Ex-ante Impact Assessment of Drought Tolerant Sorghum Cultivars under Future Climates: Integrated Modeling approach

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Abstract

An integrated modeling framework – IMPACT – which integrates partial equilibrium economic model, hydrology model, crop simulation model and climate model was used to examine the ex-ante economic impact of developing and disseminating a drought tolerant sorghum cultivar in target countries of Africa and Asia. The impact of drought tolerant sorghum technology on production, consumption, trade flow and prices of sorghum in target and non-target countries were analyzed. And also we estimated the returns to research investment for developing the promising new drought tolerant cultivars and dissemination in the target countries. The analysis indicates that development and release of drought tolerant sorghum in the target countries of Asia and Africa would provide a net economic benefit of about 1476.8 million US$ for the entire world under no climate change condition. Under climate change scenarios the net benefits derived from adoption of new drought tolerant sorghum cultivar is higher than the no climate change condition. This is due to higher production realized by sorghum under climate change scenarios. The results imply that substantial economic benefits can be achieved from the development of a drought tolerant sorghum cultivar. And also this technology will perform better than the existing cultivars in future climate change condition.

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Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is grown in the hot and dry agro ecologies of Asia, Africa, the Americas and Australia. It is the fifth most important cereal crop globally after rice, wheat, maize and barley and is the dietary staple of more than 500 million people in 30 countries. It is grown on 40 m ha in 105 countries of Africa, Asia, Oceania and the Americas. Africa and India account for the largest share (>70%) of global sorghum area. India, Nigeria, Sudan, USA, Niger, Mexico and Ethiopia are the major sorghum producers. Other sorghum producing countries include Burkina Faso, Tanzania, Mali, Brazil, Chad, Australia, Cameroon, Egypt and Argentina.

Sorghum is a staple cereal in sub-Saharan Africa, its primary center of genetic diversity (Ashok Kumar *et al.,* 2011). It is most extensively cultivated in zones of 600-1000 mm rainfall, although it is of importance in areas with higher rainfall (up to 1200 mm), where poor soil fertility, soil acidity and aluminum toxicity are common. The grain is used mostly for food purposes (55%), consumed in the form of flat breads and porridges (thick or thin with or without fermentation). Stover is an important source of dry season maintenance rations for livestock, especially in drylands; it is also an important feed grain (33%), especially in the Americas. Sweet sorghum is emerging as a multi-purpose crop. It can provide food, feed, fodder and fuel (ethanol), without significant trade-offs among any of these uses in the production cycle. ICRISAT has pioneered the sweet sorghum ethanol production technology and its commercialization (Ashok Kumar *et al.,* 2010).

Globally, sorghum production has remained more or less stable over the past 30 years, although there are notable regional differences. The area under sorghum cultivation has increased from about 40 m ha in 1960s to 51 m ha in 1980s (Figure 1). Later on, there was a fluctuation by 4 to 10 m ha in area but reached 43.7 m ha by 2008-10. The productivity increased from 900 kg ha^{-1} in 1960s to 1400 kg ha^{-1} in the period 2008-10. Adoption of improved sorghum cultivars and management practices contributed to the productivity gains though large differences exist in different parts of the world in sorghum productivity.

The yield of the sorghum in the SAT regions of Africa and Asia is very low. In the SAT regions, sorghum is cultivated under rainfed condition and also in the marginal land. Use of inputs like fertilizer, improved seeds and irrigation are very low especially in the African countries contributing to low productivity. The high rainfall variability and frequent drought conditions during the crop growing season also affect the sorghum yield. Due to poor market infrastructure in the developing countries especially in Africa, the farmers are still practicing subsistence farming and this severely limits their ability to invest in new technologies.

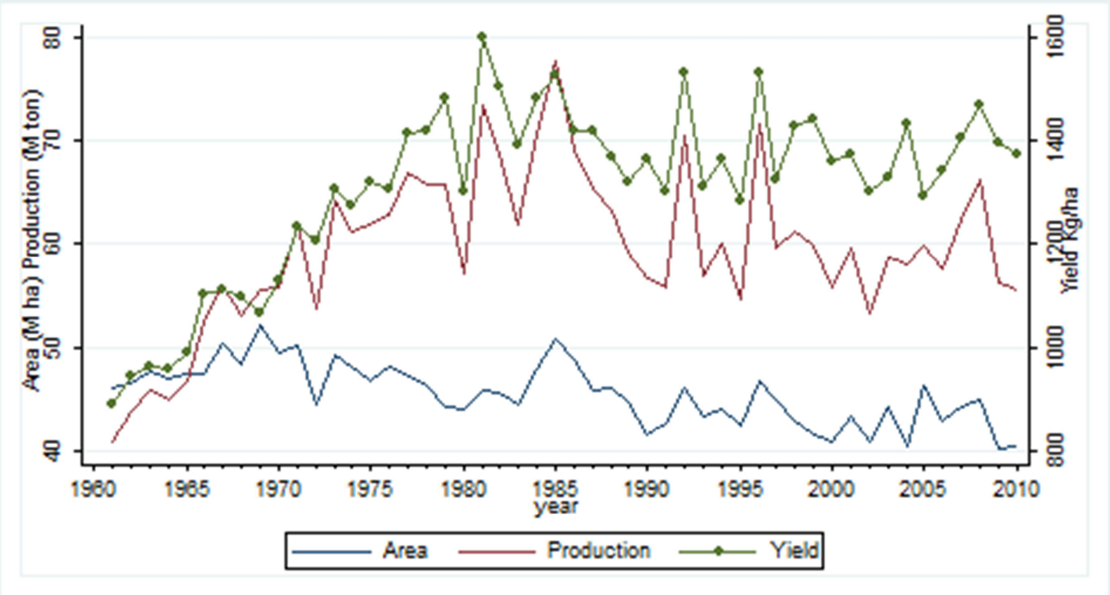

Figure 1 World Sorghum area, production and yield (1961-2010)
Source: FAOSTAT (2012)

Climate change, in terms of higher temperatures, changing precipitation patterns, changing water availability and increased frequency of extreme weather events (IPCC, 2007), will alter the current crop growing conditions on the globe and crop yields will be either negatively or positively affected by climate change. However, in the arid and semiarid tropical regions its effect will be mostly negative thus threatening the food security in these regions (Fischer et al., 2005, Howden et al., 2007). In the semi-arid tropical regions the changes in rainfall coupled with rise in temperature may reduce length of growing season as determined by the duration of soil water availability (Cooper *et al*., 2009). Therefore, in future the maturity durations of crops and cropping systems should match the periods of water availability to achieve higher and stable yields. The optimum air temperature range for vegetative and reproductive growth of sorghum is 26 to 34^{o}C (Hammer *et al*., 1993) and 25 to 28^{o}C (Prasad *et al*., 2008), respectively. In semi-arid tropics where sorghum is currently grown during the rainy season, the mean crop-season temperatures are already close to or above these optimum temperatures. As with other crops, climate change most likely will adversely impact the production and productivity of sorghum, thus interfering with the goal of meeting future food demand especially in the Africa and SAT Asia.

