilience improvements for maize and sorghum provide the largest benefits. However, the benefits from groundnut and soybean are also large, with each generating more than $100 million in economic benefits in the advanced variety development scenario.

Table ES - 1: Benefits of increase in heat tolerance (and yields for advanced technology)

			Benefits (US$, millions) by adoption and technology		
Crop	**Region**	**Old to new temperature threshold**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Adoption (% of harvested area)			*5%*	*10%*	*10%*
Technology			*Conventional*	*Conventional*	*Advanced*
Maize	West Africa	29 to 30°C	900	2,277	3,223
Maize	Southern Africa	29 to 30°C	647	1,682	3,048
Sorghum	West Africa	33 to 34°C	294	761	1213
Sorghum	East Africa	33 to 34°C	1,052	2,513	3,190
Groundnut	East Africa	30 to 31°C	58	149	502
Soybean	West Africa	29 to 30°C	149	350	407
Multi-target AMC			N/A	4,789	

Note: Table ES - 1 shows the estimated benefits of improved heat-resilient crop varieties for selected crop-region pairs. All estimates are discounted using a 2% discount rate and use temperature projections from the RCP4.5 scenario. Advanced technologies provide an additional 8% yield increase but are more expensive.

Public research institutions already invest in climate-resilient crop variety development, but more investment that encourages adoption is needed. An **advanced market commitment** (AMC) only rewards firms that successfully innovate and get farmers to adopt their new variety, providing incentives to address key market failures that underlie the sluggish adoption of improved varieties across sub-Saharan Africa. Cereal crops such as maize, sorghum, and rice are examples of crops where the private sector has established expertise and could respond to an advance market commitment. Under a moderate climate projection, the economic benefits of heat-resilient sorghum in East Africa would be between $850 million and $2.5 billion depending on the extent of adoption and yield improvements.

CGIAR and national agriculture research institutions must also play a critical role. The private sector has relatively limited expertise in developing groundnuts and vegetatively propagated crops (like sweet potatoes and cassava), but these account for a significant share of agricultural production in Africa. The Consultative Group on International Agricultural Research (CGIAR) and other public research centers have expansive experience with these crops and will continue cooperating with the private sector to develop, distribute and work towards harmonizing regulation for new climate-resilient crops.[2] With the promise of adoption-based rewards encouraging cooperation among breeders, seed multipliers, and agro-dealers, we expect that development finance institutions such as the International Finance Corporation (IFC) could see high returns from investing in the region.

The Return to Investing in Climate-resilient Crops

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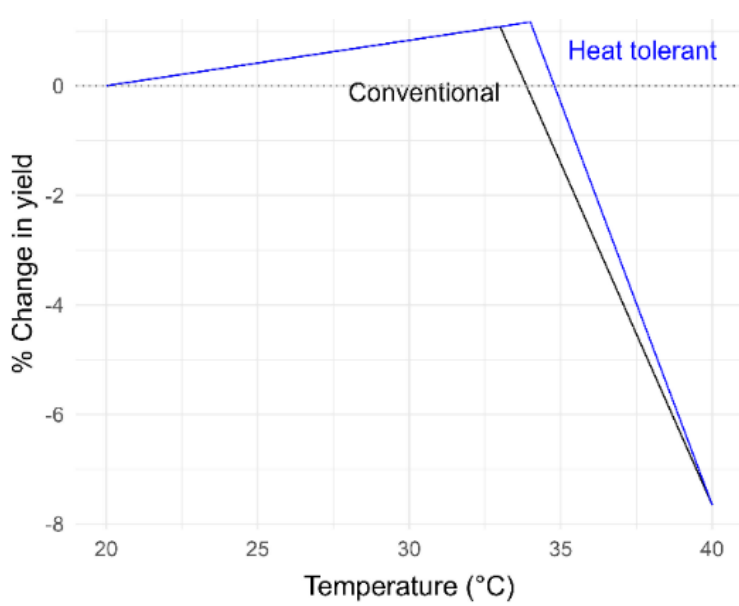
A Dire Outlook for Agriculture in sub-Saharan Africa

Temperatures above current crop heat tolerance thresholds will reduce crop yields. Figure 1 shows how annual sorghum yields change as a function of an additional day at a given temperature compared to a day at 20°C. Beyond 33°C, higher temperatures are expected to reduce sorghum yields.[3] Other crops follow a similar pattern with different temperature turning points.[4] Hultgren et al. (2022) estimate that crop yields in sub-Saharan Africa will fall by 45% by the end of the century due to climate change in the absence of adaptation and economic development. [5] Even with

Figure 1: Change in sorghum yield by growing degree day temperature



Source: MSA analysis. Yield function based on Tack, Lingenfelser, and Jagadish (2017).
Notes: Figure displays the estimated change in sorghum yiedld under an additional day of exposure to a given temperature relative to a day at 20°C for both baseline and heat tolerant varieties. The turning point occurs at the temperature at which the change in yield begins to decline; we model the turning point as one degree higher for the heat-tolerant variety.

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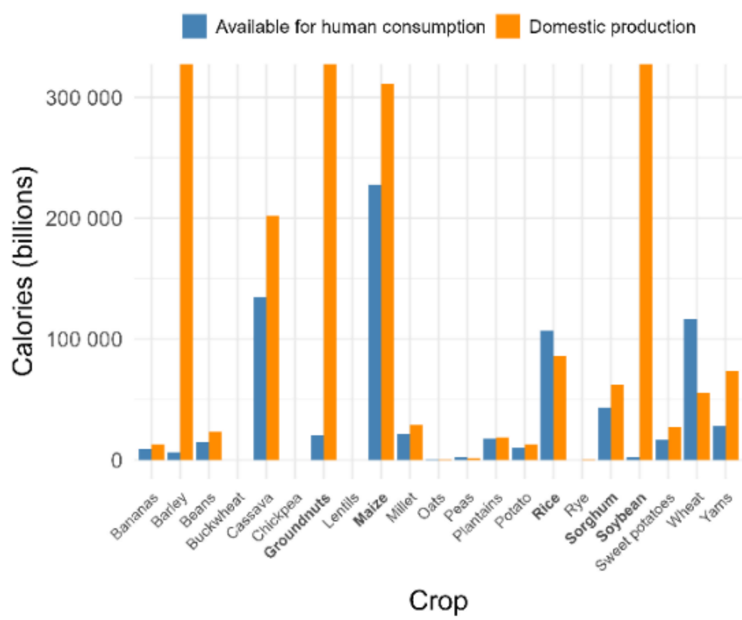
projected climate adaptation and economic development, yields are expected to decline 28% by 2100.

