Supplementary Information for

# A sustainable future for Africa through continental free trade and agricultural development

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## Supplementary Methods

### 1. The GLOBIOM model

GLOBIOM is a recursive dynamic, spatially explicit, economic partial equilibrium model of the agriculture, forestry and bioenergy sectors[1,2]. Starting in 2000, the model computes a market equilibrium in 10 year time steps by maximizing welfare (the sum of consumer and producer surplus) subject to technological, resource and political constraints. There are nine different land cover types in GLOBIOM: cropland, grassland, short rotation plantations, managed forests, unmanaged forests, other natural land, other agricultural land, wetlands, and not relevant (e.g. bare areas and artificial surfaces). The latter three land covers are held constant across the simulations. Economic activities occur in four land cover types: cropland, grassland, short rotation plantations and managed forests.

### 1.1. Supply

### 1.1.1 Primary production by sector

Economic activities are modelled at the level of sub-national supply units. In this study, the supply units are 2 x 2 degree grid cells delineated by country boundaries and agro-ecological zones (arid, humid, temperate and tropical highlands). The crop sector covers production of the 18 major world crops (barley, beans, cassava, chickpeas, corn, cotton, groundnut, millet, palm oil, potato, rapeseed, rice, soybean, sorghum, sugarcane, sunflower, sweet potato, and wheat) in 4 different production systems (subsistence, low input rain-fed, high input rain-fed and high input irrigated). The livestock sector covers production of animal products (meat, milk, eggs) from bovines, sheep, goat, pigs and poultry in eight livestock production systems: grazing systems in arid (LGA), humid (LGH), and temperate (LGT), mixed systems in arid (MRA), humid (MRH), and temperate (MRT), urban systems, and other systems. In the forestry sector, managed forests and short rotation plantations produce five different primary products (pulp logs, saw logs, biomass for energy, traditional fuel wood, and other industrial logs). Grid-level input parameters of the crop, livestock and forestry sectors such as yields and input costs are based on biophysical models and are described in previous work[1,2].

### 1.1.2 Agricultural sector: local trade costs

Building on Mosnier et al.[3], we have added local trade costs from farm-gate to market to the supply side in GLOBIOM for this study. Agricultural markets in GLOBIOM are perfectly competitive such that for each time step $t$, product $i$ and supply unit $su$ the producer price plus local trade cost equals the regional market price in region $r$ (equation 1). Producer prices in the crop sector are determined by grid-level input costs, structural costs and crop yields, and regional level resource costs (land, water) (equation 2). Input requirements and crop yields are provided by the EPIC crop model, while the structural and resource costs are endogenously determined by GLOBIOM.

$$p_{t,r,i}^{market} = p_{t,su,i}^{producer} + \tau_{t,su,i}^{local\ trade\ cost} \tag{1}$$

$$p_{t,su,i}^{producer} = \frac{\left(cost_{t,su,i}^{production} + cost_{t,su,i}^{structural} + cost_{t,r}^{land}\right)}{yield_{t,su,i}} + \frac{cost_{t,r}^{water} * input_{t,su,i}^{water}}{yield_{t,su,i}} \tag{2}$$

We define local trade costs as the transport and marketing costs from farm-gate to market, represented by the closest city of 50,000 inhabitants[a]. These trade costs (also referred to as market access costs in literature) cover the gap between the (rural) farm-gate producer price and the wholesale (urban) market price. The local trade costs are incorporated in the model only for commercial agricultural production systems, i.e. all crop and livestock production systems except for subsistence crop production and other pig and poultry production in Africa which are not marketed but used for self-consumption. Local trade costs are calculated for the base-year at product ($i$) and supply unit ($su$) level (Eq. 3).

$$\tau_{su,i}^{local\ trade\ cost} = t_{su,i}^{local\ transport} + \left(p_{c,i}^{producer} + t_{su,i}^{local\ transport}\right) * m_{c}^{marketing} \tag{3}$$

The local transport cost are calculated based on the spatially explicit map of travel time to closest city of 50,000 inhabitants from Weiss et al.[4], which is converted to distance ($d_{su}$) assuming an average speed between 30 and 50 km/hour for African countries based on an African trucker survey[5] and 60 km/hour for countries in the rest of the world. For African countries, the local transport cost is calculated for each supply unit $su$ as the sum of variable (VC, per km, e.g. fuel, tires, maintenance) and fixed costs (FC, e.g. salary and equipment) of transport, adjusted for profit margin of trucker companies (Eq. 4), which are in turn calculated for each country $c$ based on data and assumptions from survey evidence (Supplementary Table 10). The impact of varying road quality along the route from farm-gate to the city is incorporated through the use of different transport modes with different loading capacity for different sections along the route. Based on literature, we assume that the first 5 km is transported with a small vehicle with low load capacity (50 kg e.g. motorcycle)[6]. The rest is transported with a higher capacity vehicle, where for countries in Sub-Saharan Africa a distinction is made between the first 50 km (vehicle with medium load capacity, 1.2 ton) and the remaining distance (a truck of high load capacity, 12.5 ton)[6–8]. For South Africa, Egypt and countries in AMU a large load capacity truck is assumed for the full distance.

$$t_{su,i}^{local\ transport} = \frac{FC_{c,i} + VC_{c,i} * d_{su}}{load\ capacity_{c}} * \left(1 + m_{c}^{profit\ transporter}\right) \tag{4}$$

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[a] Note that in the literature transport costs are often regarded as a component of marketing costs. In this study, we split transport costs from other components of marketing costs as transport costs are the largest component of local trade costs in Sub-Saharan Africa[8,76] and poor rural road infrastructure is particularly identified as one of the critical barriers to agricultural development in the region[82,83].

For the rest of the world, we assume that per ton-km transport costs fall between 3.5 US cents/ton-km and 10 US cents/ton-km, a conservative range of values reported in literature[9]. To capture the impact of the efficiency of the transport industry, we differentiate the costs according to the Infrastructure Score in the World Bank Logistic Performance Indicator (LPI): 3.5 US cents/ton-km for LPI > 3 (e.g. USA), 5 US cents/ton-km for 3 > LPI > 2.5 (e.g. Brazil), 7.5 US cents/ton-km if 2.5 > LPI > 2 (e.g. Colombia) and 10 US cents/ton-km if 2 > LPI (e.g. Kazakhstan). Empirical studies show that the transport along poor quality roads in the first miles from the farm-gate to market leads to a doubling of total transport costs[6,10,11]. We use the World Bank Rural Access Index, which indicates the percentage of rural population without access to paved roads, to determine the share of transport costs affected by the costly transport in the first miles beyond the farm-gate in rest of the world countries. For all countries, local transport costs are set two (milk) or four times (meat, eggs) the size for animal products compared to crops as these usually require greater care or refrigeration during transport.

Marketing costs include costs of storage and distribution services (e.g. wholesaler fees and profits) and are calculated as fixed mark-up on the purchase price (producer price + local transport cost, Eq. 3). For countries in Sub-Saharan Africa (except for those in SACU), we assume a marketing margin of 30% ($m_c^{marketing} = 0.3$) based on the ratio between marketing and transport costs reported in the literature[8,12,13]. For other African countries and the rest of the world, we assume a marketing margin between 10% and 30% based on the quality of warehouse and distribution services as documented in the World Bank Domestic Logistic Performance Index.

Though the available data and literature for the compilation of spatially explicit local trade costs is limited, Supplementary Table 11 shows that there is a good match between our average producer-to-consumer price ratio's at region level with FAO prices (producer price from FAOSTAT versus wholesale price from FAO GIEWS) or producer-to-consumer price ratios reported in the literature.

### 1.1.3 Agricultural sector: land allocation mechanisms

The allocation of land across agricultural (cropland, grassland) and non-agricultural (short rotation plantations, managed forests, unmanaged forests, other natural land) land cover within a supply unit, and across specific crops, animals and management systems within agricultural land use is endogenously determined in the model optimization. For each time step and scenario, the most cost-efficient production pattern for a given demand is computed. Besides the local production and trade costs (section 1.1.2 of Supplementary Methods), also land availability, cropland expansion constraints and land conversion costs influence the cost-efficiency. This set-up results in non-linear supply functions at the regional level where the slope is determined by the distribution of cost-efficiency across supply units and management systems.

## 1.2. Demand

Demand is modelled at the level of a representative consumer for each economic region. In this study, countries are grouped into 39 economic regions, with Africa split up in 8 regions based on the largest number of exclusive regional economic communities (RECs). These are the East African Community (EAC), the Economic Community of Central African States (ECCAS), the Arab Maghreb Union (AMU), the Economic Community of West African States (ECOWAS), the Southern African Customs Union (SACU), Rest of Southern Africa (RSouthAf), Rest of Central-East Africa (RCEAf) and Egypt (Supplementary Table 1). The demand side covers demand for food, feed, wood and fuel. Food demand depends on population, GDP per capita and own product price (isoelastic function). Agricultural products are represented in primary equivalent, such that the demand implicitly covers for both primary (raw, e.g. wheat) and secondary (processed, e.g. wheat flour) products.

## 1.3. International trade

International trade is modeled between the 39 economic regions. Trade within each economic region is implicitly represented as in equilibrium total production within and imports to a certain region must match the total consumption and export of that region.

### 1.3.1. Implementation

GLOBIOM captures interregional trade through Enke-Samuelson-Takayama-Judge spatial equilibrium assuming homogenous goods[14,15]. In each time step, the sum of producer and consumer surplus minus total trade costs is maximized. Total trade costs are defined for existing trade flows (intensive margin, eq. 5) and new trade flows (extensive margin, eq. 6), respectively:

$$\int \varphi_{r,\check{r},t,i}^{trad,int}\left(T_{r,\check{r},t,i}\right) d(.) = \tau_{r,\check{r},t,i}^{policy} * T_{r,\check{r},t,i} + \frac{\varepsilon}{1+\varepsilon} * \tau_{r,\check{r},t,i}^{transaction,int}\left(\frac{T_{r,\check{r},t,i}}{T_{r,\check{r},t-1,i}}\right)^{\frac{1+\varepsilon}{\varepsilon}} * T_{r,\check{r},t,i} \tag{5}$$

$$\int \varphi_{r,\check{r},t,i}^{trad,ext}\left(T_{r,\check{r},t,i}\right) d(.) = (\tau_{r,\check{r},t,i}^{policy} + \tau_{r,\check{r},t,i}^{transaction,ext}) * T_{r,\check{r},t,i} + 0.5 * \sigma * T_{r,\check{r},t,i}^{2} \tag{6}$$

where $T_{r,\check{r},t,i}$ is the bilateral trade quantity of product $i$ from exporting region $r$ to importing region $\tilde{r}$ in period t, $\tau_{r,\check{r},t,i}^{transaction}$ the transaction costs, $\tau_{r,\check{r},t,i}^{policy}$ the policy-related costs and parameters $\varepsilon$ and $\sigma$ determine the non-linear trade expansion cost. This non-linear element allows to model persistency in trade flows and reflects the cost of trade expansion in terms of infrastructure and capacity constraints in the transport sector[b]. The maximum factor

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[b] Other studies that have adopted non-linear (i.e. convex and increasing) trade costs in modelling agricultural trade in order to avoid corner solutions in trade patterns and to derive (closed-form solutions of) smooth specialization patterns are Nolte et al.[84] and Allen & Atkin[85]. In Nolte et al. the non-linear trade costs are motivated by diversification of exporters into different destination markets in order to minimize risks. In Allen & Atkin non-linear trade costs are proposed to originate from heterogeneity in trade productivity across traders that are all equally capacity constrained. In our study, trade costs are increasing in traded quantity to reflect capacity constraints of the transport sector to deal with increasingly larger trade volumes. Port capacity

change allowed per decade for each trade flow is 7.45. Transaction costs (eq. 7 & 8) consist of bilateral transport ($t_{r,\breve{r},t,i}^{transport}$) costs and unilateral import ($t_{\breve{r},t,i}^{import}$) and export ($t_{r,t,i}^{export}$) costs from inland transport and administrative procedures (documentary and border compliance). In case of new trade flows, an entry cost ($p_{r,t,i}^{market} * m_{r,\breve{r},t}^{entrycost}$) is included to reflect the start-up cost of establishing a new trade relationship. The policy-related costs (eq. 9) consist of tariff costs ($t_{r,\breve{r},t,i}^{tariff}$) and a calibrated trade cost term ($t_{r,\breve{r},t,i}^{calib}$) that fills the importer-exporter price gap in the initial spatial price equilibrium and is kept constant across time steps and scenarios. This term captures any trade cost element that is not explicitly accounted for, but that contributes to the price gap between importer and exporter prices (e.g. import and export taxes).

$$\tau_{r,\breve{r},t,y}^{transaction,int} = t_{r,\breve{r},t,y}^{transport} + t_{r,t,y}^{export} + t_{\breve{r},t,y}^{import} \tag{7}$$

$$\tau_{r,\breve{r},t,y}^{transaction,ext} = t_{r,\breve{r},t,y}^{transport} + t_{r,t,y}^{export} + t_{\breve{r},t,y}^{import} + p_{r,t,y}^{market} * m_{r,\breve{r},t}^{entrycost} \tag{8}$$

$$\tau_{r,\breve{r},t,y}^{policy} = t_{r,\breve{r},t,y}^{tariff} + t_{r,\breve{r},t,y}^{calib} \tag{9}$$

The Enke-Samuelson-Takayama-Judge spatial price equilibrium set-up implies that interregional trade will only occur when the cost of trade between two regions is smaller than the market price difference, and this price difference will become equal to the marginal trade cost in equilibrium[16]. The spatial price equilibrium for an intensive (eq. 10) and extensive margin (eq. 11) trade flow ($T_{r,\breve{r},t,i}$) of product $i$ from exporting region $r$ with market price $p_{r,t,i}^{market}$ to importing region $\tilde{r}$ with market price $p_{\tilde{r},t,i}^{market}$ is:

$$\text{Intensive margin} \quad p_{r,t,i}^{market} + \tau_{r,\breve{r},t,i}^{policy} + \tau_{r,\breve{r},t,i}^{transaction,int} \left(\frac{T_{r,\breve{r},t,i}}{T_{r,\breve{r},t-1,i}}\right)^{\frac{1}{\varepsilon}} = p_{\tilde{r},t,i}^{market} \tag{10}$$

$$\text{Extensive margin} \quad p_{r,t,i}^{market} + \tau_{r,\breve{r},t,i}^{policy} + \tau_{r,\breve{r},t,i}^{transaction,ext} + \sigma T_{r,\breve{r},t,i} = p_{\tilde{r},t,i}^{market} \tag{11}$$

Compared to the trade implementation in earlier versions of GLOBIOM as described in Janssens et al.[17], additional transaction costs are explicitly incorporated (import & export costs) and the parameterization of the trade cost functions is updated to reflect determinants of agricultural trade growth at the extensive margin (next section). Overall, in terms of the size of trade adjustments, our trade implementation lies between the rigid Armington approach of general equilibrium models and the flexible integrated world market approach of many partial equilibrium models.