To sustain the productivity of sorghum in the changing future climate and meet the increasing demand for sorghum for food, feed and fodder, the international and national research community is investing resource to develop high yield sorghum cultivars with drought tolerance. The objective of this paper is to evaluate the ex-ante welfare benefits of drought tolerant sorghum cultivars under changing future climates using integrated modeling approach. For this study, we used four climate scenarios: the CSIRO A1B and B1 scenarios represent a dry and relative cool future; the MIROC A1B and B1 scenarios represent a wet and warmer future.

Sorghum Crop Improvement: Research Focus on Drought Tolerance

Sorghum improvement research program at national and international institutes like ICRISAT[1] has been given high priority on a range of promising traits like high yield, large grain with biotic stress resistance (shoot fly, midge and grain mold) and abiotic stress tolerance (drought and salinity), grain micronutrient (Fe and Zn) density and sweet stalk traits. In this study we focused on evaluating the potential welfare benefits derived from sorghum technology with high yield and drought tolerance which is highly adapted in rainfed farming in the semi-arid tropical (SAT) regions of Africa and Asia.

Drought tolerance in sorghum

Four growth stages in sorghum have been considered as vulnerable to drought: germination and seedling emergence, post-emergence or early seedling stage, midseason or pre-flowering, and terminal or post flowering. Terminal drought is the most limiting factor for sorghum production worldwide. In sub-Saharan Africa drought at both seedling establishment and terminal stages is very common. In India, sorghum is grown during both rainy and postrainy seasons. The variable moisture availability at both pre-flowering and post-flowering stages during the rainy season can have severe impact on grain and biomass yield. Drought and/or heat stress at the seedling stage often results in poor emergence, plant death and reduced plant stands. Severe pre-flowering drought stress results in drastic reduction of grain yield. Post-flowering drought stress tolerance is indicated when plants remain green and fill grain normally. A stay-green trait has been associated with post-flowering drought tolerance in sorghum. Genotypes with the stay-green trait are also reported to be resistant to lodging and charcoal rot (Reddy *et al.*, 2007).

Sorghum drought tolerant research process

The drought research at ICRISAT is an on-going activity for the last two decades and screening techniques for selecting drought tolerant cultivars were developed. A large number of germplasm sources and breeding lines were screened for different growth stages of sorghum. Some of the drought tolerant sources identified in sorghum at ICRISAT include Ajabsido, B35, BTx623, BTx642, BTx3197, El Mota, E36Xr16 8/1, Gadambalia, IS12568, IS22380, IS12543C, IS2403C, IS3462C, CSM-63, IS11549C, IS12553C, IS12555C, IS12558C, IS17459C, IS3071C, IS6705C, IS8263C, ICSV 272, Koro Kollo, KS19, P898012, P954035, QL10, QL27, QL36, QL41, SC414-12E, Segaolane, TAM422, Tx430, Tx432, Tx2536, Tx2737, Tx2908, Tx7000 and Tx7078 (Ashok Kumar et al., 2011).

To reduce the research lag, biotechnology[2] tools like marker-assisted selection (MAS) will be used for genetic enhancement of drought tolerance in sorghum. Six stable and major QTLs[3] (Qualitative Trait Loci) were identified for the stay-green trait and are being introgressed through MAS into elite genetic backgrounds at ICRISAT (Ashok *et al.*, 2011).

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[1] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is one of the 15 nonprofit, research and training centers funded through the Consultative Group on International Agricultural Research (CGAIR). ICRISAT's mandate crops are sorghum, pearl millet, groundnuts, chickpea and pigeonpea. ICRISAT's mission is to conduct research which can lead to enhanced sustainable production of these crops and to improved management of the limited natural resource of SAT.

[2] The conventional breeding approach will take about 12-14 years to enhancing drought tolerance in sorghum due to the quantitative inheritance of drought tolerance and yield coupled with the complexity of the timing, severity and duration of drought.

[3] Integration of the sorghum genetic map developed from QTL information with the physical map will greatly facilitate the map-based cloning and precise dissection of complex traits such as drought tolerance in sorghum. Sorghum has a compact genome size (2n=20) and can be an excellent model for identifying genes involved in drought tolerance to facilitate their use in other crops. It was reported that with respect to withstanding drought, sorghum has four copies of a regulatory gene that activates a key gene family which is present in a wide variety of plants. Sorghum also has several genes for proteins called expansins, which may be involved in helping sorghum to recover from droughts. In addition, it has 328 cytochromeP450 genes which may help plants respond to drought stress, whereas rice has only 228 of these genes.

Research cost for developing drought tolerant cultivars

ICRISAT is working on the drought related research for more than two decades and over the years the researchers characterized and evaluated different traits (root system, stay green, etc.) contributing to drought from a wide range of available germplasm material. Based on the past experience and availability of proof of concept, ICRISAT, in the recent years, has been focusing on exploiting stay green trait to develop drought tolerance in sorghum. In this study we assumed that 10 million US$ is made available to ICRISAT and NARS to fund further research to develop drought tolerant cultivars. The 10 million US$ will be appropriately allocated in developing the technology. The annual cost will include salary component of the researchers, field and laboratory costs and other operational costs. For evaluation and validation at different location and environments, the NARS partners in target countries will be involved. Extension costs for multiplication and dissemination of seeds in the target countries were borne by the NARS partners to the tune of US$ 0.25 million each. This was spread over the period until maximum adoption starting from 2019. Table 2 provides the breakup of the budget among ICRISAT and NARS partners over 7 years. This budget allocation is inclusive of the extension cost which is indicated against the year 2018 as 1 million for all target countries put together.

Table 2 Proposed budget allocation for ICRISAT and NARS partners (million US$)

S. No	Year	Research activities	ICRISAT	NARS partners
1	2012	Transfer of QTLs into farmers preferred varieties/elite lines	1.8	0.2
2	2014	Developing introgression lines	1.8	0.2
3	2015	Evaluation and validation in the fields and labs	2	0.3
4	2016	Evaluation in multi-location trails	1	1.2
5	2018	Seed Multiplication ad dissemination	0.5	1

Technology dissemination and adoption pathway

Since sorghum is mostly grown in marginal environments under rainfed conditions especially in sub-Saharan Africa and Asia, the new technology with drought tolerant traits is expected to produce a higher yield than the baseline cultivars which farmers currently grow in the rainfed farming system. The new technology will also increase the resilience of the crop, so that yield will not be affected in drought or less rainfall regimes. Hence, the drought tolerant technology helps to sustain the sorghum production even in the drought year.

