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The value of climate-resilient seeds for smallholder adaptation in sub-Saharan Africa

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Abstract

Climate change is threatening food security in many tropical countries, where a large proportion of food is produced by vulnerable smallholder farmers. Interventions are available to offset many of the negative impacts of climate change on agriculture, and they can be tailored to local conditions often through relative modest investments. However, little quantitative information is available to guide investment or policy choices at a time when countries and development agencies are under pressure to implement policies that can help achieve Sustainable Development Goals while coping with climate change. Among smallholder adaptation options, developing seeds resilient to current and future climate shocks expected locally is one of the most important actions available now. In this paper, we used national and local data to estimate the costs of climate change to smallholder farmers in Malawi and Tanzania. We found that the benefits from adopting resilient seeds ranged between 984 million and 2.1 billion USD during 2020–2050. Our analysis demonstrates the benefits of establishing and maintaining a flexible national seed sector with participation by communities in the breeding, delivery, and adoption cycle.

Keywords Climate change adaptation · Smallholders · Improved seeds · Climate policy

Acronyms

AEZ	Agro-ecological zone
BDA	Breeding delivery and adoption
CSA	Climate-smart agriculture
FAO	Food and Agriculture Organization of the United Nations

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FAO	EPIC Economics and Policy Innovations for Climate-Smart Agriculture Programme of the Food and Agricultural Organization of the United Nations
GCM	Global circulation models (also global climate models) The 4 models used are:
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model
HadGEM2-ES	Hadley Global Environment Model 2 Earth System
IPSL-CM5A	Institut Pierre Simon Laplace Earth System Model for the 5th IPCC report
NorESM1-M	Norwegian Earth System Model
IPCC	Intergovernmental Panel on Climate Change
LPJmL	Lund-Potsdam-Jena managed Land model
MAgPIE	Model of Agricultural Production and its Impact on the Environment
RCP	Representative concentration pathways
SDG	Sustainable Development Goals
SSA	Sub-Saharan Africa
SSP	Shared socioeconomic pathways
TZNPS	Tanzania National Panel Survey

1 Introduction

By reducing agricultural production and incomes, increasing risks, and disrupting markets, climate change poses a serious threat to the achievement of Sustainable Development Goal 2 (SDG 2), which aims to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture by 2030 (https://www.un.org/sustainabledevelopment/). SDG 2.3 has the objective of doubling the agricultural productivity and incomes of small-scale food producers by 2030, through secure and equal access to productive resources among other means. SDG 2.4 calls for the implementation of resilient agricultural practices that increase productivity and production. Climate change is already affecting crop and livestock production in many parts of the world, posing serious challenges to achieving SDG2 (IPCC 2014). These effects can be long lasting, as risk exposure and increased uncertainty affect investment incentives and reduce the likelihood of effective farm innovations while increasing that of low return activities (Hurley 2010; Dercon and Christiaensen 2011; Wossen et al. 2018). In the future, losses in aggregate production are projected for wheat, rice, and maize especially in tropical regions for 2 °C of local warming, unless adaptation occurs to offset these losses (Challinor et al. 2014).

Strategies that can enhance the resilience of agricultural systems are needed to reduce the risk of food insecurity in the present as well as in the future (Lipper et al. 2014; Zhang et al. 2016; Smith and Frankenberger 2018). This is particularly true for climate hotspots: areas that are characterized by both a “strong climate signal” and concentration of vulnerable populations (De Souza et al. 2015). Smallholder agricultural producers in developing countries constitute one of the most vulnerable groups to climate change, being exposed to strong climate signals with limited capacity to adapt. The vulnerability of the agricultural sector in these countries to climate change is recognized, being a dominant sector in adaptation initiatives, particularly in semiarid areas (Mkonda and He 2018).

From a policy standpoint, delivering smallholder adaptation strategies as packages may improve their effectiveness. By addressing shortcomings along the value chain, we can ensure that obstacles faced by farmers are reduced, thereby improving the chances of success. As well as removing obstacles, policy packages may provide infrastructure and incentives that enable farmers to adopt climate-smart technologies and access better markets. The policy goal is to enable autonomous adaptation to occur as farmers respond to price signals, incentives, and opportunities. Essentially, the approach helps vulnerable groups “help themselves” by developing resilience to climate shocks while also contributing toward Sustainable Development Goals.

Policy packages may involve investments such as irrigation infrastructure, improved crop varieties, grain storage facilities, and transportation networks. Here, we focus on development and delivery of climate-resilient seeds suited to local conditions. We justify this choice based on demands by African countries for crops that are heat- and drought-resistant.

Providing farmers with access to improved and adapted seeds is a fundamental and proactive adaptation strategy widely applicable in climate hotspots. The use of improved seeds in poor smallholder systems has been found to increase both productivity and incomes. Between 1980 and 2010, the use of improved crop varieties in sub-Saharan Africa was estimated to have increased productivity by an average of 47% and is known to have played a significant role in reducing poverty in several sub-Saharan African countries (Walker and Alwang 2015). There is considerable demand for this form of adaptation. The most common adaptation action across the The nationally determined contribution (NDCs) in 18 East African countries is the development and adoption of crop varieties that are better suited to future climatic conditions (Burke et al. 2009). In relation to “crop management,” drought- and heat-tolerant crop varieties feature prominently in planned adaptation measures in Africa (Richards et al. 2016, Richards 2019). Depending on local context, different traits may be needed: drought tolerance, heat tolerance, or faster biomass accumulation to offset shorter crop durations as a result of higher temperatures (Atlin et al., 2017).

