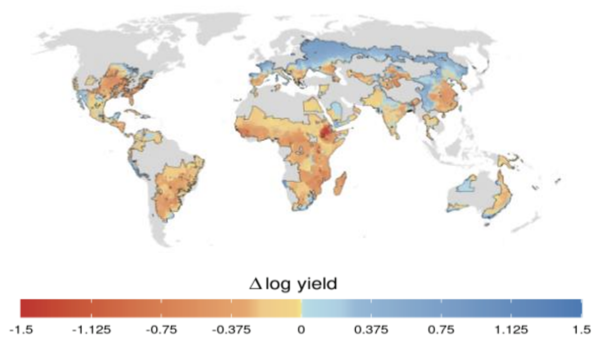
THE UNIVERSITY OF CHICAGO
MARKET SHAPING ACCELERATOR

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

Executive Summary

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



The increase in high-heat days, droughts, and floods resulting from climate change will cause falling yields for crops critical to the nutrition and livelihoods of hundreds of millions in Sub-Saharan Africa. The development and widespread adoption of crops with 1-degree greater heat tolerance would save billions of dollars of production. But such climate-resilient traits are often hidden to farmers and, therefore, crops with such traits do not always command a premium until well established. This cuts private R&D investment and delays uptake. Subsidies to develop and promote heat-tolerant sorghum could generate $6 in benefits for every $1 spent.

We identify the crops and regions in Sub-Saharan Africa with high social return on investment in heat resilience: those most vulnerable to projected climate change, feed the most people, and have fewer variety releases. We calculate the net social return of each investment by combining data on crop yield and calories, climate projections, crop heat tolerance, variety releases, and the costs of spurring innovation.

The massive scale of the challenge requires investment from both private and public sectors. Public research institutions are already investing in climate-resilient crops, but much more investment is needed.

i. **Where the private sector has expertise, Advance Market Commitments can crowd in private investment to develop and, critically, disseminate climate-resilient crops.** Examples include cereal crops such as maize, sorghum, and rice where there are firms that could respond to targeted incentives. These crop priorities align relatively well with previous research. The benefits of heat-resilient sorghum alone would be between $269 million to $974 million depending on the extent of take-up and gain in yield. These benefits are realized over 16 and 21 years, respectively.

ii. **CGIAR and national agriculture research institutions must also play a critical role.** The private sector has relatively limited expertise in developing certain crops including vegetatively propagated crops such as sweet potatoes and cassava. Groundnuts also appear neglected by the private sector. The CGIAR and public sector are relatively more present than the private sector in developing these crops in Sub-Saharan Africa. These crops also have typically seen much less innovation per hectare in Sub-Saharan Africa compared to Asia. Public research centers will also be critical in cooperating with the private sector to respond to incentives to develop and distribute new climate-resilient crops.

Table 1 shows the modeled benefits of climate-resilient crop innovation for selected priority crops.

Table 1: Benefits of 1-degree increase in heat tolerance by crop/region

			Benefits (US$, millions) by adoption and technology		
Crop	**Region**	**Old to new temperature threshold**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Adoption			*Low*	*High*	*High*
Technology			*Conventional*	*Conventional*	*Ambitious*
Maize	Southern Africa	29 to 30°C	564	1,421	2,367
Sorghum	West Africa	33 to 34°C	269	668	974
Rice	West Africa	29 to 30°C	27	68	384
Groundnut	West Africa	30 to 31°C	47	118	377
Groundnut	Southern Africa	30 to 31°C	14	35	162

Note: All estimates are discounted using a 3% discount rate. All estimates are rounded to the nearest million.

The table shows the modeled benefits of climate-resilient crop innovation under different scenarios. The table sets out the benefits under both low (plateauing at 5%) and high (plateauing at 10% and persisting for longer) adoption assumptions. We model the conventional technology as delivering a one degree increase in heat tolerance. We model the ambitious technology as delivering a one degree increase in heat tolerance with an additional 8% boost in yields. We assume that a larger reward size is required to incentivize ambitious technology relative to the reward size needed to incentivize conventional technology.