The technology dissemination process and adoption pathways vary among countries and mainly depend on infrastructure, governance and policy environment, the adaptive capacity of the NARS partners, and involvement of private seed companies in technology development and dissemination (Table 3). For example, in India ICRISAT develops the hybrid parental line with desired traits (e.g. drought tolerant lines) while the Hybrid Parental Research Consortium (HPRC) partners including the public institutions and private companies select the parental lines and cross these selected parental lines in the locally adapted cultivars preferred by farmers; then release new hybrids in the target regions. Using the HPRC novel approach of harnessing the synergies with the public and private sectors, ICRISAT is successful in catalyzing the fast diffusion of new promising technologies across the sorghum growing states in India. Furthermore, the seed to seed multiplication ratio for sorghum is high so that private companies are extensively involved in the development of hybrid seeds and its effective distribution through retail marketing. In contrast, the other poor and low income countries in Africa and Asia who lack adaptive capacity in their national breeding programs, still constrained with poor infrastructure and have not gained the technical skills in producing hybrid seed, have remained dependent on the development of open pollinated varieties (OPVs) with the desired promising traits.

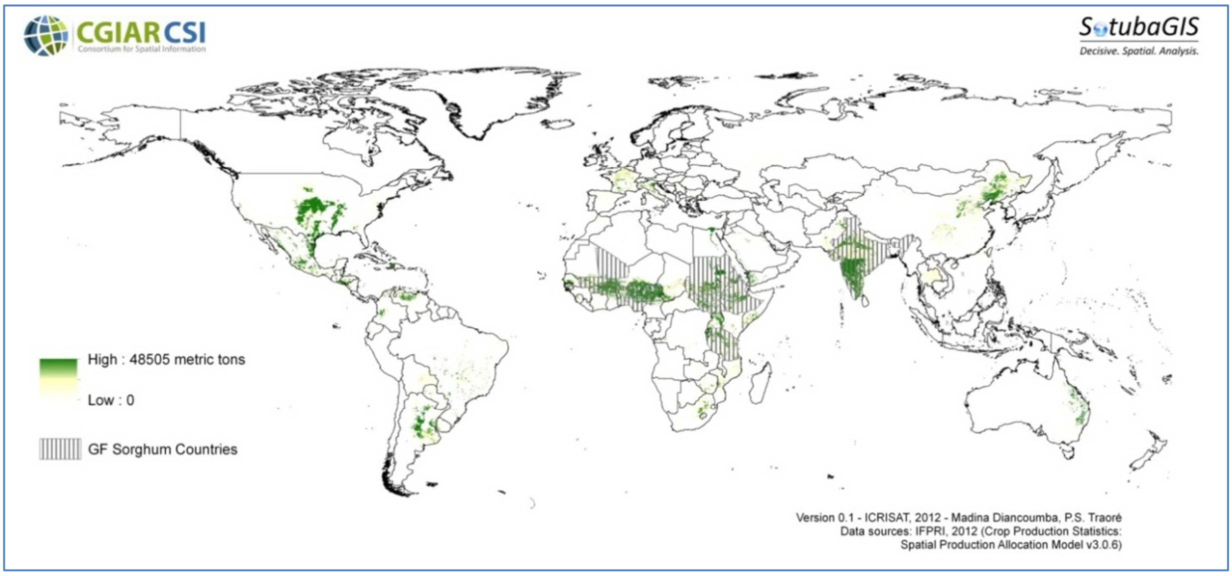

Figure 2 Sorghum production (in metric tons per pixel) and target countries (shaded) for sorghum technology dissemination

The drought tolerant cultivars developed by ICRISAT along with partners are expected to be released in the target countries in different regions globally as shown in Table 3. To estimate the *ex-ante* welfare benefits of the research investments in the target countries, we need some critical inputs like the maximum area planted with the new cultivars (i.e. ceiling adoption level) and number of years it will take to reach the maximum adoption level. These parameters will determine how fast the farmers adopt the new technologies in a target country. The adoption of the new technologies by farmers will be influenced by the profitability of the technology (depends on unit cost reduction of the new technology compared to the best available technology to the farmers), availability of the seeds to farmers at the time of sowing, government policy environments like input subsidies and infrastructures (like road networks, communication, etc.).

Table 3 Ceiling adoption levels and year of maximum adoption in target countries

Region	Target Countries	Ceiling Adoption level	Year of release of technology	Year of Maximum adoption
West and Central Africa (WCA)	Burkina Faso	20	2019	2029
	Mali	60	2019	2027
	Nigeria	60	2019	2027
Eastern and Southern Africa (ESA)	Eritrea	40	2019	2027
	Ethiopia	40	2019	2027
	Sudan	40	2019	2030
	Tanzania	40	2019	2027
South Asia	India	80	2019	2025

Methodology

IMPACT modeling framework

The International Model for Policy Analysis of Agricultural Commodity and Trade (IMPACT) model combines a partial equilibrium model that has global coverage with hydrology and water supply and demand models and the DSSAT crop modeling suite (Nelson *et al*. 2010).The IMPACT model is a partial equilibrium agricultural model for 40 commodities of crop and livestock, including cereals, soybeans, roots and tubers, meats, milk, eggs, oilseeds, oilcakes/meals, sugar/sweeteners, and fruits and vegetables. The IMPACT model includes 281 spatial units, called Food Production Units (FPUs) based on 126 major river basins within 115 regions or country boundaries. The model links the various countries and regions through international trade using a series of linear and nonlinear equations to approximate the underlying production and demand functions. World agricultural commodity prices are determined annually at levels that clear international markets. Growth in crop production in each country is determined by crop and input prices, the rate of productivity growth, investment in irrigation, and water availability. Demand is a function of prices, income, and population growth. IMPACT contains four categories of commodity demand – food, feed, biofuels feedstock, and other uses. The IMPACT model incorporates climate effects from the DSSAT modeling results as a shifter in the supply functions (Richard *et al*., 2012).

In this study two Global Climate Models are considered: CSIRO-Mk3.0, and MIROC 3.2. they are combined with the 'A1B and B1' GHG emission scenarios from the Special Report on Emissions Scenario (SRES). The 'A1' scenario carries the highest level of greenhouse gas emissions for the period under study: 2000-2050. Of these two cases, the future climate is expected to be hottest and wettest under the MIR-A1B and B1 model while under the CSI-A1B and B1 model, the future climate is expected to be drier than that of MIR-A1.

Integrating technology adoption and welfare estimation in IMPACT framework

To allow for area and yield of multiple cultivars to respond to the price of a single commodity, some minor structural changes are made in the IMPACT modeling suite. These include the addition of a nested activity structure for the cultivars. In the IMPACT model the cultivar set is named, cul, and the members of the set are called crop1, crop2, crop3, etc. To integrate the promising and existing cultivars into the activity framework, area and yield equations must be adapted.

