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ORIGINAL PAPER

Agrobiodiversity Conservation Policies: Insights from an Integrated Micro-macro Economic Model in Ethiopia

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Abstract

National strategies aiming to enhance agricultural productivity in sub-Saharan Africa have traditionally focused on encouraging the adoption of improved modern crop varieties. This approach led to genetic erosion and reduced option value for bioprospecting, an unintended consequence of the decline of locally conserved traditional varieties. Governments are often left with poor guidance to evaluate the costs and benefits of this strategy. In this paper, we propose a methodological framework for assessing agricultural policies based on local agrobiodiversity conservation. In particular, we modify a computable general equilibrium model with trade to account for the land allocated to traditional and improved modern varieties as input for the agricultural sector. As a case study we select the Ethiopian durum wheat. Several sources of data at macro, micro and agronomic levels are adopted to estimate parameters and economic effects. Accounting for climate change and technological projections up to 2050, results of a counterfactual scenario show that when policy-driven breeding programs in specific agroecological niches are implemented, they simultaneously achieves conservation and food production goals. The findings underscore the need for policy interventions aimed at promoting context-specific strategies that consider conservation and production objectives within the broader agricultural landscape.

Keywords Agricultural productivity · Crop genetic erosion · Computable general equilibrium · Ethiopia

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1 Introduction

Evidence from agricultural and development literature has demonstrated how the diffusion of high-yielding, improved modern crop varieties (MV) caused a rise in the average productivity of major staple crops in Asia and Latin America, also contributing to increased food security (Evenson & Gollin, 2003b; Pingali, 2012). Since the 1980s, the intensive modernization of agriculture led to a reduction in the number of crops used in our diets, with the consequence that more than 60% of human food energy is supplied by only four crops (Commission on Genetic Resources for Food, 2010). However, the increasing adoption of a limited number of modern, hybrid varieties is recognized as one of the causes of a significant decline of *on-farm* agricultural genetic diversity (Pallante et al., 2016; Lanz et al., 2018; Khoury et al., 2022). Worldwide, traditional local varieties are disappearing.

In sub-Saharan Africa, where 21% of the population suffers from chronic malnutrition and undernourishment[1], many governments prioritized the modernization of agriculture by fostering the substitution of local traditional varieties (TV) with MVs. MVs are genetically uniform. They were developed to thrive in simplified monoculture systems where access to complementary inputs and farmers' skills are necessary for economically outperforming TVs (Ahmad et al., 2023). Nevertheless, high transport costs, failures to deliver credit, informational barriers and, in general, poor market infrastructures (Takahashi et al., 2020) often prevent African smallholders from acquiring MVs and complementary inputs (Suri & Udry, 2022; Collier & Dercon, 2014). In this context, the "scale neutrality[2]" concept of new crop varieties, which triggered the Asian Green Revolution, did not work in sub-Saharan Africa (Fisher, 2016). The new crop varieties — not specifically developed for the local agro-climatic and market contexts — proved to be less advantageous for small scale farmers (Coromaldi et al., 2015). While cereal yields (kg/ha) grew by 90% in South Asia between 1990 and 2021, sub-Saharan Africa growth rates over the same period were only 49%.

At the same time that MV adoption increased, participatory breeding programs became an important strategy to use locally adapted TVs for building resilience to climate change and pests and diseases (Cacho et al., 2020). TVs are a by-product of an evolutionary selection process pushed by local agro-ecological conditions, farmers' livelihood strategies, and indigenous preferences (Tilman et al., 2002). The heterogeneity of this selection process implies the conservation of a set of TVs that are better suited to degraded and poor soils, rainfall variability, droughts, and pest and disease infestation (Jarvis et al., 2008, 2011). Preserving crop variability at the local level, farmers "buy" insurance against environmental risks (Di Falco

[1] Source: https://www.databank.worldbank.org/data/source/world-development-indicators.

[2] An agricultural technology is scale neutral when is expected to equally benefit small- and large-scale farmers.

& Chavas, 2009; Di Falco & Perrings, 2005), which is a particularly interesting feature in the context of climate change (Lebot, 2013; Asrat et al., 2010). Indirectly, TVs serve as "custodians" of the local agro-biodiversity stock (Quaas & Baumgärtner, 2008). In the short term, the emphasis on a few varieties leads to a decline in on-farm genetic diversity, limiting the smallholders' ability to adapt to environmental challenges (Asfaw et al., 2018). Over the long term, the loss of agro-biodiversity has significant implications for breeding efforts carried out by both the public and private sectors, as highlighted by Kahane et al. (2013). Crop genetic erosion, caused by the excessive substitution of TVs with MVs, deprives developing countries of the option value of searching for TVs adaptable to the local context and a changing climate (Bellon & Van Etten, 2014). Moreover, it exposes farmers to market risks, such as price variability in commodity markets and global value chains (Bellemare et al., 2013; Hoekman et al., 2023). Several studies have recognized the role of TVs and crop diversification in managing and coping with these shocks, smoothing agricultural income variability, and enhancing smallholders' food security and dietary diversity (Makate et al., 2022; Lourme-Ruiz et al., 2021).

The "silver-bullet" approach of sustaining agricultural intensification and the adoption of genetically standardized MVs, irrespective of the socio-economic and ecological context, is thus increasingly criticized in favor of a best-fitting sustainable strategy to be implemented at a national scale but with adaptation at the local level (Pearce et al., 2013). In this framework, modern bottom-up TV breeding programs, based on the selection and diffusion of varieties more responsive to the local conditions, would help to reach the *win-win* outcome of increasing productivity and counteracting *on-farm* genetic erosion at the national level (Gotor et al., 2021). Unfortunately, developing-country governments lack guidance on the benefits and costs associated with a MV versus a TV strategy, or a combination of both.

While the welfare impact of cultivating TVs has been investigated at the microeconomic level (Coromaldi et al., 2015; Shiferaw et al., 2014; Asfaw et al., 2018; Cheng et al., 2020) and researchers have thoroughly analyzed the micro- and macro-economic impact of MVs (Evenson & Gollin, 2003b), little evidence exists on the countrywide effects of TV-based bottom-up breeding programs. To fill this gap, we build on the existing literature by introducing a methodological procedure to evaluate the benefits of a nationally-planned TV breeding program scenario with respect to the baseline diffusion pattern of MVs. We focus on the durum wheat case study in Ethiopia, a unique centre of origin of genetic diversity for several important crop species. Durum wheat is a promising crop for agrobiodiversity research in terms of option value for future investigation, bioprospecting, and breeding programs, accounting for about 12% of the national gene bank holdings (Cheng et al., 2020, 2024; Gotor et al., 2021; Mengistu et al., 2016). Durum wheat has been cultivated in Ethiopia for over 3,000 years. However, recent politically motivated trends are leading to an increasing reliance on relatively few varieties, mainly high-yielding MVs of bread wheat, with a consequent loss of well-adapted durum wheat and its associated *on-farm* genetic diversity (Tsegaye & Berg, 2007; Shiferaw et al., 2014).

We use a recursively dynamic computable general equilibrium (CGE) model based on version 6.2 of the Global Trade Analysis Project (GTAP) model[3]. Like most neo-classical growth models, the dynamics are driven by three key factors. The first factor is the population and labor force, with exogenous growth rates. The second factor is capital accumulation, where the capital stock in any given simulation year is determined by the previous year's capital stock minus depreciation plus the previous year's investment volume. The third factor is productivity, with several productivity shifters integrated throughout the model.

The GTAP database version 9 (Narayanan et al., 2015) is used for this analysis. It is integrated with the Living Standard Measurement Survey on Agriculture (LSMS-ISA) of the World Bank to split the agricultural sector and the agricultural land supply between modern and traditional varieties for all crop categories. This approach provides reliable information on the farm-level land allocation between TVs and MVs.

At the same time, our model introduces a productivity differential projection to 2050 for both MVs and TVs, relying on climate change-based scenarios from FAO and the existing on-field durum wheat breeding programs in Ethiopia (for a synthesis of the program see Fadda et al., 2020). Simulating a gradual implementation of these programs in Ethiopian areas where the TVs outperformed the MVs, we provide results on the production, value, and importance of MVs versus TVs. Remarkably, our procedure allows us to evaluate the land allocation between modern and traditional varieties, thereby supplying policy implications for effective strategies to foster the development of the national agricultural sector without increasing the *on-farm* genetic erosion.

The results show that if governments were to invest in decentralized breeding programs focusing on promising local varieties, these in turn would yield a 95% increase in land devoted to traditional wheat varieties in 2040, compared to a baseline scenario with no investments and therefore the complete absence of a TV program. At the same time, the national cereal production growth remains constant compared to the baseline, while dependence on cereal imports is slightly reduced. This paper does not consider the cost associated with the promotion and maintenance of breeding programs focusing on promising local varieties versus cost associated with the introduction of MVs, a research gap that should be filled with further investigation.