Identifying strategies to increase the adaptive capacity of smallholder farmers in a way that can enhance productivity and incomes is essential to meeting the objectives of SDG2 and contributing to NDCs at the same time. Although there are other options, we focus on climate-resilient seeds due to their prevalence in the NDCs of countries in sub-Saharan Africa. We do not seek to compare this option with alternative investments such as irrigation.

Smallholders in sub-Saharan Africa are already adapting to perceived climate changes by adjusting planting dates and crop mixes (Ouédraogo et al. 2016), and such autonomous adaptation may be complemented by planned adaptation to reduce the damage of climate change and associated costs. However, a more proactive approach is needed if the targets of SDG2 indicators are to be met. Historical adoption rates of “improved” technology in sub-Saharan Africa have often been much lower than expected as smallholders face major barriers to access, indicating the need for deliberate and targeted interventions. Increasing access requires not only breeding climate-resilient seeds but also investments in seed production and distribution, including seed bulking facilities, expanded extension services, and input subsidies (Thornton et al. 2018). Targeted policies are needed to ensure that appropriate interventions can be adopted in the time frame and scale needed. At present, breeding, delivery, and adoption (BDA) of new crop varieties may take 30 years, and shortening this cycle is a priority for adaptation (Challinor et al., 2016).

There is limited quantitative information on the economic benefits and costs of adapting seed resilient to current and future climate shocks. This study aims to address this paucity by providing estimates on these costs and benefits to inform policy and guide investment to increase food security. We take a novel approach by combining global projections on climate and agricultural productivity and production, provided by the Model of Agricultural Production and its Impacts on the Environment (MAgPIE), with survey data at the farm level to establish the potential costs of climate change to smallholders in two climate hotspot countries: Malawi and Tanzania. We use farm household modelling to estimate the benefits of policy measures intended to generate seed production and distribution capacity as well as provide incentives to smallholders to adopt improved and adapted crop varieties at enhanced rates in the near term. The nationally representative household data available for these two countries allows us to derive national estimates while accounting for household-level constraints.

2 Modelling the cost of climate change to smallholders

Consider the case of a country divided into J agro-ecological zones (AEZ), which may differ in terms of crop suitability, climate impacts, and other factors. Within each AEZ, there is a set of I_j typical farm household types, which may differ in terms or their risk aversion, land use pattern, human and financial capital, resources available (land, labor and other inputs), and capability of adopting complex technologies.

The total farm revenue in agro-ecological zone j at time t under scenario S and policy P is denoted as $R_{\mathrm{jt}}(S|P)$. The monetary effect of climate change on farmers in zone j is:

$$G_{jt}(S|P) = R_{jt}(S|P) - R_{jt}(0|P) \tag{1}$$

where the functional relationship $(0|P)$ denotes the scenario with no climate change for the given policy P. The sign of G_{jt} $(S|P)$ indicates whether farmers in zone j are expected to gain or lose from climate change in year t under scenario S given policy P. The total effect of climate change over the planning horizon $(0,...,T)$ at a discount rate of δ is expressed as a present value:

$$G_{Tj}(S|P) = \sum_{t=0}^{T} G_{jt}(S|P)[1+\delta]^{-t} \tag{2}$$

The effect of any given policy k is quantified relative to the baseline policy for any climate scenario as:

$$V_j(P_k|S) = G_{Tt}(S|P = P_k) - G_{Tt}(S|P = P_{base}) \tag{3}$$

Policy analysis is undertaken by changing P to represent any given policy package and comparing the resulting V_j with the cost of the policy. We simulate the case where a program is introduced to produce improved seeds that are drought- and heat-resistant as well as high yielding. This allows us to estimate the value of providing improved seeds tailored to local conditions at different points in the planning horizon for different climate scenarios.

The aggregate response represented in Eqs. (1) to (3) is the result of many individual farmers making decisions on crops to grow and techniques to adopt as they experience changing yields and prices in an *autonomous adaptation* process. This means we need a behavioral model for farm households to create the link between farm-level decisions and financial impacts at the AEZ level. Our approach is based on utility maximization by risk-averse farmers subject to resource constraints and experiencing the effects of climate scenario S and policy P. The link occurs through R_{jt} in Eq. (1) using an approach similar to that of

Shively and Coxhead (2004). The total farm revenue at time t under scenario S and policy P for the population of interest is:

$$R_{jt}(S|P) = \sum_i r_{ijt}(S|P)\, n_{ijt}(S|P) \tag{4}$$

$$R_t(S|P) = \sum_j \sum_i r_{ijt}(S|P)\, n_{ijt}(S|P) \tag{5}$$

Equations (4) and (5) represent farm revenues aggregated at the agro-ecological zone (AEZ) and country level, respectively; r_{ijt} is the expected revenue of farm system $i \in (1,...,I)$ in agro-ecological zone $j \in (1,...,J)$ in year $t \in (1,...,T)$; and n_{ijt} is the expected number of farms of type i in AEZ j.