The Return to Investing in Climate-resilient Crops

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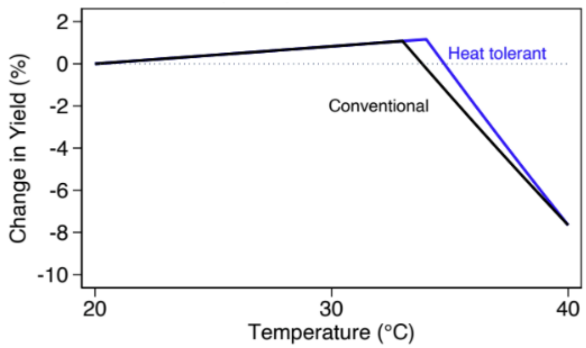
Description of analysis

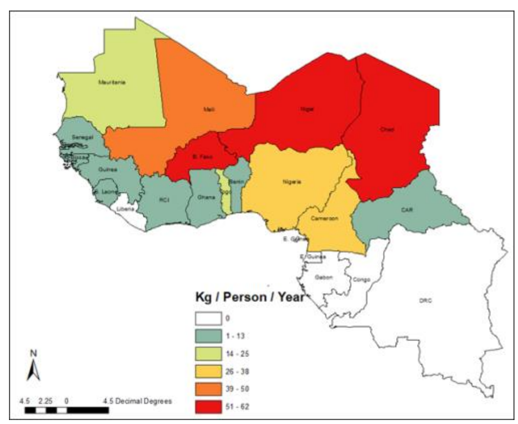
Figure 1: Change in sorghum yield by growing degree day temperature



Source: Tack, Lingenfelser, and Jagadish, 2017.

Increased heat will reduce crop yields. Crop yields are a function of temperature. Figure 1 shows the change in sorghum yields from an additional day at a given temperature relative to a day at 20°C. Beyond a turning point, higher temperatures reduce yields. End-of-century yield losses in Sub-Saharan Africa are estimated to be 45 percent in the absence of adaptation and economic development. Even factoring in current projections of climate adaptation and development, end-of-century losses in Sub-Saharan Africa are still estimated to be 28 percent.[ii]

Figure 2: Annual per capita consumption of sorghum



Key staple crops such as maize, sorghum, rice, and groundnuts are vulnerable. Their yields will fall as the number of high heat days increases (see Figure 2 for a map of annual per capita consumption of sorghum, a staple crop in West Africa).[iii] Degree days above 29°C are harmful for maize.[iv] Degree days above 30°C are harmful for groundnuts.[v] Degree days above 29°C are harmful for rice.[vi] Degree days above 33°C are harmful for sorghum.[vii] In addition, up to 60% of Sub-Saharan Africa is vulnerable to persistent drought.[viii] Stagnating yields over the last 60 years have further left households in Africa highly vulnerable to climate shocks.[ix]

These crops would benefit from greater innovation and scale-up. There have been relatively few variety releases of sorghum, rice, and groundnuts in many countries.

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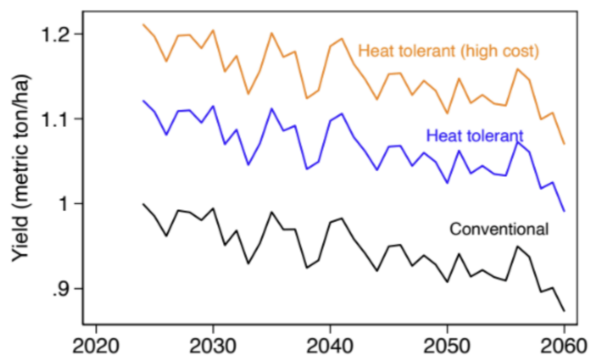
Maize is less neglected, but it is a significant source of calories. Some countries have seen few releases of maize, such as the DRC, and would benefit from new releases and farmer uptake.

Increasing the heat tolerance of crops by just 1 degree could dramatically reduce the yield losses caused by climate change. By using yield-temperature functions from the literature and modeling the impact of raising their threshold turning points alongside climate model forecasts, we can demonstrate the effect of increasing the heat threshold for a crop.[x] Benefits are estimated by calculating the expected gain in crop yields multiplied by their regional price. However, there will also be present-day benefits as high heat is already reducing yields.