Key staple crops such as maize, sorghum, and groundnuts are vulnerable to climate change. Figure 2 highlights that these crops are key sources of calories in West Africa. Their yields will likely fall as the number of high heat and low rainfall days increases.[6] These pressures exacerbate the ongoing impact of declining or stagnant crop yields in Africa.[7,8]

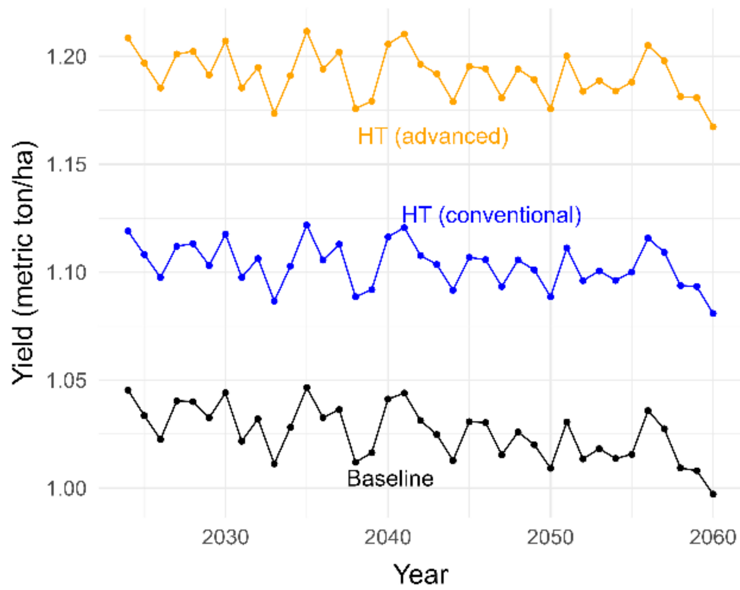
Figure 2: Crop calorie supply in sub-Saharan Africa (2021)



Source: MSA Analysis; underlying data from FAOSTAT (via Our World in Data).
Notes: Domestic production refers to the estimated quantity of food produced in the region. Available for human consumption refers to the estimated quantity of food available for human consumption after accounting for imports, exports, wastage, non human food uses, and supply chain losses. Crops included in our analysis are displayed in bold.

Increasing the heat tolerance of crops by just one degree Celsius could substantially reduce yield losses caused by climate change. We adapt recent findings on the causal effect of temperatures on crop yields to quantify the impact of greater heat resilience under various climate scenarios and innovation pathways.[9,10] Figure 3 presents our yield predictions for three different West African sorghum varieties: existing sorghum varieties, conventionally bred varieties with a 1°C higher heat tolerance threshold, and varieties bred using advanced technology that provides additional yield gains. Across all selected crop-region pairs, we estimate annual yield gains that vary between 5% and 30%.[11]

Figure 3: Estimated sorghum yield by year in Western Africa (ECOWAS)



Source: MSA analysis; Underlying data from FAOSTAT (initial yields), Tack, Lingenfelser, and Jagadish (2017) (yield function), and Andrew Hultgren/Climate Impact Lab (climate projections). **Notes**: Baseline refers to baseline projected yields without crop variety improvement; HT (conventional) refers to heat-tolerant varieties developed using conventional crop breeding; HT (advanced) refers to heat-tolerant varieties developed using advanced crop variety development techniques.

Key Market Failures Prevent the Development and Distribution of Improved Crop Varieties

Crop variety innovation of sorghum, rice, groundnuts and other African staple crops is neglected. Commercial innovation incentives fall short due to a combination of market failures. First, many small-scale farmers in sub-Saharan Africa reuse and share open-pollinated varieties (OPVs).[12] They prefer OPVs relative to hybrid seeds because OPVs can be replanted and maintain their genetic traits over time.[13] Over 90% of seeds used by small-scale farmers are not procured from commercial sources, and it is common to find seeds sold without any labeling.[14]

Second, farmers may be reluctant to pay for climate-resilience traits whose value is not immediately visible. Climate-resilient traits show their greatest potential under severe climate shocks, which occur irregularly. Thus, farmers may not internalize the value of climate-resilient traits before they are most needed, and climate-resilient seeds will not command prices reflecting their true value until it is too late, reducing R&D investment incentives.[15]

As a result, despite public and multilateral organization efforts to fund variety development for crops neglected by private markets, large innovation gaps remain. For example, Niger, a large producer and consumer of sorghum, had zero new variety releases between 2000 and 2013. Other countries, such as Côte d'Ivoire, have seen few or zero releases of maize, despite maize being relatively less neglected in sub-Saharan Africa.[16]

Even when new varieties are developed, they do not always reach farmers. Over 60 new cereal varieties were released in sub-Saharan Africa in the 2000s, yet adoption of new varieties remained only slightly above 50%.[17] New variety adoption rates can be even lower for less commercially attractive crops; only 20% of the land used to grow sorghum in Nigeria uses modern varieties.[18] In contrast, almost 500 new cereal varieties were released in Asia in the 2000s, with adoption reaching over 90%.[19]

Typical agricultural innovation financing does not incentivize widespread adoption.[20] Most crop variety development in sub-Saharan Africa is financed using push funding—upfront funding such as research grants—directed toward public sector breeders. However, public breeders are often not responsible for seed production and marketing, resulting in slower rollout of new seeds.[21] Push funding may also result in crop innovations that do not meet farmer preferences—for example, varieties that require costly training to generate high yields.[22] This misalignment of incentives feeds back into the direction of innovation. Gaps remain between the needs of low-income farmers and the output of global crop innovation, which disproportionately favors high-income farmers and large-scale agriculture.[23] Addressing these frictions could have large positive spillovers, as those farmers often adopt practices via learning from their peers.[24]

Our Solution: Tie Funding to Adoption of Innovation

An advance market commitment (AMC), a type of pull funding mechanism, can address the insufficient incentives for developing climate-resilient crops. Pull mechanisms involve paying for outcomes—in this case, uptake of novel climate-resilient crop varieties—to incentivize firms to invest in research and development (R&D) despite the market failures identified earlier. In an AMC, funders agree to reward innovators based on the measured adoption of new crop varieties that meet a list of criteria called a **target product profile (TPP)**.[25] The TPP specifies performance benchmarks for increased climate resilience as well as minimum standards for other important traits like pest resistance and nutritional value. However, TPPs do not have to specify how crop varieties with the targeted traits will be developed, thereby allowing for various approaches to innovation. AMCs reward firms based on how widely their crop varieties are adopted, so firms are also incentivized to develop varieties that meet farmers' needs on other dimensions.