### 1.3.2. Data and parameterization

**International transport costs** cover road and ocean transport costs and are compiled based on the empirical estimation of Hummels[18] using distance between country pairs and the weight-value ratio of agricultural products. Sea distance is based on CERDI-seadistance database[19] and road distance is from CEPII's GeoDist database[20]. For road transport between African countries, transport costs are directly calculated through the

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constraints are for example suggested as a constraint for the expansion of short sea shipping in the Southern African Development Community[86].

combination of variable (VC) and fixed transport (FC) costs, adjusted for the profit margin of trucking companies (eq. 12-15)[c]. Variable costs cover fuel costs as well as costs of tires, maintenance and bribes. Fixed costs include driver wages and the costs of trucks, taxes and licenses. The sources of the data and assumptions for the different cost parameters are summarized in Supplementary Table 9.

$$T_{road_{c,\check{c}}} = \frac{FC_{c,\check{c}} + VC_{c,\check{c}}}{load\ capacity} * \left(1 + m_{c,\check{c}}^{profit\ transporter}\right) \tag{12}$$

$$VC_{c,\check{c}} = fuel\ consumption_{c,\check{c}} * fuel\ price_{c,\check{c}} * \left(1 + \%\ other\ VC_{c,\check{c}}\right) * d_{c,\check{c}} \tag{13}$$

$$FC_{c,\check{c}} = daily\ FC_{c,\check{c}} * travel\ time_{c,\check{c}} * 2 \tag{14}$$

$$travel\ time_{c,\check{c}} = \frac{d_{c,\check{c}}}{speed_{c,\check{c}}} + border\ waiting\ time_{c,\check{c}} + other\ waiting\ time_{c,\check{c}} \tag{15}$$

The **import and export costs** cover the costs related to the inland transport (between warehouse and port or border), document preparation and border compliance when importing or exporting a good. The costs related to document and border compliance are based on the World Bank Doing Business Survey, in specific the “Trading Across Borders” indicators, and reflect the impact of non-tariff measures (NTMs) on African trade costs. NTMs represent a heterogeneous group of policies such as sanitary and phytosanitary measures (SPS), technical barriers to trade (TBT), price- and quantity control, or export restrictions[21]. The Tripartite Free Trade Area in Africa, which covers three RECs (COMESA, EAC and SADC) created an online tool to report, monitor and eliminate non-tariff barriers among its member states. Between 2004 and 2019, 40% of the filed complaints dealt with obstacles related to custom procedures and 19% with transport, clearing and forwarding issues (Supplementary Figure 16). The ITC NTM Business Surveys reveal that the most frequent NTMs faced by African agricultural export firms are conformity assessments (product certification, inspection requirement) and export-related measures (licenses, permits, inspection, taxes)[22]. Further, exporters perceive NTMs as burdensome often more because of procedural obstacles associated with technical measures that cause delays or demand high fees, rather than that the technical requirements themselves would be too stringent or complex to comply with[23–25]. Given that the import and export costs for documentary and border compliance from the World Bank Doing Business Survey reflect the costs of obtaining, preparing and submitting the required documents and the costs of customs clearance and inspections, we consider these as a measure for the impact of NTMs on African trade costs. The inland transportation costs are calculated based on the distance from the capital to the main port (CERDI-seadistance database[19]) or a country’s average internal distance (CEPII GeoDist database[20]) and a per ton-km transport cost based on the compilation of local transport cost (section 1.1.2 of Supplementary Methods, but excluding the first mile cost and low-loading capacity transport).

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[c] As an illustration of the challenges of cross-border trade in Africa, we refer to the following documentary on formal and informal barriers to cross-border food trade in West-Africa based on a road trip from the port in Tema, Ghana, to Ouagadougou, Burkina Faso: https://univideo.uni-kassel.de/video/Trading-Food-across-West-African-Borders-full-version/9f8eee1ab23e865b6476ce5a4d7eae19.

Data on **tariff costs** is taken from the MAcMap-HS6 2001 and 2010 releases from CEPII-ITC which provides ad valorem and specific tariffs, and shadow tariff rates of tariff rate quotas[26,27]. Tariffs are converted to specific equivalent to include in GLOBIOM in the 2000 and 2010 time steps as trade is modelled in quantity rather than value.

Trade costs between countries are aggregated to the regional level. The bilateral transport ($t^{transport}_{r,\check{r},t,i}$) and tariff ($t^{tariff}_{r,\check{r},t,i}$) costs between two regions is a weighted average of the transport cost between all country pairs with the production of the exporting countries and consumption of the importing countries as weight. When both road and ocean transport are possible between two countries, the cheapest transport mode is selected. For most African trade links ocean transport is the cheapest, the largest share of road transport occurring between SACU and RSouthAf (37.5% of trade links) and between ECCAS and RCEAf (30% of trade links). Import and export costs are aggregated to regional level ($t^{export}_{r,t,i}$, $t^{import}_{\check{r},t,i}$) weighted by consumption (import costs) or production (export costs) of the individual countries.

Default values of the trade expansion cost parameters ($\varepsilon$ and $\sigma$) are calibrated to reflect a stable trade pattern over time. We further adjust the trade expansion parameters by exporting region based on the evolution of a set of key trade growth indicators. Clark et al.[28] find that an exporter's port efficiency significantly determines maritime transport costs and that improvements in efficiency increase bilateral trade. For the intensive margin function, trade expansion is therefore made more flexible if the port efficiency index of the exporting region improved over time. In specific, the value of $\varepsilon$ is increased by factor 4 for medium port efficiency improvement (e.g. Brazil, Supplementary Figure 15) and by factor 10 for large port efficiency improvement (e.g. Russia, India or Egypt, Supplementary Figure 15). For the extensive margin function, we estimate a Probit model on the determinants of new trade flows at GLOBIOM region, product and time resolution. Given the 10-year time step in GLOBIOM, we investigate the determinants of trade growth at extensive margin over one decade (2000 – 2010 and 2006 – 2016). We define a sample of importer (i) - exporter (j) pairs that did not trade a certain product (k) in the base time period (t) (2000 or 2006) and estimate the probability to start trading $\rho_{ijk,\Delta t}$ conditional on explanatory variables with the following Probit model:

$$\begin{aligned}\rho_{ijk,\Delta t} &= \Pr\left(Y_{ijk,\Delta t} = 1 \middle| \, explanatory\ variables\right) \\ &= \Phi(\beta_0 + \beta_1 x_{1i} + \beta_2 x_{2ik} + \beta_3 x_{3ij} + \beta_4 x_{4ijk} + \alpha_k + \alpha_j)\end{aligned}$$

where $Y_{ijk,\Delta t}$ is an indicator variable equal to 1 when the exporter (j) created a trade flow of product k to importer (i) in the 2010/2016 time period and equal to 0 when it did not (based on CEPII BACI bilateral trade database) and $\Phi(.)$ is the cdf of the standard normal distribution. The explanatory variables included are exporter-specific characteristics $x_{1i}$ (World Bank GDP per capita in 2010 USD, export costs from the World Bank‘s Doing Business Survey, OECD Trade Facilitation Indicator, and WEF customs efficiency index), product-exporter specific characteristics $x_{2ik}$ (exporter experience, i.e. number of importer-product markets served by a given exporter-product pair), importer-exporter specific characteristics $x_{3ij}$ (distance, regional free trade agreement, and trade intensity, i.e. share of a region's exports going to a certain importer across all agricultural goods), and product-importer-exporter specific characteristics $x_{4ijk}$ (MAcMap tariff rates). $\alpha_k$ and $\alpha_j$ are product and importer level fixed effects. The selection of explanatory variables is based on the agricultural trade literature and the literature on extensive margin determinants in specific[29–31]. The inclusion in the 2000-2010 and/or 2006-2016 regression is based on data availability. Where the data allows, we compute a 5 year average to represent the average around that time period (e.g. for GDP in 2000, we take average of 1998 – 2002). The estimated coefficients are presented in Supplementary Table 8. The sign, size and significance of the coefficients are largely in line with expectations from literature. Bilateral distance has a negative impact and – for the 2000-2010 regression – exporter's GDP growth has a positive impact on the extensive margin of trade[29,30]. For the 2006-2016 regression, we find a negative impact of exporter's GDP growth on extensive margin trade driven by the export pattern of Ukraine, which experienced a small reduction in GDP over the 2006-2016 time period, but created a substantial number of new trade flows. Tariff levels have a small negative impact on the propensity to start trading, but in contrast with Hejazi et al.[29] we do not find that a change in tariffs has a significant effect. In line with Helpman et al.[31] and Jean and Bureau[32], we find that being partners in a FTA increases the propensity to trade at the extensive margin. Further, regions with already an existing intensive trade relationship, also have a higher propensity to create new trade flows. In a cross-sectional study, Beverelli et al.[30] estimate the impact of trade facilitation between countries, concluding that a higher TFI value results in larger extensive margins of trade. We find that an increase in trade facilitation of the exporting region over time, as measured by export costs, TFI or customs efficiency, increases the propensity to start trading, but only for the regions that initially perform low on trade facilitation. Based on these results, trade expansion at extensive margin (governed through parameter $\sigma$) is made more flexible if the WEF customs efficiency or OECD TFI index of an exporting region with an initial low index (WEF CUST < 4, TFI < 1.5) improves over time (as for example for Russia, India or EAC, cfr. Supplementary Figure 15).

Recent advances in trade theory highlight that export participation depends on sunk entry costs[33], consisting of information costs, transaction costs, or market adjustment costs[34]. To the best of our knowledge there is no comprehensive global dataset on entry costs in agricultural trade available. We therefore calculate a proxy for entry costs as a margin on the exporter's market price to reflect that it are only the more productive firms that will enter into export markets[33]. In GLOBIOM, the market price is equal to the sum of the producer price and local trade cost, so regions with more competitive producing areas and lower market access costs will have a larger likelihood to create new exports. Kandilov and Zheng[34] find that the impact of entry costs on agricultural market participation differs across commodities and bilateral trade patterns. In GLOBIOM, we differentiate the entry cost margin ($m_{r,\check{r},t}^{entrycost}$) across trade partners to reflect the bilateral drivers of the extensive margin of agricultural trade that were identified in Supplementary Table 8. In specific, the entry cost margin $m_{r,\check{r},t}^{entrycost}$ is assumed 20% by default, and is reduced to 10% under high bilateral trade intensity (i.e. larger than 6%) or in case that the trade partners participate in a regional free trade agreement.

### 1.4. Undernourishment, or Risk of Hunger

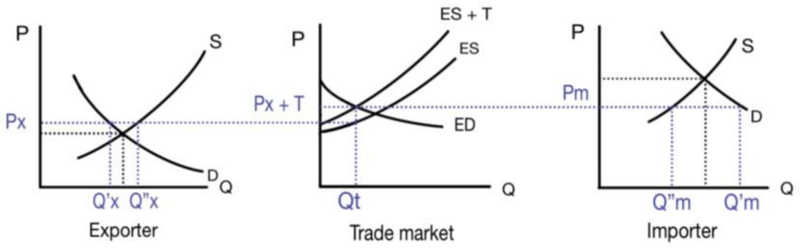
The number of people undernourished or at risk of hunger is calculated based on four parameters: average daily calorie availability, coefficient of variation (CV) of food distribution, average minimum dietary energy requirement and population. There are two changes compared to the calculation of undernourishment in previous work[17]. First, the input parameters are updated based on latest available FAO statistics[35], e.g. the CV value reported by FAO for 2018 is used for the 2020 time step. Second, we keep the CV constant to the value of the 2020 time step in the simulation period up to 2050 instead of adjusting it exogenously based on the income growth in the applied shared socio-economic pathway. This because FAO changed the methodology for calculating the CV in the SOFI 2020 report from estimation based on macroeconomic variables to linear interpolation[36]. The average daily calorie availability is endogenously determined by GLOBIOM at the regional level, while the minimum dietary energy requirement and population are exogenously determined by future demography projections. Given that the value of CV is exogenous and constant, the changes in undernourishment across our scenarios reflect changes in regional food availability, not changes in food access.

### 1.5. Land-use greenhouse gas emissions

The reported greenhouse gas (GHG) emissions from land-use activities include $NO_2$ and $CH_4$ emissions from agricultural production (synthetic fertilizer, rice cultivation, manure management and application, and enteric fermentation), $CO_2$ emissions from conversion of land across six different land cover types (cropland, grassland, management forest, unmanaged forest, short rotation plantations and other natural land), and carbon sequestration from the establishment of short rotation plantations. Data sources of the GHG emission accounts are documented in Havlik et al.[2] and Frank et al.[37,38]. GHG emissions from transport are not included. In general, transport emissions are estimated to represent only 4.8% of total food system GHG emissions[39]. Inter-continental trade occurs predominantly via maritime transport, which represents a small share in GHG emissions compared to agricultural production[40,41]. The majority of food-related transport emissions occurs at the level local and regional road transport. Quantifying these emissions for our scenarios would require an explicit representation of the road network and transport routes. The net impact of excluding these transport GHG emissions may be positive or negative. Given that our scenarios of reduced local and intra-African trade costs reflect an improvement of transport efficiency through better roads and higher capacity vehicles, we would expect lower GHG emissions per unit of product transported. At the same time trade volumes increase which could increase transport GHG emissions. In our baseline scenario, total GHG emissions from the AFOLU sector in Sub-Saharan Africa are 1.62 Gt $CO_2$eq/year in 2010 and 1.70 Gt $CO_2$eq/year in 2020, with $CO_2$ emissions from land-use change representing the largest share (1.16 Gt $CO_2$eq/year in 2010 and 1.19 Gt $CO_2$eq/year in 2020). These estimates are in the range of the observed net anthropogenic land $CO_2$ flux reported for Sub-Saharan Africa by different sources (bookkeeping models, national GHG emission inventories, FAOSTAT, and dynamic global vegetation mechanistic models (DGMVs))[42].

### 1.6. Comparison with other modelling frameworks & AfCFTA impact assessments

An important advantage of using a spatial explicit partial equilibrium (PE) model such as GLOBIOM is that it allows to explicitly represent local trade costs and their interaction with production costs at grid-level, as well as the interaction of local supply elements with international trade costs at the regional level. The interaction between local trade costs and production costs shape the location of agricultural production within regions. When local transport and marketing costs reduce, commercial agricultural production may become competitive in areas where it was not before. This affects the spatial allocation of agricultural activities with possible environmental consequences from associated land-use changes. Local production and trade costs determine aggregate regional supply curves (see also section 1.1.3 of Supplementary Methods), which in turn influence the trade equilibrium in the spatial price equilibrium approach as illustrated in the figure below for trade between two African regions. The equilibrium on the trade market ($Q_T$, $P_X$, $P_M$ with $P_X + T = P_M$) occurs at the intersection of the excess demand ($ED$) curve and the excess supply plus trade cost ($ES + T$) curve. When international trade costs are lowered (as in our *Free Trade* scenario), the excess supply plus trade cost curve shifts downward and a larger quantity can be traded.



The impact of changes in local production and trade costs on the trade equilibrium between African regions is ambiguous. When crop yields increase and local trade costs reduce (as in our *Agricultural Development* scenario), the competitiveness of a region's agricultural production increases. The supply curves in both importing and exporting region shift downward, enhancing export capacity at the exporter side, but reducing import demand at the importer side. The result will depend on how much the relative competitiveness changes between the two regions and across crops.

Another advantage of the trade implementation in GLOBIOM compared to other simulation models is that it represents trade dynamics at both intensive and extensive margin, the former indicating changes in existing trade relations and the latter representing the establishment of trade flows that are not observed in the base-year calibration period. This is not the case for models that use the Armington trade approach (the most frequently used trade implementation), while it is crucial for our research question given the scarce initial amount of agricultural trade between African regions.

A disadvantage of the partial equilibrium modelling framework is that it focuses only on one sector and does not represent capital and labor markets, nor household income or government revenues (in contrast with general equilibrium models (CGE)). We therefore do not account for the impact of policy measures on food security through changes in employment and income, which may be positive or negative. Previous studies that reflect these elements find on average beneficial impacts of intra-African trade integration on poverty, employment and the gender wage gap, though compensatory measures are needed in some countries where adjustment costs would be high[43] or distributional impacts would worsen[44]. Another limitation is that the spatial trade approach with homogenous goods does not allow for two-way trade between two regions (i.e. intra-industry trade). The homogenous goods assumption implies that goods within the same industry are perfect substitutes, as opposed to for example the Armington trade approach where goods are distinguished by origin. While the assumption of homogenous goods is disputable for processed agricultural goods, it is argued the most appropriate one for primary agricultural goods[45]. The intra-industry trade index of the historical trade pattern for the goods in our analysis (processed and primary goods combined in primary equivalent goods) is low (Supplementary Figure 17), implying that the homogenous goods assumption is justified.

As highlighted in the introduction of the main text, assessments linking continental trade integration and domestic agricultural development in Africa are scarce, limiting also the opportunity for comparison of results. One such study that relates to ours, though it differs in the modelling structure and scenario definition, is Hertel et al.[47]. These authors investigate the likelihood of Jevon's paradox – higher agricultural productivity leading to expansion of cropland area – to occur under an African Green Revolution. They further assess how this is influenced by international market integration, making it a relevant comparison for our findings of the impact of *Agricultural Development* and *Free Trade* on cropland use. Hertel et al. find that a green revolution in Africa is likely to induce cropland area expansion when implemented under fully integrated world markets, but under segmented world markets it would induce land sparing. In the former case, the excess demand is elastic, while in the latter case it is inelastic. Further, when sustained over a longer period of time a green revolution is more likely to become land sparing as the relative ratio of African yields to global yields increases. The scenarios in our study lie in between the segmented and fully integrated scenarios of Hertel et al. in terms of the flexibility of trade expansion. Our reduced trade cost scenario focuses in addition on intra-African trade and not on trade with the rest of the world as in Hertel et al. Lastly, we assess the impact of crop yield potentials, which imply a larger crop yield growth than the growth rate assumed under the green revolution scenario in Hertel et al. These elements explain why we observe a land sparing effect under the *Agricultural Development* scenario compared to the baseline scenario. Under the combined *Free Trade + Agricultural Development* scenario, cropland use is relatively higher than in the *Agricultural Development* scenario alone as increased access to African markets raises production incentives for farmers, but cropland use remains in absolute terms below the baseline level.