The remaining part of this paper proceeds as follows: Sect. 2 illustrates the Ethiopian case study; Sect. 3 describes the conceptual framework; Sect. 4 shows the methodology; Sect. 5 reports the results; and Sect. 6 concludes with final remarks.

2 Country background

In Ethiopia, the agricultural value-added share of GDP is still high, despite a decrease from 44 to 36% of GDP between 2000 and 2020. Accordingly, even if the poverty headcount ratio at $2.15 a day (2017 PPP) decreased from 69% in 1995

[3] https://www.gtap.agecon.purdue.edu.

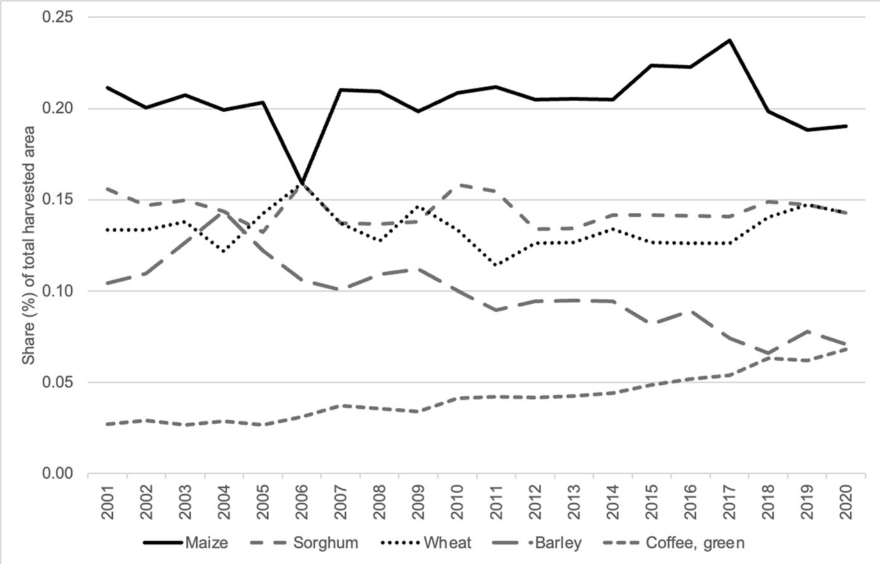

Fig. 1 Share of total cultivated area, by selected crop. *Source*: authors' elaboration on FAOSTAT data

to 27% in 2015 (WDI, 2018), agricultural modernization remains a key challenge for the Ethiopian government (Vandercasteelen et al., 2021). Drought-induced food insecurity is likely to be recurrent and intense in the future (Constenla-Villoslada et al., 2022).[4]

Most of the population lives in rural areas (78%) and depends on subsistence agriculture and livestock for their livelihoods. Maize and wheat are the main staple crops, contributing to 29% and 21% of calorie intake from cereals, respectively (FAO, 2013; Berhane & Gardebroek, 2011). As shown in Fig. 1, these cereals, together with barley and sorghum, also represent an important share of the total cultivated harvested crop area. At the same time, coffee has recently gained an important share of the harvested area.

According to FAO data, wheat imports grew rapidly from 2009 to 2016 and then turned back to initial levels (see Fig. 2), while the value of wheat imports largely increased over time. These trends follow the rapid increase of domestic wheat consumption (from 3.8 million tonnes in 2014 to 7.2 million tonnes in 2022[5]), caused by strong population growth.

Increasing yields is key to improving livelihoods and food security in Ethiopia (Benson et al., 2014), especially to spread the risk of international price fluctuations of maize and wheat, the major cereals in which Ethiopia is a large net importer (Rashid et al., 2018). Despite efforts, the productivity of cereals is

[4] For information on the drought and famine in the horn of Africa, see the Famine Early System Network at https://fews.net/.

[5] Data retrieved from USDA.

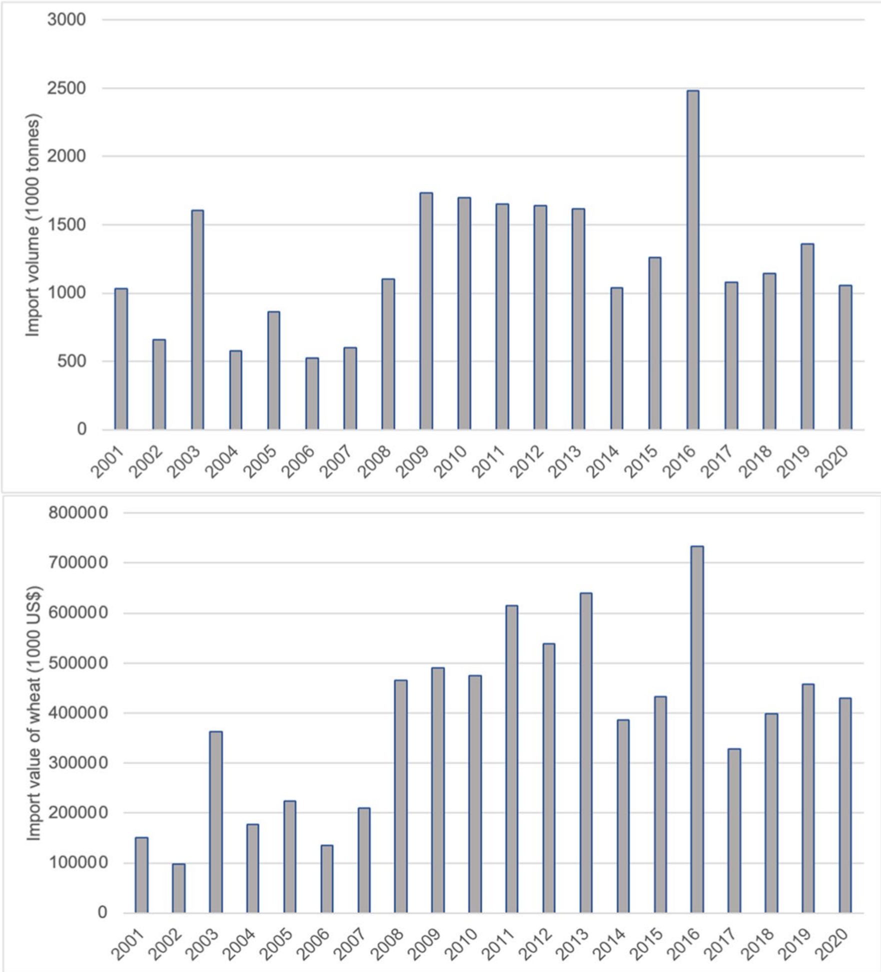

Fig. 2 Volume of wheat imports (1000 tonnes) and value (1000 US$). *Source*: authors' elaboration on FAOSTAT data

still low, with an average of 2.21 t/ha between 2010 and 2020 (WDI, 2020). Significant research efforts have focused on yield improvement and stress tolerance for maize and wheat by developing widely adapted hybrid varieties with narrow genetic bases (Haile et al., 2016; Mengistu et al., 2016). There has also been a relatively heightened policy focus on improving the availability and accessibility of improved seeds, as underlined by Veernoy et al. (2017). Ethiopian farmers are mostly small-scale producers, with lands between 0.5 and 5 hectares on which different agricultural activities are carried out in semi-subsistence agriculture. These smallholders rely heavily on traditional varieties despite the rapid conversion of land across the country to high-yielding, promising MVs.

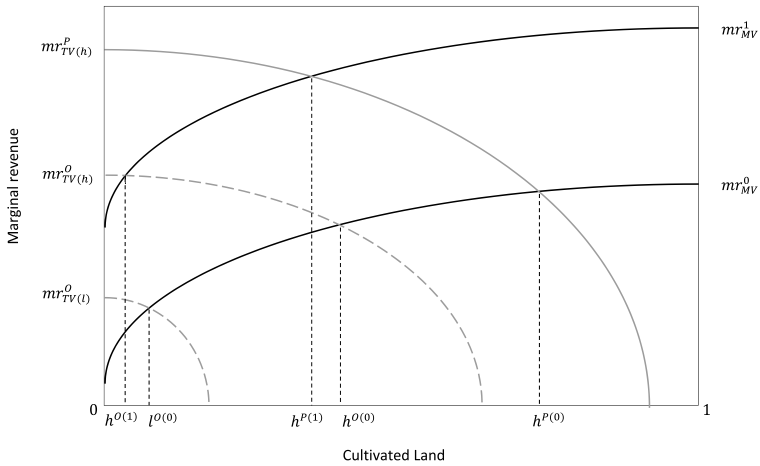

Fig. 3 Conceptual framework - the land allocation between traditional (TV) and improved modern (MV) varieties. *Source*: authors' adaptation on Pallante et al., (2016)

3 Conceptual framework

While MVs are most suitable for intensive and simplified agricultural systems (FAO, 2009), TVs have been cultivated for thousands of years under the most extreme agro-ecological conditions and in low-input farming systems, conserving the traits adapted to unique environments (Lopes et al., 2015). Their conservation is fundamental to achieving future potential productivity gains through breeding programs focused on promising varieties that reduce negative environmental externalities. The larger the genetic diversity pool conserved *on-farm*, the higher the probability of successful bioprospecting, which selects the most resilient species for the local context (Cheng et al., 2020). Genetic gains from breeding programs can be the most effective strategy to respond to the needs of small farmers in low-input agriculture, both in terms of yields and tolerance to biotic and abiotic stresses, such as water and heat stress[6] (Mengistu et al., 2016).