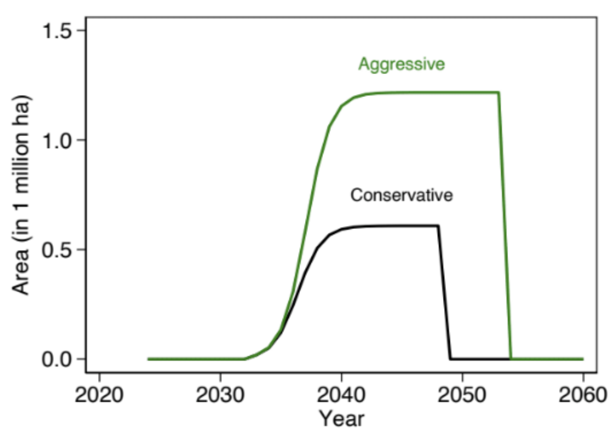
Figure 3: Estimated sorghum yield by year in Western Africa (ECOWAS)



Sources: Baseline yield: FAOSTAT. Yield function: Tack, Lingenfelser, and Jagadish, 2017. Climate projections: Andrew Hultgren and the Climate Impact Lab.

The benefits of climate-resilient crop innovation are large. The gains from adopting heat-tolerant varieties are large but depend on the extent of uptake: the high adoption assumptions follow an initial S-shaped adoption curve that plateaus at 10% of the growing area between 2043-2053 and ceases in 2054 (see Figure 4). The low adoption assumptions also follow an initial S-shaped adoption curve that plateaus at 5% of the growing area between 2043-2048 and ceases in 2049 (see Figure 4). Even under the conventional breeding technology assumptions, the benefits of increased heat tolerance of sorghum in West Africa are \$269 million, rising to \$668 million if uptake is high. The variation in benefits between crops is primarily driven by differences in each crop's selling price, baseline area of production, yield, and vulnerability to forecasted temperature increases in the region. The much larger benefits under high adoption assumptions illustrate the importance of uptake and scale. The benefits could be even larger in worse climate change scenarios with higher temperatures.

Figure 4: Assumed area of improved sorghum adopted by year



Source: Crop area: CROPGRIDS dataset (Tang et al, 2023).

Modern breeding technologies would speed up breeding cycles (enabling greater genetic gains) and allow the combination of different desirable traits. Researchers in Kenya are working on using CRISPR gene-editing to develop a variety of sorghum that is resistant to witchweed. Furthermore, Kenya, Nigeria, and Malawi have introduced a regulatory framework for the use of gene-edited crops.[xi] Beyond gene editing, there are gains to be made through greater use of advances such as genomic selection and double haploid technology. We separately model the benefits and costs of a program that incentivizes the use of modern breeding technologies, which we refer to as "ambitious" technologies. Specifically, we model the benefits of ambitious technologies as an 8% increase in yields in addition to one degree increase in heat tolerance.[xii] We assume that a larger reward size is required to incentivize the use of ambitious technology. Under the ambitious technology assumptions, the benefits of heat-tolerant sorghum with high adoption would then rise to $974 million.

Commercial markets underinvest in climate-resilient crop innovation in low-income countries despite these crops offering large social benefits for several reasons. First, many poor farmers in Sub-Saharan Africa reuse, share, and informally trade open and self-pollinated varieties.[xiii] Second, farmers may be reluctant to pay for hidden climate-resilient traits without learning or experience.[xiv] This makes it difficult for firms to command high enough prices to recoup their R&D costs.[xv] Firms also lack incentives to market open and self-pollinated varieties that do not generate regular purchases.