The table below compares our model simulation with two other recent AfCFTA impact assessments (World Bank[44], Simola et al.[48]) in terms of agricultural output and trade outcomes. We selected the studies that report results for the agricultural sector in specific and that provide a dynamic assessment of the AfCFTA (i.e. comparing the impact of the AfCFTA to a baseline development by 2030 or 2035). Two aspects stand out. First, the relative changes in trade flows are of a very different order of magnitude. This is explained by the fact that our study focuses on trade between eight major African regions, which is low in the baseline, while the other studies consider trade across 29 African regions and countries and thus start from a higher baseline intra-African trade volume. Second, the agricultural output changes are of similar magnitude: a minor impact at the aggregate African level but larger relocation effects across African regions. The sign of agricultural output changes across regions is not consistent across the models. One important structural difference to consider in this regard is that CGE models cover all economic sectors and therefore capture the comparative advantage between regions not only within but also across sectors. Still the changes are also not fully consistent between the two CGE models. There is a reduction of agricultural output in North Africa in the World Bank study, driven by a shift towards manufacturing and trade, transport and recreation services, while in Simola et al. agricultural output in the UMA and COMESA (which includes Egypt) regions increases. The result on which all three studies agree is an increase in agricultural output in Southern and Western Africa under the AfCFTA. In order to derive concrete implications from this finding, a detailed assessment of both baseline and AfCFTA results at country and product level would be needed, which are typically not fully documented in published studies. An example can however already illustrate the potential validation and complementarity when combining insights from different models. The World Bank study documents wage and employment impacts for Côte d'Ivoire (box 6.1) as an illustrative example. The largest increase in wages in Côte d'Ivoire is observed in the agricultural sector, which in particular drives an increase in unskilled wages. Increases in unskilled wages in turn are linked to poverty reduction, for West Africa in total the number of people living in extreme poverty is estimated to decline by 12 million under the AfCFTA. Consistent with and complementary to the WB study, in Simola et al. and our study, Côte d'Ivoire is projected to experience an increase in agricultural output, in particular in oilseed production, under the AfCFTA (Simola et al.: oilseed production +7.88%, our study: oil palm production +18%, cotton production – 1%). In our study the expansion of oil palm production in Côte d'Ivoire is further linked to an increase in cropland area and a reduction in natural land area. This example illustrates that combining multiple models is a promising approach to investigate in detail trade-offs between economic, social and environmental outcomes of international trade agreements.

**Table: AfCFTA scenario (tariff reduction/elimination and non-tariff barrier reduction/trade facilitation) by 2030 (this study) or 2035 (World Bank[44], Simola et al.[48]) compared to a baseline with socio-economic developments based on SSP2.**

| Intra-African Agricultural exports | | | | | |
|---|---|---|---|---|---|
| This study (PE) | | World Bank (2020) (CGE) | | Simola et al. (2021) (CGE) | |
| Africa | quantity: +528% (+43.3 million ton)<br>value (fob price): +562% (+12.4 billion, 2000 USD) | Africa | value: +49% (+12 billion, 2014 USD) | Africa | NA (*) |
| Intra-African Agricultural imports | | | | | |
| This study (PE) | | World Bank (2020) (CGE) | | Simola et al. (2021) (CGE) | |
| Africa | quantity: +528% (+43.3 million ton)<br>value (cif price): +545% (+21.6 billion, 2000 USD) | Africa | value: +72% (19 billion, 2014 USD) | Africa | NA (*) |
| Agricultural output | | | | | |
| This study (PE) | | World Bank (2020) (CGE) | | Simola et al. (2021) (CGE) | |
| Africa | agricultural output: +0.51% | Africa | agricultural output: -0.5% | Africa | primary agricultural output: +0.52 % |
| EAC | ↓ | East Africa | ↑ (1) | EAC | ↑ (1) |
| RCEAf | ↓ | | | COMESA | ↑ (2) |
| ECCAS | ↓ | Central Africa | ↑ (4) | ECCAS | ↓ |
| ECOWAS | ↑ (4) | West Africa | ↑ (2) | ECOWAS | ↑ (3) |
| SACU | ↑ (2) | Southern Africa | ↑ (3) | SADC | ↑ (4) |
| RSouthAf | ↑ (1) | | | SADC | ↑ (4) |
| Egypt | ↑(3) | North Africa | ↓ | COMESA | ↑ (2) |
| AMU | ↓ | | | UMA | ↑ (4) |

Note: there is no full overlap in definition of the agricultural sector across the models. Compared to our study, in which the agricultural sector includes 18 crops and 6 livestock products, the agricultural sector in World Bank (2020) and Simola et al. (2021) includes also fruits and vegetables, while in World Bank (2020) it in addition also includes forestry. (*) in Simola et al. (2021), intra-African trade is only reported for all sectors combined, not for the agricultural sector in specific.

## 2. Model calibration to 2000 – 2020 trends

### 2.1. Supply

Total cropland area in Africa increased from 230 Mha in 2000 to 278 Mha in 2016, with large differences between sub-regions and countries[49]. Cropland increases have been modest in Northern African countries and in South-Africa, while large in countries in Western, Central and Eastern Africa. This evolution has been largely at the expense of forest cover, with a reduction of total forest land in Africa from 710 Mha in 2000 to 652 Mha in 2016. In GLOBIOM, we match the growth in total cropland of the 18 crops covered in the model through the calibration of land use change from other land covers (e.g. other agricultural land, forest, grassland) and the calibration of area expansion of specific crops through adjustments in production costs and expansion constraints. Total forest area in Africa reduces with 44 Mha between 2000 and 2020 in GLOBIOM. There are large differences between African sub-regions in terms of the crop yield development in the past two decades. Yield improvements are only minor in Western, Central and Eastern Africa (ECOWAS, ECCAS, EAC and RSouthAf), while there have been substantial yield increases in South-Africa and Northern Africa (SACU, RCEAf, Egypt and AMU). In GLOBIOM, yields evolve exogenously according to assumed technological change and endogenously based on production system changes. We calibrate the exogenous shift in 2010 and 2020 to match the observed FAOSTAT yield trend of the past two decades. Supplementary Figures 19 and 20 show the match of GLOBIOM with the historical trend of crop area, production and yield in Africa.

Crop and livestock production systems evolved in the past two decades in Africa under the influence of urbanization and an increase of food purchases among rural households. This has spurred a transformation from the predominant consumption of own produce to a situation where an estimated 80% of the food consumed by urban and rural households is purchased on markets[50,51]. Most farmers thus commercialize at least some of their produce, and there are several examples of the evolution in farm sizes and systems e.g. rise of medium-scale crop farms in Zambia, Tanzania and Nigeria[52] or the modernization of the poultry industry in Egypt[53], Algeria[54] and Morocco[55]. In GLOBIOM, we represent the changes in agricultural systems through a shift from subsistence crop and livestock systems to commercialized farming (subsistence production -25% in 2010 and -15% in 2020). Within commercialized farming, the expansion of low-input and high-input systems is calibrated based on observed productivity growth in the 2000 – 2020 period.

Market access costs have also evolved notably in many countries in the past two decades. The efficiency of transferring agricultural produce from farm-gate to wholesale market depends on the quality of local infrastructure and the development stage of food value chains (FVCs). FVCs can be categorized into three stages: traditional, transitional and modern[51]. In Africa, food systems started to transform since the 2000s[51] and the majority is currently in the transitional stage[56]. There are several examples of how private or public investments have contributed to the modernization of food value chains e.g. large-scale private investment in grain market trading in Zambia[57], or government policies targeting the development of rice value chain in West Africa[58]. Besides case studies on specific countries and commodities, market monitoring initiatives such as FAO's Monitoring and Analysing Food and Agricultural Policies (MAFAP) program allow to track the development of FVCs over time via the margin between producer and market prices. In GLOBIOM we match the historical development of food value chains in Africa by reducing the marketing margin that contributes to the wedge between producer and market price by 2020 (Supplementary Table 12).

### 2.2. Demand & international trade

Urbanization and income growth are typically accompanied with changes in food preferences and diets[59]. In Africa these drivers have contributed to an increase in rice and wheat consumption shares in ECOWAS, ECCAS, EAC, and Rest of Southern Africa and a decrease in the consumption of more traditional commodities such as cassava, millet and sorghum in the last decades (Supplementary Figure 18). In GLOBIOM we implicitly represent the impact of urbanization trends on food demand by shifting regional-level food preferences in 2010 and 2020. Supplementary Figures 21-24 show the match between GLOBIOM and the historical trend of crop and livestock consumption in Africa. The increased food demand among urban population has largely been satisfied by increased food imports from outside Africa[60], in specific there has been a large increase in imports of wheat, rice, oil palm and sugarcane (Supplementary Figures 25 and 26). For most crops, the imports are projected to keep increasing after 2020. Exceptions are oil palm and rice imports in ECOWAS and sugarcane imports in all African regions except for AMU and Egypt. The decrease in rice imports in ECOWAS from 2020 onwards is explained by the fact that we incorporate the recent improvements in the rice value chain in West-Africa[58], but do not take different preferences of urban consumers for imported versus local rice into account[61]. Also imports of several livestock products increased in the past decades in Africa, most notably of poultry meat in ECOWAS and ECCAS and milk in AMU (Supplementary Figures 27 and 28).

## 3. Scenario design

In our study, population and income are assumed to grow according to the second Shared Socioeconomic Pathway (SSP2)[62], the most widely adopted benchmark in simulation studies. Under SSP2, income growth follows historical trends and Africa’s population grows from 1.26 billion in 2020 to 2 billion by 2050. Food preferences evolve according to FAO 2050 projections[63]. Local and international trade costs remain constant to the level of 2020 and crop yields develop according to technological progress in line with historical trends.

### 3.1. Free Trade

The *Free Trade* scenario present continental trade integration in Africa by 2030 through a combination of reduced trade policy costs (import tariffs), transaction costs (international transport, import, export and entry cost) and expansion costs (port and customs efficiency) (Supplementary Table 2), which corresponds to objectives of the African Continental Free

Trade Area (AfCFTA) to eliminate tariffs and non-tariff barriers, coordinate on customs issues and implement trade facilitation measures[64]. Under the Schedules of Tariff concessions, the African Union's member states pledged to remove 90% of tariffs on goods over a period of 5 to 15 years depending on countries' development status, with the remaining 10% excluded or sensitive goods. Considering the aggregated product, region and time dimension of our modelling framework, we adopt a simplified scenario where all import tariffs are removed by 2030. Transaction costs are reduced either to an international benchmark level or to a level that is estimated to be attainable. Supplementary Figures 8-11 present the average bilateral and unilateral trade costs under the baseline and *Free Trade* scenario. Except for Egypt, all regions impose high import tariffs on imports from African regions in the baseline, especially on those for which there is no overlap in an existing free trade agreement (e.g. EAC on imports from ECCAS, AMU, ECOWAS and SACU). Transport costs between African countries reduce by small amounts as we assume that ocean transport rates remain constant and road transport costs reduce by only 25% by 2030, which is the reduction that is estimated to be attainable through joint border posts and simplified custom procedures[65,66]. Looking at export and import costs, ECCAS and RCEAf have the highest baseline levels, followed by RSouthAf, EAC and ECOWAS. In AMU, Egypt and SACU, the baseline levels of the import and export costs are already relatively low. Given that there is currently little trade between African regions new trade routes will need to be established, which involves entry costs such as information costs, transaction costs, or market adjustment costs[34]. We proxy entry costs with a margin on the exporting region's market price and reduce this margin by half under the *Free Trade* scenario in 2030. For regions that were already participating in a free trade agreement (e.g. AMU and Egypt under the Agadir agreement, or SACU and RSouthAf under the SADC Free Trade Area), the entry cost margin is already at the lower level in the baseline. Lastly, the *Free Trade* scenario also reflects trade facilitation measures that support trade expansion at intensive and extensive margin such as the development of high-quality port infrastructure and increased customs efficiency. In specific, trade expansion costs are reduced to represent large improvements in port and customs efficiency between 2020 and 2030.

