32nd International Conference of Agricultural Economists
2-7 August 2024 I New Delhi I India

Assessing the development impacts of bio-innovations

The case of genetically modified maize and cassava in Tanzania

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Abstract

Tanzania's agriculture is characterized by low productivity due to unpredictable rainfall and the prevalence of pests and diseases. Genetically modified (GM) maize offering protection against drought and insects are being developed. Likewise, GM varieties resistant to cassava brown streak disease were developed. Building on prior crop-based analyses, we use the Rural Investment and Policy Analysis (RIAPA) CGE model to assess the impacts of the adoption of those GM crops. GM maize and cassava have positive effects on the economy, the Agri-Food System (AFS), and poverty. Given its stronger linkages in the AFS, the effects of the GM maize are stronger, especially in higher adoption and high yield scenarios. Likewise, the effects on the poorest and rural households are greater. The high variation across scenarios, and the significant effect of the high adoption/high yield scenarios, suggests a high return to investments and policies that realize these adoption rates and yield potential.

JEL Codes: O10, O30, 055.

1. Introduction

The agricultural sector is critical to the Tanzanian economy. In 2020, it contributed 27% of GDP (NBS 2020), employed about 66% of the national labor force (NBS 2021), and accounted for over 30% of all exports. Despite its great potential and central role, the sector faces serious challenges, including overall food crop yields averages that barely reach 1.5 T/ha for cereals, and about 4.4 T/ha for major root crops (NBS 2020, 2021).

Maize and cassava yield in Tanzania are estimated at 1.6 tons/ha and 8.0 tons/ha, respectively (FAO, 2022). While comparable to what is observed in many other SSA countries where the average yields are 2.1 tons/ha and 8.9 tons/ha, respectively for maize and cassava. Comparatively higher levels are observed for maize in Europe (6.4 tons/ha), the United States (11.7 tons/ha) and Latin America (7.2 tons/ha), and cassava in Latin America (14.3 tons/ha) and Asia (21.6 tons/ha) (FAO, 2022). Several endogenous and exogenous factors – including shifts in rainfall patterns, the severity of droughts, and the incidence of pests and diseases – explain these persistent low yields. Additionally, climate change is projected to have an adverse yield impact, particularly for coarse grain (Wiebe et al. 2015), unless these effects are offset by targeted policy and investment interventions (Sulser et al. 2021). Plant pests and diseases, along with market inefficiencies, will have further negative impacts on household food security and the broader economy.

Given this scenario, investments in genetically modified (GM) technologies that protect crops against pests, diseases and droughts have been supported and advanced by international and local researchers. In Tanzania these crops included TELA1 maize (a GM variety that offer protection against droughts and insects), and GM cassava that is resistant to Cassava Brown Streak Disease (CBSD), one of its main biotic limitations. Product development progress for these GM crops in Tanzania has been delayed since January 2021, despite promising local field study results.

Aside from relying on the long and 25-year-documented record of food, feed, and environmental safety and a predictable science-based regulatory system to evaluate the safety of new and evolving products, methods to assess the potential economic impacts of these novel GM crops can also inform decisions that impact their access to farmers. Although a compendium of solid literature has assessed the benefits of these technologies in many countries and regions around the world (Fischer et al. 2015; Klümper and Qaim 2014; Areal et al. 2013; Finger et al. 2011; Smale et al. 2009), including Sub-Saharan Africa (Zambrano et al. 2019), until recently, few locally led economic studies have been conducted for these specific technologies.

To address this gap, the International Food Policy Research Institute's (IFPRI) Biotechnology and Biosafety Rapid Assessment and Policy Platform (BioRAPP) conducted an ex-ante assessment of priority

[1] The word "TELA" is derived from the Latin word TUTELA which means "Protection." (AATF 2022).

GM crops in Tanzania (Ruhinduka et al. 2020) and four other Africa countries (Ethiopia, Ghana, Nigeria, and Ghana), relying on the expertise and knowledge of local economists and scientists. For Tanzania the locally identified priority GM crops were TELA maize and CBSD cassava. These locally led studies, implemented in close consultation with national experts and stakeholders, produced timely results for policy and decision makers, to inform policy conversations about biotechnology products. Since the focus of the studies were to evaluate crop-based results that could be estimated locally, the IFPRI's DREAM tool was used, which implements the partial equilibrium economic surplus model (ESM). This model assesses specific crop level effects while maintaining other crop and sectors of the economy constant (Alton et al. 1995). ESM is also known as an equilibrium displacement model as it considers shocks to the initial market structure and conditions (e.g., technology adoption shifting supply and/or demand) to examine changes in consumer's and producer's surplus. The ESM results for Tanzania (Ruhinduka et al., 2020) were complemented and cross-checked using the stochastic economic surplus and real options models.

Ruhinduka et al.'s (2020) ex ante partial-equilibrium analysis suggests that large and positive net benefits potentially accrue to consumers and producers from the adoption of both TELA maize and CBSD cassava in Tanzania. Given the greater value and extension of maize in Tanzania, the estimated benefits to consumers and producers are larger for TELA maize than for CBSD cassava. The authors conclude that, while the exact magnitude of the impact hinges on the assumed magnitude of change of critical variables and the estimation method, there is a significant likelihood that the net impact of the adoption of GM maize and cassava to consumers and producers is positive in Tanzania. Annex 2 summarizes the results of this analysis.

DREAM-based assessments provide an indication of the benefits accrued by producers and consumers of a specific crop due to the adoption of new technologies (supply shift) and DREAM is a valuable tool that has been used by many practitioners around the world. Under BioRAPP, a new version of DREAM was developed and renamed DREAMpy (IFPRI 2020). DREAMpy is a free stand-alone user-friendly tool that can be relatively easy to implement for the type of crop-based ex ante assessments designed under BioRAPP. DREAMpy requires relatively limited data and can be independently implemented by practitioners with varied degrees of specialization, so as to tailor analysis to accommodate for country-specific capacities and data availability. DREAMpy also helps users to conduct sensitivity analysis of parameters and assumptions characterized by uncertainty or high variability. However, analysts recognize that the ESM behind DREAMpy has limitations. Like other partial equilibrium models, it does not account for the macroeconomic effects that the adoption of technologies can have over the whole economy. Only with the use of more complex general equilibrium (CGE) models is it possible to quantify the trade-offs vis-à-vis other crops and sectors of the economy. General equilibrium models consider the indirect effects of adoption and yield gains on the broader economy such as agri-food systems (AFSs), GDP and employment growth, and household-level outcomes, which, collectively, can provide additional evidence useful to national dialogues about biotechnology policy and investments.

The additional evidence presented in this paper addresses some of the questions unresolved in Ruhinduka et al. (2020); including some frequently raised by national stakeholders, such as the effects of GM crop adoption on the overall economic growth, poverty reduction, and nutritional outcomes. While additional data may not, ultimately, impact policy decisions about biotechnology, it can provide complimentary evidence to answer questions raised by decision makers about how locally important GM products can address existing productivity constraints, needs and market demands, especially if local stakeholders, who understand the policy process, are involved in both R&D efforts and the generation of economic assessment data. With this context, in this paper we extend Ruhinduka et al.'s crop-based estimations using the rural investment and policy analysis (RIAPA) CGE model to assess the economy-wide effect of impacts of TELA maize and CBSD cassava bio-innovations. We expand their analysis to a comprehensive ex-ante economy-wide modeling framework with macro-micro simulation that draws from their information and assumptions. The analysis looks at four alternative scenarios, derived from combinations of low and high adoption rates and yield changes, to assess how adoption of TELA maize and CBSD cassava might impact development outcomes in Tanzania.

The application of the RIAPA model has several results. First, introducing GM maize and cassava has positive impacts on the economy, the AFS, and household poverty and welfare – particularly in rural areas and among the poorest groups in the country. Second, given maize's greater prominence in the economy, in terms of its contribution to agricultural GDP and employment, and its stronger linkages to the AFS, the effects of TELA maize on GDP and AFS growth, including those beyond direct production, and household poverty and welfare, are relatively stronger than those resulting from CBSD cassava.

Third, the analysis finds that the combined effects of a simultaneous introduction of TELA maize and CBSD cassava has stronger and reinforced effect on all outcomes. Fourth, as expected, there are greater effects from higher adoption and high yield gains scenarios than from less optimistic scenarios. Those effects are differentiated across income groups. That is, in each scenario the effects of GM crops on the poorest households (Quintile 1) are greater than for the higher quintiles. Differential impacts across scenarios are also greater amongst the poorest, while the differences in the effects of more optimistic scenarios, versus the less optimistic ones, are not substantial for the top quintile. Finally, the high variation of results across the different scenarios, and the significant effects of the high adoption/high yield change scenario, suggest that efforts will be critical to ensure the realization of the highest adoption rates and yield growth potential of the GM varieties through the efficient use of technical recommendations on crop production management, and the introduction of supportive investments and policy incentives.

The route for this paper is as follows. Section 2 summarizes the key statistics on the maize and cassava sectors in the country, discusses current production challenges, and defines the maize and cassava GM technology innovations. Section 3 describes the research methodology, including the RIAPA CGE model and the design of the simulation scenarios. Section 4 presents the analytical results, including impacts on development outcomes of the individual and combined GM scenarios of total factor productivity (TFP) growth. The final section discusses results, draws conclusions, and makes recommendations.

2. Maize and cassava sectors and biotechnology innovations

This section helps to set the context for the analysis, by presenting and discussing the relevance of the maize and cassava sectors for the economy, their structure and performance, as well as the development challenges they face. It also describes the biotechnology innovations that aim to overcome them, whose impacts are assessed later in the paper.

Maize and cassava in the agri-food system

The agricultural sector in Tanzania involves agricultural value chains related primarily to crops, livestock, fisheries, and forestry products. As shown in Table 1, crops are the major contributor to both agricultural Gross Domestic Product - GDP (55.6%) and employment (65.3%).

Among all crops, maize is the major contributor to agricultural GDP (13.7%) and agricultural employment (10.3%.) and has the greatest share of crop land in the country. Maize is primarily produced by smallholders. While planted in nearly all agro-ecological zones, maize production is concentrated in the Southern Highlands areas (Iringa, Mbeya, Ruvuma, and Rukwa) that receive reliable unimodal rainfall of over 1,000 millimeters a year, and generally produce a market surplus (Ruhinduka et al. 2020).