An Advance Market Commitment ("AMC"), a type of "pull" incentive, could help address these market failures and unlock large benefits. Pull funding involves paying for outputs or outcomes such as high uptake of new crops. Funders could promise in advance to reward firms based on the measured adoption of open-pollinated and self-pollinating heat-tolerant crop varieties that meet the target product profile. A target product profile could include minimum climate-resilience thresholds and yield thresholds. Since an AMC would pay proportional to adoption, it would incentivize firms to develop and market varieties that appeal to farmers. The AMC would be intended to cover firm costs of R&D and marketing. Farmer field days, informing agro-dealers about new seed varieties, and digital advice could be cost-effective ways to market climate-resilient seeds.[xvi]

Realizing the potential of climate-resilient crops calls for a combination of "push" and "pull" funding. Push funding involves directly paying for inputs. An example of push funding is direct research grants to public sector breeders. This includes push funding for the CGIAR system and national agriculture research institutions. A previous meta-analysis suggests the past CGIAR research portfolio generated a benefit-cost ratio on the order of 10:1.[xvii] Push funding is particularly important for crops and regions where the private sector is relatively absent. Cramer (2019) notes, "Supply systems vary depending on the type of crop, with hybridized row crops, cereals, and legumes being of greater interest to the private seed sector compared to vegetatively propagated species such as sweet potato and cassava."[xviii] Ariga (2019) notes, "Maize often leads development of the seed sector, followed closely by other grains, while pulses and vegetatively propagated crops lag behind."[xix] Groundnuts also appear to be neglected by the private sector.[xx] These crops have also typically seen less innovation per hectare in Sub-Saharan Africa than in Asia.[xxi]

Push funding is not enough. Public breeders are often not responsible for seed production and marketing, resulting in slower progress in seed sectors throughout many African countries.[xxii] The large number of adaptations (heat, drought, flood, and saline tolerance) that are needed for multiple crops means it is important to crowd in expertise from both private and public funders. Increased push funding should therefore be combined with stronger pull incentives that tie incentives to outputs including high uptake of new crops, which encourages investment in marketing and distribution as well as the development of crops that are adapted to the needs of farmers. [xxiii] This will help ensure faster uptake of new crops and leverage private sector investment and know-how but will require close cooperation with public sector research centers. A temporary subsidy from a pull incentive would enable farmers to learn about the benefits and profitability of the crop.[xxiv]

Pull incentives would also have the advantage of attracting international firms. Such firms will have the capabilities to apply modern technologies to the challenge of developing climate-resilient crops. The Access to Seed Index reports it is mainly global companies that sell varieties from their own breeding programs in Eastern and Southern Africa.[xxv] The ambitious technology, high-cost scenario includes reward payments intended to be sufficiently large to attract capable international firms.

Regional economic communities provide an opportunity for wider scale-up. The initial prioritization analysis was based on country-level data about variety releases and measures of caloric output. We present the current analysis at a regional level as new varieties may also be suited to other areas with similar agro-ecological conditions. In addition, seed regulations are harmonized through regional economic communities such as ECOWAS and SADC. This provides an opportunity for regional scale-up.

Estimated aggregate costs of incentivizing the development and marketing of heat-resilient varieties through pull incentives range from ~$44 million to ~$176 million discounted and ~$64 million to ~$261 million undiscounted.[xxvi] These estimates are intended to cover R&D costs and marketing. They also include the costs of testing and monitoring to administer incentives tied to uptake in the initial period.

The tables below and on the following page set out the benefits and costs of climate-resilient crop innovation for selected crop-region pairs and scenarios. Scenario 1 analyzes the benefits and costs of a program that offers enough reward for firms to use conventional breeding technology and uses a low estimate of adoption. Scenario 2 analyzes the benefits and costs of a program that also incentivizes the conventional breeding technology but has a high estimate of adoption. Scenario 3 analyzes the benefits and costs of a program that offers more funding and, therefore, incentivizes firms to use ambitious technology. Scenario 3 uses high adoption assumptions. Maize offers the highest benefits in all three scenarios, but it is less likely to be a neglected opportunity.[xxvii] We only provide costs and benefit-cost ratios for those crops identified as promising opportunities for pull mechanisms (maize, sorghum, rice).

Table 1: Benefits of 1-degree increase in heat tolerance by crop/region

			Benefits (US$, millions) by adoption and technology		
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Technology			*Conventional*	*Conventional*	*Ambitious*
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Groundnut	Southern Africa	30 to 31°C	14	35	162

Note: All estimates are discounted using a 3% discount rate. All estimates are rounded to the nearest million.