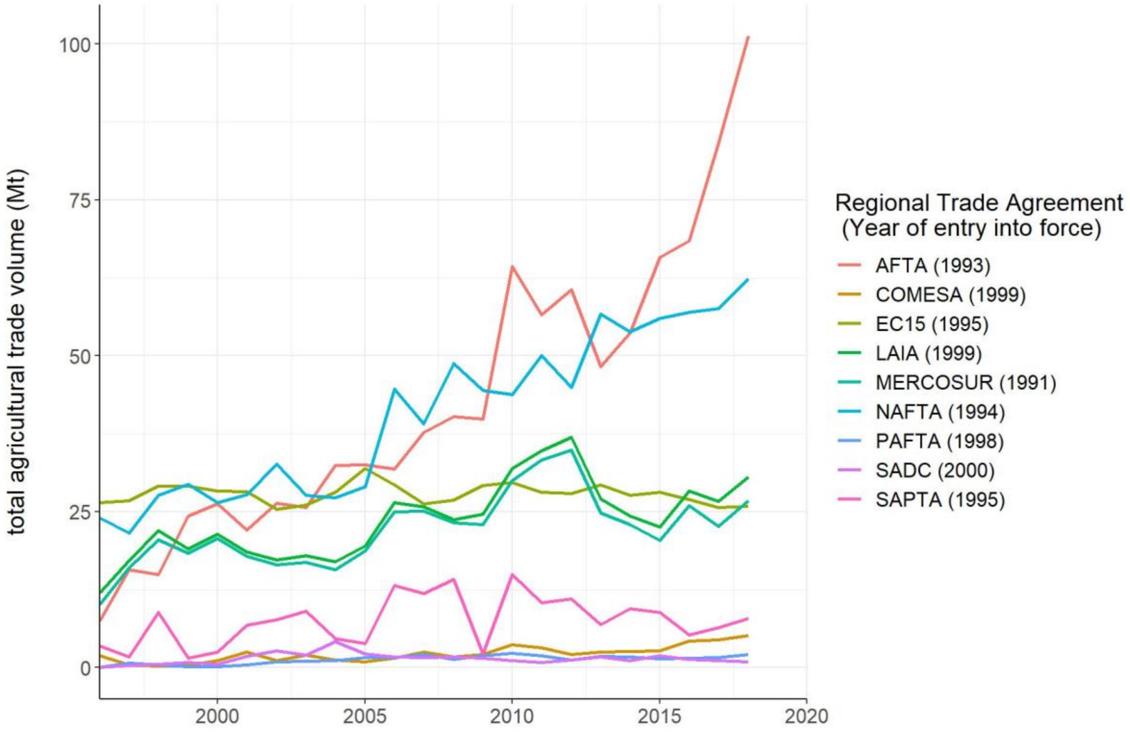
### 3.2. Agricultural Development

The *Agricultural Development* scenario assumes an enhanced development of domestic agricultural markets in African regions by 2030 by reducing local transport and marketing costs and increasing crop yields (Supplementary Table 2), reflecting progress on the Comprehensive African Agricultural Development Programme (CAADP). In the baseline scenario, local transport and marketing costs remain at the level of 2020 and crop yields develop according to the technological development assumptions of SSP2. The *Agricultural Development* scenario represents a closing of infrastructure gap by reducing farm-gate to market transport costs to an international benchmark of $0.05/t-km by 2030. While this benchmark is equal or close to the observed freight rates on some corridors in Africa, e.g. on the highway between Mombasa and Nairobi, Kenya[67] or the Durban-Lusaka corridor in Southern Africa[65], it represents a large reduction in transport costs for the majority of the continent. To represent the full market potential, African food value chains are further assumed to develop to the modern stage, reducing marketing costs to a 10% marketing margin. Lastly, crop yields in all commercial rain-fed production systems reach potential yield levels under improved fertilizer use (i.e. rate of up to 200 kg N/ha/year and increased agronomic nitrogen use efficiency). The potential yield levels are derived from spatial explicit simulations with the global gridded crop model Environmental Policy Integrated Climate–International Institute for Applied Systems Analysis (EPIC-IIASA)[68] assuming specific management practices (e.g. automatic fertilizer application, ideal sowing density, presently common crop varieties – see also Folberth et al. [68]), no limitation of K and P nutrients, and with no damage by external biotic and abiotic factors (pests, animals, diseases, extreme weather…). The response of crop output to nitrogen input – the agronomic nitrogen use efficiency – simulated by EPIC-IIASA varies across crops and locations depending on crop requirements and soil (e.g. water holding capacity) and climate (e.g. precipitation and evaporative demand) characteristics. The average agronomic nitrogen use efficiency for a shift in fertilizer use from 25 kgN/ha to 100kgN/ha in EPIC-IIASA is for rain-fed maize for example around 25-30 kg output per kg nitrogen nutrient in the African regions (median value across spatial units within the regions). These rates present approximately a doubling of the average agronomic nitrogen use efficiency currently observed in Sub-Saharan Africa (13.6 kg crop output per kg nitrogen[69]). Supplementary Figure 12 reveals the maximum nitrogen input level that induces a notable crop output response (from 25 kgN/ha up to 200 kgN/ha), i.e. the nitrogen adoption rates that are assumed under the improved fertilizer use, while Supplementary Figure 13illustrates the overall impact on aggregate crop yields. In Supplementary Table 3, the simulated crop yields under the *Agricultural Development* scenario are compared to potential yield reported by the Global Yield Gap Atlas (GYGA). Between 2030 and 2050 the yields under *Agricultural Development* further increase as driven by technological progress, e.g. due to the arrival of new crop varieties. The annual growth rates of yields under *Agricultural Development* scenario between 2030 and 2050 for example for the crops presented in Supplementary Table 3 ranges from 0.3% to 1.7%, which is within the range of observed growth rates of potential yields reported by Fischer et al.[70] (i.e. 0.3% to 2.0% p.a.). Results when assuming fertilizer rates of up to 100 kgN/ha instead of 200 kgN/ha or when assuming an international transport cost benchmark of 0.1 USD/ton-km instead of 0.05 USD/ton-km, are similar to the main set-up (Supplementary Figure 14). Agricultural market development is additionally implemented under three alternative settings: *Food*, *Export* and *Connect*. The *Food* and *Export* scenarios reduce local transport costs in the same way as under the *Agricultural Development* scenario, but implement the marketing cost reduction and yield increases only to a selected number of food or export commodity markets, respectively (Supplementary Table 4). The *Connect* scenario removes the part of local transport costs caused by the use of low capacity transport modes. It represents the development of paved roads and use of high capacity transport vehicles (load capacity = 12.5 ton) up to the farm-gate, reducing transport costs in the first 55 km beyond the farm-gate. The transport cost reductions are only implemented in areas connected to the current primary road network in Africa (Supplementary Figure 4) and are smaller than in the international benchmark scenario (Extended data Figure 8). Yield improvements are implemented in the same way as under the *Agricultural Development* scenario.

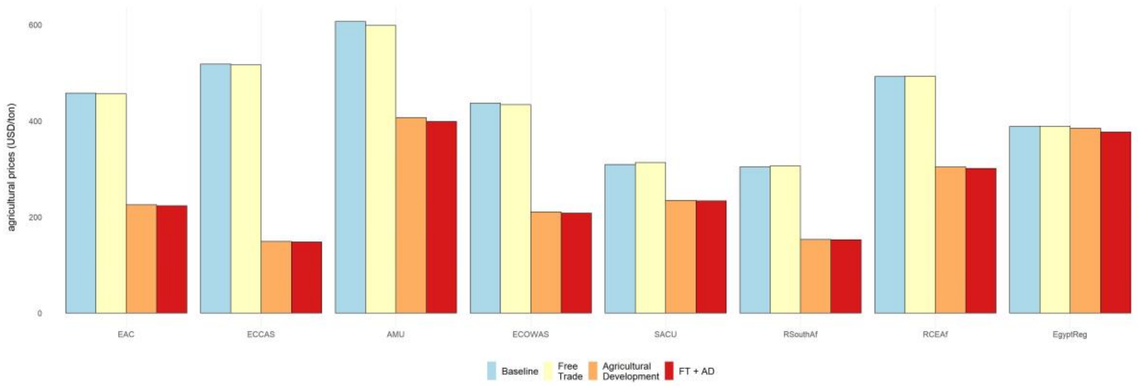
### 3.3. Scenario decomposition

We decompose the *Free Trade* and *Agricultural Development* scenarios in their individual components with a similar decomposition method as Stehfest et al.[71]. The scenarios are run with all components (total effect), with each component separately (individual effect) and without each component which allows to calculate the final effect as the difference between the total effect and the effect without the specific scenario element.

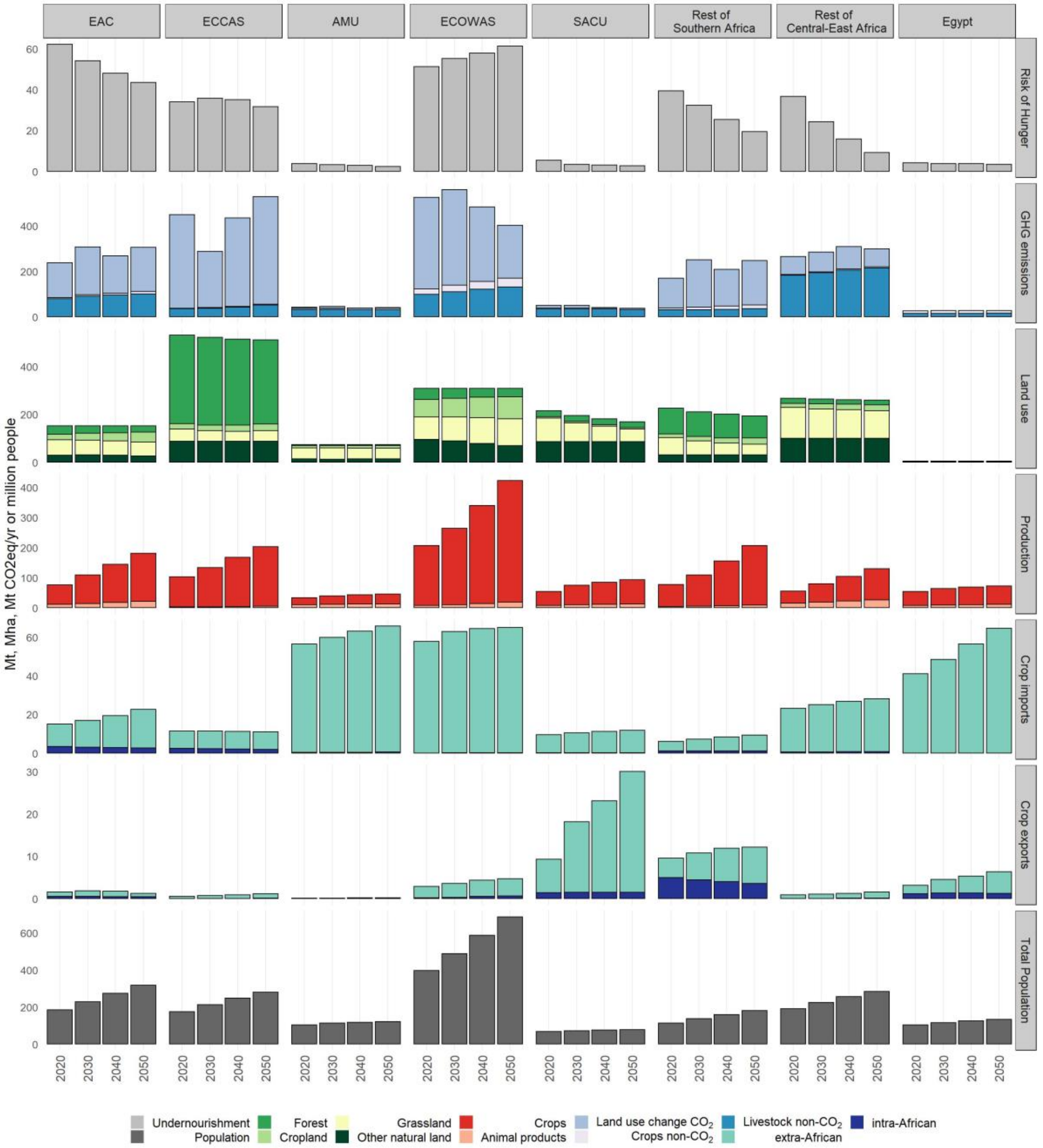
## Supplementary Figures



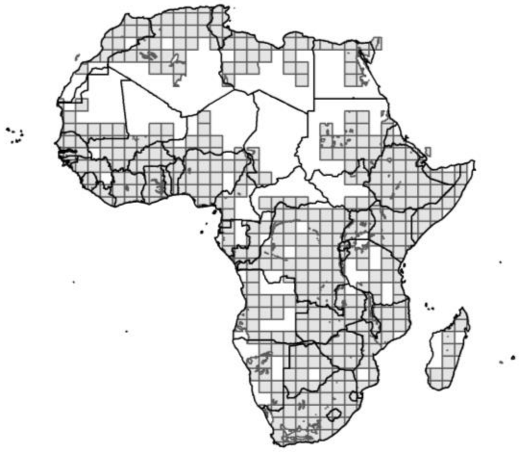
Supplementary Figure 1. Evolution of agricultural trade volume between parties of Regional Trade Agreements (RTAs) in 1996 - 2018. Total agricultural trade volume at GLOBIOM region and product level within plurilateral RTAs that entered into force between 1990 and 2000 and that cover goods trade (selection based on WTO RTAs database). Selection of GLOBIOM regions to maximize coverage of individual parties to the RTAs. ASEAN Free Trade Agreement (AFTA): Indonesia, Malaysia, RSEA_OPA, RSEA_PAC; Common Market for Eastern and Southern Africa (COMESA): Egypt, EAC, RSouthAf, RCEAf; European Community (15) Enlargement (EC15): EU_MidWest, EU_North, EU_South; Latin American Integration Association (LAIA): Brazil, Argentina, RSAM, Mexico; Southern Common Market (MERCOSUR): Brazil, Argentina, RSAM; North American Free Trade Agreement (NAFTA): USA, Canada, Mexico; Pan-Arab Free Trade Area (PAFTA): Egypt, MiddleEast, AMU; Southern African Development Community (SADC): SACU, RSouthAf; South Asian Preferential Trade Arrangement (SAPTA): India, RSAS. Decadal growth rates based on trade growth between periods 1996-1998 and 2016-2018: AFTA: 158%, COMESA: 129%, EC15: -2%, LAIA: 29%, MERCOSUR: 27%, NAFTA: 55%, PAFTA: 114%, SADC: 90%, SAPTA: 18%.



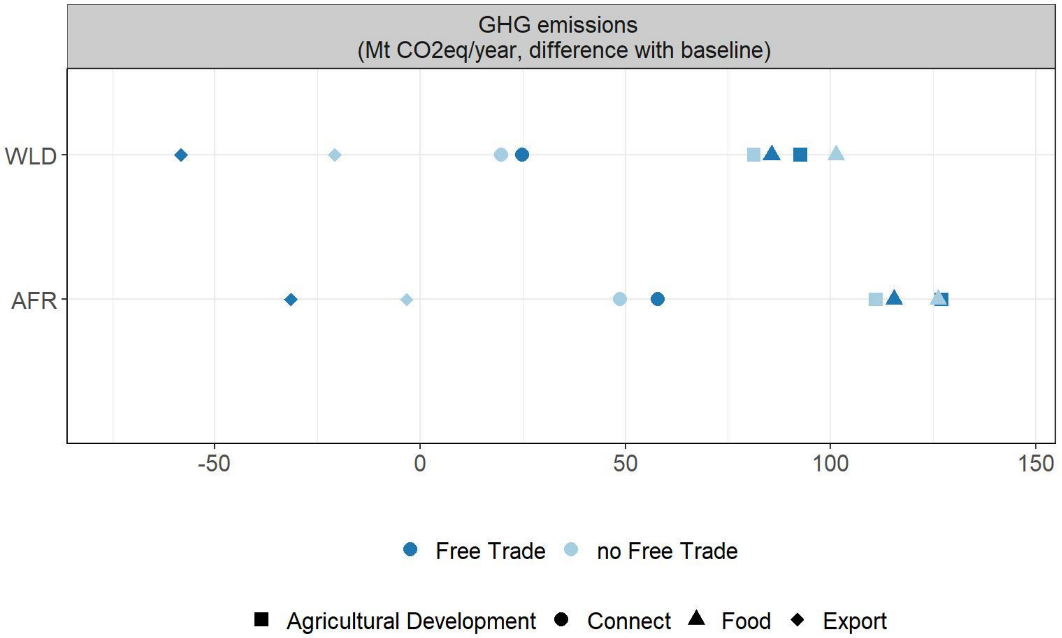
Supplementary Figure 2. Average agricultural prices by region in 2050 under the *Free Trade* and *Agricultural Development* scenarios.



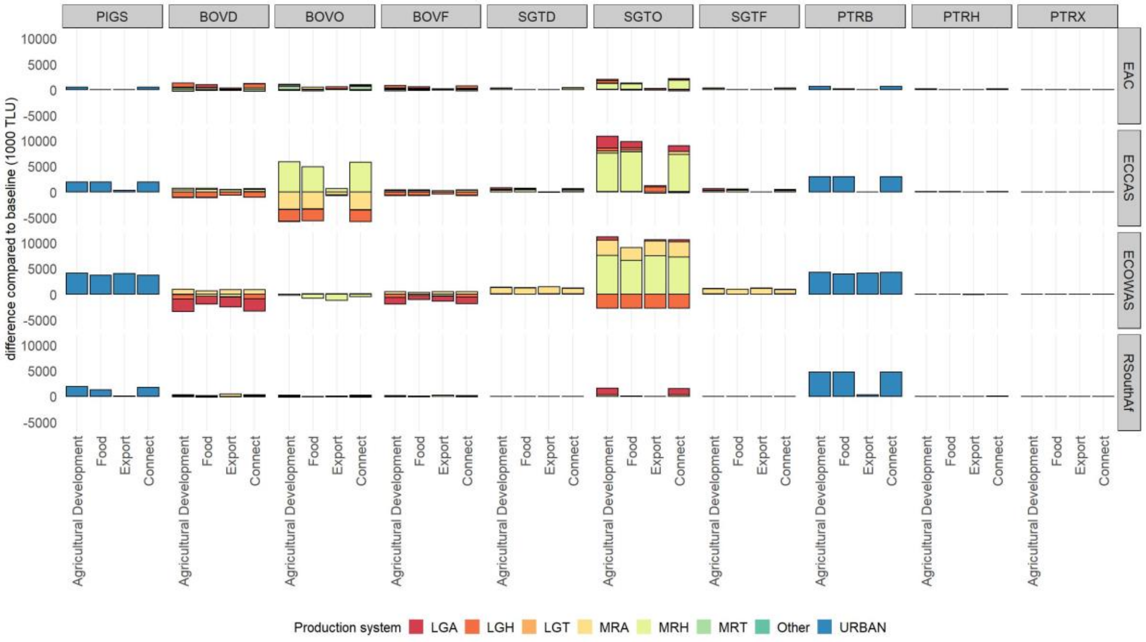
Supplementary Figure 3. Baseline development of population trade, undernourishment, GHG emission, and production across African regions between 2020 and 2050.



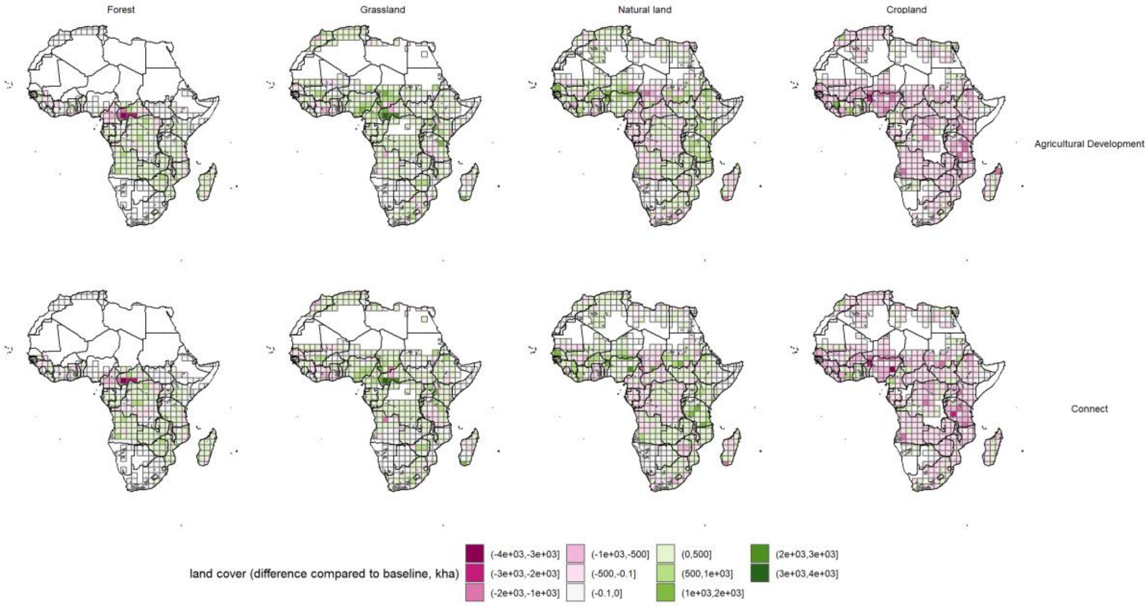
Supplementary Figure 4. Spatial units in GLOBIOM crossed by the primary road network in Africa based on the Global Roads Inventory Projects (GRIP) database. Africa includes in total 1105 spatial units.