Harvested area

To achieve the unique shares of the cultivar areas while maintaining the same total activity area, the shares of area are applied for the cultivars accordingly. Currently in the IMPACT model, the equation for area is a function of the price of the activity, the own and cross price elasticities of the activity, and the exogenous area growth rate, described in the equation below.

$$Area_{j,FPU} = \left(1 + Areagrowth_{j,FPU}\right) * PPV_{j,cty}{}^{AreaElast_{j,jj}} * Areaint,$$

where,

$Area_{j,FPU}$	=	the total area by activity, j
$Areagrowth_{j,FPU}$	=	the total rainfed area growth over time
$PPV_{j,cty}$	=	the producer price
$AreaElast_{j,jj}$	=	the own- and cross-price elasticities for the supply response
$Areaint$	=	the area intercept

To incorporate the nested cultivar shares of the area by food production unit, the equation is adapted as follows:

$$Area_{cul,FPU} = CulShare_{cul,FPU} * \left(1 + Areagrowth_{j,FPU}\right) * PPV_{j,cty}{}^{AreaElast_{j,jj}} * Areaint$$

Subject to:

$$Area_{j,FPU} = \sum_{cul} Area_{cul,FPU}$$

where,

$Area_{j,FPU}$	=	the total area by activity, j
$Area_{cul,FPU}$	=	the total area by cultivar, cul, for activity, j
$CulShare_{cul,FPU}$	=	the share of the total area by cultivar
$Areagrowth_{j,FPU}$	=	the total rainfed area growth over time
$PPV_{j,cty}$	=	the producer price
$AreaElast_{j,jj}$	=	the own- and cross-price elasticities for the supply response
$Areaint$	=	the area intercept

Yield

The initial yield for each of the cultivars will be determined by using the yield of the activity for that food production unit which is calculated as the total production per hectare of area. The yield of the cultivars will respond to the prices of the activity, fertilizers, and wages based on the activity elasticities for each. The cultivar yield will also grow over time according to the exogenous yield growth rate.

Exogenous yield growth rate

The exogenous yield growth rate for each cultivar will be determined based on the intrinsic yield growth rate for the activity as a starting point for the growth over the time period. In the equation below, this growth rate is denoted as, a. The additional exogenous yield growth that is contributed by the promising cultivars is called b in the equation. This additional growth rate along with the productivity effect of climate change namely c will be added to the intrinsic yield growth rates, to form the rate of growth for the promising cultivars.

$$Y_{cul,FPU,t} = Y_{t-1}\left(1 + \left(a_{j,FPU} + b_{cul,fpu} + c_{j,fpu}\right)\right) * \left[PPV_{j,cty}{}^{YieldPriceElast} * PFER_{j,cty}{}^{YieldFertElast} * PWAG_{j,cty}{}^{YieldWageElast}\right],$$

where,

Y	=	the yield for the cultivar of j in each FPU
PPV	=	the producer price
PFER	=	the price of fertilizer
PWAG	=	the cost of wages
a	=	the intrinsic productivity growth of yield
b	=	the cultivar specific productivity growth of yield
c	=	the biophysical effects on productivity growth due to climate change
YieldPriceElast	=	the own-price irrigated supply elasticity
YieldFertElast	=	the elasticity of the supply response with respect to fertilizer
YieldWageElast	=	the elasticity of the supply response with respect to wages
FPU	=	the food production unit index
cty	=	the country index
cul	=	the cultivar index
j	=	the activity index

Welfare Analysis

The welfare component of the calculations follows a traditional economic welfare analysis approach to estimate the benefits to society on the consumer- and producer-side. On the consumer-side this is straightforward, as the IMPACT model has a demand curve with demand elasticities, which allows us to calculate the consumer surplus. On the producer-side, it is not as straightforward, as the quantity supplied of each commodity is an area-yield equation, and does not represent the traditional supply curve that reflects the producer's marginal cost curve. Therefore, we have had to create synthesized supply-curves by land-type (irrigate, rainfed, other) for each activity and then calculate the producer surplus for each of these supply-curves and then aggregate to the national level. The total changes in consumer and producer surplus, when combined, provide us with a benefit flow, which we can use in a benefit-cost analysis, to compare a technology's overall impact in the agriculture sector.

Consumer Surplus

The demand curves in the IMPACT model has income and price elasticities, and is in the following general form:

$$QF_{c,cty} = \prod\left[\left(PCV_{c,cty}\right)^{FDelas_{c,cty,c}}\right] * \left(pcGDP_{cty}\right)^{IncDmdElas_{c,cty}} * pop_{cty} * dmdint_{c,cty}$$

where,

$QF_{c,cty}$	=	Quantity demanded for commodity c
$PCV_{c,cty}$	=	Consumer price for commodity c
$pcGDP_{cty}$	=	National per capita GDP
pop_{cty}	=	National Population
$dmdint_{c,cty}$	=	Food Demand Intercept
$FDelas_{c,cty,c}$	=	Own-price elasticity for commodity c
$IncDmdElas_{c,cty}$	=	Income demand elasticity for commodity c

For each year and commodity, we compute the slope, m, in the equation below, of the straight line from the equilibrium point of the reference scenario (designated as subscript ref in the equations below) to the price axis using the food demand elasticity. In this calculation of the slope, we use the total quantity of food demand (QF) and the consumer prices (PC).

$$m_{ref} = \frac{1}{\varepsilon_{ref}} * \frac{p_{ref}}{q_{ref}}$$

Using this slope we can now calculate the price intercept of this line. The price intercept is the upper bound of price on consumption.

$$PInt_{ref} = p_{ref} - m_{ref} * q_{ref}$$

With the price intercept, we can now calculate the consumer surplus of the reference scenario, which will be used for all comparisons with different simulations.

$$CS_{ref} = \frac{1}{2} * \left(PInt_{ref} - p_{ref}\right) * q_{ref}$$

We envision changes between simulations and the reference scenario to be parallel shifts of the line formed by m_{ref} and the simulations' equilibrium point.

$$P_{simulation} = m_{ref} * q_{simulation} + PInt_{simulation}$$

We solve for $PInt_{simulation}$, which then allows us to compute the consumer surplus in the technology simulation.

$$CS_{simulation} = \frac{1}{2} * (PInt_{simulation} - p_{simulation}) * q_{simulation}$$

The change in consumer surplus between the simulation and the reference scenario is the difference of these two triangles.