Table 2: Costs of each program by crop/region

Crop	Region	Old to new temperature threshold	Costs (US$, millions) by adoption and technology: Scenario 1	Scenario 2	Scenario 3
Adoption			*Low*	*High*	*High*
Technology			*Conventional*	*Conventional*	*Ambitious*
Maize	Southern Africa	29 to 30°C	58	58	176
Sorghum	West Africa	33 to 34°C	51	51	169
Rice	West Africa	29 to 30°C	44	44	160

Note: All estimates are discounted using a 3% discount rate. All estimates are rounded to the nearest million.

Table 3: Benefit-costs ratios by crop/region

Crop	Region	Old to new temperature threshold	Benefit-cost ratios by adoption and technology: Scenario 1	Scenario 2	Scenario 3
Adoption			*Low*	*High*	*High*
Technology			*Conventional*	*Conventional*	*Ambitious*
Maize	Southern Africa	29 to 30°C	9.8	24.6	13.4
Sorghum	West Africa	33 to 34°C	5.3	13.1	5.8
Rice	West Africa	29 to 33°C	0.6	1.6	2.4

Note: All estimates are discounted using a 3% discount rate. Benefit/cost ratios are calculated using non-rounded benefit and cost numbers. All benefit-cost ratio estimates are rounded to the nearest tenth.

Annex: Proposed model for pull funding program

Proposed program timeline

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

Figure A - 1: Gantt chart

	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																			
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

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):**[xxviii] Firms will be expected to demonstrate the impact of their crops through RCTs operating over three years, overlapping with the approval period for one year. The funder will be responsible for contracting out these evaluations to avoid conflicts of interest.[xxix]
4. **Reward payments (five years)**: Firms will be rewarded based on their crop variety's adoption rate over five years. The reward payments are intended to cover the costs of developing the crop variety and for the risk that they take on by participating (i.e., there's some chance that they do not successfully develop a new variety). Reward payments begin after crop varieties have demonstrated their benefits (and lack of undesirable varietal attributes) in RCTs. Payments could also be given as firms meet various milestones (pass agronomic field trials, achieve regulatory approval, demonstrate impact in an RCT).[xxx] This may be useful if firms face financing constraints.

5. **Monitoring (five years):** Adoption must be measured to be rewarded. Measuring adoption will require surveying farmers and DNA fingerprinting of crops. Measuring adoption will take place concurrently with reward payments.
6. **Benefits (16-21 years):** While the funding program will only last five years, the benefits will last longer. Firms will still sell the seed as their fixed costs have been covered and farmers will have had time to learn about the heat tolerance. In our conservative estimate, we expect the improved variety to continue to be used and, therefore, provide benefits for 16 years. In our high adoption estimate, we estimate these benefits last 21 years.

Breakdown of proposed funder costs

Below are estimates of key cost drivers for an example crop variety program (sorghum in West Africa). In total, the undiscounted funder costs are ~$75 million (~$51 million discounted) for the low-cost program and ~$251 million (~$169 million discounted) for the ambitious technology (i.e., high-cost) program:

The cost of a pull mechanism for sorghum has three components:

1. **The pull fund**: The pull fund rewards firms for developing new crops that are widely adopted. The fund must be large enough to compensate for firms' direct costs and the risk associated with participating. For the low-cost program, firms' costs of developing a new variety are estimated at ~$1 million per year for five years. For the high-cost program, firms' costs of R&D and agronomic field trials are estimated at nearly $6 million per year for five years. These are approximations based on available sources and conversations with relevant experts.[xxxi] We also assume firms have a 15% weighted average cost of capital which increases the size of reward necessary. This is intended to be sufficiently large to attract serious private sector interest. We also assume that each firm expects to split the reward with one other firm. The pull fund also incorporates a marketing subsidy intended to cover 60 percent of new adoption during the subsidy years under the low adoption assumptions.[xxxii] This is in anticipation that crop adoption will spread. The total, undiscounted reward payments are estimated to be ~$68 million ($46 million discounted) for the low-cost program and ~$244 million (~$164 million discounted) for the high-cost program.
2. **Monitoring**: Firms will make reward claims based on their estimate of adoption in different locations that will be independently verified. Monitoring will entail a survey of farmers and DNA sampling of crops. DNA sampling is especially necessary since previous research suggests that farmers are not always aware of the exact variety they are using. These costs are estimated at ~$450,000 per year for each year that reward payments are paid.