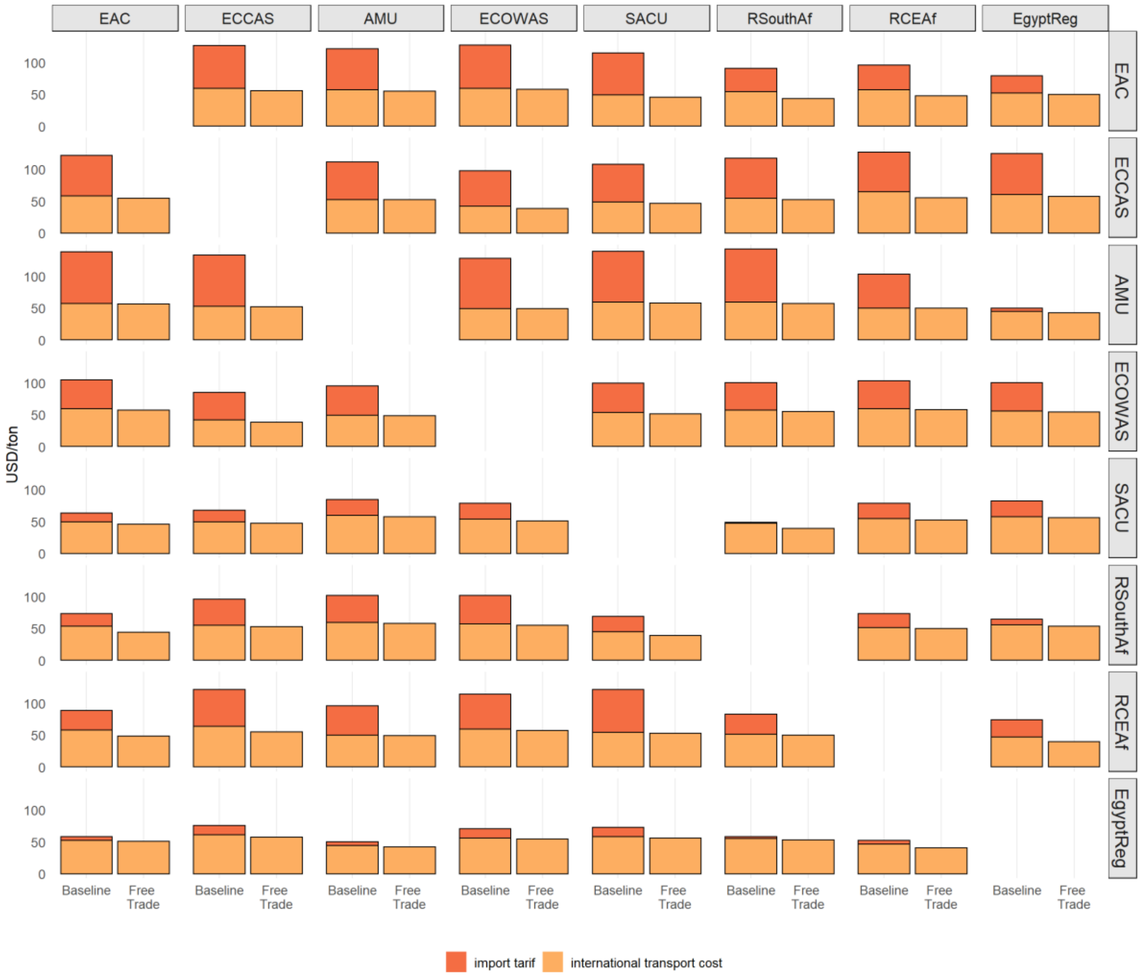
Supplementary Figure 5. Impact of prioritization strategies (*Connect*, *Food*, *Export*) for agricultural development on Global (WLD) and African (AFR) average annual GHG emissions in the period 2030 – 2050.



Supplementary Figure 6. Impact of prioritization strategies on livestock production systems across main livestock-producing African regions in 2050. Animals are grouped into pigs, bovine dairy (BOVD), followers (BOVF) and bovine other (BOVO), sheep and goat dairy (SGTD), followers (SGTF) and other (SGTO), and poultry broiler (PTRB), hens (PTRH) and other (PTRX). There are eight livestock production systems: grazing systems in arid (LGA), humid (LGH), and temperate (LGT), mixed systems in arid (MRA), humid (MRH), and temperate (MRT), urban systems, and other systems.

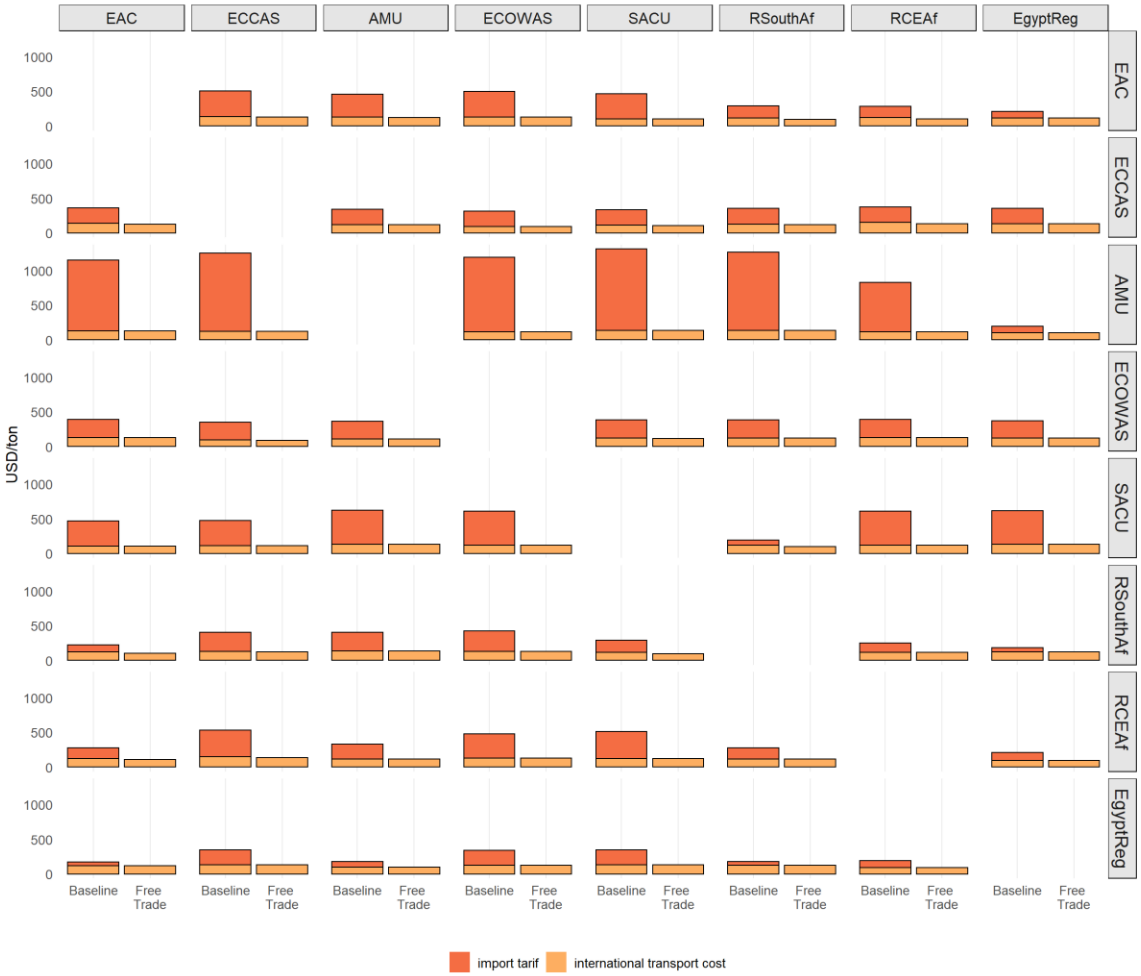


Supplementary Figure 7. Impact of *Agricultural Development* and *Connect* scenarios on forest (managed + unmanaged forest), grassland, natural land and cropland across supply units by 2050.



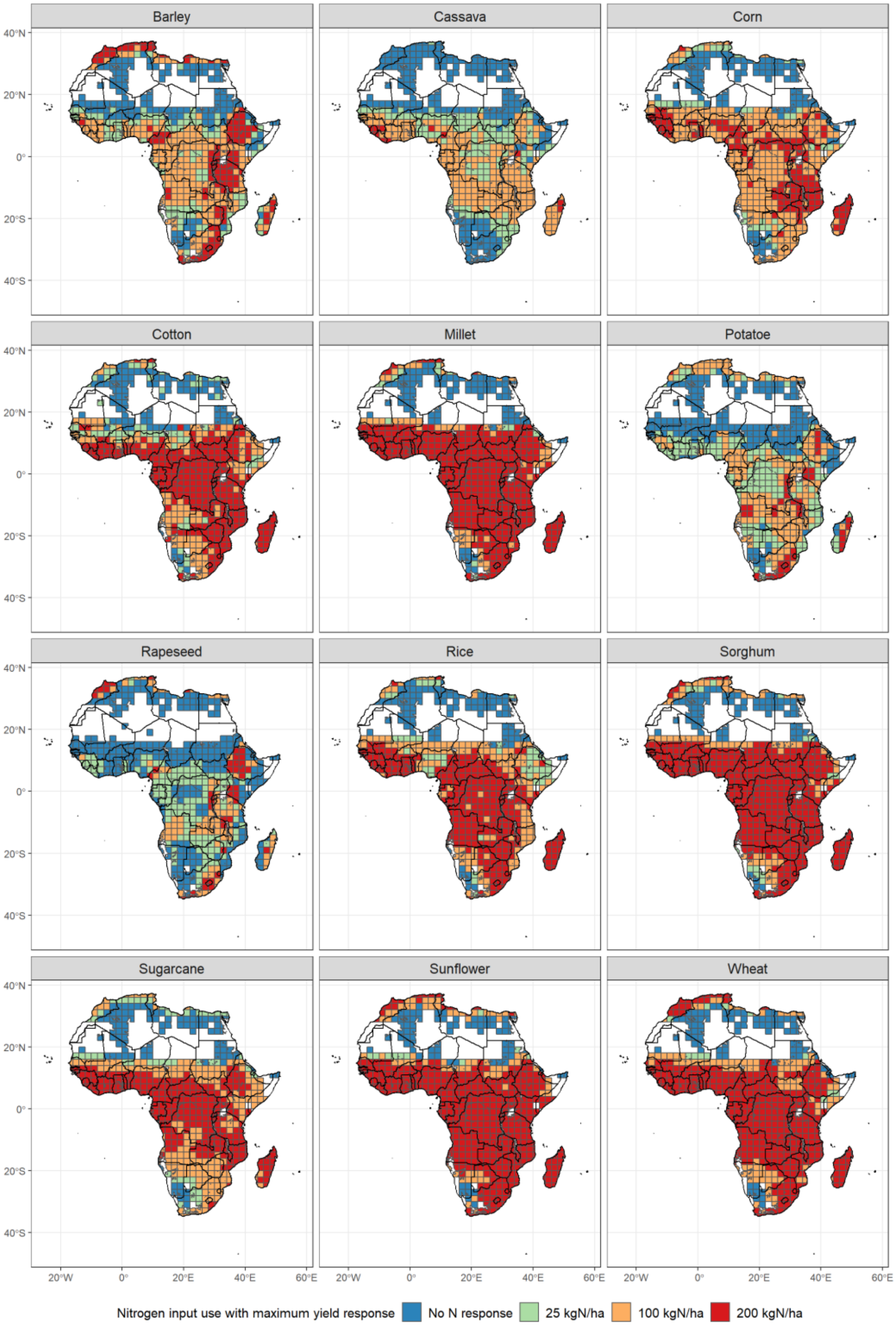
Supplementary Figure 8. Bilateral import tariffs and international transport costs between African regions in the baseline and *Free Trade* scenario in 2030 for crop trade (simple average across crops). Exporting region in column, importing region in row.

Supplementary Figure 9. Unilateral import and export costs across African regions in the baseline and *Free Trade* scenario in 2030 for crop trade (simple average across crops).

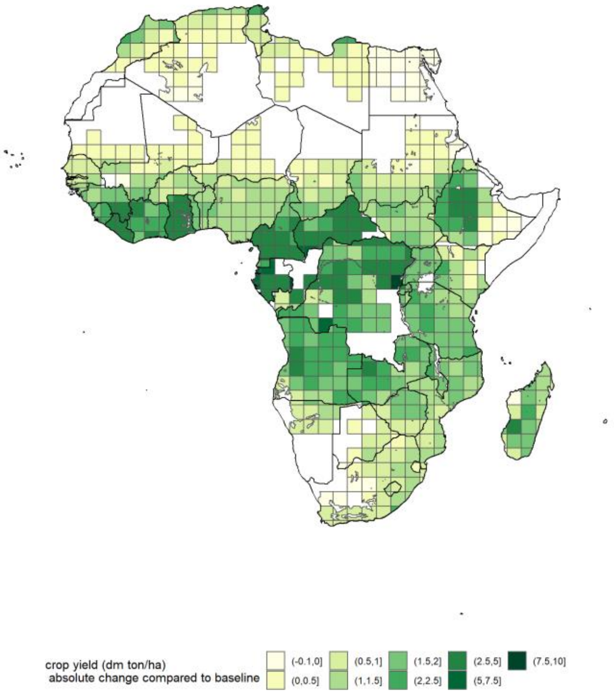


Supplementary Figure 10. Bilateral import tariffs and international transport costs between African regions in the baseline and *Free Trade* scenario in 2030 for livestock trade (simple average across animal products). Exporting region in column, importing region in row.

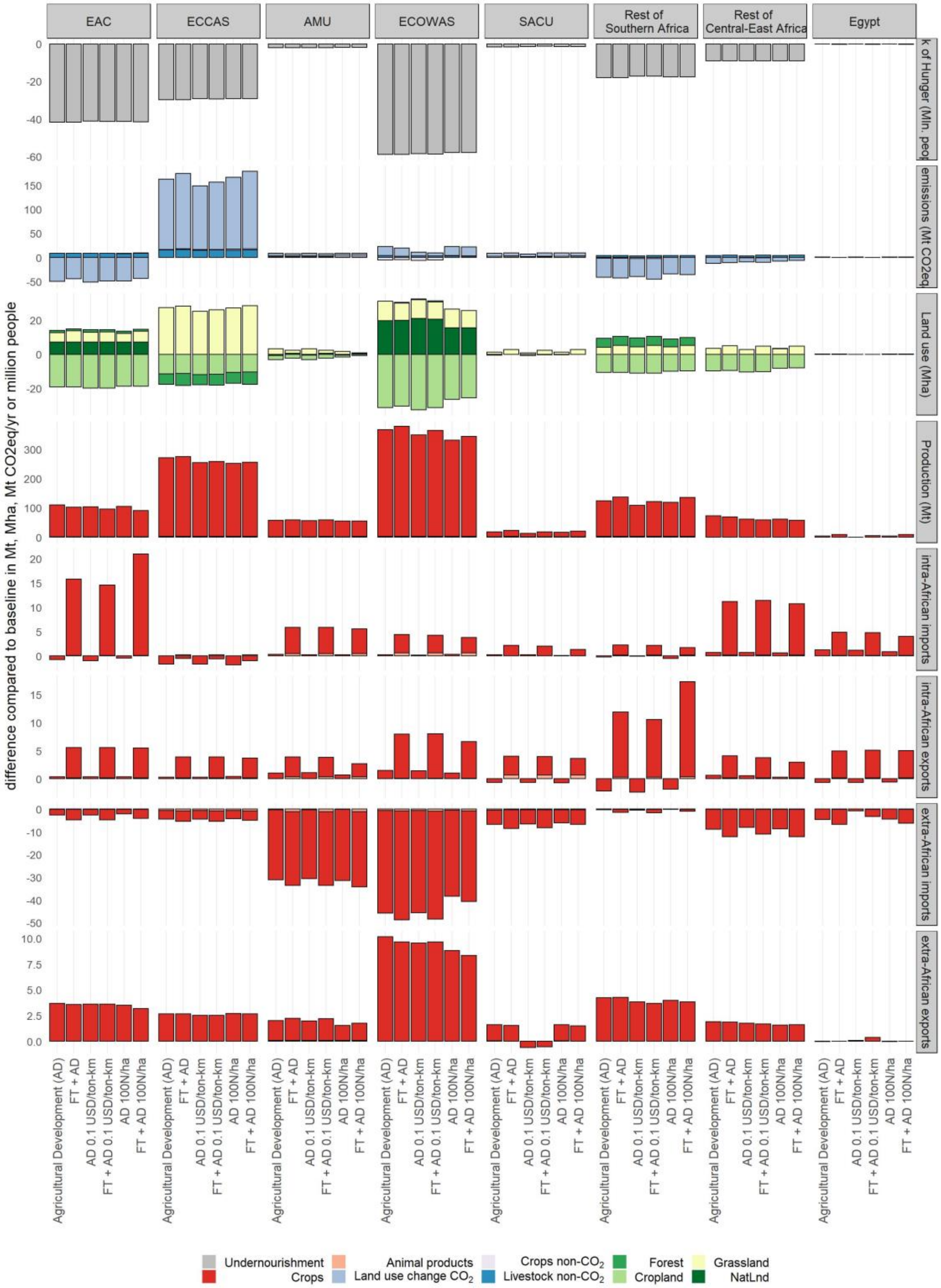
Supplementary Figure 11. Unilateral import and export costs across African regions in the baseline and *Free Trade* scenario in 2030 for livestock trade (simple average across animal products).