To decompose the price and income effects we have to calculate the demand of the new simulation demand curve, but at the reference scenario prices, which we will call Q*

$$Q^* = \frac{p_{ref} - PInt_{simulation}}{m_{ref}}$$

Now, using Q* we can compute the areas of the price and income effects. First, we calculate the hypothetical consumer surplus if the equilibrium was at reference scenario prices and Q*.

$$CS_{Q^*} = \frac{1}{2} * \left(PInt_{simulation} - p_{ref}\right) * Q^*$$

Then we subtract triangles to calculate the price and income effects.

$$Price\ Effect = CS_{Q^*} - CS_{simulation}$$

$$Income\ Effect = CS_{Q^*} - CS_{ref}$$

To test if this decomposition is correct we can check to see if the following holds:

$$\Delta CS = Income\ Effect - Price\ Effect$$

Producer Surplus

To calculate the producer surplus we need to be able to calculate the area above the supply curve and under the equilibrium price. In effect, we calculate the agricultural revenue at the equilibrium point and subtract the total cost of production, which is the area under the supply curve. Without a traditional supply curve, derived directly from a marginal cost curve, we have to derive a supply-curve from IMPACT's area-yield functions, which generally speaking give us the quantity supplied (QS) in the following way.

$$QS = Area \times Yield$$

To calculate the total cost, we need to make QS a function of price. First the area[4] and yield[5] equations as functions of their own-price (PP).

$$Area = K_{area} * PP^{\varepsilon_{area}}$$
$$Yield = K_{yield} * PP^{\varepsilon_{yield}}$$

Now we can make QS a direct function of its own-price.

$$QS = K * PP^{\varepsilon}, where$$
$$K = K_{area} \times K_{yield}\ and$$
$$\varepsilon = \varepsilon_{area} + \varepsilon_{yield}$$

We then get the inverse supply function.

$$PP = P(Q) = K^{\left(\frac{1}{\varepsilon}-1\right)} \times QS^{\frac{1}{\varepsilon}}$$

Now with the inverse supply function, we are ready to calculate the producer surplus (PS), which is agricultural revenue (AR), less the total cost (TC) of production, which is the area under the inverse supply function, which we can calculate by taking the integral of P(Q)[6].

$$PS = AR - TC, where$$
$$AR = P \times QS\ and$$
$$TC = \int_0^{Q_0} P(Q) = \frac{1}{\left(\frac{1}{\varepsilon}+1\right)} \times (P \times QS), so$$
$$PS = (P \times QS) - \left[\frac{1}{\left(\frac{1}{\varepsilon}+1\right)} \times (P \times QS)\right] = \left[1 - \frac{1}{\left(\frac{1}{\varepsilon}+1\right)}\right] \times P \times QS = \left[\frac{\left(\frac{1}{\varepsilon}\right)}{\left(\frac{1}{\varepsilon}+1\right)}\right] \times P \times QS$$
$$= \frac{1}{1+\varepsilon} \times P \times QS = \frac{P \times QS}{1+\varepsilon}$$

Using this equation, the producer surplus for all of the scenarios is calculated and the change in producer surplus due to technology adoption from the reference case is calculated as follows,

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[4] K_{area} is a constant that includes growth rates, the IMPACT area intercept, and the effects of cross price elasticities.

[5] K_{yield} is a constant that includes growth rates, the IMPACT yield intercept, and the effects of input costs

[6] $\int_0^{Q_0} P(Q) = \int_0^{Q_0} K^{\left(\frac{1}{\varepsilon}-1\right)} \times QS^{\frac{1}{\varepsilon}} = \frac{K^{\left(\frac{1}{\varepsilon}-1\right)}}{\frac{1}{\varepsilon}+1} \times QS^{\left(\frac{1}{\varepsilon}+1\right)} = \left(QS\frac{1}{\frac{1}{\varepsilon}+1}\right) \times \left(K^{\left(\frac{1}{\varepsilon}-1\right)} \times QS^{\frac{1}{\varepsilon}}\right) = P(Q) \times \left(QS\frac{1}{\frac{1}{\varepsilon}+1}\right)$

$$\Delta PS = PS_{simulation} - PS_{ref}$$

Cost

The cost of developing and implementing a new crop cultivar is differentiated by the source of the funding, whether it is at the global or national level. Global costs are the costs of research and development that cannot be tied directly to any specific country. The role of research and development at CG centers is a good example of global costs, as the research done in developing new crop varieties is done for the benefit of many countries.

National costs are broken up into two different types of expenditures. First there is the cost of adapting a new crop variety or technology to the country-specific conditions. The cost is borne at the country-level, often by national research institutions and universities. Secondly there is the cost of agricultural extension required for the diffusion of the new technology.

This bifurcation of the costs allows for a more nuanced analysis of benefit-costs at both the national and global level. The national cost cash flow does not include global costs. This makes the assumption that from the perspective of the country that all work done at the global level (in CG centers) is a public good and is received by national research institutions free of charge. Global costs include both the global costs and the national costs.

Benefit-Cost Analysis

The Benefit-cost measures can only be used in simulations, where there is a cost component and a defined discount rate associated with a new technology. These measures can be broken up into indicators that compare simulations with their respective costs and observed changes in:

- Food Security
- Welfare

Food Security Measures

There are three food security measures, which provide insight into the effects of different simulations on food security. These measures compare simulations to show the greatest positive returns in improving food security. The following equations describe these measures:

- Food Availability: $\frac{Kcal_{simulation} - Kcal_{ref}}{NPV(Cost_{investment})}$
- Malnourished Children: $\frac{Malnourished_{simulation} - Malnourished_{ref}}{NPV(Cost_{investment})}$
- Share at Risk of Hunger: $\frac{Share_{simulation} - Share_{ref}}{NPV(Cost_{investment})}$

Welfare Measures

Net Benefits and Benefit-Cost Ratio

To allow for better comparisons between the benefits of different technologies, we need to discount the benefits over time and compute the present value of change in consumer surplus and agricultural revenue between simulations. We do this by discounting future benefits at a given discount rate (r) for the years that the simulation is run.

$$NPV(CS_{simulation}) = \sum_{i=1}^{n} \frac{\Delta CS_{simulation}^{i}}{(1+r)^{i}}$$
$$NPV(AR_{simulation}) = \sum_{i=1}^{n} \frac{\Delta AR_{simulation}^{i}}{(1+r)^{i}}$$
$$NPV(Total\ Benefits_{simulation}) = NPV(CS_{simulation}) + NPV(AR_{simulation})$$

We then need to do the same with cash flow of costs for implementing the changes in technology.

$$NPV(Cost_{simulation}) = \sum_{i=1}^{n} \frac{Cost_{simulation}^{i}}{(1+r)^{i}}$$

Once we have a total benefits measure and a total cost measure we can create the Benefit-Cost ratio and calculate the Net Benefits of the technology for each crop and country.

Benefit-Cost Ratio: $\frac{NPV(Total\ Benefits_{simulation})}{NPV(Cost_{simulation})}$

Net Benefits: $NPV(Total\ Benefits_{simulation}) - NPV(Cost_{simulation})$

Summing over countries or commodities provides measures by crop and country, globally by crop, national totals, and global total.