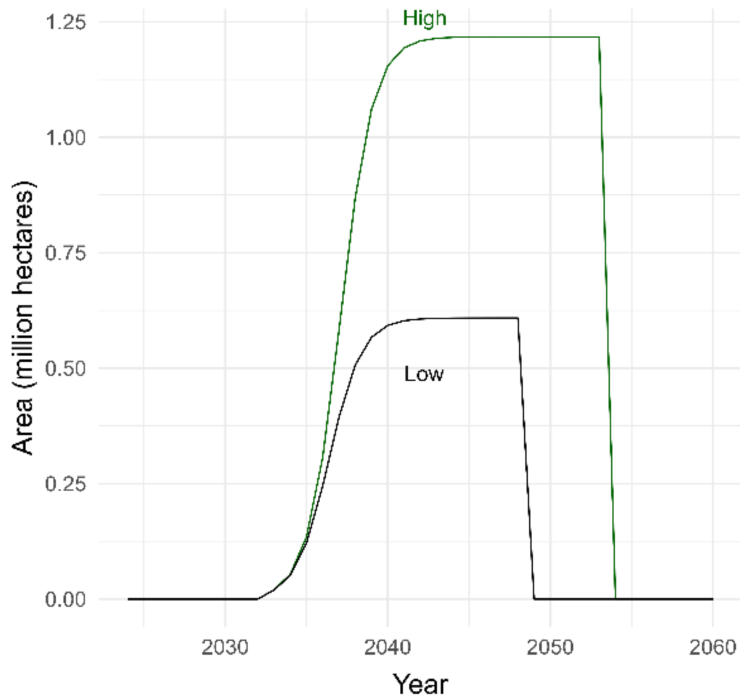
An AMC can play a critical role in incentivizing cutting edge research to improve agricultural outcomes. With breakthroughs such as CRISPR, advancements in RNA methylation and synthetic apomixis, there is a wealth of biotechnological innovation to harness for crop variety development. Applications of these innovations can significantly improve the resilience of agriculture to climate change. Relative to push funding, pull mechanisms have the additional advantage of attracting international firms who possess unique expertise in leveraging these new technologies. According to the Access to Seed Index, multinational seed corporations with a presence across Eastern and Southern Africa tend to sell varieties from their own breeding programs which result in a larger proportion of new variety releases relative to the breeding programs of regional companies.[26]

We model the benefits and costs of an AMC that incentivize the development and adoption of new heat-resilient crop varieties. We identify a subset of crops with high dietary importance for which genetic variety innovation has been neglected. Specifically, we choose crops that provide more than 2 billion calories annually (70th percentile) in any country and crops that had fewer than six new variety releases in any country (bottom 20th percentile). We further narrowed our list of crops to those for which we were able to identify well-established causal relationships between temperature and crop yields to form temperature-yield functions, following the approach of Burke and Emerick (2016).

We then define two technological pathways for improved heat resilience. First, we model heat resilience from conventional breeding as a 1°C increase in the temperature threshold above which yields start to decline. Second, we model an advanced technological pathway which, despite higher R&D costs, produces crop varieties that provide 8% yield gains in addition to increasing heat tolerance by 1°C.[27]

Next, we use the temperature-yield functions to estimate crop yields under low and high adoption rates across various climate scenarios. The low and high adoption scenarios follow S-shaped curves, plateauing at 5% and 10% of baseline harvested areas, respectively. The high adoption scenario lasts four additional years (see Figure 4). These assumptions are based on an analysis of the DIIVA database which tracks adoption rates for recent variety releases in sub-Saharan Africa.[28]

Figure 4: Assumed area of improved sorghum adopted by year



Source: MSA analysis. Underlying data from CROPGRIDS dataset (Tang et al. 2023)

We convert yield gains into economic gains by multiplying the yield gains across adopted hectares with current regional crop prices. These prices are calculated as the weighted average crop price of each country within a region, weighted by their production shares (see Appendix 4 for details). Notably, we do not model potential health and mortality effects, nor the welfare value of income gains due to the technical complexity of modeling these features.

To estimate the cost of innovation, we consider two AMC designs. First, we calculate the reward required to incentivize enough innovation attempts to reach a 70% probability of successfully developing and getting to market each new variety. Each stage of development features different costs and success probabilities, which are calibrated from existing literature on the cost of developing new crop traits.[29] The stages include discovery, field testing, regulatory approval, seed production, and marketing and distribution. We also account for the cost of validating the efficacy of new traits in randomized control trials (RCTs) and monitoring the uptake of the new crop variety. More details on our proposed AMC design and cost analysis, including a sensitivity analysis, can be found in the appendix.

Second, we study an alternative design in which we pool all crop-region pairs into a single AMC. In this **multi-target AMC** design, funders specify multiple crop variety targets and allow successful innovations to absorb funds initially allocated to unsuccessful targets. This design reduces the total reward size needed to spur innovation across several targets and reduces the risk that funders select targets that firms consider prohibitively infeasible or expensive. It also reduces the risk of promoting targets that do not respond to farmers' needs. We provide much more details of this design in Annex 2 of the Appendix.

Heat Tolerance Provides Billion Dollar Benefits

Table 1 below shows the estimated benefits of AMCs in West, Southern, and East Africa across different crops, adoption scenarios, and technology pathways. The table only includes crop-region pairs with estimated benefits exceeding $50 million in each scenario; Table A7 contains estimates for all modeled crop-region pairs.

Across all three scenarios, heat-resilient maize in West Africa and Southern Africa, and heat-resilient sorghum in East Africa provide the largest benefits, reaching up to $3 billion in the advanced technology scenario with high adoption. Heat-resilient West African sorghum and soybean varieties are also estimated to generate benefits exceeding $100 million. Benefits from heat-resilient groundnut and rice varieties are lower but generally exceed $100 million in the advanced technology scenario and the high adoption scenario. The variation in benefits across crops and regions is primarily driven by differences in crops' sensitivity to high temperature, predicted temperature changes, baseline harvested area, and crops' market prices. The notably larger benefits under high adoption assumptions illustrate the importance of uptake and scale.

For both conventional and advanced technologies, benefits exceed costs for most of our identified crops. Table 2 showcases estimated AMC costs for promising crop-region pairs (maize, sorghum, rice, and soybean). These costs represent the amounts that a funder would need to commit today to reward firms upon successful innovation. We did not model costs for AMCs targeting groundnuts because private sector firms have limited expertise in developing groundnuts and other vegetatively propagated crop varieties. Estimated aggregate costs of AMCs for conventionally bred heat-resilient crop varieties range from $50 million to $95 million.[30] For crop varieties bred with advanced technologies, costs are approximately four to six times higher, ranging from $302 million to $376 million, reflecting higher R&D costs and lower success probabilities due to potential regulatory barriers.

Table 1: Benefits of increase in heat tolerance (and yields for advanced technology) by crop/region

			Benefits (US$, millions) by adoption and technology		
Crop	**Region**	**Old to new temperature threshold**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Adoption (% of harvested area)			*5%*	*10%*	*10%*
Technology			*Conventional*	*Conventional*	*Advanced*
Maize	West Africa	29 to 30°C	900	2,277	3,223
Maize	Southern Africa	29 to 30°C	647	1,682	3,048
Sorghum	West Africa	33 to 34°C	294	761	1,213
Sorghum	East Africa	33 to 34°C	1,052	2,513	3,19
Groundnut	East Africa	30 to 31°C	63	161	612
Soybean	West Africa	29 to 30°C	149	350	407
Multi-target AMC			N/A	4,789	

Note: All estimates are discounted using a 2% discount rate. All estimates are rounded to the nearest million. Estimates are derived using projections from the RCP4.5 scenario, which represents a moderate emissions pathway. Adoption reflects peak adoption rates relative to total production of the specified crop in the specified region.