Cassava production ranks next after maize as the most important food security crop in the country, in terms of its contribution to calorie intake (FAO 2022). Table 1 shows that cassava is the fifth most important crop in terms of its contribution to agricultural GDP (4.6%) and ranks fourth for its contribution to all agricultural employment. Despite its importance as a food security crop, it covers a relatively smal area (5.3% of all croplands), which is mostly concentrated around arid and semi-arid lands that spread throughout the Eastern, Southern, Lake, Southern Highlands, and Western Zones (Ruhinduka et al. 2020).

Table 1. Structure of agricultural production, employment, land use, and yields, 2017

Description	Agriculture GDP share (%)	Agriculture employment share (%)	Land area share (%)	Crop yields (tons/ha)
AGRICULTURE	100	100	-	-
Crops	55.6	65.3	100	-
Maize	**13.7**	**10.3**	**24.1**	**1.5**
Bananas	6.3	7.7	4.7	5.1
Potatoes	6.0	9.1	6.0	5.9
Rice	4.8	3.4	6.9	2.5
Cassava	**4.6**	**6.7**	**5.3**	**5.6**
Pulses	4.1	5.6	12.6	0.9
Edible oilseeds	3.8	5.2	14.6	1.0
Vegetables	2.5	2.9	2.4	6.9
Nuts	2.5	4.7	3.3	0.4
Groundnuts	1.5	2.1	6.3	0.9
Fruits	1.5	1.6	1.0	10.2
Sorghum & millet	1.1	1.0	6.6	1.0
Tobacco	1.0	1.7	0.7	0.9
Beverage crops	0.7	1.2	1.3	0.5
Wheat & barley	0.5	0.6	0.6	1.1
Cotton & fibers	0.2	0.3	2.2	0.7
Other crops	0.9	1.1	1.7	-
Livestock & fisheries	30.6	28.8	-	-
Forestry	13.8	5.8	-	-

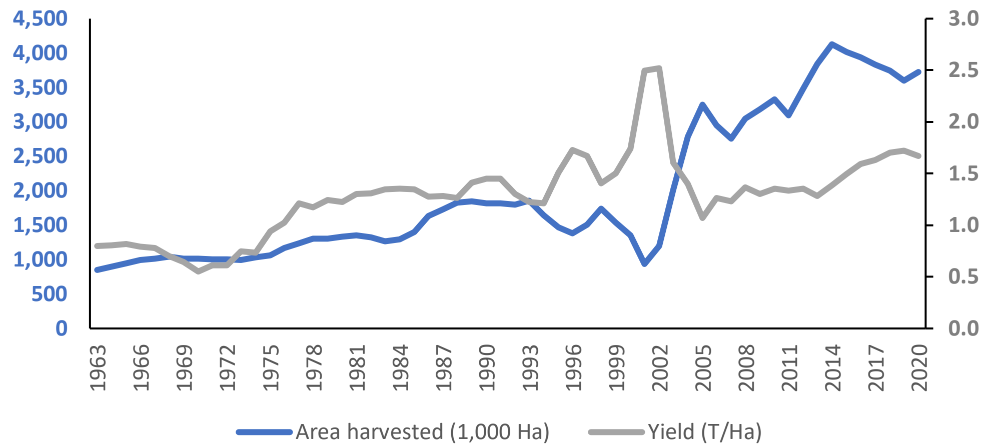
Source: Tanzania SAM and RIAPA model database.

Challenges in maize and cassava production

Despite their importance in the Tanzanian economy in both production and food security, maize and cassava face critical challenges that demand crop-specific adaptive strategies. Maize yields are low; levels today are similar to those of 1996. As illustrated in Figure 1, yields grew steadily from 1963 through 2001 from 0.8 t/ha to 2.5 t/ha, at an estimated annual rate of 4%. This was an era of intensification when areas barely grew at an annual rate of 1.3%. This trajectory was reversed after 2002, when areas annual rates of expansion (2.6%) started to outpace yield annual growth rates (1.5%). Currently, maize yield average is just about 1.6 t/ha, while yield potential is about 5.9 t/ha for rainfed maize.

Maize production faces two major constraints. The first relates to episodes of severe drought that Tanzania has faced over the last 30 years. These drought conditions have been particularly severe in the northern and central regions of the country (NBS 2015), and these areas are projected to face increased exposure to drought and risk vulnerability over the coming years. Accompanying production losses are projected to double, due to more severe droughts because of climate change.

Figure 1. Maize: Area and yields in Tanzania, 1963–2020



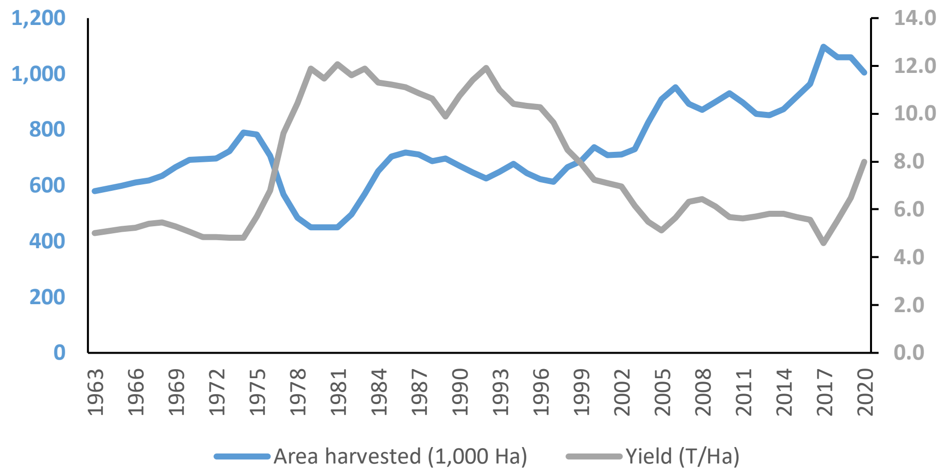
Source: Data from FAO (2022). Three-year moving averages.

The second identified constraint for maize is pests and disease. Stemborers are a prevalent insect pest, including the maize stalk borer (*Busseola fusca*) and the spotted stalk borer (*Chilo partellus*). These insects can cause average yield losses of 15%. Complete crop losses can occur during drought years or when measures to control stemborers are absent (De Groote et al. 2011). While stemborers can be controlled with timely and accurate insecticide applications, the relatively high cost of these, coupled with limited farmer knowledge of insecticide control measures, results in suboptimal insecticide application among smallholder producers (Gouse 2012; Huesing and English 2004). This dual challenge calls for technological innovations that can better address changes in rainfall patterns (leading to drought) and the continual insect pressures (Ruhinduka et al., 2020).

Cassava is the second most important food security crop in Tanzania. It is also a strategic famine rescue crop, given its availability when other crops fail. Unlike other food crops, cassava has high resistance to climatic variations and can be safely stored in the ground for long periods. Additionally, the entire cassava plant (roots, leaves and stems) is a food source that provides caloric and nutritional value. Cassava also provides commercial value chain opportunities through processing, marketing, and export of processed products.

Over the last 60 years, cassava yields and growth rates by area can be characterized by three distinct periods, as shown in Figure 2. It shows two periods of cassava area expansion (1963–1977 and 1999–2020) and one of intensification (1977–1999.) It also shows a decrease trend in yields from 1992 to 2017, which only started an upward trend in 2018 reaching a level of close to 8 t/ha.

Figure 2.Cassava: Area and yields in Tanzania, 1963–2020



Source: Authors' elaboration from FAO (2022) data, three-year averages.

As in other East African countries, cassava production in Tanzania is hampered by CBSD and the cassava mosaic disease.2 Economic damage from CBSD (Cassava Brown Streak Disease) in Sub-Saharan Africa is significant. In Tanzania alone losses approximate $51 million or more than 860 thousand tons (Ndyetabula et al. 2016) – a large proportion of losses of something over $70 million annually continent-wide (Manyong et al. 2012). Finding ways to address these two diseases can potentially lead to increased farmer income and new business opportunities throughout the value-chain.

Biotechnology innovations to overcome production challenges

Biotechnology innovations present opportunities to overcome production challenges through the development of new crop varieties that offer advantages by being climate-smart, scale-neutral, and more durable. Recognizing almost three decades of safe use and benefits from global agriculture biotechnology applications, national researchers collaborated with international research partners to conduct research to develop GM varieties of maize and cassava. These efforts specifically included the following:

TELA maize: This new variety of maize, developed under the Water Efficient Maize for Africa Project, used transgenic technology to introduce both drought tolerance and insect-resistant traits. The TELA project is a public-private partnership for Africa that Tanzania scientists have contributed to. It has been funded by the Bill and Melinda Gates Foundation as a collaborative effort of the African

[2] CBSD is caused by two distinct species of *ipomoviruses*, both belonging to the family *Potyviridae* (Patil et al. 2016). These are defined in the literature as two serotypes: the cassava brown streak virus and the Ugandan cassava brown streak virus. The vector for CBSD appears to be the whitefly (*Bemiscia tabasci*).

Agricultural Technology Foundation (AATF 2022). Participating countries include Ethiopia, Kenya, Nigeria, Mozambique, South Africa, Tanzania, and Uganda. Research efforts in Tanzania were suspended in early 2021, despite promising field trial results.

Brown Streak Disease (CBSD)-resistant cassava: In this R&D effort, transgenic technologies have been used to develop new varieties of cassava to address production constraints caused by the virus complex known as CBSD. The research has involved several countries and organizations, including the Cassava Diagnostics Project, led by the International Institute of Tropical Agriculture and the Donald Danforth Plant Science Center. The project was active in Tanzania through involvement of the Mikocheni Agricultural Research Institute until January 2021, when, as with the TELA project, research was halted.

3. Methodology

This analysis acknowledges the importance of the ESM models, but also recognizes its limitations. Like other partial equilibrium models, it does not account for the macroeconomic effects that the adoption of technologies can have over the whole economy. Therefore, the extension to an economy-wide framework (RIAPA CGE model) is a useful development towards the generation of reliable policy evidence of the impact of technology in a country context. Annex 1 details side by side, the features of the two models. This section focuses on the full presentation of the RIAPA CGE model, the definition of the baseline dynamics and counter-factual impact analysis, and the specification of the GM maize and cassava biotechnology scenarios.