Internal Rate of Return

In addition to the net benefits measures, we can also compute the internal rates of return (IRR) of the technology simulations. The internal rate of return of the technology is the discount rate (r)[7], which makes the NPV of total cash flows (benefits – costs) equal zero.

$$NPV = \sum_{i=1}^{n} \frac{(\Delta CS_{simulation}^{i} + \Delta AR_{simulation}^{i}) - Cost_{simulation}^{i}}{(1+r)^{i}} = 0$$

Scenario Results

Economic and social benefits of the sorghum drought tolerant technology

The welfare benefit of the adoption of new drought tolerant cultivars of sorghum in the target countries/regions and its impact on world price, production, consumption, change in malnutrition and poverty is assessed using the IMPACT model. For this analysis, it is assumed that the drought tolerant technology will have 20% higher yield advantage over the baseline technology (earlier used by farmers). A framework illustrating the technology development, dissemination, adoption pathway and its outcomes and impacts in the target countries as well as in the world is given in the Figure 3.

[7] Traditionally, solving for r would require using a root solving algorithm (i.e. Secant Method, or Müller's Method). However, we can let the GAMS solver do the work for us, and solve for r by creating a basic model representing the previous relationship. As we are solving for a root, there is an additional requirement for computing the IRR. In addition to a cash flow, the time discounted benefits must be non-negative, meaning no IRR can be calculated for any simulations where the benefits do not at least match the cost of investment.

In this study, we also assessed the change in the welfare benefits by adopting the new promising drought tolerant technology in different climate change scenarios. These climate scenarios used in the analysis are the MIROC (MIR A1B and B1) scenarios representing warmer and wetter climates while the CSIRO (CSI A1B and B1) scenarios represent the dry and relatively cool climates (Nelson et al ., 2010).

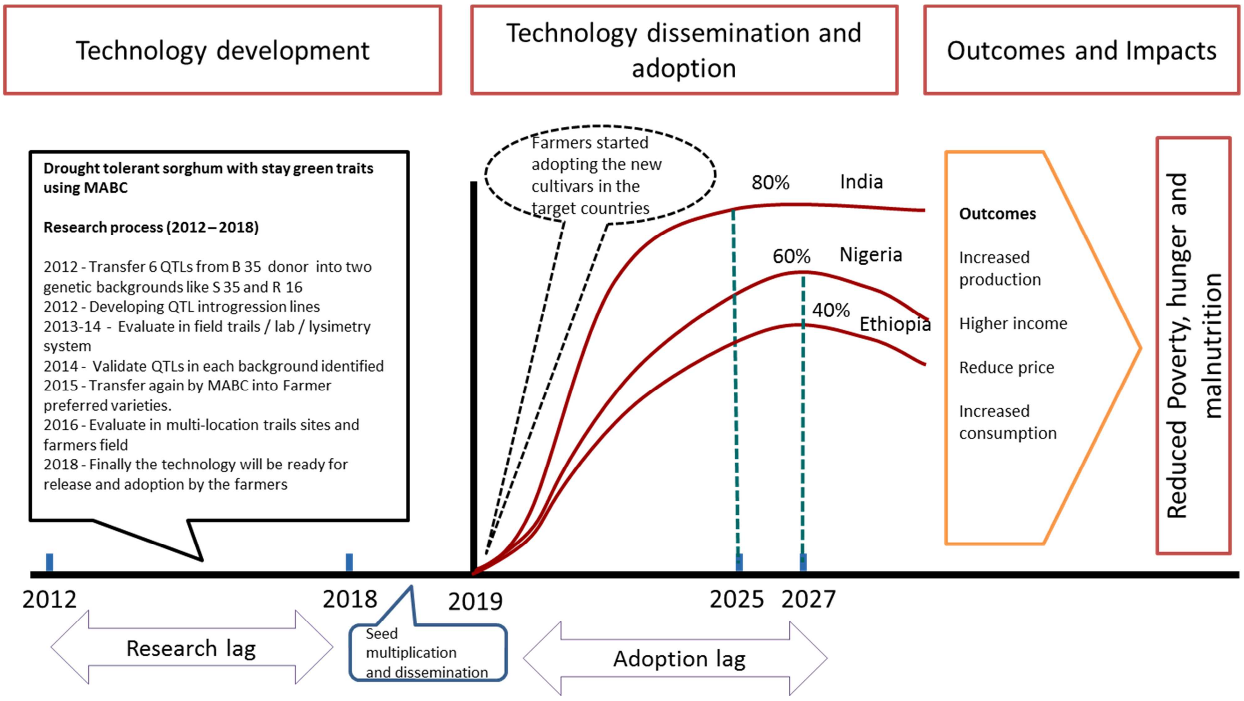

Figure 3 The framework of technology development and adoption pathways linked with outcomes and impacts

Global welfare benefits under different climate change scenarios

The likely global welfare benefits due to the adoption of drought tolerant sorghum cultivars under different climate change scenarios are given in the Table 4. The net welfare gains under the no climate change scenario are about US$ 1481 million. The global producers lose because of decrease in world market price, the negative producer surplus from the non- target countries (mainly the big exporting counties like USA, Australia, etc.) where new technology is not adopted is offsetting the positive producer surplus gained in the target countries where the new technology is adopted. The global consumers are gaining significantly due to decrease in the consumer price in the world market caused by the increased production. The net benefits under CSIRO climate scenario are higher than the without climate change (Table 4). Under both CSIRO climate scenarios, the adoption of new technology increased the global net welfare benefits and also higher than the no climate change condition.

The IRR for the sorghum drought research investment under no climate change condition is about 59% and BC ratio is 292:1.

Table 4 Global welfare benefits of drought tolerant sorghum technologies

		Climate change scenarios			
Welfare and returns on investment	**No climate change**	**MIROC 369 A1B**	**MIROC 369 B1**	**CSIRO 369 A1B**	**CSIRO 369 B1**
Net Welfare change (NPV, m US$)	1481.93	1443.33	1450.48	1769.04	1662.57
Cost (NPV, m US$)	5.06	5.06	5.06	5.06	5.06
Benefit-Cost ratio	292.79	285.16	286.58	349.52	328.48
Net benefits (NPV, m US$)	1476.87	1438.27	1445.42	1763.98	1657.50
IRR (%)	59.03	58.35	58.52	60.56	60.01

[a]369 is the assumed CO2 concentration by 2050 in ppm. A1B and B1 refer to the corresponding SRES climate change scenarios.
[b] Reported changes are over baseline, represented by the respective climate change scenario without the promising technology.
Source: Authors' calculation

Economic benefits in the target countries

The estimated net benefits of a sorghum drought tolerant cultivar developed and released in 2019 in the target countries under no climate change condition ranges from 692.8 US$ to 16.4 US$ depending upon the adoption rates and period until maximum adoption (Table 5). The net benefits are high in the larger sorghum producing countries like India, Nigeria and Sudan. The rate of return on research investments (i.e., IRR) for developing and releasing the new drought tolerant sorghum cultivar is ranging from 134.2% in India to 49.3 % in Eritrea (Table 5). These return on investment measures suggest that the returns to the development and release of drought tolerant sorghum variety in the target countries are worth the costs incurred. The net benefits of the sorghum drought tolerant cultivars in the target countries under climate change are above the no climate change condition. Even in the dryer CSIRO climatic scenario, the net benefits are higher than under no climatic change scenario. It reveals that the sorghum drought tolerant cultivar has produced higher yield and maintained the production level even in the drier climate in the target countries. In the wetter and high temperature MIROC climate scenario the economic benefit of the new technology is lower than the no climate change condition in the target region. The higher precipitation in the climate scenario contributed to the increased yield in rainfed sorghum, where more than 80% of the sorghum area is under rainfed farming around the world.