The individual farm revenues that enter Eqs. (4) and (5) are those obtained by applying the optimal crop mix $\mathbf{w}^*$ for the given farming system:

$$r_{ijt}(S|P) = \mathbf{f}_t^{\prime\prime}(S|P)\, \mathbf{w}_{ijt}^{*}\, a_{ijt} \tag{6}$$

where $\mathbf{w}^*$ is a vector of optimal crop proportions, $\mathbf{f}$ is a vector of revenues per hectare of crop, and a is the area of the farm. The value of $\mathbf{w}^*$ is obtained by solving the optimization problem:

$$\max_{\mathbf{w}} : \quad U_{ijt}(S|P) = \mathbf{f}'(S|P)\mathbf{w}_{ijt} - \frac{1}{2}\mathbf{w}'_{ijt}[r_i\mathbf{V}(S|P)]\mathbf{w}_{ijt} \tag{7}$$

Subject to:

$$A_i(S|P)w_{ijt} \leq b_i(S|P) \tag{8}$$

$$[\mathbf{1}]'\mathbf{w}_{ijt} = 1 \tag{9}$$

$$\mathbf{w}_{ijt} \geq 0 \tag{10}$$

where $\mathbf{V}$ is the variance-covariance matrix of crop revenues, r is the risk-aversion coefficient of the farmer, $\mathbf{A}$ is a matrix of technical coefficients, and $\mathbf{b}$ is a vector of constraints. The solution to this problem yields the optimal crop mix $\mathbf{w}^*$ expressed as the proportion of farm area planted to each crop. The matrix $\mathbf{A}$ contains technical coefficients related to the requirements of each crop for land, labor, capital, and other resources.

Equation (7) implies that farmers make decisions based on expected prices and yields of crops and their variability, both of which are affected by climate and policy scenarios. The revenues per hectare of crop (f) are calculated as yield × price for each crop. For any particular climate scenario, farmers react to changes in prices and yields by adjusting their crop mix to maximize their utility, subject to constraints in available resources, knowledge, and ability. The quadratic utility function for a risk-averse individual (Eq. (7)) is positively related to expected returns and negatively related to variability of returns. The maximization is based on revenues as a proxy for household welfare.

3 Data and methods

We consider four scenarios, $S \in (0,...,3)$, representing no climate change (0) and three representative concentration pathways (RCP), RCP 2.6, RCP 6.0, and RCP 8.5 (Moss et al. 2008), which can be characterised as optimistic, intermediate, and pessimistic respectively. We used SSP 2, the "middle of the road" shared socioeconomic pathway (Kriegler et al. 2014; O'Neill et al. 2015) in all simulations. R_{jt} is calculated by aggregating the revenues of individual farms (see Eqs. (4) and (5)). Farm households select their crop mix based on a utility maximization process (Eqs. 7–10). In the behavioral model, risk-averse farmers select the crop mix that maximizes their utility for the expected yields and prices under climate scenario S.

The time horizon of the analysis is 30 years (2020–2050), in line with other studies on impacts of climate change in agriculture. Projections of climate change to 2100 show an accelerating trend, implying that more severe damages are expected after 2050. However, we limited our analysis to 30 years, as this is the relevant horizon for policies aimed at strengthening the seed sector in developing countries. We used a discount rate of 5%, reflecting the public good nature of the proposed policy (help vulnerable farmers adapt), for which the use commercial discount rates is not appropriate.

We use two types of input data: nationally representative farm household survey datasets and projections of crop prices and yields under alternative climate scenarios. Geo-referenced survey data used consists of panels for Malawi (2281 households) and Tanzania (2213 households) with two waves of sampling (Figs. 1 and 2). For Malawi, farm household-level data were from the nationally representative sample from the Third Integrated Household Survey (IHS3) for 2010/2011 and 2013, implemented by the Malawi National Statistics Office. For Tanzania, farm household-level data were from the nationally representative sample from the 2008/2009 and 2010/2011 waves of the Tanzania National Panel Survey (TZNPS). Both datasets were matched to historical measures of temperature and rainfall variability by the FAO-EPIC team.

The crops available for selection in the optimisation model were based on those present in the farm household survey datasets. The main crop cultivated in both countries was maize, with 79% and 49% of households cultivating this crop in Malawi and Tanzania, respectively. Maize was followed by legumes in both countries: 19% of households planted groundnut in Malawi and 20% of households planted beans in Tanzania. There were variations in crop proportions among agro-ecological zones (see Tables A4 and A5 in Supplementary Information for more details).

Price and yield projections for 2010–2050 for the crops of interest were generated through simulations under alternative representative concentration pathways (RCP) (Moss et al. 2008) with no CO_2 fertilization using the MAgPIE/LPJml model (Popp et al. 2017; Lotze-Campen et al. 2008; Bondeau et al. 2007). MAgPIE results for yields and prices were obtained for 4 global circulation models (GCMs). The GCMs used were: (1) Geophysical Fluid Dynamics Laboratory Earth System Model (GFDL-ESM2M); (2) Hadley Global Environment Model 2 Earth System (HadGEM2-ES); (3) Institut Pierre Simon Laplace Earth System Model for the 5th IPCC report (IPSL-CM5A); and (4) Norwegian Earth System Model (NorESM1-M).