The RIAPA CGE Model

The Rural Investment and Policy Analysis (RIAPA) model is a computable general equilibrium (CGE) modelling system developed by the International Food Policy Research Institute (IFPRI) to assess the impacts on development of policies and investments and inform their prioritization. While the general system can be used for all countries, it is calibrated to each country's individual circumstances, using the country’s Social Accounting Matrix (SAM) as well as other country-specific data and parameters for specifying the behaviors, contributions, and consumption of economics agents. Unlike input-output models that only account for the demand side and assume no capacity constraints, CGE models also consider the supply side, model agent behaviors, and allow for price movements. Compared to macro-econometric forecasting models, CGE models have a much stronger foundation in economic theory (West, 1995; Pollitt et al., 2018).

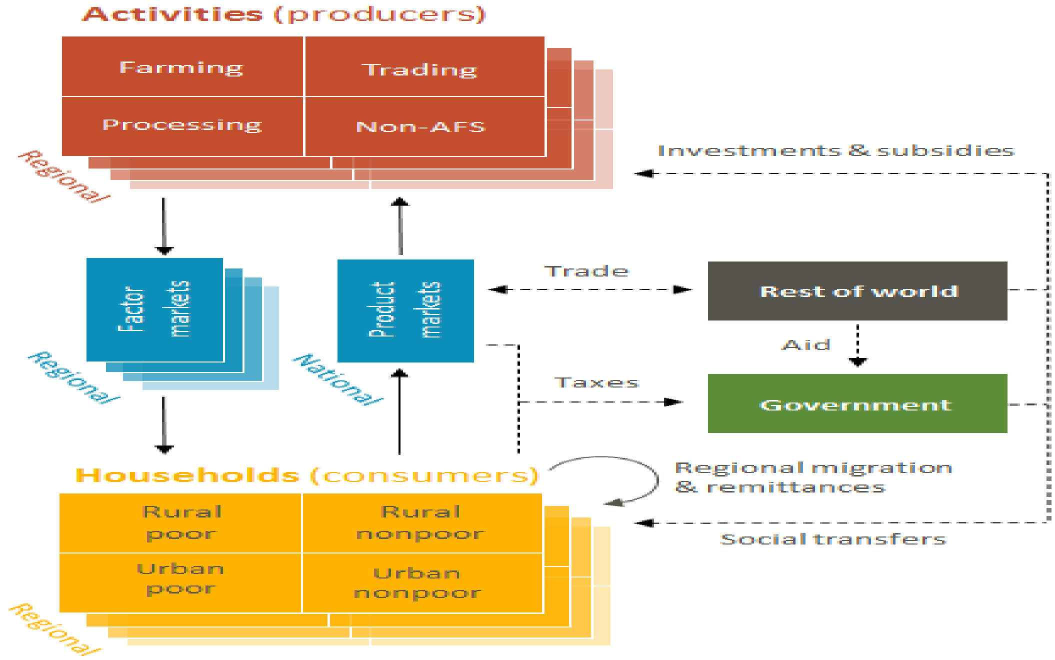
The RIAPA model was used to assess the economy-wide effects of TELA and CBSD innovations. RIAPA simulates the functioning of a market economy and captures linkages between sectors, rural and urban economies, and changes throughout the Agri-Food System (AFS)3 that comprises all the agriculture-related Value Chains (VCs) in an economy. The total value-added generated by all farmers represents the agricultural GDP for all crops, livestock, forestry, and fisheries activities. The total value-added generated by all forms of agricultural processing is the agricultural processing GDP. The AFS also includes a portion of the value-added generated by domestic producers of the intermediate inputs used in the agricultural and agro-processing sectors. RIAPA tracks the flow of inputs between sectors and differentiates between domestically produced and imported goods and services. Finally, the AFS also includes the value of food prepared and consumed away from home in restaurants and that supplied by small food retailers. As economic growth and structural transformation progresses and the share of agriculture (output and employment) in GDP drops, the overall share of the AFS in the economy, measured by the agricultural GDP plus the off-farm nodes of the food value chain (trading, processing, etc.), also falls, but a greater share of the drop is in the primary agriculture component. The share of the food processing and services components remains relatively stable overtime.

Economy-wide models are ideal for evaluating impacts of large-scale interventions, especially those involving complex relationships between producers and consumers. At the same time, larger-scale interventions are more likely to generate economy-wide spillovers. When production in a sector is scaled up, it is important to consider *positive spillovers* and *negative trade-offs*. Value chains are also complex by nature: they involve multiple sectors and actors. Actors compete for scarce resources and market opportunities. When one component of the VC (such as production) faces constraints or new opportunities, other components of the same VC, and other VCs are affected. Due to both resource and market constraints, it is critical to consider how expanding production in a VC may come at the expense of existing VCs. For example, the introduction of high-yielding GM maize (or cassava) varieties into the economy may displace existing traditional maize (or cassava) varieties, due to both resource constraints and evolving market conditions.

RIAPA simulates the functioning of an economy, including markets for products and factors of production, i.e., land, labour, and capital (Figure 3). The model measures how production changes are mediated through prices and resource reallocations, while all resource and macro-financial constraints are respected (Thurlow et al. 2020). RIAPA provides a consistent “simulation laboratory” for quantitatively examining interactions and spillovers at national, sub-national and household levels.

[3] This section draws on Thurlow et al. (2020) and RIAPA Model training materials.

Figure 3. Economy-wide framework



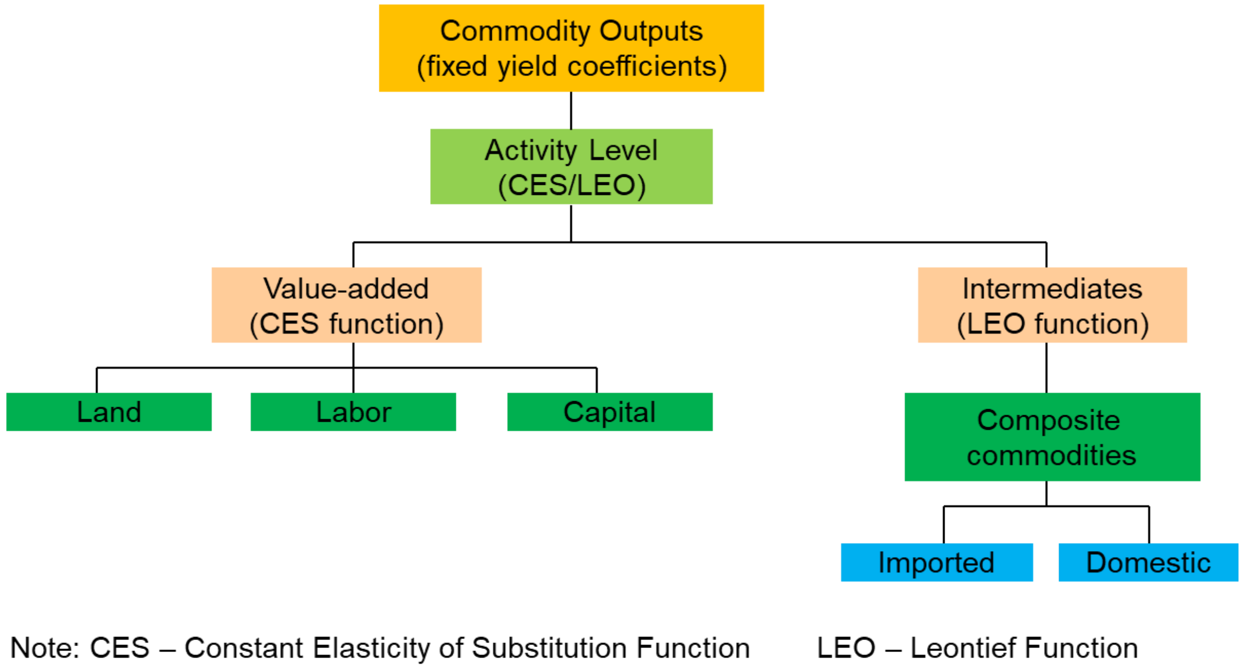
Source: Thurlow et al. (2020).

The model divides the economy into **producers** (or activities) and **consumers** (household groups) that interact with each other in factor and product markets. It consists of behavioral and structural equations. The former governs the decision-making behavior of economic agents, the latter maintains consistency between the incomes and expenditures of agents and within the macro-economy.

Production Activities and Factor Market Closures

Producers combine factors (land, labor, capital, machinery, etc.) and intermediate inputs (fertilizer, purchased seeds, etc.) using sector-specific technologies to maximize profits. Workers are divided by education levels, and agricultural capital is separated into crop and livestock activities. Labor and capital are in fixed supply, but less-educated workers are treated as underemployed. Factor demand is governed by constant elasticity of substitution (CES) functions that allow producers to imperfectly substitute between labor, land and capital based on changes in the relative factor prices. The ease with which producers shift between factors is determined by elasticities of factor substitution, which are econometrically estimated for a country or drawn from literature. RIAPA also captures differences in production technologies (i.e., intermediate input demand). The combination of inputs that sectors use is determined by price-insensitive engineering relationships, through a Leontief specification (Figure 4).

Figure 4. Structure and specification of production technology



Source: Lofgren et al. (2002).

Each activity produces one or more commodities according to fixed yield coefficients. As profit maximizing agents, producers choose their levels of production and input use based on prices in product and factor markets. Factor wages/rents may differ across activities when markets are segmented or even for mobile factors, when discrepancies emerge because of sector specific determinants.

The model offers alternative Factor Market Closures (FMC), i.e., mechanisms for equilibrating supply and demand in specific factor markets (land, labor, or capital). A description of factor market closure follows (Table 2).