Table 5 Net Economic Benefit Drought tolerant sorghum cultivars in the target countries under Climate Change Scenarios

		No Climate Change		MIROC 369 A1B		MIROC 369 B1		CSIRO 369 A1B		CSIRO 369 B1	
Regions	Target Countries	Net Benefits	IRR	Net Benefits	IRR	Net Benefits	IRR	Net Benefits	IRR	Net Benefits	IRR
		in m US$	%	in m US$	%	in m US$	%	in m US$	%	in m US$	%
WCA	Burkina Faso	90.7	75.8	82.4	74.1	80.0	73.9	99.8	76.4	100.8	76.6
	Mali	61.0	72.1	60.1	71.3	57.9	71.0	66.4	50.7	66.3	72.7
	Nigeria	479.6	116.0	526.7	116.7	513.6	116.4	584.6	90.0	528.1	116.6
ESA	Eritrea	16.4	49.3	15.8	49.5	16.8	49.5	19.2	134.2	18.2	50.3
	Ethiopia	138.8	89.6	121.4	87.5	117.8	87.2	150.1	72.5	140.1	89.1
	Sudan	187.6	87.4	205.0	87.2	200.8	87.1	226.0	117.7	218.1	88.6
	Tanzania	54.7	68.0	45.7	65.7	50.5	66.9	63.2	89.1	57.8	68.4
South Asia	India	692.8	134.2	547.1	133.6	578.3	133.8	776.3	69.4	722.3	134.1

Source: Authors' calculation

Change in Production, consumption and net trade in the target countries

The IMPACT model projections of production, consumption, and net trade of sorghum in 2050 for no climate change scenario with and without drought tolerant technology intervention are presented in Table 6.

The model results suggest that in 2050 sorghum production and consumption in the target countries will be higher after a drought tolerant sorghum cultivar is developed and adopted as compared to the case where the variety was not developed and adopted by the farmers in the target countries. The results show that the percentage increase in production (i.e. change in production after the new technology adopted compare to baseline) ranges from 14.6% in Eritrea to 4.9 % in Burkina Faso. It reveals that production in the target countries will have been smaller if the new drought tolerant cultivars are not developed and disseminated.

Due to increase in the sorghum production of the target countries after the adoption of new technology, the world price of sorghum reduced by 4.3 % in 2050 under no climate change condition (Figure 4). Among the climate change scenarios, CSIRO A1B scenario has reduced the world price by 4.97%. The lower sorghum world price has reduced the consumer price in the target countries as well as in other non-target countries. Because of decrease in the country level consumer price, the demand for sorghum consumption has slightly increased in the target countries ranging from 1.4 % in Burkina Faso and Mali to 3 % in Tanzania (Table 6).

Table 6 Change in Production, consumption and net trade in the target countries in 2050 after the adoption of drought tolerant sorghum in target countries

Regions	Target Countries	Particulars	2010	Projected value in 2050 without new technology	Projected value in 2050 with new technology	% change
WCA	Burkina Faso	Production ('000 tons)	1637.3	3985.1	4179.0	4.9
		Consumption ('000 tons)	1480.7	3930.0	3986.9	1.4
		Net trade ('000 tons)	159.7	58.2	195.3	
	Mali	Production ('000 tons)	821.4	2299.3	2527.0	9.9
		Consumption ('000 tons)	733.1	1861.7	1887.8	1.4
		Net trade ('000 tons)	64.3	413.7	615.2	
	Nigeria	Production ('000 tons)	9428.5	18103.5	19590.2	8.2
		Consumption ('000 tons)	8801.1	21660.1	22049.0	1.8
		Net trade ('000 tons)	488.6	-3695.5	-2597.7	
ESA	Eritrea	Production ('000 tons)	109.3	241.2	276.9	14.8
		Consumption ('000 tons)	235.4	539.6	548.5	1.6
		Net trade ('000 tons)	-72.0	-244.3	-217.4	
	Ethiopia	Production ('000 tons)	2482.2	6332.4	6663.8	5.2
		Consumption ('000 tons)	2015.6	4805.6	4884.7	1.6
		Net trade ('000 tons)	676.1	1736.3	1988.6	
	Sudan	Production ('000 tons)	4881.7	10396.4	10954.9	5.4
		Consumption ('000 tons)	3890.6	7796.2	7923.9	1.6
		Net trade ('000 tons)	1201.2	2810.3	3241.1	
	Tanzania	Production ('000 tons)	997.6	3492.8	3675.4	5.2
		Consumption ('000 tons)	767.5	2443.9	2516.5	3.0
		Net trade ('000 tons)	232.8	1051.6	1161.6	
South Asia	India	Production ('000 tons)	7953.4	10345.0	11713.6	13.2
		Consumption ('000 tons)	8028.3	10223.2	10430.3	2.0
		Net trade ('000 tons)	-371.6	-174.9	986.7	