Farmers face a choice in terms of land allocation. Figure 3 conceptually represents this choice on a fixed land endowment. On one side, they could allocate the land to MVs. These outperform landraces in intensified agricultural production systems and are often supported by governments and extension systems. The larger the proportion of total land allocated to MVs, the higher their marginal value, as specialization is triggered. This is represented by the curve, mr^0_{MV}. Therefore, smallholders

[6] Several studies show that there is evidence of continuing high rates of return for crop breeding improvements that have wide adaptability to local conditions and a changing climate. The evidence also shows high returns for improvements in orphan traditional local crops and marginal lands characterized by small-scale farming and poor access to modern and complementary agricultural inputs (Pingali, 2012).

face increasing opportunity costs for maintaining diversity within such production systems (Jackson et al., 2007).

The optimal land allocation is determined at the point where the marginal revenue of land allocated to TVs is equal to MVs. Assume that a farmer is cultivating two TVs with a currently observed (O) marginal value given by $mr^{O}_{TV(h)}$ and $mr^{O}_{TV(l)}$, representing respectively high (h) and low (l) bioprospecting potential (P). Without bioprospecting on TV, the land allocation would be $h^{O(0)}$to TV h, $l^{O(0)}$ to l and $1 - h^{O(0)} - l^{O(0)}$ to MV. If the MVs were incentivised, their marginal value for unit of land would increase. This situation is represented by the curve mr^{1}_{MV}. In this case, the genetic erosion increases over time since $h^{O(0)} + l^{O(0)} < h^{O(1)}$. The low potential TV is no longer cultivated, while the high potential TV risks neglection.

On the other hand, the genetic erosion occurs as farmers and policy makers do not account for the positive externalities spreading from biodiversity conservation (Narloch et al., 2011). A breeding program that triggers the yield potential of the TV h, causes an upward shift, up to $mr^{P}_{TV(h)}$, of the marginal revenue curve. In this case, the land allocated to the high potential TV would be $h^{P(1)} > h^{O(1)}$.

One issue worth highlighting is that if MV were not being supported at the national level, then policymakers would have a policy portfolio entailing the following mix: they can sustain MVs in intensive and simplified agricultural systems areas; on the other hand, they can sustain national breeding programs in agro-ecological niches with the aim to create resilient communities of small-scale farmers and special zones of genetic diversity conservation. This approach would avoid the shift of the MV marginal revenue curve to mr^{1}_{MV} in selected agroecological niches by ensuring a large and effective cultivation for the high potential TV ($h^{P(1)}$), but also the maintenance of the low potential TV. This approach to the agricultural policy has the scope to increase positive externalities related to agricultural biodiversity conservation and balance against agricultural subsidies to MVs. It aims to trigger a win-win option in terms of food security at the national level since it guarantees large-scale food production through MVs while still allowing for the conservation of a diversified mix of local crop varieties in the face of climate change and other stresses to small-scale farmers.

In this context, our paper explores the macroeconomic impacts of such policy intervention scenarios in Ethiopia. Our approach includes the value of land allocated to MVs and TVs within a computable general equilibrium model, accounting for the different productivity these crops could have in various agro-ecological zones.

4 Methods and data

4.1 Baseline, policy scenario and data

We develop a baseline and a policy scenario based on several data sources and modeling choices. The baseline (business as usual - BAU) is centered on current MV and TV productivity trends and land allocation trends. The policy scenario establishes a national wheat TV breeding program (WTBP) to select the most promising TVs at

Table 1 Agricultural area allocation (%), production (%) and input share (%) in 2011–2013, by crop species and variety

Crop	Production (% of total production)		Area (% of total land)		Labor (% of crop labor)		Chemical fertilizers (% of crop fertilizers)	
	TV	MV	TV	MV	TV	MV	TV	MV
Rice	0.938	0.063	0.824	0.177	0.928	0.072	0.541	0.459
Wheat	0.909	0.091	0.910	0.090	0.883	0.117	0.873	0.127
Maize	0.648	0.352	0.790	0.210	0.708	0.292	0.225	0.775
Other cereals	0.981	0.020	0.973	0.027	0.980	0.020	0.970	0.030
Vegetables and fruits	0.981	0.020	0.992	0.009	0.992	0.008	0.989	0.011
Oil seeds	0.992	0.009	0.995	0.006	0.993	0.007	0.969	0.031
Sugar cane, sugar beet	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000
Plant-based fibers	1.000	0.000	1.000	0.000	1.000	0.000	1.000	0.000
Other crops	0.994	0.006	0.993	0.008	0.983	0.017	0.921	0.079

Source: authors elaboration on the base of Ethiopia 2013–2014 LSMA-ISA survey of the World Bank

the agroecological level zone level and improve the farmers' incentives to cultivate them instead of switching to MVs (Vanloqueren & Baret, 2009).

The research relies on four data sources. First, we use the Global Trade Analysis Project (GTAP) database to compute the welfare effects of a policy that incentivizes the conservation of TVs. Second, since the GTAP database does not include details on the allocation of land to different crop varieties, we retrieve information on national markets for MV and TV crops from the nationally representative Living Standard Measurement Survey (LSMS-ISA) of the World Bank, collected in 2011 and 2013. Using farm-level statistics at the national level, this survey allows us to allocate land, production, labor, and chemical fertilizers between traditional and modern varieties of different crops. The SplitCom software (Horridge, 2005) allows us to allocate traditional and modern variety production of different crops to different inputs such as land area, labor, and chemical fertilizer. Table 1 reports the results of the split. We can observe that while the largest share of the production and land at the national level was allocated to TVs, the use of inputs such as labor and chemical fertilizers is differently balanced. Exploring the wheat sector in detail, in 2013, we noticed that while production and cultivated land of TVs of wheat account for 90% and 91%, respectively, the related use of labor and chemical fertilizers is lower.

Since GTAP is a global database, we need to split the crop types from the rest of the world. In the absence of microeconomic data like those for the Ethiopian case, the best alternative is to rely on data from the literature. We use information provided by Evenson (Evenson & Gollin, 2003a) that covers the main geographical regions: Latin America, Asia, Middle East–North Africa, Sub-Saharan Africa, and the rest of developing countries.

Third, we calibrate the BAU and the policy scenario by adopting the productivity growth pattern under standard technology variations and according to climate change effects at crop and country levels. The source of these data is the FAO (FAO, 2018) report "*The Future of Food and Agriculture – Alternative Pathways to 2050*." The report explores three scenarios for the future of food and agriculture based on alternative trends for key drivers, including income growth and distribution, population growth, technical progress, and climate change. We based our dynamic reference scenario (baseline) on FAO data and calibrated model population, GDP and crop yield growth rates to replicate their projections up to 2050.[7]

Since the FAO report does not distinguish between TVs and MVs, we develop our WTBP scenario using validated on-farm data on the TV breeding programs for promising wheat varieties. Our fourth source of data is a study published by Mengistu et al. (2016), which shows that properly selected TVs have an average gain over the best-performing MVs in an experimental layout for durum wheat in Ethiopia. Their results show that it is possible to identify traditional durum wheat varieties that have better performance in terms of grain yield when compared to MVs. While microeconomic data from the LSMS-ISA survey highlight that, on average, the initial differential TV productivity for wheat was around 1000 kg/ha less than the MV, Mengistu et al. report a significant 14.3% gain of TVs over the improved MVs on average in the two locations under proper management approaches. Thus, while under the BAU, the initial productivity differential is that one resulting from the LSMS-ISA survey, when we simulate the policy scenario, we adopt the Mengistu et al. productivity gap that represents, on average, what would have been the observed advantage of a breeding program had it been implemented in the selected agro-ecological zone.

4.2 Methodology

The GTAP database is a global economic database that provides detailed data on international trade, production, and consumption for a wide range of goods and services. It is used to model and analyze the impacts of various economic policies, such as changes in trade barriers, taxation, and technology[8] (among others, Orecchia & Parrado, 2014; Costantini et al., 2018; Fusacchia et al., 2021) and recently, the impact of agrobiodiversity on the economy of the Euro-Mediterranean region (Nicita et al., 2024). For additional technical details on the model adopted, see the Appendix. Here, we focus on technology since we modify the agricultural land productivity, assuming that land for each crop can be allocated to MVs or TVs. Four main adjustments were made to the standard GTAP CGE model to achieve the goals of this analysis.