Table 2. Alternative factor market closures

Variables		Factor Market Closures					
		Full Employment (Neoclassical) (FMOBFE)		Unemployment (FMOBUE)		Factor Market Segmentation (FACTFE)	
Variable	Description	FXD	FLX	FXD	FLX	FXD	FLX
QFS(F)	Quantity Supplied of Factor F	•			•		•
QFD (F, A)	Quantity Demanded of Factor F by Activity A		•		•	•	
WF (F)	Economy-wide wage/rent for Factor F		•	•		•	
WFDIST (F, A)	Activity-Specific Wage Distortion for Factor F	•		•			•

Notes: FXD – Factor is fixed; FLX – Factor is flexible; F – Factor; A – Activities. FACTFE – Factor is activity specific and fully employed; FMOBFE – Factor is mobile and fully employed; FMOBUE – Factor is mobile and unemployed. Source: Benfica (2006)

The first factor closure is *the Factor is Mobile and Fully Employed (FMOBFE)*. The default closure is to fix the supply of the factor at the observed base level and allow variation in an economy-wide factor price variable. This ensures that the sum of demands from all activities equals the total quantity supplied in the system (full employment). Under this closure, factors are mobile between the demanding activities. Each activity pays an activity-specific wage that is the product between the endogenously determined economy-wide wage and an exogenous activity-specific wage distortion term that is fixed in this closure.

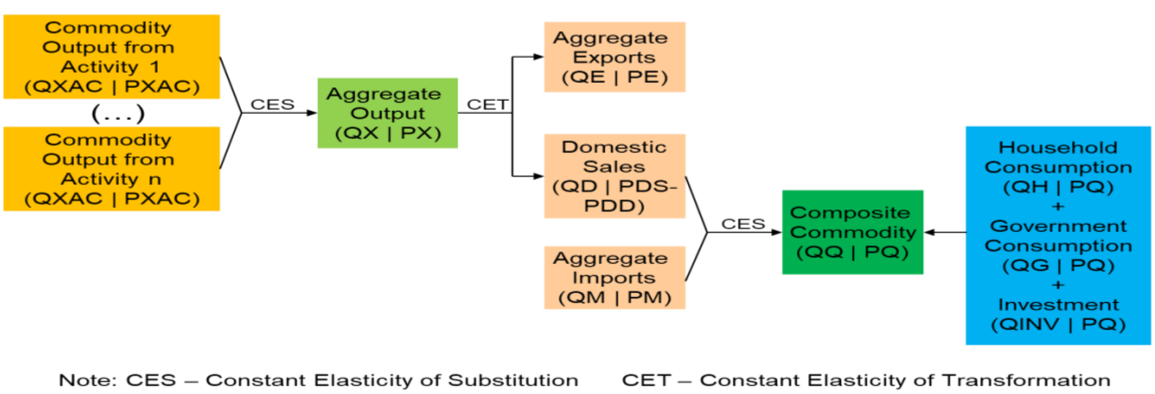
A second closure rule is *the Factor is Mobile and Unemployed (FMOBUE)*. This assumes that a factor is unemployed, and the real wage/rent is fixed. In this closure, the economy-wide variable is fixed (exogenized) and the supply variable is endogenized. Each activity is free to hire any desired quantity of the factor at its fixed activity-specific wage. In essence, the supply variable merely records the total quantity demanded.

The Factor is Activity Specific and Fully Employed (FACTFE) is a third closure rule. Under this closure, the factor market is assumed to be segmented and each activity is forced to employ the observed base year quantity, i.e., the factor is activity specific. More generally, it is appropriate when there are significant quality differences (or activity specificity) between units of a factor used in different activities (Lofgren *et al.*, 2002). In this closure, the quantity of activity-specific factor demands, and the economy-wide wage are fixed while the activity specific wage terms and the supply variables are flexible.

Commodity Markets

The output produced domestically, except home consumed output, enters markets. Figure 5 shows the physical flow for marketed commodities with the indication of quantity and price variables relevant in each case.

Figure 5. **Specifications of aggregation of marketed commodities**



Source: Lofgren *et al.* (2002).

For marketed output, the first stage is the aggregation of each commodity produced by different activities. As a result of differences in timing, location and quality between different activities, these outputs are imperfectly substitutable. Therefore, commodity aggregation is done using a Constant Elasticity of Substitution (CES) function.

$$QX_c = \alpha_c^{ac}\left(\sum_{a\in A}\delta_{ac}^{ac} QXAC_{ac}^{-\rho_c^{ac}}\right)^{-\frac{1}{\rho_c^{ac}-1}} \qquad c \in CX \qquad (1)$$

where:

CX	set of domestically produced commodities.
QX_c	aggregate market production of commodity c.
$QXAC_{ac}$	market output quantity of commodity c from activity a.
α_c^{ac}	shift parameter for domestic commodity aggregation function.
δ_{ac}^{ac}	share parameter for domestic commodity aggregation function.
ρ_c^{ac}	domestic commodity function exponent.

The aggregated domestic output (QX) is allocated to exports (QE) and domestic sales (QD) to maximize sales revenue for any given aggregate output level, subject to imperfect transformability between exports and domestic sales expressed by a Constant-Elasticity-of-Transformation (CET) function.[4] For all commodities with output, we have:

$$PX_c QX_c = PDS_c QD_c + PE_c QE_c \qquad c \in CX \qquad (2)$$

For commodities with both domestic sales (set CD) and exports (set CE),[5] such as maize, groundnuts, potatoes, goats, etc., the CET function is given by:

$$QX_c = \alpha_c^t\left(\delta_c^t QE_c^{\rho_c^t} + \left(1-\delta_c^t\right)QD_c^{\rho_c^t}\right)^{\frac{1}{\rho_c^t}} \qquad c \in \left(CE \cap CD\right) \qquad (3)$$

First-order conditions for maximization of producer revenues given the two prices (PDS and PE) subject to the CET function and fixed quantity of domestic output QX, indicates that the optimal mix between exports and domestic sales is defined by the Export-Domestic Supply Ratio

[4] Following the small country assumption, export demands are infinitely elastic at given world prices. The supply price for domestic sales is equal to the price paid by domestic demanders.
[5] The set of domestic commodities without domestic sales is referred to as CDN, and the set on non-exported commodities as CEN.

$$\frac{QE_c}{QD_c} = \left(\frac{PE_c}{PDS_c} \cdot \frac{1-\delta_c^t}{\delta_c^t} \right)^{\frac{1}{\rho_c^t - 1}} \qquad c \in (CE \cap CD) \tag{4}$$

Equation 4 indicates that an increase in the export-domestic price ratio generates an increase in the export-domestic supply ratio, i.e., a shift towards the destination that offers the higher return.
For domestically sold output without exports and for exports without domestic sales, the output transformation is given by:

$$QX_c = QD_c + QE_c \qquad c \in (CD \cap CEN) \cup (CE \cap CDN) \tag{5}$$

This equation allocates the entire output volume to one of these two destinations.

Domestic sales (QD) and aggregate imports (QM) make up the composite supply in domestic markets (QQ). Absorption, i.e., the total domestic spending on domestic output and imports at domestic demander prices (net of sales tax, but inclusive of cost of trading inputs), is defined as:

$$PQ_c QQ_c = PDD_c QD_c + PM_c QM_c \qquad c \in (CD \cup CM) \tag{6}$$

The demand for these commodities is derived under the assumption that domestic demanders minimize costs subject to imperfect substitutability, captured by a CES aggregation function, also referred to as the Armington Function:

$$QQ_c = \alpha_c^q \left(\delta_c^q QM^{-\rho_c^q} + (1-\delta_c^q) QD_c^{-\rho_c^q} \right)^{-\frac{1}{\rho_c^q}} \qquad c \in (CD \cap CM) \tag{7}$$

The domain of the CES function is limited to commodities that are both imported and domestically produced. The optimal mix between imports and domestic output is defined by:

$$\frac{QM_c}{QD_c} = \left(\frac{PDD_c}{PM_c} \cdot \frac{\delta_c^q}{1-\delta_c^q} \right)^{\frac{1}{1+\rho_c^q}} \qquad c \in (CD \cap CM)$$

(8)

Equations 6 through 8 define the first-order conditions for cost minimization given the two prices (PDD and PM) and subject to the Armington function and a fixed quantity of the composite commodity (QQ). Equation 8 ensures that an increase in the domestic-import price ratio causes an increase in the import-domestic demand ratio, i.e., a shift away from the relatively more expensive source.

The composite commodity (QQ) is demanded in the domestic market in the form of Household consumption (QH); Government Consumption (QG); Investment (QINV); Intermediary input use (QINT); and demand for transaction inputs (QT):

$$QQ_c = \sum_{a \in A} QINT_{ca} + \sum_{h \in H} QH_{ch} + QG_c + QINV_c + QT_c \qquad c \in C \tag{9}$$

Households, Government and Rest of the World

The model tracks changes in incomes and expenditures for representative **household groups**, including changes in food and nonfood consumption. Households are separated by location (rural or urban), farm or nonfarm status, and nationally defined per capita expenditure groups. Households choose between producing goods for their own consumption and purchasing goods from markets. They are the main owners of the factors of production, and their earned wages, rents, and profits (factor incomes) are used to consume goods and services, pay taxes, and save.

Formally, household consumption behavior of market and home commodities is modeled according to Linear Expenditure System (LES) demand functions, derived from maximization of a Stone-Geary utility function subject to a consumption expenditure constraint.[6]

$$\text{Max U} = \sum_{c=1}^{n} \beta_c \ln\left(q_c - q_c^0\right) \tag{10}$$

$$\text{Subject to} \quad \sum_{c=1}^{n} p_c q_c^0 + \sum_{c=1}^{n} p_c \left(q_c - q_c^0\right) = E$$

$$\text{With} \quad q_c \geq q_c^0$$

$$0 < \beta_c < 1$$

$$\sum_{c=1}^{n} \beta_c = 1$$

Where, q_c is the quantity of consumption of commodity c, q_c^0 is the subsistence or minimal amount of the consumption of commodity c that must be bought by the household, β_c is the marginal share of consumption of commodity c, p_c is the price of commodity c, and E is the total household consumption expenditure.

The first-order condition results in a Linear Expenditure System (LES) which can be written as:

$$p_c q_c = p_c q_c^0 + \beta_c \left(E - \sum_{c=1}^{n} p_c q_c^0 \right) \tag{11}$$

[6] This utility function is a generalization of the Cobb-Douglas function and incorporates the idea that certain minimum amounts of each good must be bought.

This system can be interpreted as stating that expenditure on good c, given as $p_c q_c$, can be decomposed in two components. The first is the expenditure on a “base amount” q_c^0 of good c which is the minimum expenditure for which the consumer is committed. The second is a fraction β_c of the *supernumerary income*, defined as the income above the “subsistence income”, $\sum_{c=1}^{n} p_c q_c^0$, needed to purchase base amount of all goods (Intriligator *at al.*, 1996). These two components correspond, respectively, to committed and discretionary expenditure on commodity c. Demand functions are derived by dividing both sides of the equation by the relevant price.