Source: Authors' calculation

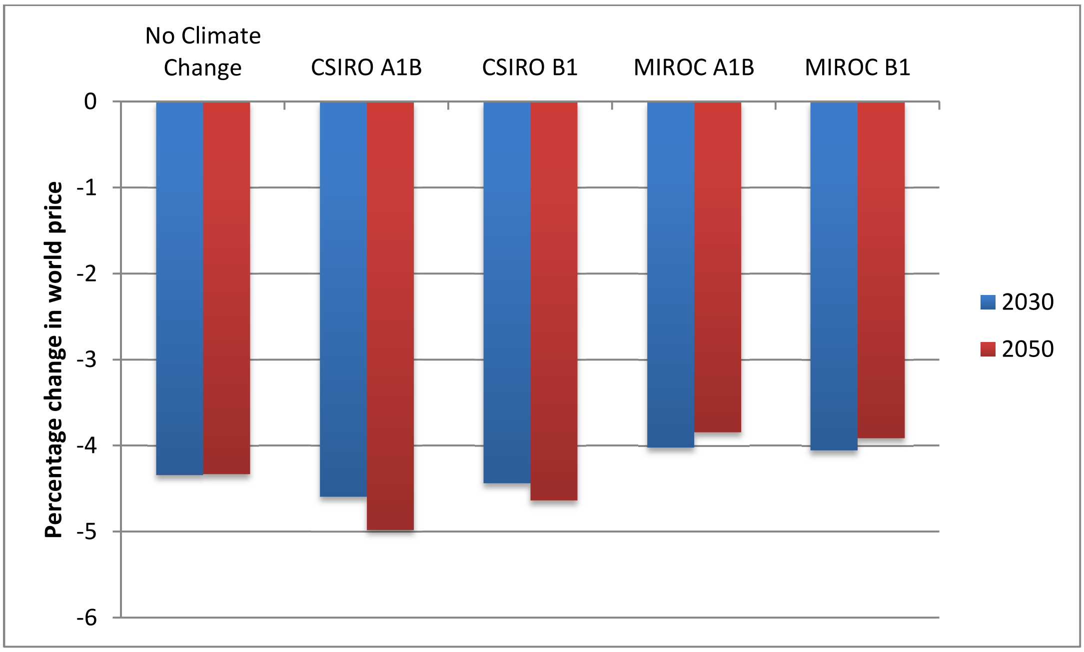

Figure 4 Change in the World price of sorghum under different climate scenarios

Spillover benefits of the sorghum technology intervention in non-target countries

The estimated positive net economic benefits for countries[8] after the technology intervention under no climate change in presented in the Figure 5. The decrease in consumer price of sorghum after the technological intervention has benefitted consumer around the world. The positive net benefits for some of the non-targeting countries has revealed that the consumers gained by the price spillover effect of the drought tolerant sorghum technology adoption. Countries like Niger, Chad, Somalia, etc., where sorghum is consumed as staple food has benefited due to price spillover effects of the technology intervention.

[8] The countries with net benefits greater other 5 million US$ is presented in the Figure 5.

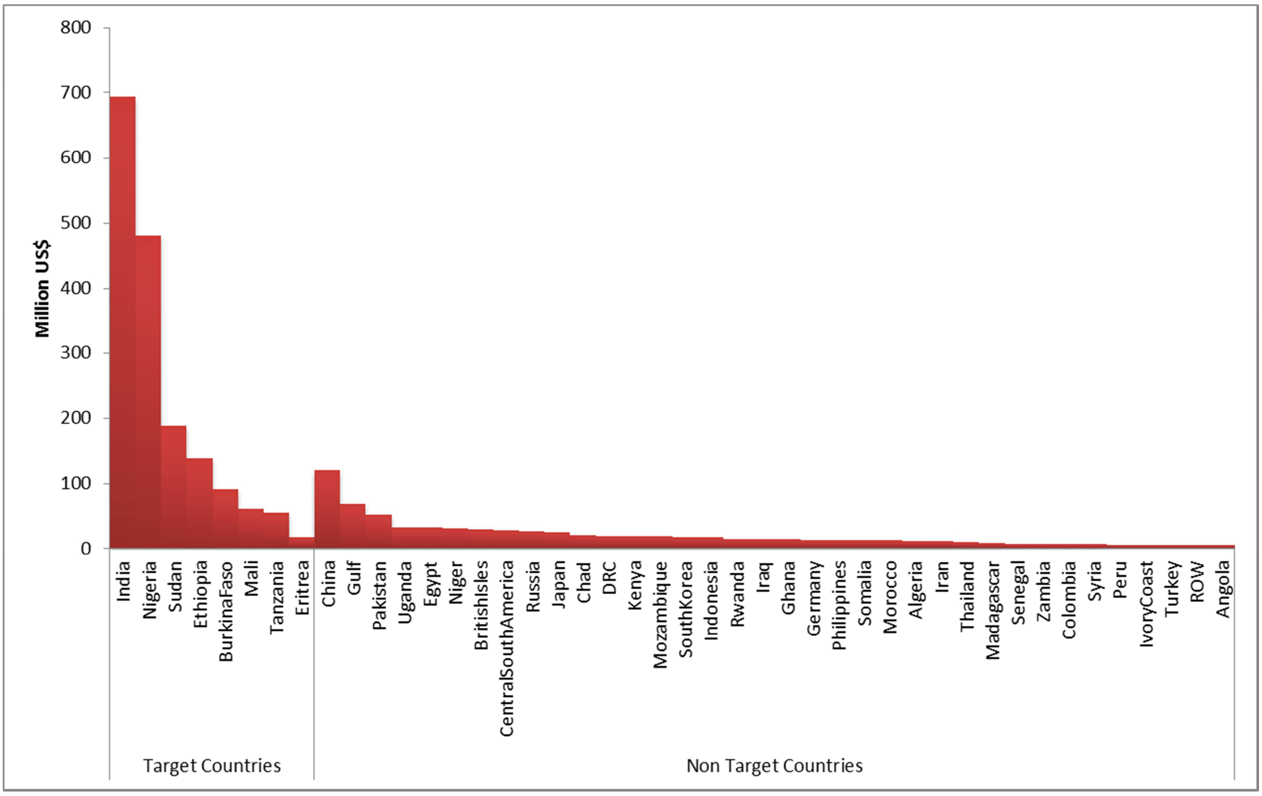

Figure 5 The net welfare benefits (million US$) for the target countries and non-target countries under no climate change

Summary and Conclusion

In this study we used the integrated modeling framework – IMPACT – which integrates partial equilibrium economic model, hydrology model, crop simulation model and climate model to examine the ex-ante economic impact of developing and disseminating a drought tolerant sorghum cultivar in target countries of Africa and Asia under no climate change and two different climate change scenarios (MIROC and CSIRO GCMs). Specifically, we estimated the potential yield advantage of the promising new drought tolerant sorghum cultivars over the baseline cultivar using crop simulation model and its impact on production, consumption, trade flow, prices of sorghum and welfare indicators like change in poverty, malnourished children and change in the number people under hunger risk in target countries and as well as the non-target countries. In addition, we estimated the returns to research investment for developing the promising new drought tolerant cultivars and dissemination in the target countries.

The analysis indicates that the economic benefits of drought tolerant sorghum cultivar adoption in the target countries outweighs the cost of developing this new technology. The development and release of this new technology in the target countries of Asia and Africa would provide a net economic benefit of about 1476.8 million US$ for the entire world under no climate change condition. Under climate change scenarios, the net benefits derived from adoption of new drought tolerant sorghum cultivar is higher than the no climate change condition. This is due to higher production realized by sorghum under climate change scenarios.

In addition, results of the IMPACT model projections suggest that the new technology intervention reduced the children malnourished under the age group of 5 years in the target countries ranging from 97,114 in Nigeria to about 2,198 children in Eritrea for a million US$ investment.

These results imply that substantial economic benefits can be achieved from the development of a drought tolerant sorghum cultivar. And also this technology will perform better than the existing cultivars in future climate change condition. Thus, we strongly encourage policy makers and donors to fund the sorghum research to develop more tolerant to droughts, so that farmers can better cope and adapt to changing climate in the future.

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