Table 2: Costs of each AMC by crop/region

			AMC Costs (US$, millions) by adoption and technology		
Crop	**Region**	**Old to new temperature threshold**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Adoption (% of harvested area)			*5%*	*10%*	*10%*
Technology			*Conventional*	*Conventional*	*Advanced*
Maize	West Africa	29 to 30°C	85	85	361
Maize	Southern Africa	29 to 30°C	94	94	376
Sorghum	West Africa	33 to 34°C	83	83	358
Sorghum	East Africa	33 to 34°C	82	82	355
Soybean	West Africa	29 to 30°C	52	52	305
Multi-target AMC			N/A	250	

Note: AMC costs represent the amount that a funder would need to commit today to reward firms upon successful innovation assuming 2% annual interest accrual on reserved funds. All estimates are rounded to the nearest million. Expected costs consider both the monetary cost and the probability of success at each stage of R&D.

West African maize and East African sorghum are the most cost-effective targets for a heat-resilient crop AMC (see Table 3). For both crop-region pairs, the estimated **benefit-cost ratios** are above 8 in the low adoption scenario and above 22 in the high adoption scenario. These benefit-cost ratios remain above five under robustness checks as indicated by bold highlighting. Generally, AMCs for conventionally bred crops are more cost-effective than AMCs for crops bred with advanced technologies, although the reverse is true for rice.

Targeting multiple crop variety innovations in a single AMC can reap greater dividends. We find that a $250 million fund size can yield benefit-cost ratio of 24.5 when targeting improves sorghum and maize varieties across East and West Africa. Notably, the probability that at least one successful innovation is obtained is significantly higher when pooling several crop variety targets.

Table 3: Benefit-costs ratios by crop/region

			Benefit-cost ratios by adoption and technology		
Crop	**Region**	**Old to new temperature threshold**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Adoption (% of harvested area)			*5%*	*10%*	*10%*
Technology			*Conventional*	*Conventional*	*Advanced*
Maize	West Africa	29 to 30°C	8.7	22.6	7.5
Maize	Southern Africa	29 to 30°C	5.7	15.3	7.1
Sorghum	West Africa	33 to 34°C	3.1	7.9	3.1
Sorghum	East Africa	33 to 34°C	10.4	25.7	7.7
Soybean	West Africa	29 to 30°C	2.6	5.9	1.4
Multi-target AMC			N/A	24.3	

Note: Benefit-cost ratios are calculated using the formula in Appendix 2. Estimates are derived using projections from the RCP4.5 scenario. Table values in bold indicate that the benefit-cost ratios remain larger than five and the marginal benefit-cost ratios remain larger than one under robustness checks to key AMC cost inputs. Details of the robustness analysis procedure can be found in Appendix 2. See Appendix 4 for benefit-cost ratios for all crop-region pairs meeting our selection criteria.

Key Takeaways

Our analysis demonstrates the potential of pull mechanisms, like advanced market commitments, to generate climate-resilient crop varieties that provide large benefits farmers in sub-Saharan Africa. We find that maize and sorghum stand out as especially cost-effective candidates. However, funders should also consider the neglectedness of different crops and technological pathways. For instance, maize innovation is less neglected than innovation for sorghum, as most breeding activities across sub-Saharan Africa focus on maize.[31] AMCs targeting crop variety development using advanced technology may also yield greater benefits as CGIAR and national research institutions already use conventional breeding techniques to develop new varieties. By incentivizing the innovation efforts of international seed corporations, an AMC can play a critical role in scaling up the development of advanced biotechnologies such as CRISPR, RNA methylation, and synthetic apomixis. Applications of these innovations has the potential to significantly improve the resilience of agriculture to climate change.

While our analysis focuses on the benefits of heat-resilience, other climate-related crop traits, such as tolerance to droughts, floods, diseases, pests, may also be valuable targets for an improved crop variety AMC. The World Meteorological Organization estimates that severe droughts have led to over $70 billion in economic losses in Africa over the past 50 years, with losses likely to increase further due to continued climate change.[32] Common crop diseases can be similarly devastating, with one estimate finding that cassava mosaic virus disease reduces African cassava yields by 24%, with some countries losing almost 50% of their yields.[33] Floods and pests also significantly harm agricultural output.[34,35] While we have not quantified benefits to greater crop resilience to these threats, they may be valuable to include in AMC target product profiles.

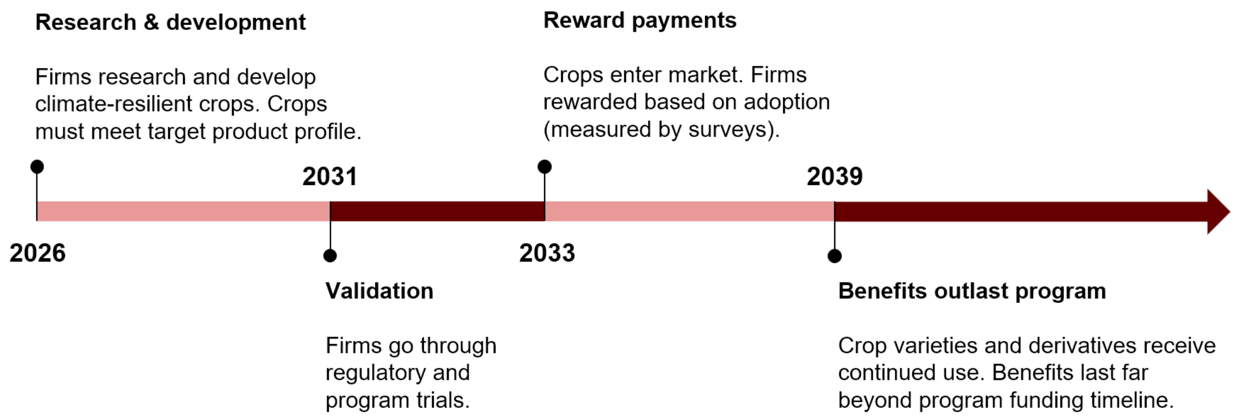
Appendix

Annex 1: Proposed AMC design

Proposed program timeline

A multi-stage pull mechanism could incentivize the development and large-scale adoption of climate-resilient crops. We envisage the following stages and timelines:

Figure A1: Timeline



1. **R&D and agronomic field trials (five years)**. Firms engage in R&D and demonstrate their crops have the desired properties (e.g., increased heat-tolerance) in agronomic field trials.
2. **Approval period (two years)**: We set aside two years for firms to seek regulatory approval in the relevant regions and countries.
3. **Randomized controlled trials ("RCTs") (three years):**[36] Firms demonstrate the impact of their crops through RCTs operating over three years, overlapping with the approval period for one year.
4. **Reward payments (five years)**: Firms are rewarded based on their crop variety's adoption over five years. Reward payments cover the costs of crop variety development and for technological failure and competition risk.[37] Reward payments begin after crop varieties have demonstrated their benefits (and lack of undesirable varietal attributes) in RCTs. In theory, funders should be able to reward parties at any point along the supply chain and expect that these parties will efficiently reward other members of the supply chain. For example, if the funder specifically rewards the firm that registers the new variety, this firm will have a higher willingness to pay for the variety from the breeder(s) and greater incentive to pay downstream firms that help increase adoption.[38]

5. **Monitoring (five years):** Adoption must be measured to be rewarded. Adoption is measured using farmer surveys and crop DNA fingerprinting. Monitoring will occur concurrently with reward payments.
6. **Benefits (16-21 years):** While the funding program will only last five years, the benefits will last longer. Firms continue to sell the seed as their fixed costs have been covered and farmers will have had time to learn about heat tolerance. In our low adoption scenario, we expect the improved variety to continue to be used and, therefore, provide benefits for 16 years. In our high adoption scenario, these benefits last 21 years.

Each step and its associated timeline are captured below in Figure A2:

Figure A2: Gantt chart

sual

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053
R&D and field trials			1	2	3	4	5																							
Approval period								1	2																					
RCT									1	2	3																			
Mileston payments										1																				
Reward payments												1	2	3	4	5														
Monitoring												1	2	3	4	5														
Benefits incurred										1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

Key
Conservative and aggressive
Aggressive only

Annex 2: Benefit-cost analysis methodology

2.1 Benefits

Crop yield modeling

We follow Schlenker and Roberts,[39] Burke and Emerick[40] and others by modeling the relationship between crop yields and temperature as a piecewise linear function of cumulative exposures to temperatures above given temperature thresholds, also known as "degree days." "Growing degree days" are a measure of the cumulative amount by which average daily temperatures exceed a base temperature under which a given crop doesn't grow, up to some threshold. "Exceedance degree days" (or "harmful degree days") refers to the cumulative amount by which average daily temperatures exceed a temperature threshold at which crop yields begin to decline. For our analysis, we identify yield functions in the academic literature parametrized in terms of growing degree days and exceedance degree days that use a similar set of controls and fixed effects to those used in Burke and Emerick's baseline specification. Table A1 below summarizes the turning points and yield function sources for each of the crops that we model.

Table A1: Yield function turning points and source

Crop	Base turning point	Source
Groundnut	30°C	Schlenker and Lobell (2010)
Maize	29°C	Burke and Emerick (2016)
Rice[41]	29°C	Deng, Xie, & Wang (2023)
Sorghum	33°C	Tack, Lingenfelser, and Jagadish (2017)
Soybean	29°C	Burke and Emerick (2016)

We model an increase in heat tolerance as a one degree increase in the temperature turning points separating growing degree days and exceedance degree days (see Figure 1 for a visualization of how our heat tolerance threshold increase affects predicted crop yields). To account for the fact that heat tolerance improvements may dissipate at extreme temperatures, we adjust the gradient of the exceedance degree days piecewise linear component for the heat tolerance variety to make its predicted` yields converge with the baseline variety at 40 degrees centigrade. For our "advanced" crop variety development scenario, we model an additional 8% gain in yields relative to the crop variety with an increased heat tolerance threshold.

Temperature projections

We obtain future temperature projections from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) CMIP5 dataset, which is comprised of high-resolution climate scenario projections from each of the 21 global climate models run under the Coupled Model Intercomparison Project Phase 5 (CMIP5). The NEX-GDDP climate projections increase the resolution of CMIP5 projections while correcting for local biases observed when comparing CMIP5 model projections to observational data.[42] We restrict our analysis to the RCP4.5 scenario, which represents a "stabilization" scenario in which total radiative forcing stabilizes shortly after 2100. We use daily average temperature as our measure of daily temperature from which we construct our degree day time series.

Each of the twenty-one models predict unique temperature pathways over our modeling time horizon (2024 to 2060) – and therefore different number of growing and exceedance degree days. We compute annual predicted growing and exceedance degree day exposures for each crop under each model's climate projection by summing daily growing and exceedance degree day projections during the crop's growing season. Data on crop growing seasons is obtained from Sacks, et al. dataset of global crop planting and harvest dates.[43] To obtain a central estimate of annual crop degree day exposures for each crop, we compute the simple average of the annual degree day exposure estimates across the twenty-one climate models.

Modeling future yields and economic gains
The yield functions we identify from the literature are generally estimated in setting outside of sub-Saharan Africa, raising concerns about their validity in our domain of interest. To mitigate external validity concerns, we do not directly predict yields using the identified yield functions, but instead use the degree day coefficients from the baseline and improved variety yield functions to project future sub-Saharan Africa yields from current yields observed in FAO data. For each crop, we compute current yield estimates at the regional level by taking the weighted average of the most recent yield observation for each country using the country's output of the crop as weights.

To estimate economic gains from heat resilient varieties, we consider two different adoption scenarios: a low scenario in which improved crop variety adoption follows an S curve that plateaus at 5% of the crop's current growing area, and an high scenario in which the improved variety's adoption follows an S curve plateauing at 10% of the current growing area.[44] As our rice yield functions most closely correspond to upland rice varieties we subset to share of rice growing area corresponding to upland rice (40%).[45]For each scenario, we compute the difference in predicted crop output from the baseline and improved crop varieties. We then multiply these differences by the current regional crop price as observed in FAOSTAT data. We discount economic benefits estimates at 2% per year starting from 2026.

We emphasize that our benefits estimates only consider the market value of improved yields under moderate future warming projections. This omits several important considerations for the value of benefits provided by climate-resilient crop varieties, such as the marginal value of income to sub-Saharan African farmers, and the potential health or mortality benefits of improved crop yields.

2.2 Funder costs

The cost of an AMC for heat-resilient crops has five components: a pull fund, an initial marketing subsidy, RCT costs, and monitoring costs.

Pull fund

The pull fund rewards firms for developing new crops based on their level of adoption. We model the objective of the pull fund as incentivizing sufficient firms to attempt crop innovation to yield a 70% chance that at least one heat-resilient variety is successfully brought to market. The reward must be large enough to incentivize enough firms to incur the direct costs associated with crop variety innovation attempts and accept the risk of innovation failure and competition from other participating firms.

We model firms' innovation attempts as consisting of a sequence of stages with associated costs and probabilities of success. When deciding to enter, innovators consider the number of competitors they expect to face. If multiple innovators are successful, the AMC fund is split equally among all the winners. The entry of additional firms thus reduces the expected payoff of each individual firm, while expected costs remain constant because costs are not shared between competing firms. The equilibrium is characterized by a free entry condition in which firms keep entering until the expected profit of each firm is driven to zero.