Top-down micro-simulation modules estimate changes in poverty rates. Households in the survey are mapped to their representative household groups in the CGE model. The poverty module transfers proportional real consumption changes from the CGE model down to the households in the survey and then recalculates each households’ consumption levels and their poverty status (using official poverty lines).

RIAPA includes other actors, such as the **government** and the **rest of the world**. Governments collect tax revenues via several direct and indirect tax instruments, including sales, value-added and excise taxes on products, and corporate and personal income taxes on enterprises and households. Interactions with the rest of the world include international trade flows and international transfers (worker remittances, repatriated profits, foreign direct investment, and foreign aid).

Macro System Closures

The model maintains macroeconomic consistency by using “closure rules” governing three macroeconomic accounts (default closure rules). Table 3, summarizes the alternative closure rules, highlighting the defaults adopted in RIAPA. These closure rules reflect how a country’s macroeconomy is assumed to adjust to exogenous shocks. First, a government account (fixed tax rates, adjustable deficit). Second, a savings-investment account is balanced through a savings-driven investment closure, i.e., the levels of investment in the economy depend on the levels of savings generated in the economy. Finally, a current account (trade and foreign flows), assuming fixed foreign capital flows and a flexible exchange rate.

Table 3. RIAPA model macro closures

Macro balances	Definition of macro closures	RIAPA Model closures	
		Default closures	Alternative closures
Government Balance (GOV-B)	GOV savings are flexible, direct tax rates are fixed	●	
	GOV savings are fixed, uniform direct tax rates		●
	GOV savings are fixed, scaled direct tax rates		●
Savings-Investment Balance (SI-B)	Investment Driven Savings (Savings levels adjust to given level of Investment)		●
	Savings Driven Investment (Investment level defined as a function of existing savings)	●	
	Investment is fixed absorption share		●
Rest of the World Balance (ROW-B)	Flexible Exchange Rate and Fixed Foreign Savings	●	
	Fixed Exchange Rate and Flexible Foreign Savings		●

Source: Authors.

The RIAPA model described above has evolved from early work from Lofgren et al. (2002) and was expanded to applications such as the prioritization of value chains to inform R&D investments (Benfica 2022), compare the efficiency of public investments (Benfica et al., 2019), and the prioritization of public sector investments (Aragie et al., 2022).

Baseline dynamics and counter-factual impact analysis

The model is initially calibrated to the base year reflected in the social accounting matrix (SAM) for Tanzania (Randriamamonjy and Thurlow 2017). It is then run forward over time in a recursive dynamic fashion to create a baseline growth path, in this case 2017–2019.[7] While the model's general equilibrium specification is based on economic theory, its detailed calibration to observed data provides a "quasi-empirical" laboratory for conducting complex experiments within a consistent framework.

After a suitable baseline scenario has been calibrated, we conduct counterfactual simulations considering the scenarios define in the next section. In this case, we use comparative statics in the final year (2019) of the baseline scenario to look at the impacts on selected development indicators. The model is re-solved and observed deviations from the baseline end-year levels are attributed to the simulated shocks in TFP as defined by the alternative individual and combined GM maize and cassava scenarios.

[7] The baseline scenario is therefore determined by annual growth in factor supplies and productivity. Except for capital, factor and productivity growth rates are calibrated to observed historical trends.

Defining the GM maize and cassava biotechnology scenarios

The analysis runs simulations of the impacts of biotechnology innovations under four different scenarios that run from pessimistic to optimistic and vary according to alternative value assigned to three parameters: (1) probability R&D and regulatory compliance success; (2) projected adoption rate; and (3) expected change in yields with the introduction of the GM crops.

Following Ruhinduka et al (2020), the probability used in the analysis is a composite outcome indicator resulting from two probabilities: R&D success and regulatory compliance success. The probability of R&D success accounts for the stage in the product life cycle the application is at, while the probability of regulatory compliance success considers the current regulatory environment in the country of release and deployment. This probability also has to do with the accumulated safety knowledge and regulatory experience with the application under scrutiny. Adoption rates correspond to the share of crop producers assumed to switch from the conventional seed technology to the GM varieties of the crops under consideration. Expected yield gains refer to the anticipated increase in output per hectare as a result of the adoption of the new varieties. The parameters and ranges used for the scenarios are based on information collected by Ruhinduka et al. (2020) from extensive expert consultations and stakeholders' discussions, used in their DREAMpy-based assessment.

The expected total change in the total factor productivity (TFP) of each crop with the introduction of the GM variety is computed as the product of these three parameters (adoption, yields, R&D probability of success.) The alternative scenarios are summarized in Table 4. The analysis also considers scenarios that combine the simultaneous introduction of both GM maize and GM cassava under the alternative combinations of adoption and yields.

The TELA maize scenarios assume a probability of R&D and regulatory compliance success of 82% and comprise four scenarios that result from alternative combinations of low and high rates of adoption and expected changes in yield (Ruhinduka et al. 2020), as follows: (a) a low rate of adoption (15%) and a low level of the expected change in yield (25%); (b) a low rate of adoption (15%) and a high expected change in yield (40%); (c) a high rate of adoption (40%) and a low expected change in yield (25%); and (d) a high rate of adoption (40%) and a high the expected change in yield (40%). Considering the current levels of maize productivity presented in section 2, the scenarios assume yield improvements from 1.6 t/ha under the baseline to between 2.0 t/ha (low) and 2.3 t/ha (high), respectively. Based on these assumptions, the estimated levels of expected total change in TFP for maize with the introduction of the GM variety range from 3.1–13.1%.

The Cassava Brown Streak Disease scenarios are based on the same combination of high and low yield and adoption values, with relatively lower probability of R&D and regulatory compliance success (72%). Parameters are drawn also from Ruhinduka et al. (2020) and are as follows: (a) a low rate of adoption (17%) and a low level of the expected change in yield (20%); (b) a low rate of adoption (17%) and a high expected change in yield (30%); (c) a high rate of adoption (34%) and a low expected change in yield (20%); and (d) a high rate of adoption (34%) and a high the expected change in yield (30%). The scenarios assume cassava yield improvements from 8.0 t/ha under the baseline to between 9.6 t/ha (low) and 10.4 t/ha (high), respectively. Based on these assumptions, the levels of the expected total change in TFP with the introduction of the GM cassava ranges from 2.5–7.3%.

Table 4. Key parameters and total factor productivity

Crop parameters *Scenarios*	**Probability of R&D and regulatory success* (%)**	**Adoption rate (%) ***		**Yield change (%) ***		**Total factor productivity change (%)**
		Low*	**High***	**Low***	**High***	
TELA Maize parameters	82	15	40	25	40	
Low adoption/Low yield	✓	✓		✓		3.1
Low adoption/High yield	✓	✓			✓	4.9
High adoption/Low yield	✓		✓	✓		8.2
High adoption/High yield	✓		✓		✓	13.1
CBD Cassava parameters	72	17	34	20	30	
Low adoption/Low yield	✓	✓		✓		2.5
Low adoption/High yield	✓	✓			✓	3.7
High adoption/Low yield	✓		✓	✓		4.9
High adoption/High yield	✓		✓		✓	7.3

Source: *Parameters from Ruhinduka et al. (2020, Table 7.2); TFP: Author's estimations.

4. Model simulation results

The analysis evaluates the impacts of TELA maize and CBSD cassava GM varieties that address drought- and pest-related challenges faced by Tanzanian farmers. We look, in turn, at the impacts on several indicators such as GDP and AFS GDP structure and growth, and poverty and welfare outcomes. Tables 7 and 8, and Figures 6 and 7 summarize results for the introduction of TELA maize, CBSD cassava, and jointly of TELA and CBSD cassava. All impacts are measured as deviations in the indicators from the baseline scenario.

TELA maize results

The successful introduction of TELA maize varieties aimed at addressing the effects of droughts and the incidence of pests has significant effects on the economy, AFS and levels of poverty reduction and welfare gains of the population, particularly the poorer in rural areas. Table 5 presents the key results for the impacts of TELA maize, highlighting the deviations that those scenarios generate on selected indicators from the baseline. As expected, the outcomes are greater under the higher adoption rates and higher projected yield changes scenarios; in addition, these outcomes show significant variability across all four scenarios.

Table 5. TELA maize: Impacts on the economy, agri-food system, and poverty

Description	**Baseline scenario**	**GM Maize scenarios with 82% probability of R&D and regulatory compliance success**			
		Low adoption/ low yield	**Low adoption/ high yield**	**High adoption/ low yield**	**High adoption/ high yield**
	Annual growth (%)	*Deviation from baseline growth rate (% points)*			
Total GDP	5.3	0.04	0.06	0.11	0.17
Agriculture	3.6	0.12	0.19	0.32	0.50
Food crops	3.4	0.22	0.36	0.59	0.93
Maize	3.1	0.76	1.20	1.97	3.10
Cassava	1.7	0.05	0.08	0.14	0.22
Export crops	3.5	0.02	0.04	0.06	0.10
Livestock	3.5	0.01	0.01	0.02	0.02
Non-agriculture	6.1	0.00	0.01	0.01	0.01
	Percent	*Deviation from baseline share (% points)*			
Agriculture share (%)	30.7	0.07	0.12	0.19	0.3
	Annual growth (%)	*Deviation from baseline growth rate (% points)*			
AFS GDP	4.0	0.10	0.16	0.26	0.41
Direct production	3.9	0.11	0.18	0.29	0.46
Agriculture	3.7	0.12	0.19	0.32	0.50
Agro-processing	5.8	0.01	0.01	0.02	0.04
Input production	5.6	0.05	0.08	0.14	0.22
Agriculture	5.1	0.10	0.17	0.28	0.43
Agro-processing	6.1	0.01	0.01	0.02	0.03
Trade/transportation	4.8	0.04	0.06	0.10	0.16
Agriculture	3.8	0.07	0.10	0.17	0.27
Agro-processing	5.5	0.01	0.02	0.02	0.04
Food Services	4.5	0.02	0.03	0.05	0.08
	Percent	*Deviation from baseline share (% points)*			
AFS in total GDP (%)	41.4	0.07	0.11	0.18	0.29
	Rate, 2019 (%)	*Deviation from final baseline poverty rate, 2019 (% points)*			
Poverty headcount	46.4	-0.34	-0.54	-0.82	-1.58
Rural	53.1	-0.42	-0.59	-0.97	-1.95
Urban	29.9	-0.15	-0.40	-0.45	-0.67
	Number, 2019	*Deviation of number of poor people from baseline (#)*			
People out of poverty	19,624,250	-143,757	-226,948	-345,100	-668,098
Rural	15,980,169	-125,456	-178,409	-290,440	-585,848
Urban	3,644,080	-18,301	-48,539	-54,660	-82,250

Source: Model simulation results.