The gridded data obtained from the MAgPIE/LPJml model were at a spatial resolution of 0.5°. Each crop was simulated with and without irrigation for all global grid cells for all RCP-GCM combinations. Yield values were extracted for the pixels corresponding to Malawi (1419 points) and Tanzania (10,547 points). Price projections relative to 2010 were uniform for the whole African region, and they were adjusted by AEZ based on price data from the country datasets prior to use in our simulations. We used only non-irrigated yields in this analysis, as the study is based on dryland systems, and options for investment in irrigation infrastructure were not considered.

The model described in Eqs. (1)–(10) was solved for the 4 climate scenarios and using projections from the 4 GCMs listed above. We simulate a policy measure intended to generate

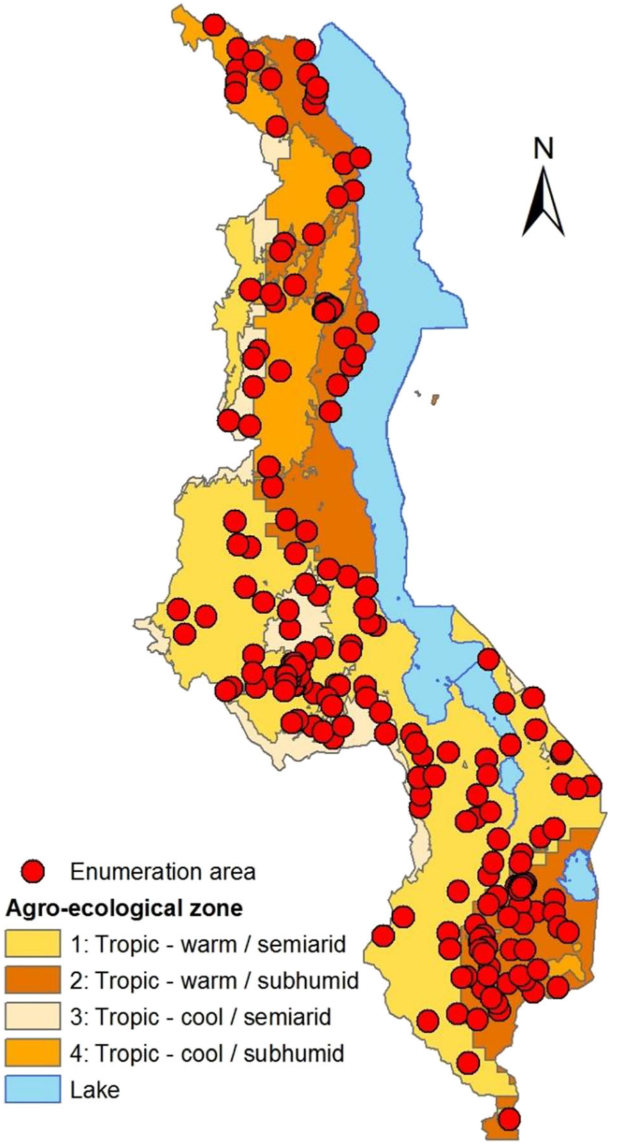

Fig. 1 Agro-ecological zones and enumeration areas in Malawi. Data were geo-referenced farm household-level data from the nationally representative sample from the Third Integrated Household Survey (IHS3) for 2010/2011 and 2013 implemented by the Malawi National Statistics Office. This dataset was also matched to historical measures of temperature and rainfall variability by the FAO-EPIC team

seed breeding, production, and distribution capacity as well as provide incentives to smallholders to adopt improved and adapted seeds at enhanced rates. This policy is compared against a baseline where no such incentives exist to obtain a measure of the value of the policy from the standpoint of improving the welfare of vulnerable smallholder farmers experiencing the effects of climate change.

Parameters for the household model were obtained from the country survey data. Four different farm types were identified for each AEZ depending on two variables: (1) whether they apply climate