Our cost and probability of success inputs, primarily based on Bullock, et al.[46] and conversations with experts, can be found in Table A2 and A3. We use the probability that a single innovation attempt succeeds to back out the number of firms required to reach the funder's target probability of at least one success. Next, we estimate the cost of each stage for an innovation attempt by multiplying the stage cost by the probability that an attempt reaches that stage. We account for opportunity and borrowing cost by adjusting costs by a 9% internal rate of return relative to the pull fund payout date.[47] We then sum expected costs across stages to obtain the total cost of an innovation attempt. We reach a final pull fund size estimate by multiplying the cost of innovation attempts by the number of innovation attempts required to reach the targeted probability and divide by the targeted probability to adjust for technical failure risk.

A key component of a pull fund is that firms are only rewarded if their variety is adopted by farmers. The pull fund will therefore not be expended should no firm develop a crop with the desired traits.

Table A2: Conventional breeding RCT stages and probability of success

Phase	Start year	Number of years	Firms cost per candidate ($)	Probability of success (%)
Variety development and validation	2026	5	$5,000,000	90%
Regulatory approval	2031	2	$300,000	80%
RCT	2032	3	$4,500,000	70%
Overall success	***N/A***	***10***	***$10,000,000***	***50%***

Table A3: Advanced breeding technology RCT stages and probability of success

Phase	Start year	Number of years	Firms cost per candidate ($)	Probability of success (%)
Discovery	2026	1	$2,000,000	25%
Creation of genome edited lines	2027	1	$2,000,000	50%
Field validation and testing	2028	2	$2,000,000	75%
Seed production and pre-launch	2030	1	$2,000,000	90%
Regulatory approval	2031	2	$1,000,000	90%
RCT	2032	3	$4,500,000	80%
Overall success	***N/A***	***10***	***$13,500,000***	***6%***

Marketing costs

In addition to the crop variety development costs above, we also model the costs of firms marketing their varieties to achieve adoption. We model marketing costs as consisting of expenditures on field days to achieve adoption on the farms that adopt their seeds within the first four years. Additional adoption is then driven by social information sharing and learning. We estimate the total cost of field days by multiplying the cost of a field day per hectare by the number of hectares on which new crop yields are adopted. Our field day cost per hectare estimate is based on Emerick and Manzoor.[48]

RCT costs

Firms will have to demonstrate the heat tolerance benefits of the new varieties they develop to meet the target product profile. The target product profile will require firms to contract with pre-approved vendors that conduct agricultural randomized control trials (RCTs) to ensure trials are of high quality. RCT costs are estimated at ~$1.5 million per year for three years covering three countries.[49]

Monitoring costs

Firms will make reward claims based on the extent to which their crop variety is adopted. Adoption must be measured. Monitoring will entail crop DNA fingerprinting and a manual survey of farmer practices. DNA sampling is especially necessary as since previous research suggests that farmers are not always aware of the exact variety they are using.[50] Total monitoring costs are estimated at ~$450k per year for five years.

Robustness analysis

We identify key parameters that we are uncertain about for sizing our pull mechanisms. For each chosen parameter, we define a scenario varying the parameter and calculate the required pull fund size and number of entrants required to reach a target probability, and further obtain the benefit-cost ratio and marginal benefit-cost ratio. Tables A4 and A5 below summarize the robustness scenarios we model for a conventional and advanced technology AMC, respectively.

Table A4: Robustness analysis scenarios for conventional breeding AMC

Sensitivity scenario	Pipeline probability of success (%)	Pipeline annual cost ($)	RCT probability of success (%)	Regulatory approval probability of success (%)
Default	90%	1,000,000	50%	80%
Low pipeline probability of success	50%	1,000,000	50%	80%
High cost	90%	1,500,000	50%	80%
Low RCT success probability	90%	1,000,000	43%	80%
Low regulatory success probability	90%	1,000,000	50%	60%

Table A5: Robustness analysis scenarios for advanced technology AMC

Sensitivity scenario	Technological failure risk	RCT probability of success	Trait identification probability of success
Default	10%	80%	25%
Technological failure risk	25%	80%	25%
Low RCT success probability	10%	50%	25%
High trait identification probability of success	10%	80%	50%

We use our cost model to estimate the pull mechanism size required to reach a 70% probability of success under each sensitivity analysis scenario and recalculate benefit-cost ratios and marginal benefit-cost ratios with these cost numbers. Table 3 bolds the benefit-cost ratio value which remain above five under each of our sensitivity analysis scenarios.

2.3 Benefit-cost ratio

Pull mechanism are unique investment opportunities in that funders either receive the social return of successful innovation or, should no firm succeed at innovation, the chance to spend their funds on other opportunities at a later date. We therefore calculate benefit-cost ratios using the following formula

$$BCR = \frac{p \cdot B + (1-p) \cdot F \cdot \gamma}{F}$$

where *p* is the probability that at least one firm succeeds at innovation, *B* are the benefits should the innovation succeed, *F* is the funder's budget, and *γ* is the social ROI of the funder's marginal alternate investment opportunity. For our estimates, we set *γ* = 1, which is the most conservative assumption. Our formulation here also abstracts from considering funder discount rates. A more extensive treatment of the benefit-cost ratio is available upon request.

2.4 Multi-target AMC design

In our analysis, we also consider a single advanced market commitment that covers all possible innovations (crop-region pairs) simultaneously. The key motivating idea is that if an innovation fails, funds that were initially allocated to that innovation can be reallocated to successful innovations. The potential benefit is that the funder is less likely to leave money unspent on the table when innovations fail, effectively sharing risk across innovations. This increases the expected payout of each innovation and encourages more firm participation.

Since we are pooling different crop-region pairs and different technology pathways, the probability of success and the expected cost of innovation are going to vary. The amount of money that an innovation gets from the funder upon success is now a function of the success of all of the other innovations. If all innovations succeed, each innovation gets a lower bound corresponding to what that innovation would've gotten in a separate AMC. If only one innovation succeeds, that innovation gets the entire fund. Anything between that, and each innovation gets a weighted share of the total fund.

On the firm side, we maintain the assumption that firms are homogeneous and decide to enter based on a free-entry condition that drives expected firm profits to zero. In this context, an equilibrium must satisfy two criteria: expected profits are at least greater than expected costs for each firm entering, and no firm has an incentive to deviate, such that a marginal firm would find it unprofitable to enter. The expected payout by the funder is then straightforward: either at least one innovation succeeds, in which case the funder pays the entire pool, or no innovation succeeds, and the funder pays nothing. It should be noted that this design can be generalized.