First, TELA maize scenarios produce a GDP growth rate that is higher, mainly driven by growth in agricultural GDP ranging from positive deviations from baseline growth rates that are between 0.12 higher for the low-adoption/low-yield scenario to 0.50 for the most optimist scenario. Notably, maize GDP growth rates increase from 3.1% at baseline to an additional 0.76 percentage points under the low-adoption/low-yield change scenario or an additional of over 3 percentage points in the high-adoption/high-yield change scenario. TELA maize expansion appears to have significant effects on the broader agriculture food crops GDP (including cassava) as well as on livestock and export crops, as signaled by their growth observed in those scenarios, relative to baseline trends.

Second, TELA maize TFP effects are noteworthy in the agri-food system, ranging from direct production, input production, trade and transportation and food services, in both the agriculture and processing dimensions, reflecting strong linkages and spillover in the AFS implied by significant deviations from the baseline growth rates.

Third, the poverty effects of TELA maize expansion scenarios are strong. Poverty rates, at the baseline scenario, are more accentuated in rural areas (53.1%) than in urban areas (29.9%). TELA maize expansion brings poverty rates significantly down, ranging between -0.34 (low adoption/low yield change) and -1.58 percentage points (high adoption/high yield change) nationally, and -0.42 and -1.95 percentage points in rural areas. This poverty reduction means that TELA would lift between 125,456 and 585,848 people out of poverty in rural areas.

Brown Streak Disease-resistant cassava results

The introduction of the cassava brown streak disease (CBSD)-resistant crop variety has some positive but relatively limited effects on the economy, the agri-food system, and levels of poverty and welfare, given cassava's weaker linkages with the rest of the economy. As expected, at higher adoption rates and projected yield changes, those outcomes are more notable. Table 6 presents the impacts of CBSD-resistant cassava under the different scenarios and shows the deviations that those scenarios generate from the baseline scenario.

First, all four projected scenarios for CBSD-resistant cassava produce a GDP growth rate that is relatively higher, mainly driven by growth in agricultural GDP, ranging from positive deviations from baseline growth rates that are between 0.03 (for the low adoption/low yield scenario) to 0.10 higher (for the high adoption/high yield change scenario). Notably, cassava GDP growth rates increase from 1.7% at baseline to an additional 0.79 percentage points in the low adoption/low yield change scenario, or 2.3 percentage points in the high adoption/high yield change scenario. CBSD-resistant cassava expansion appears to have some effects on agriculture food crops GDP more broadly, but, unlike TELA maize, the CBSD-resistant cassava expansion scenarios are not associated with growth in maize, other crops, and livestock exports – likely due to the competition of resources created by CBSD-resistant cassava expansion that constrains the growth of other crops, which is reflected in the relatively slower growth in agricultural and overall GDP as compared to TELA maize expansion.

Table 6. GM CBSD-resistant cassava: Impacts on the economy, agri-food system, and poverty

Description	Baseline scenario	GM Cassava scenarios with 72% probability of R&D and regulatory compliance success			
		Low adoption/ low yield	Low adoption/ high yield	High adoption/ low yield	High adoption/ high yield
	Annual growth (%)	*Deviation from baseline growth rate (% points)*			
Total GDP	5.3	0.01	0.02	0.02	0.03
Agriculture	3.6	0.03	0.05	0.07	0.10
Food crops	3.4	0.07	0.10	0.13	0.19
Maize	3.1	0.00	0.00	0.00	-0.01
Cassava	1.7	0.79	1.18	1.57	2.33
Export crops	3.5	0.00	0.00	0.00	0.00
Livestock	3.5	0.00	0.00	0.00	0.00
Non-agriculture	6.1	0.00	0.00	0.00	0.00
	Percent	*Deviation from baseline share (% points)*			
Agriculture share (%)	30.7	0.02	0.03	0.04	0.06
	Annual growth (%)	*Deviation from baseline growth rate (% points)*			
AFS GDP	4.0	0.03	0.04	0.06	0.08
Direct production	3.9	0.03	0.05	0.06	0.09
Agriculture	3.7	0.03	0.05	0.07	0.10
Agro-processing	5.8	0.00	0.00	0.00	-0.01
Input production	5.6	0.00	0.00	0.00	0.00
Agriculture	5.1	0.01	0.01	0.01	0.02
Agro-processing	6.1	0.00	0.00	0.00	-0.01
Trade/transportation	4.8	0.02	0.02	0.03	0.05
Agriculture	3.8	0.03	0.05	0.06	0.09
Agro-processing	5.5	0.00	0.00	0.00	-0.01
Food Services	4.5	0.00	0.00	0.00	0.01
	Percent	*Deviation from baseline share (% points)*			
AFS in total GDP (%)	41.4	0.02	0.03	0.04	0.06
	Rate, 2019 (%)	*Deviation from final baseline poverty rate, 2019 (% points)*			
Poverty headcount	46.4	-0.07	-0.09	-0.10	-0.14
Rural	53.1	-0.08	-0.09	-0.10	-0.15
Urban	29.9	-0.06	-0.09	-0.09	-0.11
	Number, 2019	*Deviation of number of poor people from baseline (number of people)*			
People out of poverty	19,624,250	-31,219	-37,828	-40,628	-57,534
Rural	15,980,169	-23,883	-26,852	-29,653	-44,429
Urban	3,644,080	-7,336	-10,976	-10,976	-13,105

Source: Model simulation results.

Second, although CBSD-resistant cassava expansion scenarios have positive effects on poverty, they are smaller than those for TELA maize. This is partially explained by the smaller size of the cassava sector and its limited growth linkages. CBSD-resistant cassava expansion brings national poverty rates down slightly, ranging from -0.07 (low adoption/low yield change scenario) to -0.14 percentage points (high adoption/high yield change scenario). These percentages are like those for rural areas, ranging from -0.08 to -0.15 percentage points. These percentage reductions translate into lifting between 23,883 and 44,429 people in rural areas out of poverty. The effects on poverty in rural areas are only notable in the most optimistic scenario. With low adoption and yield changes, CBSD cassava expansion makes little difference in rural poverty reduction.

Genetically Modified maize and cassava combined results

The simultaneous introduction of GM TELA maize and GM CBSD-resistant cassava has a greater effect on development outcomes than each variety individually. Table 7 shows the results for the combined scenarios. First, the combined scenarios generate growth in agricultural GDP ranging from positive deviations from baseline growth rates that are between 0.16 higher for the low adoption/low yield scenario to 0.61 for the most optimist scenario of high adoption/high yield change. Second, the combined TELA maize and CBSD-resistant cassava expansion have broader effects on agriculture food crops GDP, particularly in the agricultural nodes of direct production, input production, and trade/transportation.

Finally, the poverty effects of the combined expansion scenarios are positive and relatively strong. It brings poverty rates down, ranging from -0.40 (low adoption/low yield change scenario) to -1.62 percentage points (high adoption/high yield change scenario) nationally, and from -0.44 to -2.00 percentage points in rural areas. This percentage reduction translates into lifting out of poverty between 131,579 and just over 600,000 people.

Table 7. Combined TELA maize and CBSD-resistant cassava: Impacts on the economy, agri-food system, and poverty

Description	Baseline scenario	GM maize combined with GM cassava (82% and 72% probability of R&D and regulatory success, respectively)			
		Low adoption/ low yield	Low adoption/ high yield	High adoption/low yield	High adoption/ high yield
	Annual growth (%)	*Deviation from baseline growth rate (% points)*			
Total GDP	5.3	0.05	0.08	0.13	0.20
Agriculture	3.6	0.16	0.24	0.39	0.61
Food crops	3.4	0.29	0.45	0.72	1.12
Maize	3.1	0.75	1.20	1.97	3.09
Cassava	1.7	0.85	1.27	1.71	2.55
Export crops	3.5	0.03	0.04	0.07	0.10
Livestock	3.5	0.01	0.01	0.02	0.03
Non-agriculture	6.1	0.00	0.01	0.01	0.02
	Percent	*Deviation from baseline share (% points)*			
Agriculture share (%)	30.7	0.09	0.15	0.23	0.36
	Annual growth (%)	*Deviation from baseline growth rate (% points)*			
AFS GDP	4	0.13	0.20	0.31	0.49
Direct production	3.9	0.14	0.22	0.35	0.55
Agriculture	3.7	0.16	0.24	0.39	0.61
Agro-processing	5.8	0.01	0.01	0.02	0.03
Input production	5.6	0.05	0.09	0.14	0.22
Agriculture	5.1	0.11	0.18	0.29	0.45
Agro-processing	6.1	0.01	0.01	0.02	0.03
Trade/transportation	4.8	0.06	0.09	0.14	0.21
Agriculture	3.8	0.10	0.15	0.23	0.36
Agro-processing	5.5	0.01	0.01	0.02	0.03
Food Services	4.5	0.02	0.04	0.06	0.09
	Percent	*Deviation from baseline share (% points)*			
AFS in total GDP (%)	41.4	0.09	0.14	0.22	0.35
	Rate, 2019 (%)	*Deviation from final baseline poverty rate, 2019 (% points)*			
Poverty headcount	46.4	-0.40	-0.59	-0.85	-1.62
Rural	53.1	-0.44	-0.67	-0.96	-2.00
Urban	29.9	-0.30	-0.40	-0.57	-0.71
	Number, 2019	*Deviation of number of poor people from baseline (number of people)*			
People out of poverty	19,624,250	-168,517	-248,726	-357,836	-686,420
Rural	15,980,169	-131,579	-200,187	-287,941	-600,354
Urban	3,644,080	-36,938	-48,539	-69,895	-86,066

Source: Model simulation results.