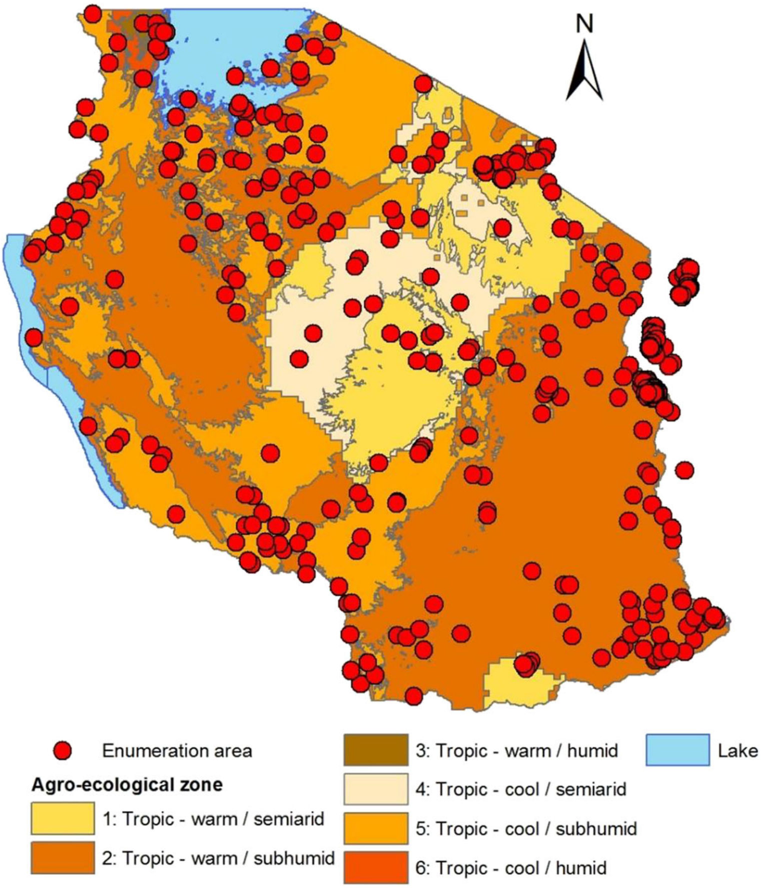

Fig. 2 Agro-ecological zones and enumeration areas in Tanzania. Data were geo-referenced farm household-level data from the nationally-representative sample from the 2008/2009 and 2010/2011 waves of the Tanzania National Panel Survey (TZNPS). This dataset was also matched to historical measures of temperature and rainfall variability by the FAO-EPIC team

smart agriculture (CSA) farming or conventional methods and (2) whether their resilience is at the low or high end within the sample. Farmers at the low resilience end of the spectrum tend to be more risk averse. The risk aversion coefficient (*r*) for each farmer type was obtained numerically using Eq. (7) to find the value of *r* that results in a crop mix similar to the average for the group.

4 Results

4.1 Yield projections

Crop yields are expected to be below the no climate change reference scenario by 2050 for most crops, with average yields as low as 0.83 relative to 2010 (Table 1). However, there is substantial geographical variation in the projections of different global climate models (GCMs), and yield increases are expected to occur in some areas for maize, the main staple crop (Fig. 3). Similar maps were produced for the main crops in each country (see Supplementary Information).

Table 1 Relative yield projections in 2050 for the main crops grown by smallholders in Malawi and Tanzania, expressed as the ratio of yields under each RCP to yields under the no climate change reference scenario, with no CO_2 fertilization (mean ± SD)

	RCP*		
Crop	2.6	6.0	8.5
	Malawi		
Maize	0.966 ± 0.085	0.937 ± 0.090	0.918 ± 0.097
Groundnut	0.901 ± 0.082	0.864 ± 0.094	0.832 ± 0.102
Beans	0.932 ± 0.022	0.905 ± 0.024	0.882 ± 0.014
Soybean	0.903 ± 0.050	0.868 ± 0.064	0.825 ± 0.033
Rice	0.914 ± 0.027	0.877 ± 0.039	0.846 ± 0.017
Tobacco	0.966 ± 0.086	0.938 ± 0.090	0.919 ± 0.097
	Tanzania		
Maize	0.929 ± 0.079	0.916 ± 0.087	0.880 ± 0.101
Beans	0.924 ± 0.029	0.911 ± 0.031	0.877 ± 0.018
Cassava	0.961 ± 0.091	1.067 ± 0.148	1.039 ± 0.146
Sorghum	0.924 ± 0.030	0.915 ± 0.035	0.875 ± 0.022
Rice	0.905 ± 0.036	0.888 ± 0.047	0.839 ± 0.027

Projections were generated using four GCMs and a grid of 5-arcmin pixels. The mix of crops differs between countries based on the farm household datasets used in the analysis

*Representative concentration pathways (RCP) are used by the IPCC as the new standard to represent a range of climate scenarios through time. The numbers (2.6, 6.0, and 8.5) refer to radiative forcing, with higher numbers representing more severe warming (Moss et al. 2008)

4.2 Climate change impacts on smallholders

The financial impacts of climate change on smallholders were estimated as the difference in cropping revenues between the no climate change case and each RCP scenario (Eq. (1)). Results indicate that expected farm revenues beyond 2020 will be lower for both countries under climate change compared with the no climate change case, despite farmers adjusting their crop mix to respond to changing prices and yields (Table 2).

The total costs of climate change to smallholders, in present-value terms, for the period 2020–2050 are $1.6 (± 1.3) billion and $8.1 (± 1.0) billion for Malawi and Tanzania, respectively (Table 2). There is a wide range of uncertainty around these expected values, especially for Malawi, reflecting differences in yield projections from the four GCMs combined with spatial variation as shown in in Fig. 3.

In annual terms, the costs of climate change to smallholders in Table 2 are equivalent to $103 (± 79) million per year for Malawi and $520 (± 64) million per year for Tanzania. At the farm level, these represent average annual income reductions of 7.7% and 5.1%, respectively, and this is after autonomous adaptation to yield and price changes caused by climate change. In short, without more concentrated adaptation actions, some of the poorest people on Earth are likely to experience significant cuts in their incomes—and food security.