First, we must introduce the distinction between TVs and MVs within the GTAP database. Using data reported in Table 1 and the SplitCom software (Horridge, 2005), we sequentially split each crop's global and national data to obtain the TV and MV shares. In this way we can characterize the GTAP database to include the production structure of the new sectors. This procedure is based on a

[7] According to FAO (2018) the BAU scenario portrays a future where socio-economic, technological and environmental patterns fail to address many challenges for food access and utilization, as well as for sustainable food stability and availability, despite efforts to achieve and maintain SDG targets.

[8] An alternative method is the use of the national Social Accounting Matrix as in Ahmed et al. (2018).

few assumptions.[9] A key assumption is that the TV and MV products are homogeneous. Homogeneity implies the reasonable assumption that the two farming systems produce the same crop commodity, which is identical to consumers (Pallante et al., 2016). Using the example of wheat, the market prices of TV and MV wheat-based products are the same.[10] A second assumption regards the price of inputs, which we assume to be the same for the two sectors. This implies that the price of the seeds is the same for improved and traditional sectors. Third, we modified the input-output ratio for TV and MV production based on ratios derived from Table 1.

These first three assumptions imply that the cost shares for each input differ between the TV and MV farming systems. For example, the cost share of land in the traditional wheat farming system differs from that in the modern wheat farming system. Consequently, following our conceptual framework, the value of maintaining genetic diversity is an implicit input embodied in the traditional land system. Higher marginal revenues due to crop diversity will be reflected in the rent of land allocated to TVs. To allow the production of a single homogeneous crop commodity by two different farming systems, we followed the modeling approach used by Taheripour et al. (2013), introducing a multi-input crop production structure with the following set of equations:

$$pi_{TV} = pi_{MV} = ps_c, \textit{ for each } c \in \textit{ set of crop commodities} \tag{1}$$

$$pi_j = \sum_{c \in crop\_comm}^{c} S_{jc}\ pf_{jc} \textit{ for all } c \in \textit{ crop commodities and for all } j \in \textit{ set of crop farmers} \tag{2}$$

$$qf_{jc} = qi_j - \epsilon\left(pf_{jc} - pi_j\right) \textit{ for all } c \in \textit{ crop commodities and all } j \in \textit{ set of crop farmers} \tag{3}$$

$$qo_c = \sum_{j \in \textit{ traditional, modern}}^{j} Shr_{cw}\ qi_j \textit{ for all } c \in \textit{ set of crop commodities} \tag{4}$$

Where *pi* and *qi* represent percent changes in the price and quantity of crop *j* at the farming system level, and *ps* and *qo* represent their corresponding percentage changes at the commodity market level (where there is no distinction among methods of production). The variables *qf* and *pf* stand for percentage changes in price and quantities of inputs *j* used for crop production c. Finally, S_{jc} represents the cost share of input *j* in production of crop c, ε is the elasticity of substitution among

[9] Those assumptions allow us to isolate the impact of genetic diversity per se, without considering other arguments that are often used to support the work on traditional varieties, such as the potential of assigning value to the products derived from traditional varieties in specific value chains or the potential of reducing the use of inputs and their costs. This model, using the assumptions described herein, does not consider such arguments that are not easy to be included in a CGE modeling framework and focuses only on the potential of genetic diversity of traditional varieties.

[10] The reality of the Ethiopian context is that TVs serve potentially different markets, as improved varieties are generally introduced for making bread, while TVs are generally use for other purposes. The price for TV is higher in the market and costs of inputs (seeds and fertilizers) is lower.

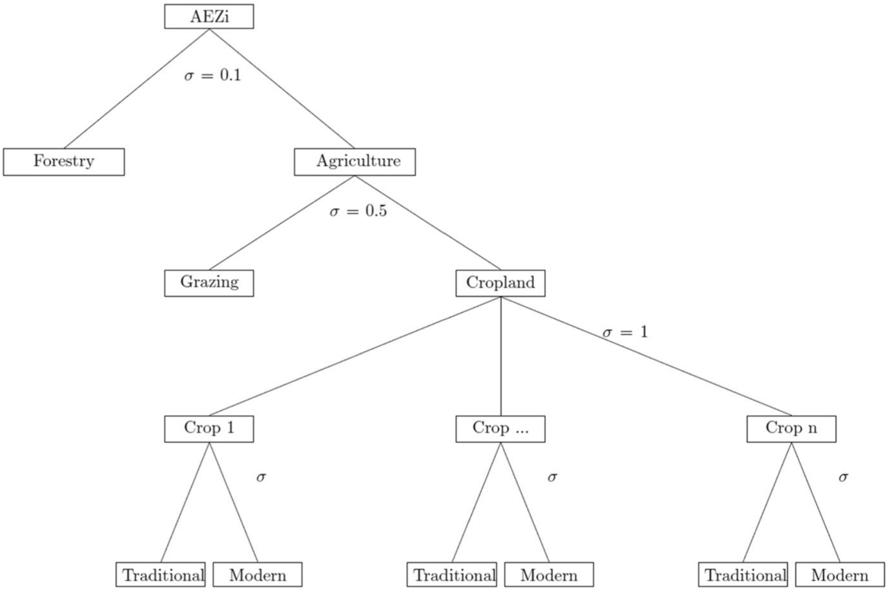

Fig. 4 Structure of land supply disaggregation

intermediate inputs and Shr_{cw} is the share of commodity crop c supplied by diversification type (TV or MV) w.

Equation 1 ensures that TV and MV farmers who produce the same crop (e.g., wheat) will receive the same price and that the prices at farmer and commodity levels are the same. Equation 2 is the zero-profit condition for each crop farming system. Equation 3 represents the demand for intermediate input j in crop c, and finally, Eq. 4 ensures market clearing conditions for each crop.

A fourth assumption is that, to cope with increasing land demand and rents, we allow substitution between land and other inputs to reflect how producers change their mix of inputs using more fertilizers and other factors of production to increase yields per hectare.

A second step in our methodology introduces land heterogeneity. As explained in the conceptual framework, TVs might outperform MVs in specific ecological niches. Nationally driven breeding and conservation programs should account for this. To model the potential differential performance of TVs across agroecological zones and to provide useful insights for program targeting, land heterogeneity across sectors and regions is modelled using the GTAP-AEZ database extension (Pena Levano et al. 2015). The GTAP-AEZ complements the GTAP database, providing information for 2011 on land rents, harvested area and crop production for 18 Agro Ecological Zones (AEZs) for all crops and regions of the GTAP database.[11] We also

[11] The construction methodology the database relies on is explained in Avetisyan et al. (2011). Each AEZ is an area with specific characteristics in terms of length of growing period (LGP) and other climatic factors (e.g. moisture regime and climatic zone). The important implication is that different regions and agricultural activities have different AEZ endowments with different rents and production costs allowing for more realistic land transfers across different uses.

adjust the land supply structure to allow for competition among the different agricultural sectors and between traditional and modern agriculture.

The land supply tree at the top level allocates land among forest and agriculture (Fig. 4). The second level of the new structure allocates agriculture between grazing and cropland categories. The third level allocates land between cropping activities. Finally, the lower level of the new tree governs the supplies of traditional and modern areas among the traditional and modern cropping activities. For each cropping activity, the degree of substitutability between traditional and modern land is governed by a specific elasticity of transformation parameter. To some extent, this parameter measures how easy it is for landowners to transform land cultivated with traditional varieties into land cultivated with modern varieties and vice versa.

The third step of our methodological approach is to introduce a credible dynamic for the growth rate of crop productivity for both the TV and MV farming systems. We use FAO (2018) data to calculate the initial and final productivity for each region and crop as the ratio between tonnes produced and land area harvested (ha). To use these productivity changes in our scenario simulations, we modified the GTAP model, adding an equation that calculates the percentage change of yield per region, AEZ and crop sector:

$$y_{Z,C}^{RG} = \frac{Q_{Z,C}^{RG}}{A_{Z,C}^{RG}} \tag{5}$$

where y, Q and A are the productivity (in tonnes/ha), production (in tonnes) and harvested area (in hectares) of crop C at the AEZ Z and region RG. The production and harvested area come from the AEZ database of the model. Then, we calculate the difference in both terms to obtain a percentage change:

$$\%\Delta\, y_{Z,C}^{RG} = \%\Delta\, Q_{Z,C}^{RG} - \%\Delta\, A_{Z,C}^{RG} = S_{Z,C}^{RG} \tag{6}$$

In this way, the percentage change of yield ($y_{Z,C}^{RG}$) is equivalent to our crop productivity change ($S_{Z,C}^{RG}$). Thus, the model can easily replicate crop yield patterns by endogenizing productivity shift parameters of the land demand.