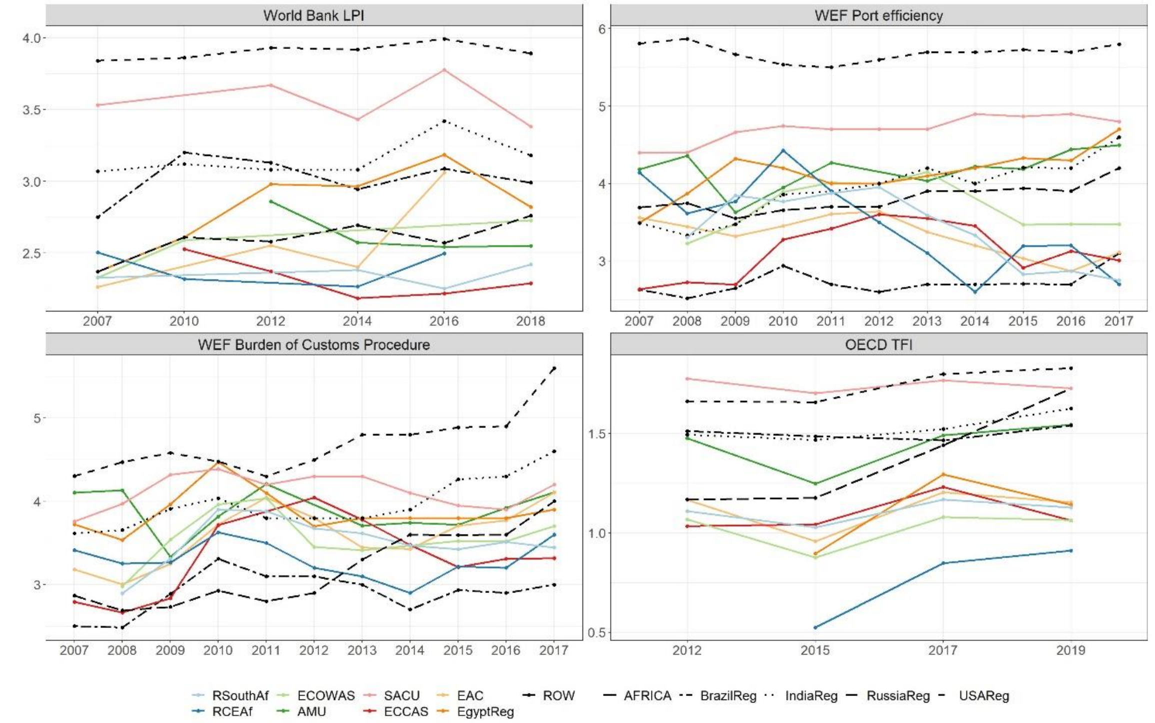
Supplementary Figure 12. Maximum nitrogen input use with crop output response as modelled by the EPIC-IIASA crop model.. The crop response to nitrogen input in EPIC-IIASA varies across crops and locations due to differences in the growing season length and water-stress sensitivity of crops, and soil (e.g. water holding capacity, nutrient resources, nitrogen loss intensity) and climate (e.g. precipitation and evaporative demand) characteristics.



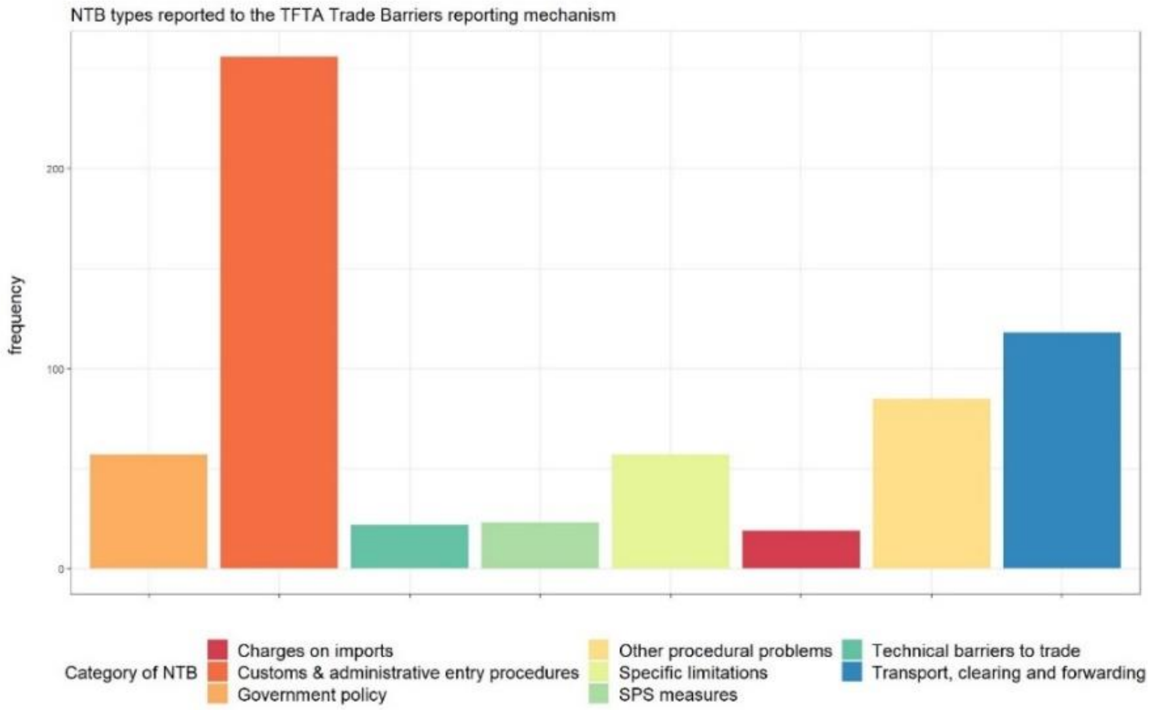
Supplementary Figure 13. Impact of the *Agricultural Development* scenario on average crop yields in GLOBIOM in Africa in 2030. Absolute difference between average crop yield in *Agricultural Development* scenario and average crop yield in baseline with individual crop yields weighted by baseline crop area in 2030. Regional averages are provided in Supplementary Table 3. The yields under *Agricultural Development* reflect water-limited potential yields under improved fertilizer use (with adoption rates up to 200kgN/ha and no limitations in P and K nutrients) and are based on simulations with the EPIC-IIASA crop model (see section 3.2 of Supplementary Methods).



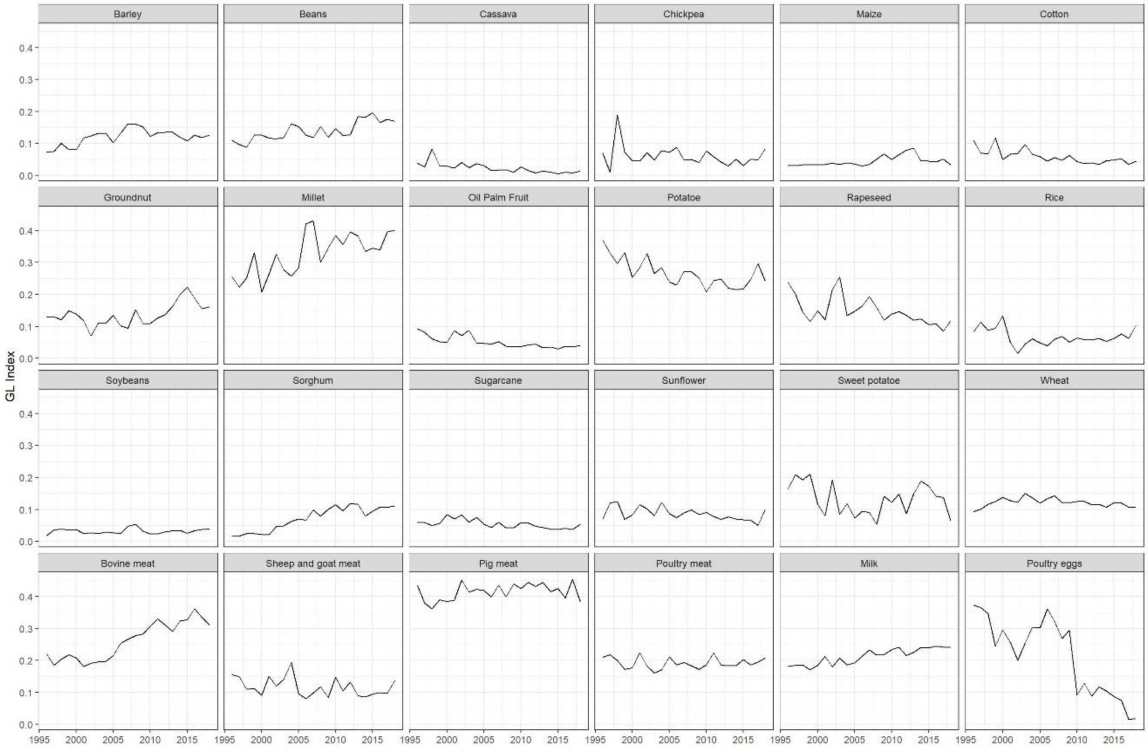
Supplementary Figure 14. Impact of *Agricultural Development* sensitivity scenarios (transport cost reduced to benchmark of 0.1 USD/ton-km; nitrogen input rate up to 100 kg N/ha) on undernourishment, GHG emissions, land use and agricultural production, imports and exports by 2050 across African regions. GHG emissions present the average annual emissions in the period 2030 – 2050. FT + AD: combined *Free Trade* + *Agricultural Development* scenario.



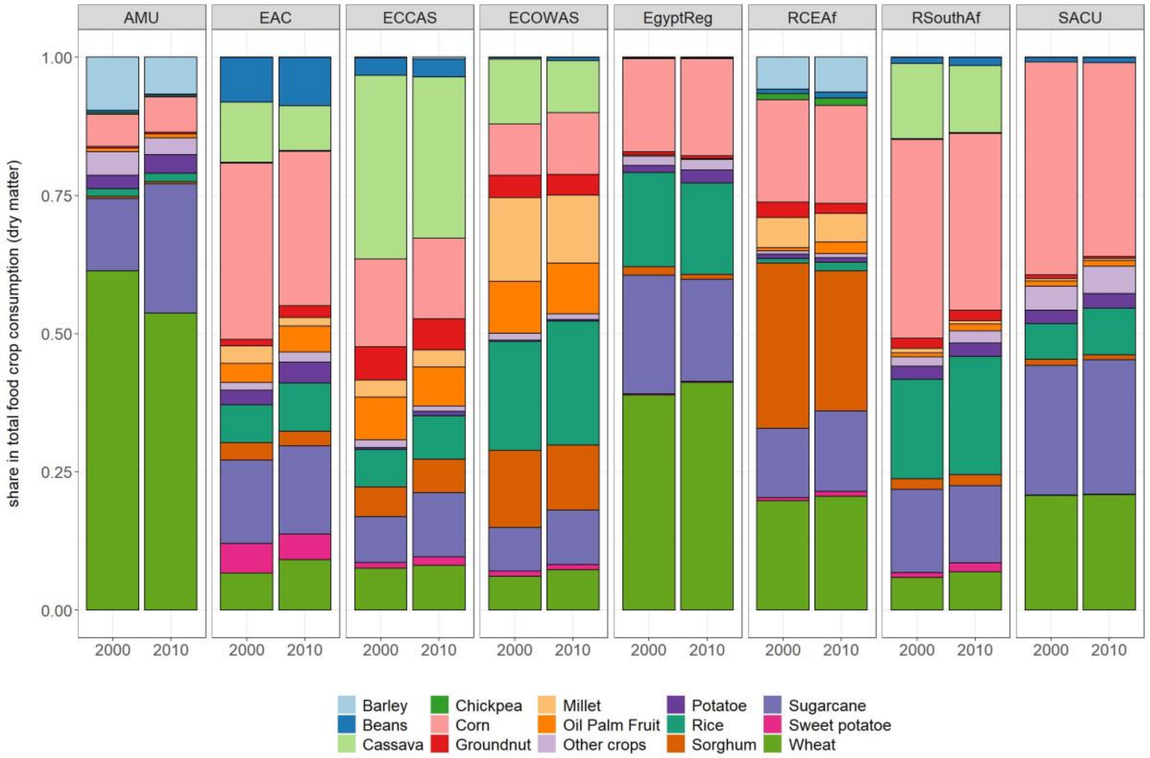
Supplementary Figure 15. Evolution of key trade facilitation indicators over time in African regions, compared to large agricultural exporting countries (USA, Russia, Brazil and India). LPI = Logistic Performance Indicator from the World Bank; Port Efficiency = Quality of port infrastructure from the World Economic Forum (WEF) Global Competitiveness Index; Burden of Customs Procedure = measure of perceptions of country's efficiency of customs procedures from WEF Global Competitiveness Index; TFI = Trade Facilitation Index from the OECD. For the GLOBIOM economic regions that consist of multiple countries, we compute an export-weighted average of the country-level indices based on a balanced panel dataset (e.g. if a certain country only has data for a few years, it is not included). ECCAS = Economic Community of Central African States, EAC = East African Community, ECOWAS = Economic Community of West African States, AMU = Arab Maghreb Union, SACU = South African Customs Union, RSouthAf: Rest of Southern Africa, RCEAf: Rest of Central-East Africa (cfr. Supplementary Table 1 for region definitions).