In our analysis, given a $250 million fund pledged by the funders, we were able to find an equilibrium that incentivizes three firms that enter to develop sorghum for East Africa and three firms that enter to develop maize for West Africa, all using conventional breeding. This is in no way the only equilibrium, but our calculations show the potential benefits of such a design.

Appendix 3: Country-region pairings

Table A6 below is a list of our definitions of country-region pairs. Countries are paired to the region associated with their regional economic communities updated as of August 2023. The list includes both member and suspended member states. To align regions with regional economic communities, we define East Africa as Common Market for Eastern and Southern Africa (COMESA) countries minus any countries that are also members of the Southern African Development Community (SADC).

Regional economic communities provide an opportunity for wider scale-up since seed regulations are harmonized through regional economic communities. This is important because varieties developed for one country may provide benefits in other regions.

Table A6: Country-region pairings

Country	Region	Regional Economic Community

Benin	West Africa	ECOWAS
Burkina Faso	West Africa	ECOWAS
Cabo Verde	West Africa	ECOWAS
Côte D'Ivoire	West Africa	ECOWAS
Gambia	West Africa	ECOWAS
Ghana	West Africa	ECOWAS
Guinea	West Africa	ECOWAS
Guinea-Bissau	West Africa	ECOWAS
Liberia	West Africa	ECOWAS
Mali	West Africa	ECOWAS
Niger	West Africa	ECOWAS
Nigeria	West Africa	ECOWAS
Senegal	West Africa	ECOWAS
Sierra Leone	West Africa	ECOWAS
Togo	West Africa	ECOWAS
Angola	Southern Africa	SADC
Botswana	Southern Africa	SADC
Comoros	Southern Africa	SADC
Democratic Republic of Congo	Southern Africa	SADC
Eswatini	Southern Africa	SADC
Lesotho	Southern Africa	SADC
Madagascar	Southern Africa	SADC
Malawi	Southern Africa	SADC
Mauritius	Southern Africa	SADC
Mozambique	Southern Africa	SADC
Namibia	Southern Africa	SADC
Seychelles	Southern Africa	SADC
South Africa	Southern Africa	SADC
Tanzania	Southern Africa	SADC
Zambia	Southern Africa	SADC
Zimbabwe	Southern Africa	SADC
Burundi	East Africa	COMESA

Djibouti	East Africa	COMESA
Egypt	East Africa	COMESA
Eritrea	East Africa	COMESA
Ethiopia	East Africa	COMESA
Kenya	East Africa	COMESA
Libya	East Africa	COMESA
Rwanda	East Africa	COMESA
Sudan	East Africa	COMESA
South Sudan	East Africa	COMESA
Uganda	East Africa	COMESA

Note: The countries' listed regional economic communities are updated as of August 2023. The list includes both member and suspended members. East Africa is defined as COMESA minus SADC.

Appendix 4: Complete benefit-cost tables

Table A7: Benefits of 1-degree increase in heat tolerance by crop/region (all crop/region pairs)

			Benefits (US$, millions) by adoption and technology		
Crop	**Region**	**Old to new temperature threshold**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Adoption (% of harvested area)			*5%*	*10%*	*10%*
Technology			*Conventional*	*Conventional*	*Advanced*
Maize	West Africa	29 to 30°C	900	2,277	3,223
Maize	Southern Africa	29 to 30°C	647	1,682	3,048
Sorghum	West Africa	33 to 34°C	294	761	1,213
Sorghum	East Africa	33 to 34°C	1,052	2,513	3,190
Sorghum	Southern Africa	33 to 34°C	11	29	75
Rice	West Africa	29 to 30°C	21	55	507
Rice	East Africa	29 to 30°C	3	7	68
Rice	Southern Africa	29 to 30°C	6	16	164
Groundnut	East Africa	30 to 31°C	63	161	612
Groundnut	West Africa	30 to 31°C	58	149	502
Groundnut	Southern Africa	30 to 31°C	14	37	222
Soybean	West Africa	29 to 30°C	149	350	407

Note: All estimates are discounted using a 2% discount rate. All estimates are rounded to the nearest million. Estimates are derived using projections from the RCP4.5 scenario, which represents a moderate emissions pathway. Adoption reflects peak adoption rates relative to total production of the specified crop in the specified region.

Table A8: Costs of each AMC by crop/region (all crop-region pairs)

			AMC Costs (US$, millions) by adoption and technology		
Crop	**Region**	**Old to new temperature threshold**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Adoption (% of harvested area)			*5%*	*10%*	*10%*
Technology			*Conventional*	*Conventional*	*Advanced*
Maize	West Africa	29 to 30°C	85	85	361
Maize	Southern Africa	29 to 30°C	94	94	376
Sorghum	West Africa	33 to 34°C	83	83	358
Sorghum	East Africa	33 to 34°C	82	82	355
Sorghum	Southern Africa	33 to 34°C	53	53	307
Rice	West Africa	29 to 30°C	59	59	316
Rice	East Africa	29 to 30°C	50	50	302
Rice	Southern Africa	29 to 30°C	53	53	307
Groundnut	West Africa	30 to 31°C	69	69	333
Groundnut	East Africa	30 to 31°C	54	54	308
Groundnut	Southern Africa	30 to 31°C	58	58	315
Soybean	West Africa	29 to 30°C	52	52	305

Note: AMC costs represent the amount that a funder would need to commit today to reward firms upon successful innovation assuming 2% annual interest accrual on reserved funds. All estimates are rounded to the nearest million. Expected costs take into account both the monetary cost and the probability of success at each stage of R&D. We do not include estimated AMC costs for groundnut as we do not think private companies have a comparative advantage in developing new groundnut varieties.

Table A9: Benefit-costs ratios by crop/region (all crop/region pairs)

			Benefit-cost ratios by adoption and technology		
Crop	**Region**	**Old to new temperature threshold**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Adoption (% of harvested area)			*5%*	*10%*	*10%*
Technology			*Conventional*	*Conventional*	*Advanced*
Maize	West Africa	29 to 30°C	8.7	22.6	7.5
Maize	Southern Africa	29 to 30°C	5.7	15.3	7.1
Sorghum	West Africa	33 to 34°C	3.1	7.9	3.1
Sorghum	East Africa	33 to 34°C	10.4	25.7	7.7
Sorghum	Southern Africa	33 to 34°C	0.5	0.8	0.5
Rice	West Africa	29 to 30°C	0.6	1.1	1.6
Rice	East Africa	29 to 30°C	0.3	0.4	0.5
Rice	Southern Africa	29 to 30°C	0.4	0.5	0.7
Groundnut	West Africa	30 to 31°C	1.0	2.1	1.6
Groundnut	East Africa	30 to 31°C	1.2	2.8	2.0
Groundnut	Southern Africa	30 to 31°C	0.5	0.8	0.9
Soybean	West Africa	29 to 30°C	2.6	5.9	1.4

Note: Benefit/cost ratios are calculated using the methodology described in Appendix 2. All benefit-cost ratio estimates are calculated using non-rounded benefits and cost numbers and are rounded to the nearest tenth. Estimates are derived using projections from the RCP4.5 scenario, which represents a moderate emissions pathway. Table A9 values in bold indicate that the benefit-cost ratios remain larger than five and the marginal benefit-cost ratios remain larger than one under robustness checks to key AMC cost inputs. Details of the robustness analysis procedure can be found in Appendix 2.