Since FAO does not distinguish between TV and MV, to differentiate yield between modern and traditional wheat varieties in the baseline, we used information from the LSMS-ISA survey of the World-Bank for Ethiopia. As shown in the data section, MVs were on average 52% more productive than TVs in 2013. Yield growth rates are estimated using 2011 and 2013 survey waves. From cross-referencing the two surveys, we found an increase in yield of 0.5% and 1.2% for TVs and MVs, respectively.

In the baseline, we used Eq. (6) to introduce growth rates into the model to endogenize the land productivity. Then, growth rates are assumed to decrease linearly from 2013 to 2050, following the same percentage reductions estimated by FAO (2018) for the wheat crop. Crop yield changes in the model are thus driven by increases in exogenous efficiency[12]. They also reflect changes at the extensive margin when land devoted to a crop is expanded, as well as the intensive margin when more inputs (capital, labor, fertilizers, etc.) are used to increase yield per unit area. To consider the latter effect, we follow the approach suggested by Keeney and Hertel (2009), calibrating the crop production function to a given price yield elasticity. In particular, the substitution parameter in the Constant Elasticity of Substitution (CES) production function is used to calibrate the Allen-Uzawa elasticity of substitution (AUES) of inputs entering the value-added nest in the production structure. The estimate we used for wheat is an average value taken from the literature as reported in Keeney and Hertel (2009) and Haile et al. (2016), equivalent to 0.2.[13]

4.3 Model aggregation

Table 2 presents the regional and sectoral details used in the simulation. Given the focus of our study, we emphasize the primary sectors with nine agricultural products. Similarly, country aggregation has been set to single out Ethiopia's most important trading partners. The 18 GTAP AEZs are also grouped into four classes: arid, semiarid, subhumid, and humid.

5 Results

In the baseline,[14] with no investment on decentralized breeding programs, modern wheat varieties gradually substitute the traditional ones. Yield of modern varieties are on average 50% greater than traditional types. It is worth highlighting the large increase in production of the improved modern wheat variety, which peaks in 2030–2040, while the traditional wheat variety increases in terms of production up to 2030 but then shows a sudden decrease. In particular, Fig. 5 shows that production of TVs will thus drop to less than 1 million tonnes, a 65% reduction compared to 2020. Land hectares used for TV farming systems fall as well by the same

[12] Total land quantity is exogenous and calibrated to FAO projections. However, land allocated to each crop, modern and traditional, is endogenously calculated by the model. The same is true for crop production. We introduce into the model the Eq. (6) that determines yield so that we can calibrate it to FAO projections but let the model determine land quantities as well as production.

[13] Another important model adaptation is the use in the land supply nest structure of the Additive Constant Elasticity of Transformation (ACET) functional form in place of the standard CET, following van der Mensbrugghe and Peters (2016) and Zhao et al. (2017). The CET function has one potential drawback as it does not preserve additivity which means that the sum of physical quantities does not add up to the total quantity. In the case of land-use, for example, this implies that the sum of hectares devoted to different crops do not necessarily add up to total crop-land. To introduce the ACET functions in the land supply nest structure, the objective function that is being optimized has an additional constraint which is the additivity condition (i.e. the sum of all crops volumes must be equal to the total volume).

[14] See the Appendix for details on baseline construction and reliability.

Table 2 Sectoral and regional detail of the model

Regions	Commodities	Farming systems	AEZs
Ethiopia	Rice	Rice TV / MV	arid
SSA (Sub-saharan Africa)	Wheat	Wheat TV / MV	semiarid
Oceania (Australia, New Zealand)	Maize	Maize TV / MV	subhumid
China	Cereal grains nec	Other cereals TV / MV	humid
Asia	Vegetables, fruits, nuts	Vegetables and fruits TV / MV	
SEAsia	Oil Seeds	Oil Seeds TV / MV	
SouthAsia	Sugar cane, sugar beet	Sugar cane & sugar beet TV / MV	
USA	Plant-based fibers	Plant-based fibers TV / MV	
Rest of North America	Crops nec	Other crops TV / MV	
Latin America	Timber	Timber	
European Union 28	Livestock and Meat Products	Livestock and Meat Products	
Russia	Coal, Oil and Gas	Coal, Oil and Gas	
Middle East and North Africa	Petroleum Products	Petroleum Products	
Rest of the World	Electricity	Electricity	
	Processed Food	Processed Food	
	Textiles and Clothing	Textiles and Clothing	
	Chemicals	Chemicals	
	Light Manufacturing	Light Manufacturing	
	Heavy Manufacturing	Heavy Manufacturing	
	Transport and Communication	Transport and Communication	
	Other Services	Other Services	

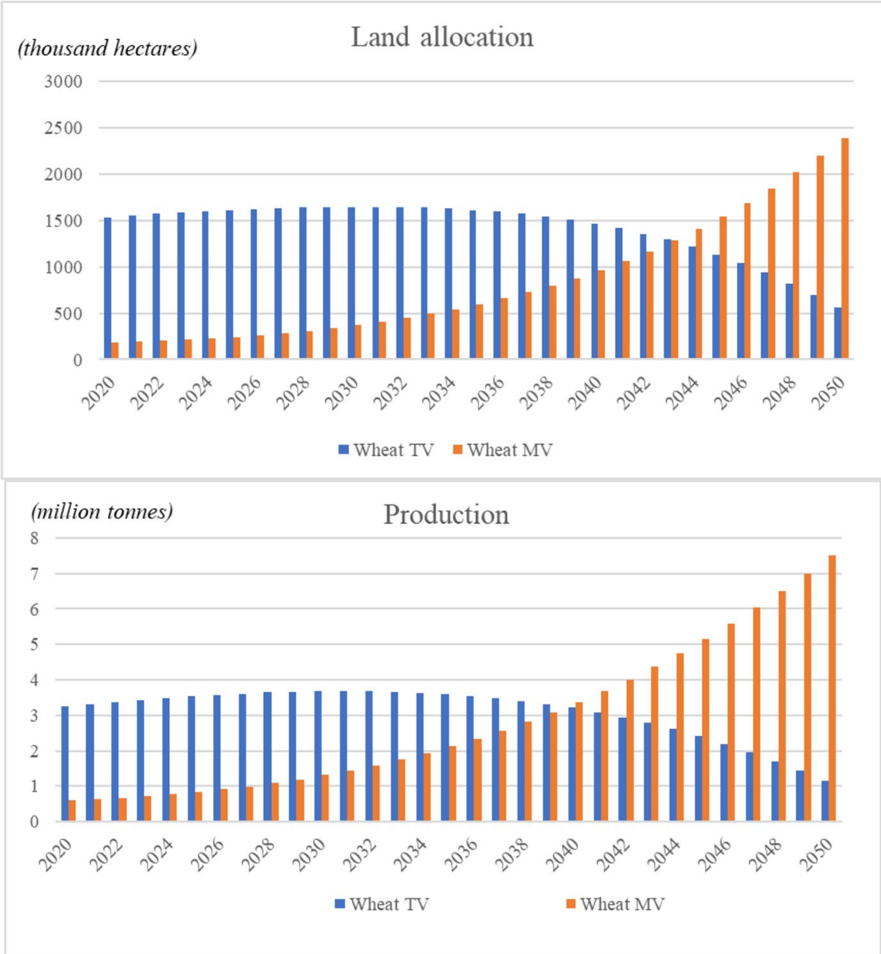

Fig. 5 Baseline outcomes by TV and MV: top graph – land allocation (ha); bottom graph -wheat production (tonnes)

magnitude. In this baseline, the conservation of TVs is endangered by the productivity gains obtained by switching to MVs.

In Fig. 6, baseline results confirm that wheat imports will still be relevant in 2050, although some improvements are detectable. Wheat self-sufficiency, measured as the share of imported wheat over domestic production, deteriorates from 0.78 in 2020 to 0.94 in 2030. Domestic production grows considerably, reaching 9 million tonnes at the end of the period. Imports initially grow by the same magnitude, almost surpassing domestic production around 2030, but remaining 30% below production between 2035 and 2045.