Impact of TELA maize and CBSD-resistant cassava on household consumption spending

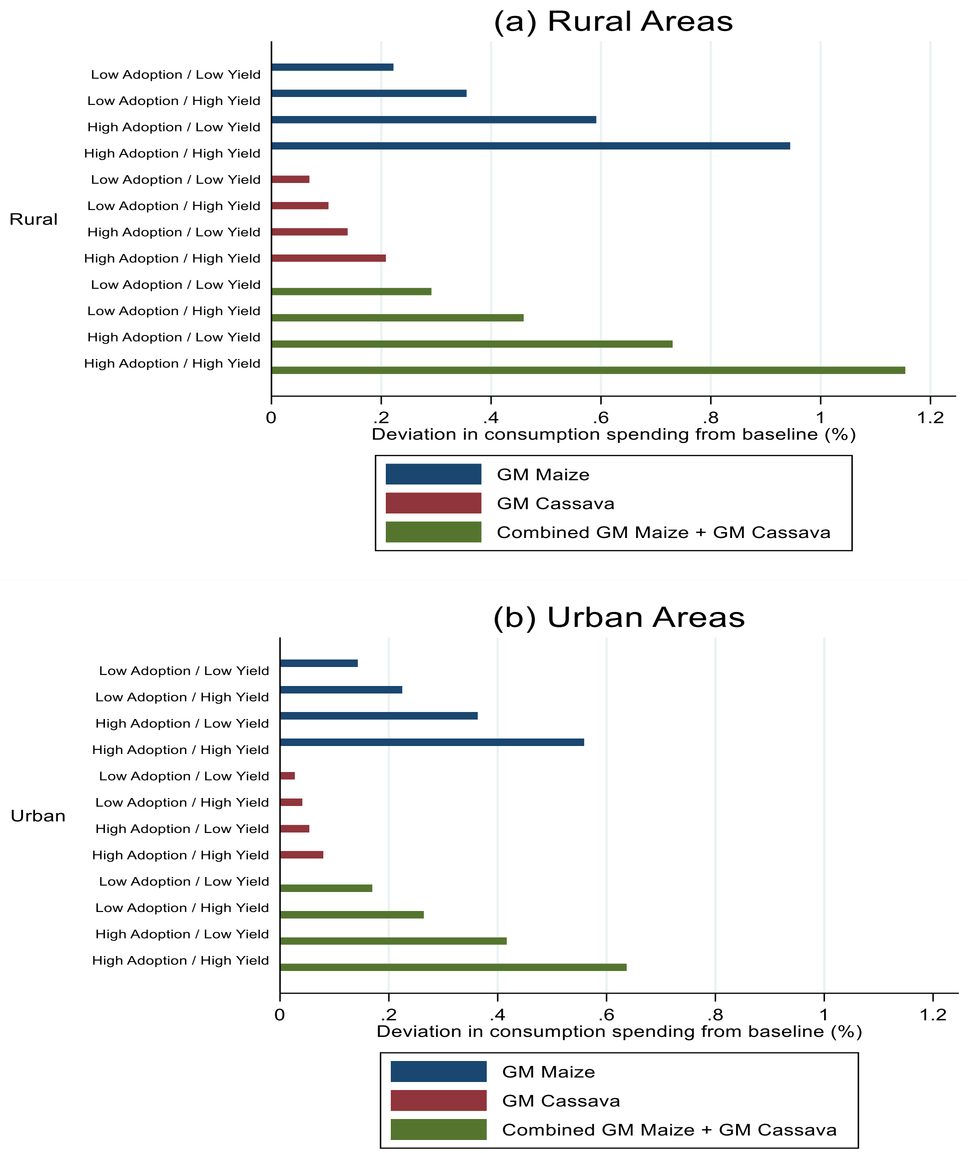
In addition to the poverty effects discussed, the analysis looks closely at the effects of TELA maize, CBSD-resistant cassava, and combined expansion scenarios on household consumption spending across area of residence (rural vs. urban), poverty status (poor vs. non-poor) and income distribution (expenditure quintiles). These effects on households are not only brought through direct effects but rather through the implications on non-farm production and the changes in the economy, including on the non-agricultural sector, as well as at different nodes of individual value chains, that has a net positive effect on the consumption of good and services by households.

Figures 6 and 7 and Table 8 present a summary of all results for these indicators. Like the results discussed earlier, all scenarios assume an average probability of R&D and regulatory compliance success (82% and 72% for TELA maize and CBSD-resistant cassava respectively), and the alternative combinations of the adoption rates and yield change scenarios. Several results are outstanding.

First, TELA maize and CBSD-resistant cassava have positive effects on household consumption spending. Given the differential contribution of those crops to the national GDP and employment and the relative strengths of the inter-sectoral linkages, TELA maize results have relatively stronger effects than CBSD-resistant cassava across all dimensions. Second, while deviations from the baseline in consumption spending are positive in all cases, they are more accentuated under the high adoption/high yield scenario and more significant in rural areas. For example, under the TELA maize high yield/high adoption scenario, consumption spending increases in rural areas are almost 1% higher than in the baseline increase, which is 0.4% higher than for urban areas (Figure 6a). For cassava these figures are over 0.2% and 0.1% higher, respectively (Figure 6b). The combined scenario of TELA maize and CBSD-resistant cassava is consistent with these results, showing a relatively higher magnitude of the effects across rural and urban areas.

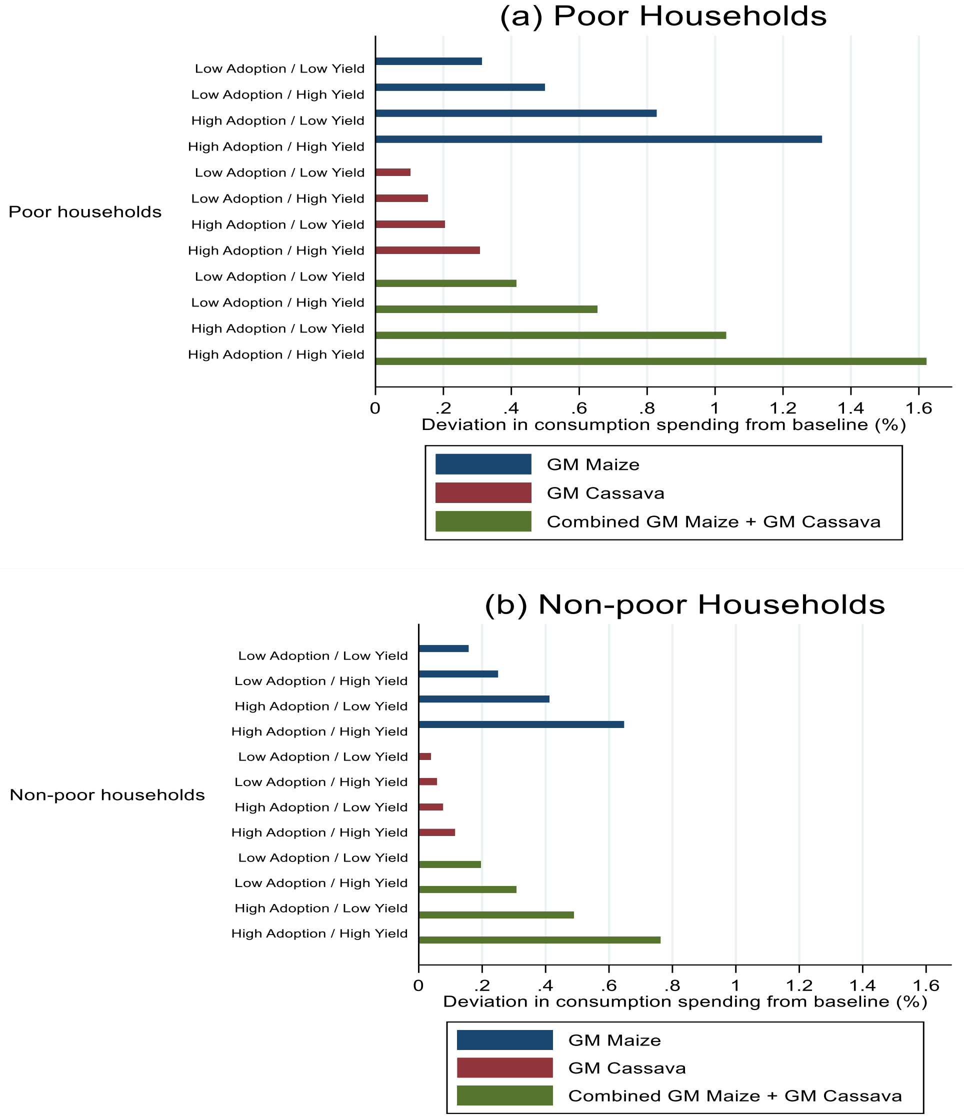
Second, when looking at differences by poverty status, effects are much stronger for poor households (close to 1.4% for TELA maize and 0.4% for CSBD-resistant cassava) than non-poor households that experience increases just below 0.6% for GM maize (Figure 7a) and 0.1% greater than the baseline scenario for GM cassava (Figure 7b). Consistent results are also found when comparing poor and non-poor households under the combined GM maize and cassava scenarios.

Figure 6. Impact of TELA maize and CBSD-resistant cassava on household consumption spending, under alternative adoption and yield scenarios, rural vs. urban



Source: Model simulation results

Figure 7. Impact of TELA maize and CBSD-resistant cassava on consumption spending alternative adoption and yield scenarios, by poverty status



Source: Model simulation results.

Corroborating this result, Table 8 shows that the relatively greater effects of higher adoption and yield gains are differentiated across income groups. In each individual GM crop or combined scenario, the effects of GM crops on the poorest households (Quintile 1) are greater than that for the higher quintiles; the differential impact across scenarios is also greater amongst the poorest (Quintile 1), e.g., while the differences in the effects of more optimistic scenarios are not substantial for Quintile 5.

TELA maize effects for Quintile 1 range from below 0.4% (low adoption/low yield change scenario) to approximately 1.5% (high adoption/high yield scenario), while for Quintile 5 the difference ranges between 0.1% and 0.3%. For the case of cassava, the figures range from 0.1% to over 0.4% for the poorest and are almost invariable at just over 0.1% for the relatively better off households (Quintile 5).

The same pattern is found for the combined TELA maize and CBSD cassava with figures ranging from a wide gap – between about 0.5% and 1.9% for the poorest quintile – to just 0.1–0.4% for the relatively better off.