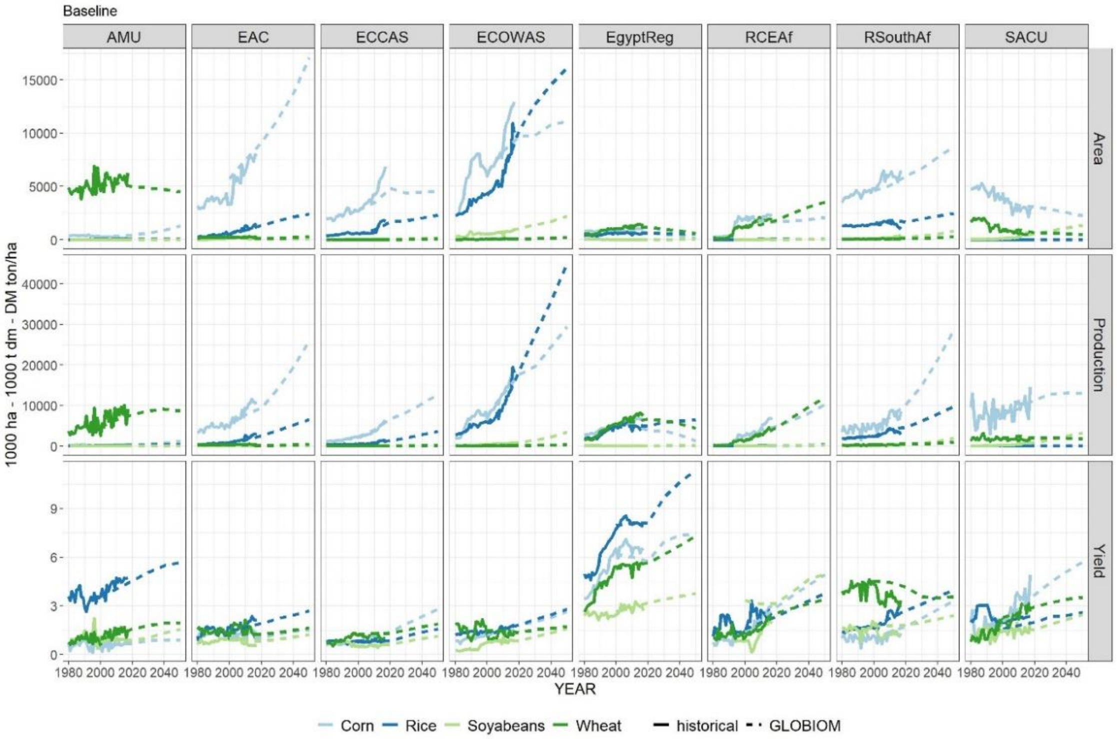
Supplementary Figure 16. NTB types reported to the TFTA Trade Barriers reporting mechanism. Resolved complaints on https://www.tradebarriers.org/ at September 4, 2019.



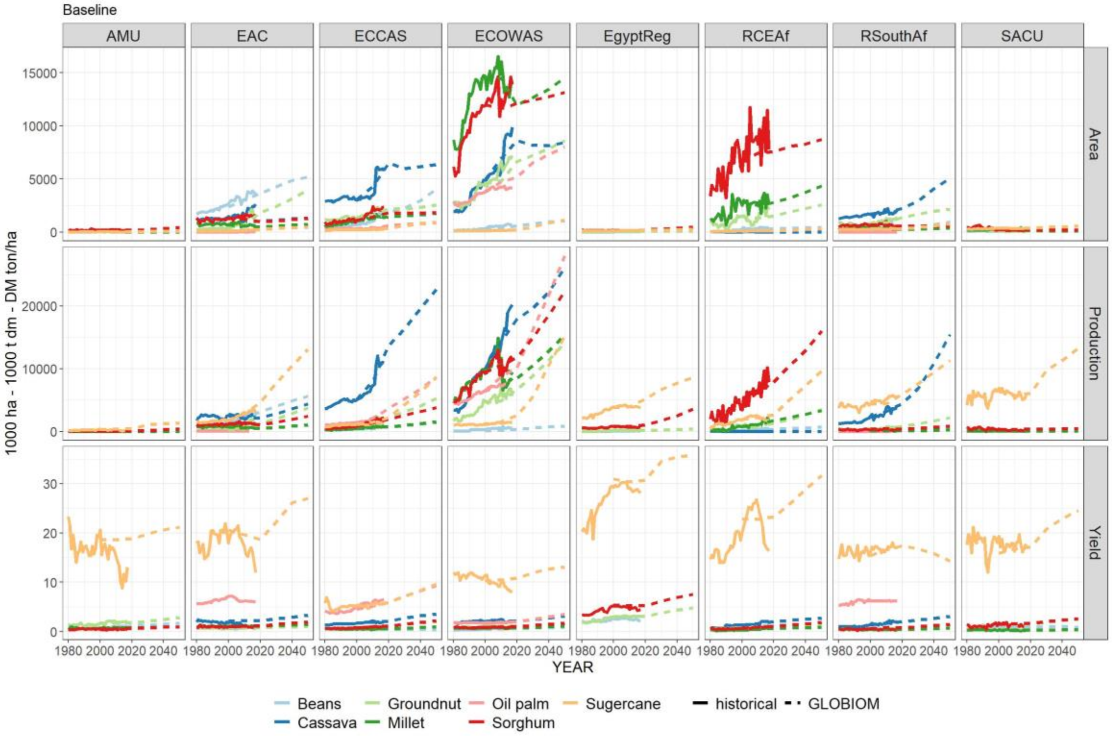
Supplementary Figure 17. Grubel–Lloyd Index for intra-industry trade of different agricultural goods in GLOBIOM. The index is calculated based on region r exports (Xrr') to and imports (Mrr') from another region r' for a particular good i: $\boldsymbol{GL_{rr'i} = 1 - \frac{|X_{rr'i} - M_{rr'i}|}{(X_{rr'i} + M_{rr'i})}}$ [72]. The index lies between 0 and 1, with 0 no intra-industry trade and 1 fully intra-industry trade. We calculate a trade-weighted average of the bilateral GL indices for each good i. Data: BACI bilateral trade database, aggregated to GLOBIOM product and region dimension by authors.



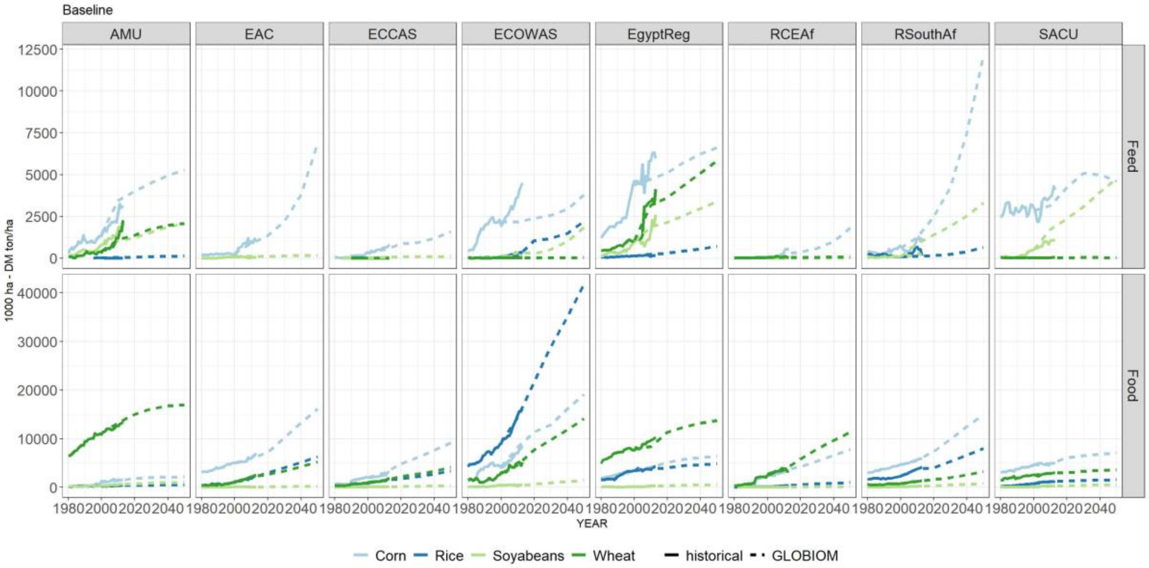
Supplementary Figure 18. Share in total food crop consumption of the 18 GLOBIOM crops from FAOSTAT commodity balances (average 1998 – 2002 vs average 2008 – 2012). Other crops are sunflower, rapeseed, soya, cotton and chickpea.



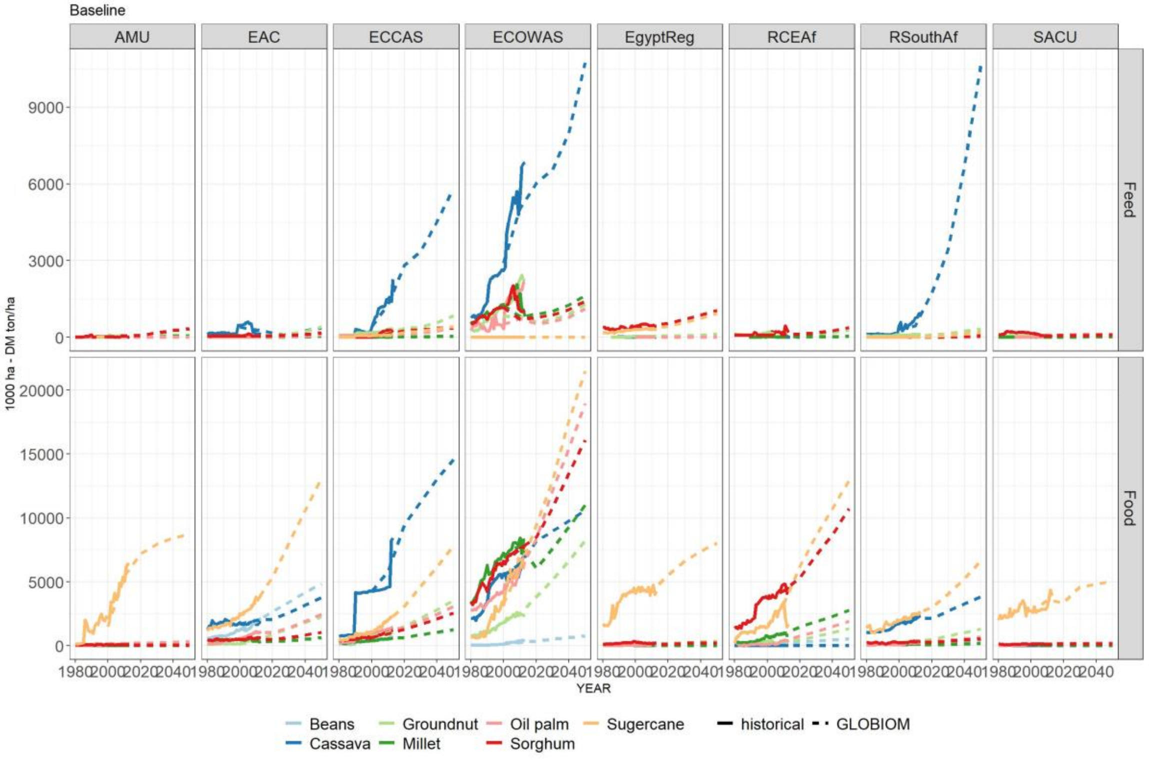
Supplementary Figure 19. Comparison between historical (FAOSTAT) and GLOBIOM trend on production area, quantity and yield. Production volume and yield in dry matter (dm).



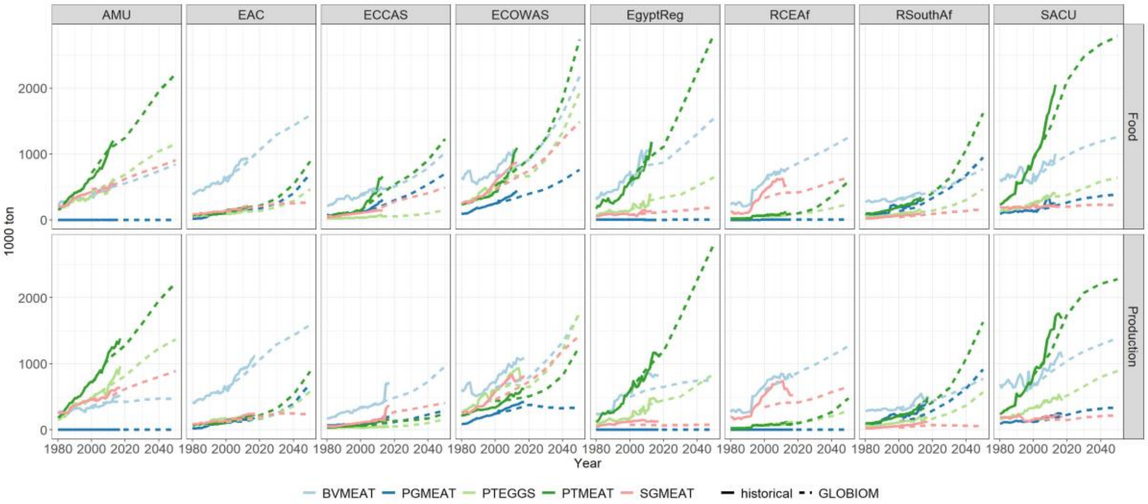
Supplementary Figure 20. Comparison between historical (FAOSTAT) and GLOBIOM trend on production area, quantity and yield. Production volume and yield in dry matter (dm).



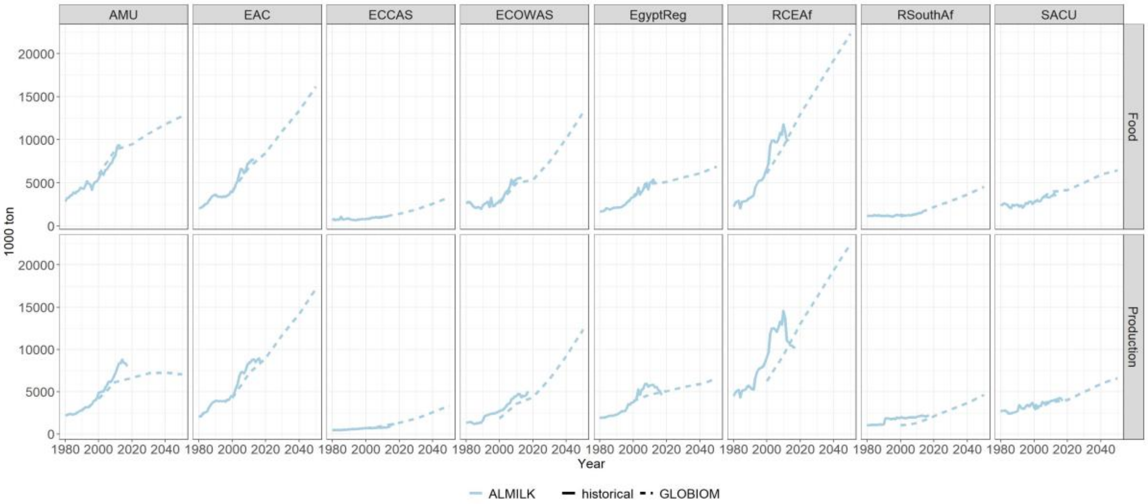
Supplementary Figure 21. Comparison between historical (FAOSTAT) and GLOBIOM trend on crop food and feed demand.



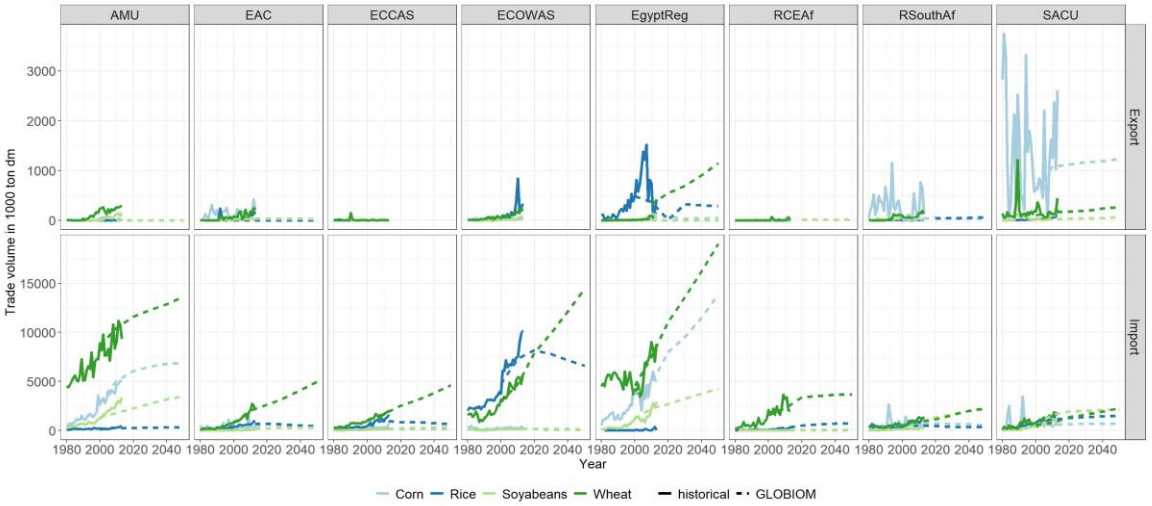
Supplementary Figure 22. Comparison between historical (FAOSTAT) and GLOBIOM trend on crop food and feed demand.