As a counterfactual scenario, we evaluate the implementation of new crop breeding programs that can exploit the potential of the most diversified TVs (see Mengistu

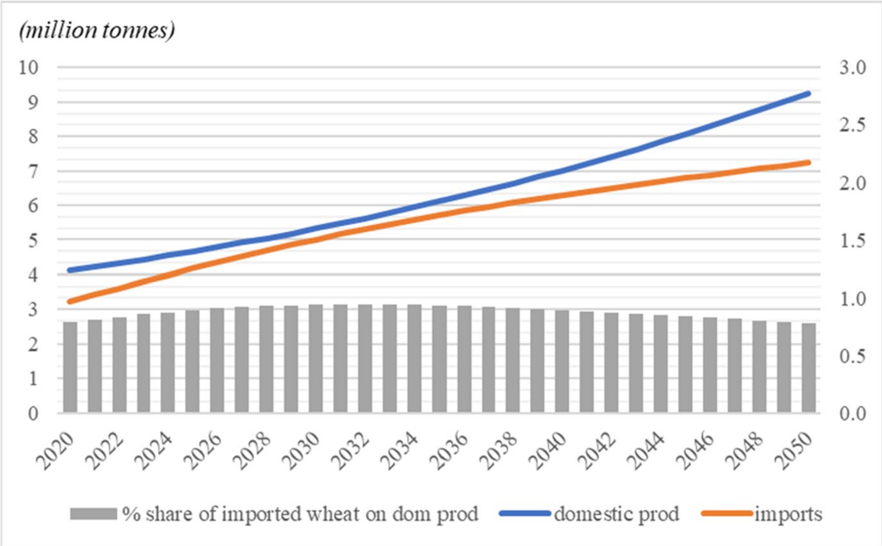

Fig. 6 Baseline: wheat production and imports (left axis); self-sufficiency measured as the share of imported wheat over domestic production (right axis) in Ethiopia

et al., 2016 and 2019). Given the diverse agro-ecologies and cultural farming systems, decentralized and participatory genotype evaluation and selection for target traits could be a successful breeding approach. According to Mengistu et al. 2019, local traditional varieties can yield 14.3% more wheat than modern varieties. We assume that the new TV breeding program will be gradually implemented only in the "humid" agro-ecological zone starting in 20,252,031 and that TVs will increase yields gradually to catch up to MV productivity levels. Due to the new program, the yields of traditional and modern varieties tend to converge around a value of 2.96 t/ha.

The WTBP scenario highlights a substantial change in the traditional variety allocation pattern (Fig. 7). Selecting promising local varieties at the agro-ecological zone level avoids their substitution by MVs. Introducing this breeding program to protect TVs makes them more competitive than the MVs and prevents their disappearance.

Furthermore, the presence of selected MVs and TVs leads to a slight increase in domestic wheat production and a further reduction in imports, thereby improving the self-sufficiency index, as reported in Fig. 8.

Table 3 shows the results for the main macroeconomic and agricultural outcomes considered in this analysis for the WTBP scenario, reporting the percentage variation of the WTBP scenario over the baseline changes. Not surprisingly, the main macroeconomic indicators, namely GDP, consumption, welfare (measured by the equivalent variation), exports, and imports, do not change much. Two results should be emphasized. First, agricultural production remains the same as in the baseline scenario, indicating that the program does not significantly affect output in the other agricultural sectors, which remain unchanged. Second, domestic wheat production

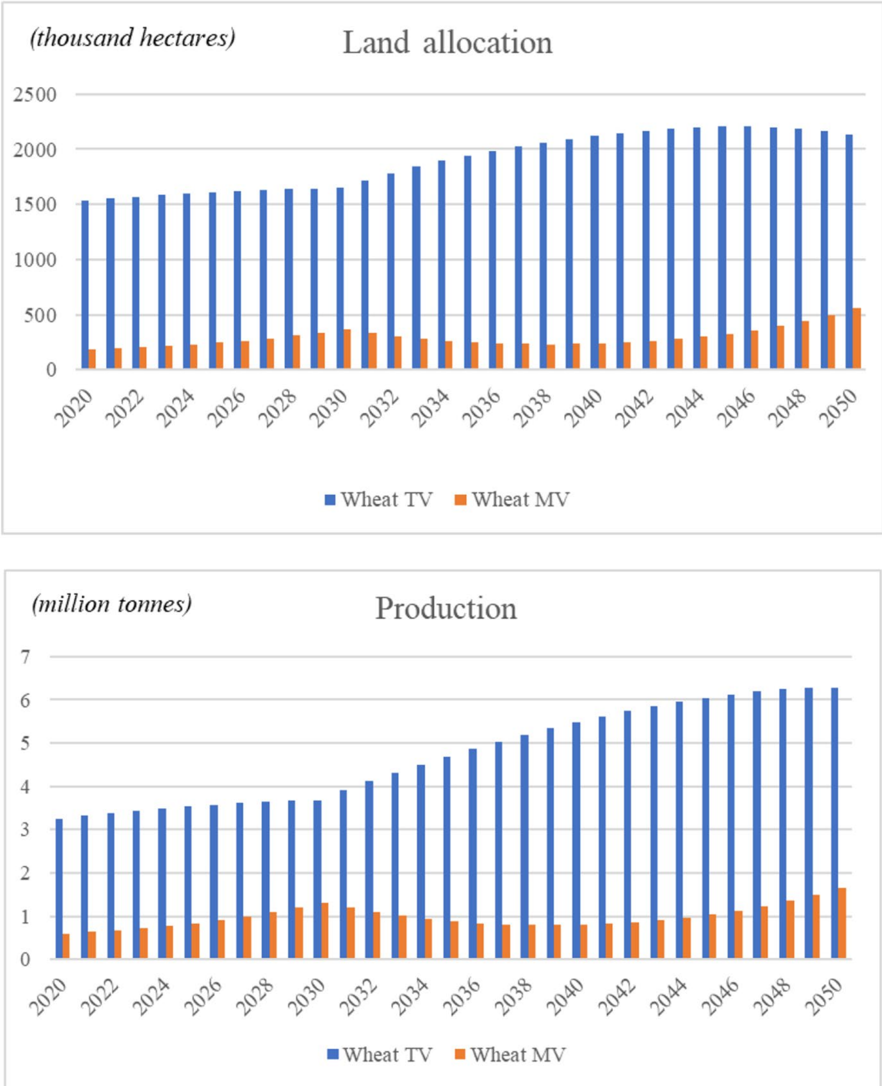

Fig. 7 WTBP scenario: outcomes by TV and MV: Top graph – land allocation (ha); Bottom graph -wheat production (tonnes)

increases in the WTBP scenario by 2.8% while imports decline by 3.3%, confirming that the program can increase Ethiopia's food self-sufficiency.

In Table 4, we provide detailed results of the land allocation within the agroecological zones. In the top part of the table, we observe how MVs and TVs are distributed across AEZs. For example, for the baseline scenario, around 50% of the land allocated to the wheat traditional varieties was in the humid zone in 2020, compared to 56.3% in 2050, In contrast, TVs increased their share to 68.9% in the WTBP scenario. Therefore, in the WTBP scenario, the MVs will be mainly allocated in sub-humid or semiarid zones.

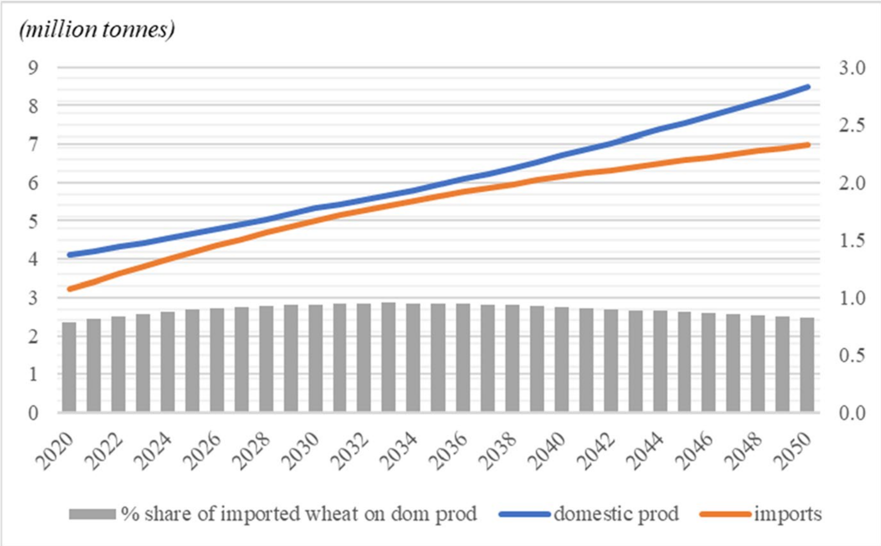

Fig. 8 WTBP scenario: wheat production and imports (left axis); self-sufficiency measured as the share of imported wheat over domestic production (right axis) in Ethiopia

Table 3 Economic outcomes - WTBP scenario (% change compared to baseline)

	2030	2040	2050
GDP %	0.0	0.0	-0.1
Welfare % (equivalent variation)	0.0	0.0	-0.2
imports	0.0	-0.2	-0.4
exports	0.0	-0.3	-0.4
Agricultural production	0.0	0.0	0.0
- wheat	0.0	1.8	2.8
TV	0.0	70.7	448.6
MV	0.0	-76.2	-77.9
- maize	0.0	-0.1	-0.2
Rest of cereals	0.0	-0.1	-0.1
Food industry	0.0	0.0	0.0
Agricultural imports	0.0	-1.1	-1.8
- wheat	0.0	-2.3	-3.3
- maize	0.0	0.9	1.3
- other cereals	0.0	0.3	0.5