4.3 Evaluating climate-resilient seeds

Seeds that are drought- and heat-resistant can increase yields by up to 25% under climate patterns expected in Africa by 2050 with RCP 8.5, compared with expected yields with current seeds (Islam et al. 2016). We explore the potential benefits of farmers adopting these adapted seeds under three different scenarios (Table 3). First, an optimistic scenario where these

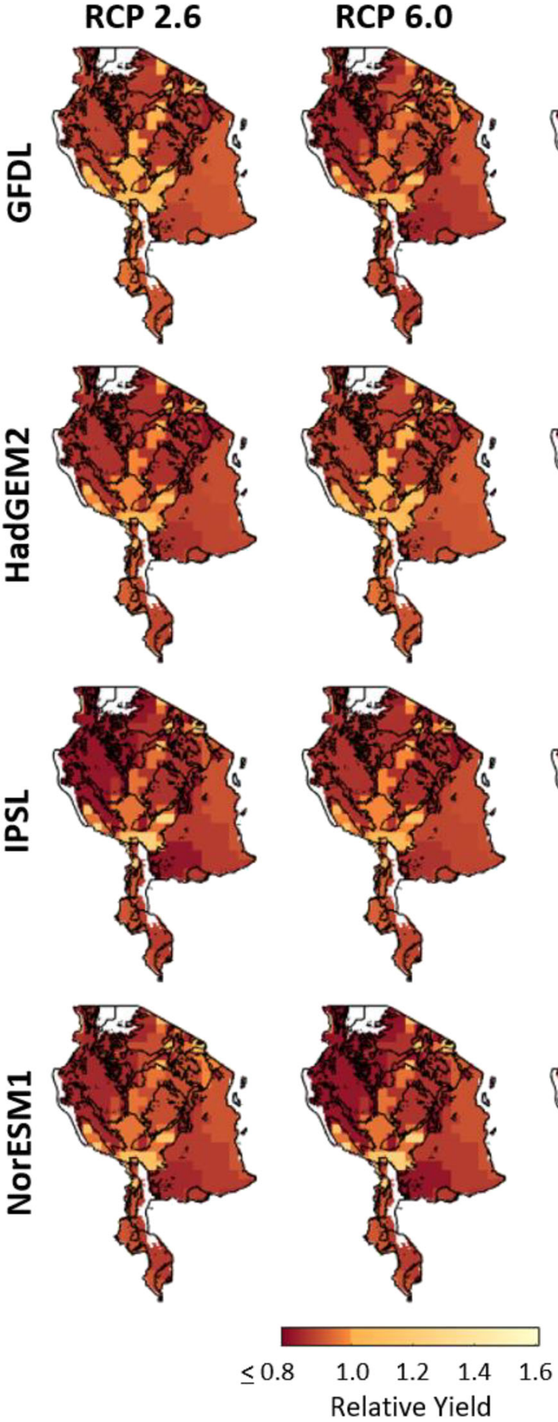
RCP 2.6
RCP 6.0
RCP 8.5
GFDL
HadGEM2
IPSL
NorESM1
≤ 0.8
1.0
1.2
1.4
1.6
Relative Yield

Fig. 3 Maize yields projected in 2050 for three representative concentration pathways (RCP 2.6, RCP 6.0, and RCP 8.5) relative to the reference no climate change case in Malawi and Tanzania. Projections were obtained with four different global circulation models (NorESM1, IPSL, HadGEM2, and GFDL) with no CO_2 fertilization. The three RCP scenarios selected represent the range from optimistic (RCP 2.6) to pessimistic (RCP 8.5). Details of projected yields and prices of all crops considered are presented in the Supplementary Information. Blank pixels are water

improved seeds are available for all main crops starting in 2020 results in aggregate benefits of \$635 million in Malawi and \$1470 million in Tanzania. Although this will not be achievable, it shows the potential benefits of early planning for climate change adaptation, focusing on the main crops in addition to maize. In a second scenario, we assumed that these improved seeds only become available in 2030. In this case, smaller but still significant benefits are obtained (at \$524 million in Malawi and \$1156 million in Tanzania). In the third scenario, we assumed that the availability of improved seeds starts only in 2040 (Table 3 final column). In this most pessimistic case, the benefits of policies to promote adoption of improved seeds have decreased to \$315 million for Malawi and \$669 million for Tanzania. In terms of annual benefits per hectare, there are variations among agro-ecological zones, with higher benefits generally accruing to warmer regions compared with cooler regions, but with some variation arising from geographical differences within agro-ecological zones.

5 Discussion

Uncertainty in climate projections means that climate-resilient seeds need to be readily available to farmers for a range of possible climate change outcomes rather than a single expected outcome. It follows that programs to propagate improved seeds adapted to local conditions, and the seed

Table 2 Present value of the cost of climate change to smallholders in Malawi and Tanzania (mean ± SD)

Country/AEZ*	Total cost ⁺($ million)	
Malawi	1600 ± 1227	
Tanzania	8102 ± 1000	
	Cost by AEZ ($/ha)	Total area (1,000 ha)
Malawi		
Tropic–warm/semiarid	765 ± 536	857
Tropic–warm/subhumid	786 ± 525	1,046
Tropic–cool/semiarid	460 ± 545	256
Tropic–cool/subhumid	35 ± 622	133
Tanzania		
Tropic–warm/semiarid	852 ± 73	703
Tropic–warm/subhumid	964 ± 88	4178
Tropic–warm/humid	1096 ± 156	140
Tropic–cool/semiarid	689 ± 101	647
Tropic–cool/subhumid	707 ± 125	3997
Tropic–cool/humid	1068 ± 160	45

Based on projections for the period 2020–2050 under RCP8.5 using four GCMs. The top portion of the table presents total costs considering all smallholder farmers in each country. The bottom portion of the table presents results per hectare by agro-ecological zone (AEZ)*. Figures are in 2010 US Dollars at a discount rate of 5%.