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Endnotes

[1] This is a draft document for comment which MSA will update periodically.
[2] Dowd-Uribe, Rock, Spreadbury, Chiril, and Uminsky (2023)
[3] This piecewise linear modeling yield functions is widespread in the agricultural economics literature (Miller, et al., 2021, Hsiang, 2016, Burke and Emerick, 2016), Moreover, it has shown to be a robust approximation to more flexible functional form assumptions such as higher-order polynomials (Schlenker and Roberts, 2016).
[4] Degree days above 29°C are harmful for maize (Burke and Emerick, 2016). Degree days above 30°C are harmful for groundnuts (Schlenker and Lobell, 2010). Degree days above 29°C are harmful for rice (Deng, et al., 2023). Degree days above 33°C are harmful for sorghum (Tack, et al., 2017)
[5] Hultgren, et al., 2022. See Table 1.
[6] Hannah Ritchie (2024) - "How will climate change affect crop yields in the future?" Published online at OurWorldinData.org. Retrieved from: 'https://ourworldindata.org/will-climate-change-affect-crop-yields-future' [Online Resource]
[7] Hadebe, et al., 2017
[8] Wollburg, et al., 2024, Suri and Udry, 2022, Ritchie, 2022, Tian and Yu, 2019

[9] These yield-temperature functions are rough approximations. For rice, we are using a yield temperature function estimated for "middle rice" in China and applying it to the proportion of rice in West Africa covered by lowland varieties.
[10] RCP4.5 is one of the RCPs adopted by the Intergovernmental Panel on Climate Change. To estimate temperatures, we use.a straight average of 21 climate models. Each model is weighted equally in our analysis. The complete list of models includes the following: ACCESS1-0, bcc-csm1-1, BNU-ESM, CCSM4, CESM1-BGC, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, NorESM1-M.
[11] Ariga, et al., 2019
[12] McGuire and Sperling, 2016; Kremer and Zwane, 2005, Kuhlmann and Dey, 2021. According to Masuka, et al., 2017, OPVs are a significant share of the maize sector in Sub-Saharan Africa .
[13] Bohr et al 2024
[14] McGuire and Sperling (2016); The Rise of the Seed-producing Cooperative in Western and Central Africa (2018)
[15] Carter et al 2021; Boucher et al 2024
[16] These descriptive statistics are based on an initial analysis of the CGIAR DIIVA database, which tracks varietal releases and variety adoption in Sub-Saharan Africa. The International Food Policy Research Institute maintains this data.
[17] Gatto, Marcel, et al. "Trends in varietal diversity of main staple crops in Asia and Africa and implications for sustainable food systems." *Frontiers in Sustainable Food Systems* 5 (2021): 626714.
[18] The modern variety growing area as a percentage of total crop's growing area comes from the DIIVA database (see earlier endnote for more details).
[19] Gatto, Marcel, et al. "Trends in varietal diversity of main staple crops in Asia and Africa and implications for sustainable food systems." *Frontiers in Sustainable Food Systems* 5 (2021): 626714.
[20] Alston, et al., 2022
[21] Kuhlmann and Zhou, 2016
[22] One such example is the NERICA-3 experiment in Sierra Leone, in which untrained farmers who adopted the improved rice variety saw a 14% decline in yields. See Glennerster, et al., 2016.
[23] Puerto, 2024
[24] Carter, et al., 2014, Conley and Udry, 2010
[25] According to Gitonga, et al., 2023, CGIAR estimates open-pollinated maize varieties – which yield less than hybrids – comprise over 90% of the market in every West African country except for Nigeria, where they account for 60-70% of the market.
[26] Access to Seed Index – Eastern and Southern Africa portfolio
[27] We believe this is reasonable given that many CGIAR crop variety target product profiles listed on the Global Market Intelligence Platform target yield gains from variety improvements ranging from 5% to 25%. Furthermore, the five-year window we assume for R&D and the generally low yields in Sub-Saharan Africa. Many crops have experienced annual yield growth of 1% or greater elsewhere – see discussion in Xu, et al., 2017. Chen, et al., (2002) finds a ~8% yield boost from gene-editing for maize and rice, though it is looking at hybrid lines.
[28] CGIAR DIIVA Database
[29] Bullock, et al., 2021
[30] This is based on pull mechanism cost estimates for maize, sorghum, and rice.
[31] Access to Seeds Index 2019 Synthesis Report
[32] World Meteorological Organization, "2021 State of Climate Services: Water."
[33] Legg, et al., 2006
[34] World Health Organization, "State of the Climate in Africa 2023."
[35] Neuenschwander, et al., 2023
[36] The current timetable assumes a one-year overlap between the approval period and the RCT period.
[37] The cost estimates assume that each firm earns 50% of the new market created by each crop-region pair's program. As stated previously, we have modeled low and high adoption scenarios. In the low scenario, we assume that all varieties developed through the program will collectively capture 5% of the total crop-region market at peak adoption. The high adoption scenario doubles this figure to 10%. Given our assumption of 50% market share, this translates to individual firm market shares of 2.5% and 5% at peak adoption for the low and high adoption scenarios, respectively.
[38] Kremer and Zwane, 2005 discuss rewarding firm that first registers variety.
[39] Schlenker and Roberts, 2009
[40] Burke and Emerick, 2016

[41] We use the yield function estimated for middle rice in Deng, et al., 2023 as middle rice most closely corresponds to the upland rice variety grown in West Africa (which is the region with the largest rice production in Sub-Saharan Africa).
[42] Thrasher, et al., 2012
[43] Sacks, et al., 2010
[44] Crop harvest areas are obtained from Tang, et al., 2024
[45] Maclean, et al., 2013
[46] Bullock, et al., 2021
[47] Our 9% internal rate of return assumption is based on the average corporate discount rate estimated in Kilian and Huber (forthcoming) after accounting for corporate cash flow accounting errors and inflation expectations. Gormsen, Niels Joachim, and Kilian Huber. "Corporate Discount Rates." Working Paper. Working Paper Series. National Bureau of Economic Research, June 2023. https://doi.org/10.3386/w31329.
[48] Emerick and Dar, 2021
[49] Conversations with academic agricultural RCT experts gave us annual RCT cost estimates ranging from $150,000 to $300,000. We conservatively adjust upward to $500,000 per year to account for private sector RCT vendor premiums, and multiply by three under the assumption that the RCT will be conducted across three countries in each region.
[50] Bohr et al 2024