Table 8. Impact of combined TELA maize and CBSD-resistant cassava on consumption spending, by income quintiles

Crop/Scenarios	Quintiles of rural farming households (poorest to richest) *(% deviation in consumption spending from baseline)*				
	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
GM Maize					
Low adoption/low yield	0.360	0.287	0.295	0.187	0.063
Low adoption/high yield	0.575	0.459	0.472	0.300	0.101
High adoption/low yield	0.958	0.765	0.786	0.501	0.172
High adoption/High yield	1.529	1.222	1.257	0.803	0.280
GM Cassava					
Low adoption/low yield	0.126	0.100	0.079	0.047	0.032
Low adoption/high yield	0.189	0.151	0.120	0.072	0.049
High adoption/low yield	0.252	0.202	0.160	0.096	0.065
High adoption/High yield	0.380	0.304	0.241	0.144	0.098
GM Maize and GM Cassava, combined					
Low adoption/low yield	0.486	0.387	0.375	0.235	0.095
Low adoption/high yield	0.764	0.610	0.592	0.372	0.151
High adoption/low yield	1.210	0.967	0.947	0.597	0.238
High adoption/high yield	1.908	1.526	1.499	0.948	0.380

Note: Assumes average probability of R&D and regulatory compliance success (82% for maize and 72% for cassava). Source: Model simulation results.

The high variation of results among the alternative scenarios, and the desirability of reaching the significant higher effects of the optimistic high adoption/high yield change scenario, suggest that the realization of these effects would require significant efforts. Those efforts need to be oriented towards investments and policies that enable the maximization of adoption rates and yield growth through the efficient use of technical recommendations on crop production management and the introduction of supportive investments and policy incentives.

5. Summary of conclusions and implications

Tanzania's agriculture faces persistent low productivity, due to several endogenous and exogenous factors, including biotic and abiotic shocks, particularly unpredictable and changing rainfall patterns, drought, and the high incidence of poorly controlled pests and diseases. In the absence of appropriate policy and investment interventions, climate change is expected to further reduce critical crop yields, creating significant additional negative consequences on household food security and the broader economy.

These challenges call for actions that better articulate the country's response to relevant policies and investment strategies, including those for agriculture innovations like modern biotechnology to support improved crop varieties that address agriculture constraints and critical development challenges. Until early 2021 the government of Tanzania, in collaboration with various international partners and local scientists, pursued the development of two transgenic crops – TELA maize and CBSD-resistant cassava. TELA maize GM varieties were designed to offer durable genetic enhancements for drought tolerance and insect resistance while CBSD-resistant cassava varieties included durable genetic changes for resistance to the complex of viruses that cause CBSD. Until recently, R&D and accompanying regulatory assessment efforts were being pursued to ensure that these higher yielding varieties were efficacious and safe for consumption and cultivation.

Ruhinduka et al.'s (2020) ex-ante partial-equilibrium analysis (DREAMpy Partial Equilibrium Economic Surplus Model) suggested large and positive net benefits associated with the potential adoption of TELA maize and CBSD cassava varieties in Tanzania, with adoption maize holding the largest net benefits. Ruhinduka et al. provided an interactive and participatory rapid assessment of the benefits of each of these GM crops for producers and consumers, designed to initiative conversations about technology governance. However, the model they used was not designed to account for impacts in other crops and the broader sectors of the economy. To expand the modeling choices and explore those impacts, we conducted an assessment to consider a wider set of outcome indicators that could be additionally relevant to decision makers, including broader impacts of agricultural biotechnology innovations on the economy. Our analysis used an economy-wide modeling framework (RIAPA) with macro-micro simulation that draws directly on a range of information from the economic surplus model and other relevant assumptions on the probability of R&D and regulatory compliance success, GM crop adoption rate, and their anticipated yield gains. The analysis looks at different scenarios, considering combinations of levels of adoption rate and yield gains parameters, to estimate the development outcomes of TELA maize and CBSD-resistant cassava.

We found several important results. First, the introduction of TELA maize and CBSD-resistant cassava has positive impacts on the economy, the AFS, and poverty and welfare – particularly for those in rural areas and among the poorest groups in the country. Second, given its relatively greater prominence in the economy in terms of contributions to GDP and employment, and the stronger linkages in the AFS, the effects of TELA maize on GDP and AFS growth, including beyond direct production, and household poverty and welfare are stronger than those for CBSD cassava. This is consistent with the earlier crop-based analysis of Ruhinduka et al. (2020), but now demonstrated at an economywide context. Third, the analysis finds that the combined effects of a simultaneous introduction of TELA maize and CBSD-resistant cassava have the strongest effect on all outcomes. Fourth, as expected, we find greater effects from higher adoption and high yield gains scenarios than from less optimistic ones. Also, in addition to those being differentiated across income groups (i.e., in each scenario the effects of GM crops on the poorest households are greater than that for the higher quintiles), differential impact across scenarios is also greater amongst the poorest (Quintile 1), while the differences in the effects of more optimistic scenarios versus the less optimistic are not substantial for the top quintile.

Finally, the high variation of results across the different scenarios, and the significant effects of the high adoption/high yield change scenario, suggest that it is critical that efforts be made to ensure the maximization of adoption rates for the high yield growth potential of the GM varieties, through efficiently using technical recommendations on crop production management, and introducing appropriate investments and policy incentives.

Technology governance and the enabling environment for GM applications (tools and products) is complex. The effects of political economy issues impacting GM technology adoption have been documented in the literature, including the influence of pressure group opinions that rarely consider the established performance and economic impacts of the technology. The BioRAPP project showed that, despite a participatory research approach, impacts of evidence-based information may not be singularly effective in changing relevant policy dialogues around the use of GM tools in agriculture. This has been the case in many countries, including Tanzania, where the R&D efforts for both TELA maize and CBSD-resistant cassava remain stalled due to the 2021 decision to suspend the research. The economy-wide results that this paper presents reinforce and expand earlier results about the benefits of these GM products and show that they can support progress in the agricultural sector and promote sustainable development.

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Annex 1. Key features of the DREAMPy and RIAPA models

Feature	RIAPA Rural Investment and Policy Analysis	Dynamic Research Evaluation for Management, Python update (DREAMPy)	BioRAPP-related notes
Model type	Computable general equilibrium using macro-micro simulation modules.	Partial equilibrium economic surplus.	The project demanded a model like ESM that could be used by local practitioners and could be implemented independently using locally available data.
Primary purpose	Assessment of development impacts (economic growth, employment, poverty, and dietary diversity) of country policy and investment interventions. Used for value chain, and public policy and investment prioritization.	To assess priorities and returns (benefit/cost ratios and internal rate of returns) to R&D investments in a single country value-chain.	Have a user-friendly tool (DREAMpy) that allowed local economists and practitioners to assess and evaluate economic benefits of nationally identified priority GM crops
Accessibility	Relatively recent tool. Mostly used by specialized researchers and trained developing country practitioners. Capacity building efforts underway will increase accessibility. Online version for the RIAPA-AIDA tool will make it widely accessible and easily applied to a wide set of countries.	Open – A user-friendly software tool, freely available that can be quickly and independently be implemented by any practitioner around the world who has access to the internet and has some experience with Excel.	The RA in BioRAPP: Developed a tool that allowed local practitioners with diverse and even limited degrees of specialization to implement a rapid ex ante assessment.
Scale of application	Applied to the national economy (country level) allowing for sub-national (region, urban/rural) disaggregation, with development impacts assessed at the macro (growth and jobs) and micro (poverty, and nutrition) levels.	Scale-neutral. Compares B&C streams arising from a single project/technology to change impacting national and larger markets	Seemingly, some of the priority GM crops in BioRAPP did not have the necessary scale to translate into significant national impacts.
Data needs	Data needs are intensive. The economy wide with macro-micro simulation scope requires the building of a social accounting matrix (SAM) using national accounts, supply-use tables, government budgets, and household level consumption and expenditure surveys. These data sources are widely available for many countries.	Parsimonious. Production, consumption, growth & price elasticity data for single commodity. Optional sub-region/ market breakdown.	Use of locally available data was a priority for local stakeholders and donor.
User base	IFPRI RIAPA team and trained developing country practitioners. User base and applications in expansion.	DREAM has been used by hundreds of independent analysts around the world.	

Source: Authors.

Annex 2. Summary results of Ruhinduka et al. (2020) GM maize and cassava estimates

The DREAM and stochastic simulations for the potential adoption of GM maize and cassava in Tanzania summarized below are expressed in million 2018 International PPP dollars and are a midpoint for the "pessimistic" and "optimistic" scenarios considered in the assessment for the deterministic DREAM results.

For GM maize, DREAM results show that, if adoption occurs in Tanzania, total additional economic surplus amounts to 5,573 million as a baseline NPV for the simulation period. A five-year delay reduces baseline NPV by 1,883 million or 33%. Stochastic economic surplus simulations show a baseline NPV of 7,508 million (5th–95th percentile confidence interval of 2,269–16, 344 million). For GM cassava, results using DREAM in a deterministic approach, show that if adoption occurs in Tanzania, total economic surplus amounts to 553 million as a baseline NPV for the simulation period. A five-year delay reduces baseline NPV by 213 million, equivalent to a 38% decrease. Stochastic economic surplus results show that the baseline NPV is 2,814 million, (5th–95th percentile confidence interval of 126–17,275). For both GM maize and cassava cases, the deterministic estimates done using DREAM lie within the 5th-95th percentile, calculated using probability distributions in the stochastic simulations. This serves as a cross-check for the deterministic economic surplus estimates. The mean results for the cassava study, however, are significantly different between the mid-point in the deterministic estimations and the mean in the stochastic simulations. This just reflects the skewness of the probability distributions used in the simulations.

The real options approach for the maize case study for considering irreversibility, flexibility and uncertainty yields an estimate for total additional benefits of 5, 942 million and 155 million for GM maize and cassava respectively. The hurdle used to weight estimates benefits was 2.196 for maize and 1.18 for cassava. These results are qualitatively consistent in the case of maize with the deterministic and stochastic economic surplus estimates, enhancing the overall results from the simulations. This is not the case for cassava, where results differ although within the confidence interval estimated in the stochastic simulations. Defining the level and reasons behind these differences merit further research.