The central part of the table shows how the wheat cropland within each AEZ is distributed between the TV and MV farming systems. According to the baseline, in 2020, in the humid zone 92% was devoted to traditional varieties and the remaining part to the MVs. In 2050, we have an opposite result with an allocation to traditional varieties equal to 19.1%. In the WTBP scenario, especially in the humid zone where the breeding program is implemented, the land is completely allocated to the

Table 4 Environmental outcomes – land diversification and yield

	Baseline			WTBP		
	2020	2030	2050	2020	2030	2050
Land allocation between AEZs (% shares)						
- Wheat TV						
- arid	0.6	0.6	0.4	0.6	0.6	0.3
- semiarid	24.9	24.3	19.9	24.9	24.3	14.8
- subhumid	25.3	25.0	23.4	25.3	25.0	16.0
- humid	49.2	50.1	56.3	49.2	50.1	68.9
Total	100	100	100	100	100	100
- Wheat MV						
- arid	0.3	0.3	0.2	0.3	0.3	0.4
- semiarid	35.1	34.4	29.2	35.1	34.4	52.2
- subhumid	27.8	27.6	26.8	27.8	27.6	44.0
- humid	36.8	37.6	43.8	36.8	37.6	3.4
Total	100	100	100	100	100	100
Land allocation of TVs as a percentage of all wheat varieties (% shares)						
- Wheat TV	92.0	81.6	19.1	92.0	81.6	50.0
- arid	0.4	0.5	0.4	0.4	0.5	0.4
- semiarid	24.0	24.2	21.2	24.0	24.2	23.1
- subhumid	25.6	25.0	24.1	25.6	25.0	24.9
- humid	49.9	50.2	54.4	49.9	50.2	51.6
Yield (t/ha)						
- Wheat TV	1.95	2.23	2.04	1.95	2.23	2.95
- Wheat MV	2.94	3.54	3.15	2.94	3.54	2.96

traditional wheat. In all the other AEZs, there is a reduction of cropland cultivated with the traditional wheat, but with a trend significantly lower than the baseline case[15].

Finally, the bottom part of Table 4 shows the implicit yield that is obtained in the baseline and the WTBP scenario as a result of the ratio between production and land allocated to the traditional and improved modern wheat. The 2013 difference of 1 t/ha, highlighted in the LSMS-ISA survey data, is reduced over time in the WTBP scenario. The convergence in yield occurs after the breeding program is applied in the humid AEZ. Under the WTBP scenario, farmers avoid switching to MVs, in contrast to the changes in the baseline scenario.

[15] Despite an almost 500% increase appearing significant, the absolute level is modest. This is because the initial base value was quite low, so even a substantial percentage increase does not translate into a proportionately large absolute figure. Consequently, while the percentage increase is impressive, the overall impact in terms of absolute numbers is not as dramatic as it might seem at first glance.

6 Discussion and conclusions

Governments often lack guidance on the impacts of their strategies to improve agricultural productivity and food security. In sub-Saharan Africa, where the Green Revolution proved to be inefficient in achieving its goals, an agro-genetic erosion threatens the conservation of a valuable pool of local crop varieties. Governments subsidized and distributed modern improved varieties that replaced local varieties without ensuring stable and constant yield growth, even more so under climate changes that reduce the predictability of the cropping seasons and increase the risk of yield losses in monoculture. A new approach at the national level should pursue a diversified, cost-effective strategy, with goals beyond yield increases. This diversified strategy can have multiple benefits - including climate change adaptation, conservation of agrobiodiversity, improved nutrition, reduced used of chemicals, and others - without undermining food security. In some contexts, improved modern varieties can be adopted in areas where markets are functioning with complementary agricultural inputs available, and where the agricultural system is responsive to a standardized production process (Zewdie, 2022). In other contexts, bioprospecting and decentralized breeding programs should focus on incentivizing the *on-farm* conservation of local varieties in rich agro-ecological niches. These niches supply vital gene pools with traits from traditional varieties needed to tackle adaptation challenges. These genetic resources are critical for adapting to a rapidly changing climate and weather conditions while simultaneously increasing crop productivity in these areas (Cheng et al., 2024). By doing so, there will be a significant increase in productivity in these areas.

This paper is among the first to explore a procedure to account for welfare effects from introducing explicit objectives of agrobiodiversity conservation in selected agroecological zones, while maintaining diffusion of improved modern varieties in other areas. We use the case study of Ethiopian durum wheat, a representative example of a country and crop with both productivity and conservation objectives. Historically, Ethiopians tried to improve agricultural productivity by reducing transaction costs associated with obtaining modern varieties. However, in many rural areas this strategy was ineffective and reduced the rich genetic diversity of locally cultivated durum wheat, undermining food security embedded in the genetic potential of selected traditional varieties.

Our approach introduces a distinction between land cultivated with modern and traditional crop varieties in the GTAP database, using farm-level micro data from nationally representative socio-economic and agricultural surveys (LSMS-ISA survey of the World Bank). Dividing land allocation between improved modern and traditional varieties serves as a proxy for understanding how farmers maintain their traditional farming system while also adopting new technologies. We build a baseline and a counterfactual scenario by using productivity differences based on historical geo-referenced data from the World Bank survey and from FAO projections based on climate change and technological improvement dynamics.

The counterfactual, where a traditional wheat variety is conserved and cultivated in humid agro-ecological zones where it has proved to be highly productive, shows that *on-farm* agro-biodiversity conservation goals can be achieved with improved national wheat production, a slight reduction in cereal import dependence, and a negligible decrease in GDP and aggregate consumption in 2040 and 2050. In particular, the national agricultural production based on traditional varieties would increase by 95% over the baseline scenario in 2040, while imports would decrease by 0.3%. These results confirm that diversified strategies can boost national agricultural productivity and address climate change as a win-win option. The IPCC widely recognises and recommends such a solution (Mbow et al., 2019). Breeding programs, particularly those based on participatory variety selection, are technically feasible at a low cost since they allow farmers to work with varieties they already know. The most promising variety can be widely adopted in a community in around three years. The largest obstacles are on the political side. There is limited interest and financial support for traditional varieties. This reduces the incentive for local research institutions to work on them. As a consequence, a main policy implication stemming from our analysis is that governments should improve their ways of evaluating the benefits and costs associated with their national agricultural policies. They should balance the objectives of modernizing agricultural systems and of agrobiodiversity conservation driven by decentralized bioprospecting activities in rich agro-ecological niches. These activities are not driven, per se, to maintain option values for future conditions but can be shaped to improve agricultural productivity in the medium term. Recently, Ethiopia has adopted a very aggressive policy to improve the production and productivity of wheat in irrigated areas as part of the Homegrown Economic Reform, with some successes already visible. Investments and training have grown significantly. While this initiative lacks full consideration of medium- to long-term environmental sustainability dimensions, it shows Ethiopia's commitment to investing in reducing the yield gap and import dependence on wheat (Effa et al., 2023). Interestingly, the program builds on promoting locally developed varieties, well adapted to different agroecologies. Our approach balancing traditional and modern varieties of durum wheat builds on some of the dimensions of the Wheat Initiative.

Future research calls for continuous improvement of our method. First, researchers need to collect data on administrative and operational costs of decentralized breeding programs versus a national subsidy program for distributing modern, improved varieties. Second, they should further explore how to distinguish modern versus traditional varieties in the outlet market. In our model, consumers are not able to distinguish the two varieties for the same crop, as they might be able to do in the real world. Finally, future research should explore and model the effects of including two separate markets with different premium prices as a policy option.

Such an approach could help producers create niche markets for orphan and neglected varieties of crops and could be a promising strategy to increase the farmers' marginal utility from participating in agrobiodiversity conservation (Pallante et al., 2016). These caveats stem directly from the assumptions of CGE models. Since CGE models assume perfect competition and fully flexible prices and wages, market frictions, imperfect information, and limited institutional capacity could limit the advantages of our policy scenario. In the context of a developing country, these frictions are expected to be significant. Therefore, accounting for them is essential to improve the precision of expected benefits and provide a reliable policy guideline.

Appendix

The CGE model

To address our hypothesis, we develop a CGE model able to incorporate the productivity differentials of MVs and TVs. The CGE multi sector models' main strength are their ability to capture endogenous demand and supply reactions to different shocks transmitted through changes in relative prices.

To better capture international trade feedback in the wheat market, we use a global CGE model, modified from the original version of the GTAP model (Hertel, 1997), with endogenous dynamics for capital accumulation. The calibration year is 2013. Data comes from the GTAP9 database (Narayanan et al., 2015) with a simulation period of 2020–2050.