3. **RCT**: Funders will directly cover RCT costs. Note that in other industries that require RCTs for regulatory approval – such as the pharmaceutical industry – the firm bears these costs directly and, therefore, future profits would need to justify each firm's expenditure. This is not the case here – the funder will directly cover costs to ensure the trial is independent and of high quality. These costs are estimated at ~$1.5 million per year for three years covering three countries based on previous agriculture RCTs.

Such a pull financing model offers value for money. We estimate a benefit-cost ratio for sorghum of 5.3 in Scenario 1, 13.1 in Scenario 2, and 5.8 in Scenario 3. Firms would only be rewarded for achieving higher adoption among farmers and meeting milestones.

References

[i] This is a draft document for comment which MSA will update periodically.
[ii] Hultgren et al. 2022. See Table 1
[iii] Hultgren et al., 2022. Figure 3 covers the global impact of climate change on staple crops. Supplementary Figure S. 14 provides regional impacts including for Sub-Saharan Africa.
[iv] Burke and Emerick, 2016
[v] Schlenker and Lobell, 2010
[vi] Deng, Xie, and Wang 2023
[vii] Tack, 2017
[viii] Hadebe et al., 2017
[ix] Suri et al., 2022, Ritchie 2022, Tian et al. 2019
[x] 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.
[xi] CRISPR-edited crops break new ground in Africa - Nature 2024-01-24
[xii] We believe this is reasonable given 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.
[xiii] McGuire and Sperling 2016; Kremer and Zwane 2005; OPVs are a significant share of the maize sector in SSA - Masuka et al 2017.
[xiv] Carter et al 2021, Boucher et al 2024
[xv] Kremer and Zwane 2005 report even in "the United States the United States, seed companies retained only 30–50% of the economic benefits from enhanced hybrid seed yields and only 10% of benefits from nonhybrid seed during 1975–90 (Fuglie et al., 1996)."
[xvi] Emerick and Dar 2021, Dar et al 2024, Fabregas et al 2021
[xvii] Alston et al., 2021
[xviii] See Cramer (2019); Parker et al; Das et al in Rosenstock et al 2019
[xix] Ariga et al 2019
[xx] The Access to Seed Index reports no firms with groundnut breeding programs in Eastern and Southern Africa while breeding programs were limited more generally in West and Central Africa
[xxi] This is based on an initial comparison of DIIVA and SIAC data
[xxii] Kuhlmann and Zhou, 2016
[xxiii] Glennerster and Suri, 2015
[xxiv] Carter et al 2021
[xxv] Access to Seed Index - Eastern and Southern Africa portfolio
[xxvi] This is based on pull incentive cost estimates for maize, sorghum, and rice.
[xxvii] Maize is likely to be attractive even if the benefits are significantly less than modeled here.
[xxviii] The current timetable assumes a one-year overlap between the approval period and the RCT period.
[xxix] We envisage the funder only covering RCT costs for the initial candidates that meet the relevant criteria.

[xxx] For our benefit-cost analysis we assume funders only make reward payments linked to farmer adoption, but this is just a simplification for modeling costs.
[xxxi] The low cost (conventional technology estimate) is partly informed by CGIAR System 3-Year Business Plan Companion Document, 2018, Page 24 which states, "The cost of planning and implementing modernized breeding programs is estimated to be in the order of USD 2 million per cluster of related crop product profiles delivered by the same breeding team, in total, over about three years." The high-cost (ambitious technology estimate) is partly informed by the estimated cost of gene editing in Bullock et al 2019 and Lassoued 2019.
[xxxii] This size of the marketing subsidy is informed by the cost of a farmer field day in Emerick and Dar 2021. We assume the targeted farmers initially cover only 25% of their farm with the new variety.