*Agro-ecological zones are as classified by IFPRI -Sebastian, K. (2015). Agro-ecological zones of Africa (Publication no. hdl/1902.1/22616) from Harvard Dataverse http://hdl.handle.net/1902.1/22616

⁺ These costs were estimated from Eq. (2) as $-\sum_{j} G_{Tj}(S|P)$, with $S = 4$ and $P = P_{\text{base}}$

Table 3 Present value of benefits provided by adapted seeds (mean ± standard deviation) to cope with climate change under RCP 8.5

Country/AEZ	Seed improvement assumption (2020–2050)	(2030–2050)	(2040–2050)
	Total benefit of seeds to smallholders, PV ($ million)*		
Malawi	635 ± 179	524 ± 134	315 ± 50
Tanzania	1470 ± 379	1156 ± 363	669 ± 183
	Benefits by AEZ, annualized PV ($/ha/year)		
Malawi			
Tropic-warm/semiarid	16.5 ± 4.6	13.7 ± 3.4	8.2 ± 1.2
Tropic–warm/subhumid	19.1 ± 5.3	15.7 ± 4.0	9.4 ± 1.5
Tropic–cool/semiarid	3.8 ± 1.2	3.1 ± 1.0	1.9 ± 0.4
Tropic–cool/subhumid	1.4 ± 0.4	1.2 ± 0.3	0.7 ± 0.1
Tanzania			
Tropic–warm/semiarid	11.1 ± 1.6	8.4 ± 2.2	4.9 ± 1.0
Tropic–warm/subhumid	45.5 ± 12.1	36.0 ± 10.6	20.5 ± 5.3
Tropic–warm/humid	1.9 ± 0.5	1.5 ± 0.5	0.8 ± 0.2
Tropic–cool/semiarid	6.6 ± 1.2	5.1 ± 1.6	3.1 ± 0.8
Tropic–cool/subhumid	28.6 ± 8.8	22.8 ± 8.5	13.4 ± 4.6
Tropic–cool/humid	0.5 ± 0.2	0.4 ± 0.2	0.2 ± 0.1

[a] Based on the potential yield increase of drought + heat tolerance + high yield maize in Africa according to Islam et al. (2016)

*These figures were obtained using Eq. (3) with differing policy assumptions and assuming 30 percent adoption, based on Thornton and Herrero (2010)

Assumptions on the timing of improved seed availability differ between columns. The improved seeds are assumed to reduce the yield gap by a maximum 25% relative the no climate case[a]. The planning horizon is 2020–2050 and values are in 2010 US dollars at a discount rate of 5%

production facilities needed to support them, will be important proactive adaptation strategies. It will be necessary to have seed systems capable of producing a wider range of traits that can respond to the multiple threats of climate change, and these systems need to be flexible and sensitive to local conditions. This in turn implies the need for adaptation measures to increase the flexibility and scope of local seed systems, including access to a diversity of cultivars. A focus of breeding for increased diversity to provide cultivars that are more resilient in changing and uncertain conditions would be an asset for the success of the proposed policy.

The cost of delays in these actions can be estimated by comparing the three columns of Table 3. For the two countries, considered investment delays of 10 and 20 years, respectively, cost 425 and 1221 million USD in present value of foregone benefits for 2020–2050 (Table 4).

Table 4 Cost of delaying investment in seeds adapted to cope with climate change under RCP 8.5 compared with implementation in 2020

Country	Cost by implementation year ($/ha) 2030	2040
Malawi	111 ± 45	320 ± 129
Tanzania	314 ± 65	801 ± 219
Total	425 ± 101	1121 ± 348

Assumptions on delay in improved seed availability differs between columns and values are present value terms (mean ± standard deviation). Values in 2010 US Dollars at a discount rate of 5%

These differences can be viewed as the benefits of early action to justify investments that enhance adoption of adapted varieties by vulnerable farmers. To make this happen, the whole seed supply chain needs to be considered, starting from the breeding phase. In this regard, it is important to have a diversity of cultivars available to breed for desirable traits.

The analysis focuses on the main crops present in the country datasets (Table 1), with maize being the most prominent. The optimal solution at the farm level involves crop mixes that maximize utility for risk-averse farmers. There are other promising crops for climate adaptation in Africa that were not included in the analysis (such as cowpea and millet) because of their absence in the datasets.

Maize will be hit hard by climate change in low latitudes (Mbow et al. 2019), and at the same time, maize continues to be of critical importance in diets, with more than a 30% contribution to the calories consumed by the population of sub-Saharan Africa. There is a reluctance by farmers and consumers to shift to other staple crops. This is evidenced by the adoption rates of modern maize varieties, about 50% in sub-Saharan Africa, which is quite high compared with other crops (Ekpa et al. 2019). In our analysis, we express the costs of climate change in terms of lost cropping revenues to smallholder farmers in the climate hotspot countries of Malawi and Tanzania. We use these costs to estimate the expected impact of a policy designed to enhance adoption rates of adapted seed varieties and find that there is an immediate and significant benefit to such policies in reducing the negative impacts of climate change for some of the world's poorest and most food-insecure people. The analysis indicates that accelerating the adoption of adapted crop varieties can be an effective means of achieving the SDG2 objectives while explicitly accounting for the challenges posed by climate change. It is important to recognize that although the adaptation strategy considered here is one that countries already have considerable institutional capacity and experience in implementing, they may lack financial resources to achieve the scale of implementation envisioned here.