As standard in CGE models, this modified version of the GTAP model makes use of the Walrasian perfect competition paradigm to simulate market adjustment processes. A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, land, labor, and capital). Capital and labor are perfectly mobile domestically, but immobile internationally. The income is used to finance three classes of expenditure: aggregate household consumption, public consumption, and savings (Fig. 9). The expenditure shares are generally fixed, as the top-level utility function has a Cobb-Douglas specification.

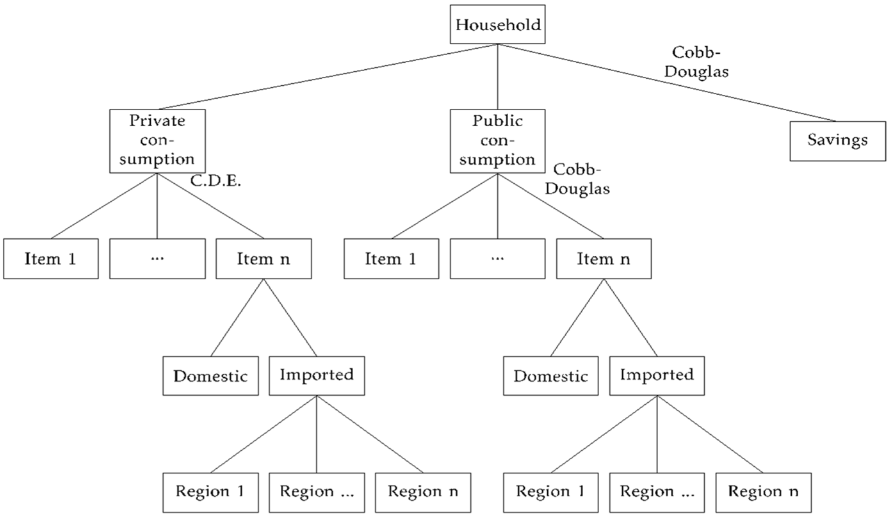

Fig. 9 Demand structure

Public consumption is split in a series of alternative consumption items, also according to a Cobb-Douglas specification. However, almost all expenditure is concentrated in one specific industry: public services. In a lower nest, public consumption is split in a series of alternative composite Armington aggregates. These postulate the imperfect substitutability across domestic and imported commodities. Private consumption is analogously split in a series of alternative consumption items. However, the functional specification used at this level is the Constant Difference in Elasticities form: a non-homothetic function, which is used to account for possible differences in income elasticities for the various consumption goods

Industries are modelled through representative firms, minimizing production costs while taking prices as given. In turn, output prices are given by average production costs. Production functions are specified via a series of nested constant elasticity of substitution (CES) functions. Domestic and foreign inputs are imperfect substitutes, according to the "Armington" assumption

All sectors use primary factors such as labor and capital, and intermediate inputs. In some sectors (fossil fuel extraction industries and fisheries), primary factors include natural resources (e.g., fossil fuels or fish) and land. The nested production structure depicted in Fig. 10 is the same across all sectors. Diversity in production processes as well as technologies is captured through sector-specific productivity and substitution elasticity parameters

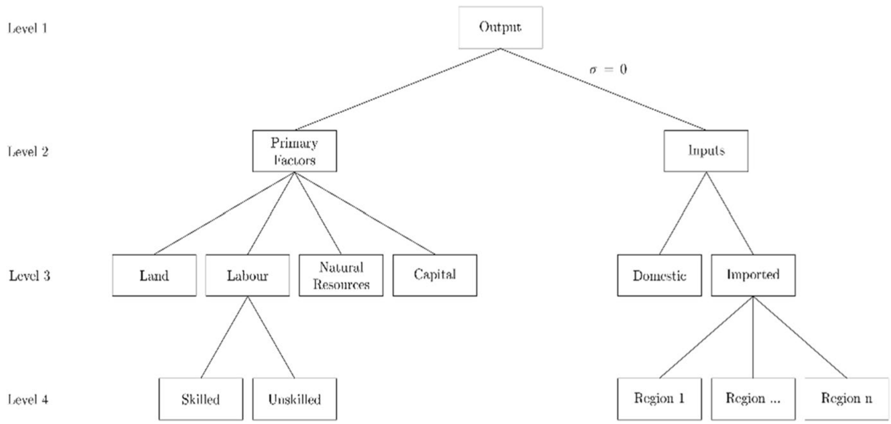

Fig. 10 Supply structure

The dynamics of the model rely on the idea of "recursiveness" where a sequence of static equilibria is connected by the process of capital accumulation. Capital growth is standard along exogenous growth theory models and follows: $Ke_r = I_r + (1 - \delta) Kb_r$ where Ke_r is the "end of period" capital stock, Kb_r is the "beginning of period" capital stock, δ is capital depreciation and I_r is endogenous investment. Sources of world investments are savings from households. Allocation of investments across regions follows Pant (2007) and is given by:

$I_r = \phi_r RGDP_r\, e^{[(\rho_r(R_r^E - R^w)]}$ where RGDP is real GDP, ρ_r and ϕ_r are given parameters, R_r^E and R^w are the expected rate of return to capital in region r and the world rate of return to capital respectively.

Baseline construction

The GTAP 9 base year has been updated to 2020 to let it match with the national accounts information as provided by the World Development Indicators (WDI) released by the World Bank. Particular attention was devoted to reproduce the main macro-aggregates and sectoral composition of the Ethiopian economy.

Figure 11 reports the percentage macro-sectoral composition of Ethiopia value added as reported by the World Bank (WDI) in 2020 and the shares calibrated with the model. The matching between the two is almost perfect, featuring the agricultural, industrial and services macro-sectors contributing the 32%, 24% and 43% to total value added respectively in constant 2015 US$.

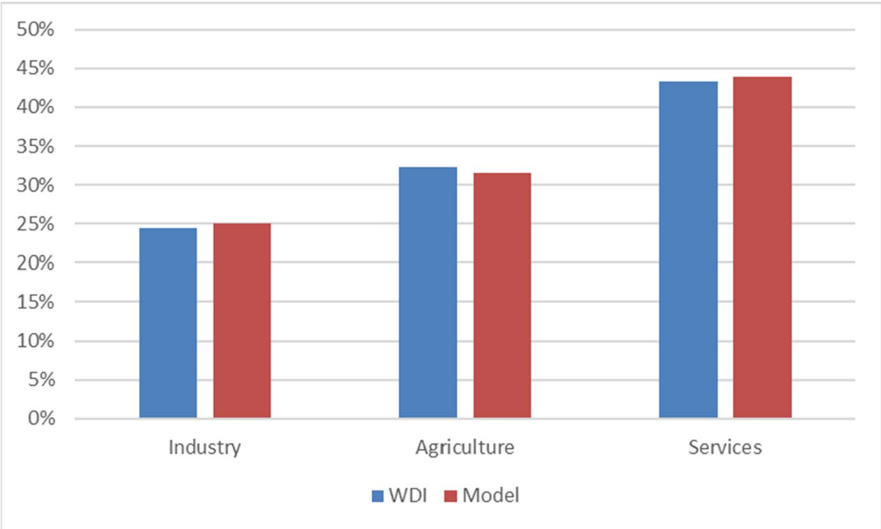

Fig. 11 (%) shares of sectoral Value Added in Ethiopia (2020)

For the 2020–2050 period, the simulation horizon, we calibrate the model using information from an FAO baseline scenario. Ethiopian GDP and population growth rates, coinciding with those featured by the model are reported in Fig. 12. Both GDP and population are projected to increase significantly in the baseline scenario, highlighting for Ethiopia a GDP increase of nearly 200% in 2050 with respect to 2020 levels. The population of Ethiopia is projected to almost double between 2020 and 2050

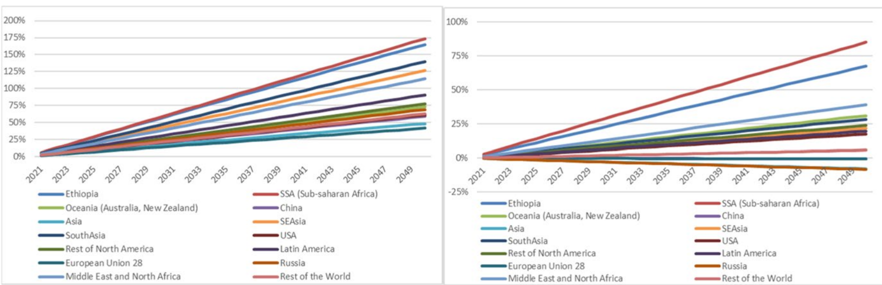

Fig. 12 GDP (left) and population (right) % growth rates 2020–2050

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Statements and declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Opinions expressed in this presentation are those of the author(s) and do not necessarily reflect views of the public administration.

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