The costs of producing seeds and making them available to farmers depend on a range of factors, including the time required for seeds multiplication in sufficient quantities for marketing and the time it takes to disseminate the new varieties and for farmers to adopt them (Challinor et al. 2016). The mean times required for new varieties to complete national testing and go to market were estimated at 4.9 years in Malawi and 4.2 years in Tanzania by Challinor et al. (2016). The FAO Investment Assessment Project (FAO 2011) estimated the costs of establishing decentralized seed production facilities at a global average of US$500,000 per 1,000 t of certified seed for cereal crops, pulses, and oilseeds. This estimate is based on the cost of decentralized seed production facilities including buildings, equipment, early generation seed production, and support to the national seed sector, with plant refurbishment and equipment replacement assumed by 2025. Assuming an application rate of 25 kg of seed per ha (based on data for maize in Tanzania), 1,000 t of seed would cover 40,000 ha, resulting in an average cost of $12.50/ha/year for building and maintaining seed production facilities and supporting the national seed sector. This rough estimate does not account for economies of scale which may occur as the seed sector expands and local suppliers become established.

To establish the conditions under which the policy we consider here compares favorably with alternative policies, we need to know two types of costs: the cost of strengthening the national seed sector to enable rapid response in the BDA cycle for adapted seeds and the cost of complementary policies required to enhance adoption rates to help meet SDG2. Obtaining those costs will require more research work focusing on the seed sectors of the target countries.

Our analysis focusses on only one aspect of climate change adaptation—enhancing the production and adoption of improved seeds adapted to changing climate conditions. Even with our conservative assumptions regarding potential yield improvements, our results indicate that the benefits to pursuing this strategy can be sizeable in some agro-ecological zones, but obviously, we expect that a richer portfolio of complementary policies would lead to higher benefits.

A major uncertainty is the magnitude of the CO_2 fertilization effect for different plant groups with Ciscar et al. (2018) finding that additional research is required to understand this effect. In this study, we modelled only the case of no CO_2 fertilization. This reflects the case of low input cropping systems where little scope exists for crops to express CO_2 yield benefits because of other constraints to crop growth. Also, estimating the potential cost of inaction under the worst scenario (RCP8.5 with no CO_2 fertilization) provides a useful starting point for evidence-based policy analysis using large household datasets. The probability of this scenario coming to pass can be estimated separately and adjusted over time as international negotiations and emission outcomes progress. This type of analysis can help countries plan to prevent the worse-case outcomes.

Seeds that are heat- and drought-resistant and high yielding are a key tool for adaptation of vulnerable farmers in sub-Saharan Africa (SSA) and ultimately for achieving SDG2. New seeds represent relatively straightforward adaptation: farmers know the crops and varietal changes generally present few challenges, provided there are no issues around acceptability with respect to taste, color, or other plant attributes, for example (Thornton et al. 2018). The time required to develop and disseminate these seeds depends on a number of factors, to do not only with access to expertise, facilities, and appropriate germplasm (Challinor et al. 2016), but also with the efficiency of supply chains and national-level requirements for testing and approval. This means there is room for improvement in streamlining regulation, funding capacity building, and forming integrated networks for seed production and testing. Systems that integrate participatory breeding and dissemination have the potential to improve the overall efficiency of the BDA process (Challinor et al. 2016). The right balance between centralized and decentralized approaches needs to be found based on the specific situation of each country.

6 Concluding comments

Evidence from previous studies indicates that for effective adaptation, an entire package of complementary measures is needed. In the case of a policy to subsidize the dissemination and use of improved seeds, farmers' participation in the scheme is a necessary but not sufficient condition for success. Once the improved seeds are produced, they should be distributed in conjunction with complementary technologies, such as nutrient, water, and carbon management packages appropriate to local conditions. This means not only improving the coverage and quality of extension services but also supply chain capacity to provide inputs in a timely manner. The costs of an integrated adaptation package will be higher than those of an intervention into a single sector as presented here, but the benefits will also be higher. Integrated adaptation strategies can also provide local employment and training opportunities, allowing households to diversify their income sources or exit agriculture, thereby reducing land fragmentation that can lead to farm sizes becoming unviable for maintaining livelihoods from farming activities (Thornton and Herrero 2015; Rippke et al. 2016).

Using an integrated modelling approach, we have shown that investments in the seed sector now can avoid some of the considerable costs that climate change is likely to impose on poor and food-insecure farmers in sub-Saharan Africa and allow them to achieve the productivity and income gains embodied in SDG 2.3.

There is significant overlap in the types of policies that are good for agricultural development in general and those required for climate adaptation, but climate change brings urgency to these actions and requires investments to focus on expected future conditions that differ spatially and are subject to high uncertainty. Investing now in capacity to develop and apply key technologies may take a decade or longer to bear fruit, hence the urgency to act now. There is a need to apply similar analyses for broad sets of climate-smart practices, especially now as countries are seeking to implement their NDCs. This kind of information can help them to identify policy mixes that will provide the highest return on investment.

Authors' contributions OJC designed the initial conceptual model. OJC, JM, PKT, MH, BH, and LL refined the initial model and contributed to iterative analysis of results. OJC and JM undertook statistical analyses and implemented the numerical model. BB, FH, and AP undertook yield modelling under climate change to obtain the key inputs for the analysis. Everyone wrote the paper.

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