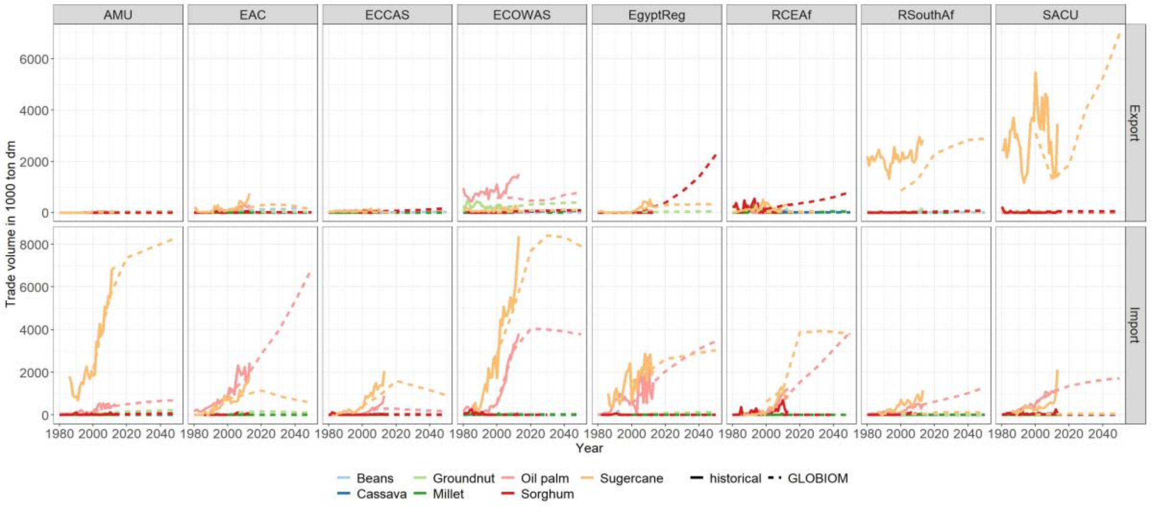
Supplementary Figure 23. Comparison between historical (FAOSTAT) and GLOBIOM trend on livestock production and demand.



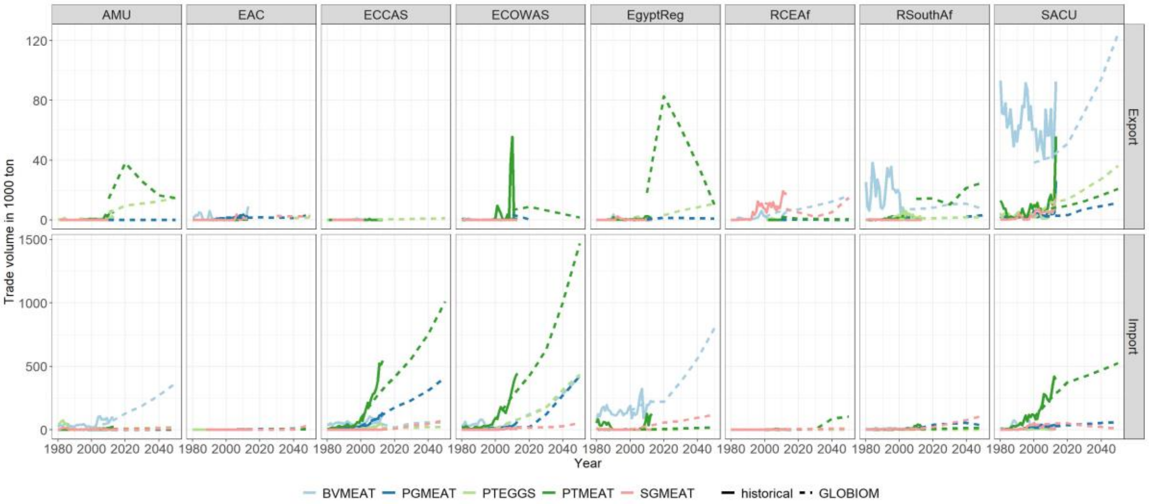
Supplementary Figure 24. Comparison between historical (FAOSTAT) and GLOBIOM trend on milk production and demand.



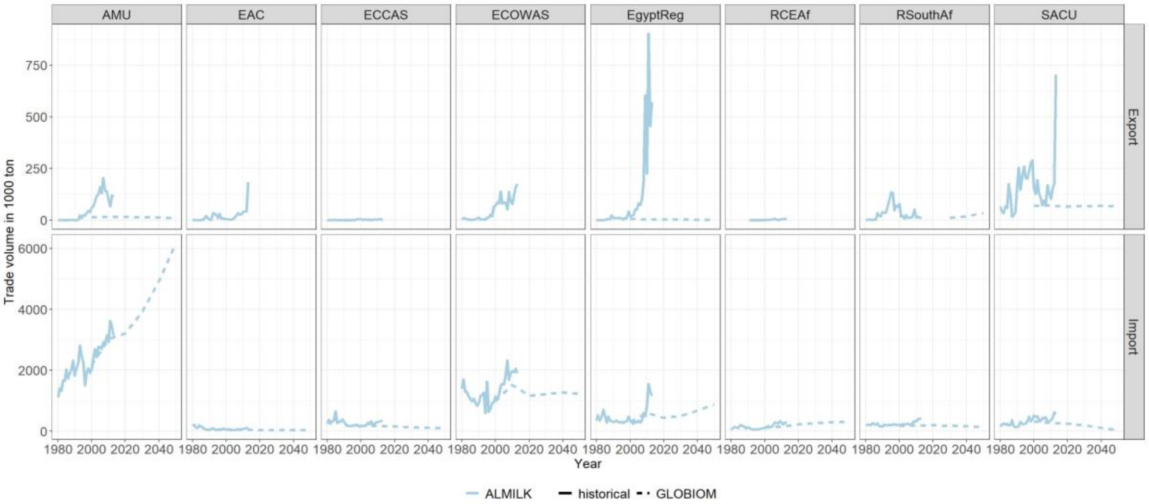
Supplementary Figure 25. Comparison between historical (FAOSTAT) and GLOBIOM trend on crop imports and exports.



Supplementary Figure 26. Comparison between historical (FAOSTAT) and GLOBIOM trend on crop imports and exports.



Supplementary Figure 27. Comparison between historical (FAOSTAT) and GLOBIOM trend on livestock imports and exports.



Supplementary Figure 28. Comparison between historical (FAOSTAT) and GLOBIOM trend on milk imports and exports.

## Supplementary Tables

Supplementary Table 1. African sub-regions

| Region | Country |
|---|---|
| East African Community (EAC) | Burundi, Kenya, Rwanda, Tanzania, Uganda |
| Economic Community of Central African States (ECCAS) | Angola, Cameroon, Central African Republic, Chad, Democratic Republic of the Congo, Republic of the Congo, Equatorial Guinea, Gabon |
| Arab Maghreb Union (AMU) | Algeria, Libya, Mauritania, Morocco, Tunisia, West Sahara |
| Economic Community of West African States (ECOWAS) | Benin, Burkina Faso, Cape Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, Togo |
| Southern African Customs Union (SACU) | Botswana, Lesotho, Namibia, South-Africa, Swaziland |
| Rest of Southern Africa (RSouthAf) | Comoros, Madagascar, Malawi, Mauritius, Mozambique, Reunion, Zambia, Zimbabwe |
| Rest of Central-East Africa (RCEAf) | Djibouti, Eritrea, Ethiopia, Somalia, Sudan, South Sudan |
| Egypt (EgyptReg) | Egypt |

Supplementary Table 2. Adjustments to costs and model parameters under the *Free Trade* and *Agricultural Development* scenarios.

| Scenario | | Implementation in GLOBIOM |
|---|---|---|
| Baseline | International and local trade costs | Constant at 2020 level |
| | Crop yields | Technological development according to historical trends |
| *Free Trade* | Bilateral cost elements | |
| | Import tariffs: | Elimination of all bilateral import tariffs on intra-African agricultural trade flows from 2030 onwards. |
| | International transport cost: | Overland international transportation costs reduced with 25% from 2030 onwards[65,66]. Ocean transport costs remain constant to the baseline level. |
| | Entry cost: | Entry cost margin between exporter and importer reduced to 10% from 2030 onwards. |
| | Unilateral cost elements | |
| | Import & Export cost (inland transport): | Inland transport costs from capital to border/ port (export) or from port/border to capital (import) are reduced to 5 US cents/ton-km from 2030 onwards, the international benchmark level of transport cost[67]. |
| | Import & Export cost (administrative): | Border & documentary compliance costs for importing/exporting are reduced to an international benchmark from 2030 onwards (using the cost level of USA export and import in 2019 as benchmark). |
| | Unilateral cost parameters | |
| | Expansion cost intensive margin: | Shift in trade expansion parameter $(\varepsilon * 10)$ to reduce intensive margin expansion costs between 2020 and 2030 reflecting a large increase in port efficiency in the exporting region. |
| | Expansion cost extensive margin: | Shift in trade expansion parameter $(\sigma/10)$ to reduce extensive margin expansion costs between 2020 and 2030 reflecting a large increase in customs efficiency in the exporting region. |

Supplementary Table 2 (continued). Adjustments to costs and model parameters under the *Free Trade* and *Agricultural Development* scenarios.

| | | |
|---|---|---|
| *Agricultural Development* | Local transport cost: | Transport costs from farm-gate to local market reduce to the international benchmark of 5 US cents/ton-km from 2030 onwards. |
| | Local marketing cost: | Marketing costs from farm to local market is reduced by lowering marketing margins to 10% from 2030 onwards. |
| | Crop yields: | Technological development according to historical trends + all commercial rain-fed production systems achieve potential yield levels under improved fertilizer use (rate up to 200 kg N/ha/year and increased agronomic nitrogen use efficiency) from 2030 onwards with the high-input yields based on simulations with the EPIC-IIASA crop model[68]. |
| *Food* | Local transport cost: | As in *Agricultural Development* |
| | Local marketing cost & crop yields: | As in *Agricultural Development*, but only for selection of food markets (Supplementary Table 4). |
| *Export* | Local transport cost: | As in *Agricultural Development* |
| | Local marketing cost & crop yields: | As in *Agricultural Development*, but only for selection of export markets (Supplementary Table 4). |
| *Connect* | Local transport cost: | Partial reduction in local transport costs by use of high capacity transport vehicles (load capacity = 12.5 ton) in the first 55km beyond farm-gate by 2030 in spatial units connected to the current primary road network (Supplementary Fig. 4). |
| | Local marketing cost & crop yields: | As in *Agricultural Development*, but only for spatial units connected to the current primary road network (Supplementary Fig. 4). |

Supplementary Table 3. Average crop yields under the baseline and *Agricultural Development* scenario (AgDev) in African regions in GLOBIOM and comparison with current water-limited yield potentials of a number of African countries from the Global Yield Gap Atlas (GYGA) database. Yields (in fm ton/ha) of the 4 crops with largest African production in the baseline in 2030 and crop average yield (in dm ton/ha) across all 18 crops weighted by crop area.

| Region | Yield | Maize (fm ton/ha) |  | Cassava (fm ton/ha) |  | Sugarcane (fm ton/ha) |  | Rice (fm ton/ha) |  | Crop Average (dm ton/ha) |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | Base | AgDev | Base | AgDev | Base | AgDev | Base | AgDev | Base | AgDev |
| AMU | 2030 | 0.62 | 2.61 | / | / | 62.04 | 62.04 | 5.63 | 5.63 | 1.14 | 2.12 |
|  | 2050 | 0.78 | 3.46 | / | / | 65.46 | 65.46 | 6.72 | 6.72 | 1.50 | 2.60 |
| EAC | 2030 | 1.36 | 3.53 | 10.67 | 18.00 | 72.82 | 79.00 | 2.89 | 4.80 | 1.81 | 3.48 |
|  | 2050 | 1.79 | 4.55 | 13.35 | 22.46 | 80.87 | 87.84 | 3.53 | 5.84 | 2.21 | 4.14 |
| ECCAS | 2030 | 1.94 | 3.83 | 10.94 | 22.28 | 25.06 | 90.52 | 1.40 | 4.05 | 1.71 | 4.19 |
|  | 2050 | 2.73 | 5.19 | 14.58 | 29.46 | 31.91 | 112.21 | 2.05 | 5.72 | 2.17 | 5.43 |
| ECOWAS | 2030 | 2.34 | 3.42 | 11.45 | 23.92 | 43.10 | 73.05 | 2.48 | 4.25 | 1.77 | 3.45 |
|  | 2050 | 2.85 | 4.12 | 13.90 | 28.71 | 48.27 | 80.85 | 3.21 | 5.18 | 2.18 | 4.25 |
| EgyptReg | 2030 | 8.59 | 8.59 | / | / | 125.53 | 125.53 | 11.09 | 11.09 | 8.32 | 8.32 |
|  | 2050 | 10.93 | 10.93 | / | / | 132.46 | 132.46 | 13.23 | 13.23 | 9.76 | 9.76 |
| RCEAF | 2030 | 3.00 | 5.06 | 14.35 | 19.93 | 121.22 | 121.22 | 3.36 | 3.36 | 3.04 | 4.67 |
|  | 2050 | 4.08 | 6.87 | 16.89 | 22.43 | 135.72 | 135.72 | 4.45 | 4.45 | 3.76 | 5.74 |
| RSouthAf | 2030 | 2.39 | 4.24 | 10.51 | 24.63 | 64.66 | 66.57 | 3.45 | 5.06 | 2.21 | 3.71 |
|  | 2050 | 3.40 | 5.80 | 13.39 | 31.23 | 72.07 | 74.19 | 4.50 | 6.60 | 2.83 | 4.65 |
| SACU | 2030 | 3.85 | 4.56 | / | / | 68.42 | 69.03 | 2.46 | 4.92 | 2.56 | 3.43 |
|  | 2050 | 4.76 | 5.22 | / | / | 78.36 | 79.13 | 3.01 | 6.02 | 2.96 | 3.90 |
| EAC |  |  |  |  |  |  |  |  |  |  |  |
| Kenya | GYGA |  | 7.86 |  |  |  |  |  |  |  |  |
| Tanzania | GYGA |  | 5.96 |  |  |  |  |  | 6.35 |  |  |
| Uganda | GYGA |  | 6.85 |  |  |  |  |  | 4.08 |  |  |
| ECOWAS |  |  |  |  |  |  |  |  |  |  |  |
| Burkina Faso | GYGA |  | 6.25 |  |  |  |  |  | 5.34 |  |  |
| Côte d’Ivoire | GYGA |  |  |  |  |  |  |  | 6.10 |  |  |
| Ghana | GYGA |  | 8.64 |  |  |  |  |  | 6.63 |  |  |
| Mali | GYGA |  | 9.68 |  |  |  |  |  | 6.12 |  |  |
| Nigeria | GYGA |  | 10.77 |  |  |  |  |  | 6.09 |  |  |
| Senegal | GYGA |  |  |  |  |  |  |  | 8.53 |  |  |
| RCEAF |  |  |  |  |  |  |  |  |  |  |  |
| Ethiopia | GYGA |  | 12.49 |  |  |  |  |  |  |  |  |
| RSouthAf |  |  |  |  |  |  |  |  |  |  |  |
| Zambia | GYGA |  | 11.33 |  |  |  |  |  | 7.89 |  |  |

Note: the yields under the *Agricultural Development* scenario represent average regional yields in GLOBIOM (weighted by baseline area in 2030 or 2050) based on potential yield levels under non-irrigated conditions and improved fertilizer use from EPIC-IIASA crop model simulations (cfr. section 3.2 of Supplementary Methods). The yield shifts are only implemented for rain-fed systems, so there is little impact on average yields of regions and crops that are dominated by irrigated systems, such as e.g. rice in RCEAf, AMU and EgyptReg. Average crop yield is provided in dry matter (dm) to reduce crop composition effects and the large influence of high-weight crops such as cassava and sugarcane in fresh matter (fm) average.

Supplementary Table 4. Selection of commodities for targeted agricultural development scenarios. The Food scenario includes the 4 food and 2 feed products that are projected to experience the largest absolute growth in food or feed consumption, respectively, between 2020 and 2030. The Export scenario selects 6 products for which a region has a comparative advantage, measured by the Revealed Comparative Advantage (RCA) index. The RCA index is calculated as a region's share of a product's export in total crop or livestock exports versus Africa's share of the product's export in total African crop or livestock exports (RCA is also used in development studies to identify industries with growth opportunity e.g. Dinh and Monga[73]). Commodities for which RCA is larger than 1 in the *Free Trade + Agricultural Development* (FT + AD) scenario are identified as commodities for which a region has a comparative advantage compared to the other African regions. When a region has more than 6 commodities with an RCA > 1, the commodities with the largest RCA values are selected. When a region has less than 6 commodities with an RCA > 1, commodities are included for which the region has a surplus production under FT + AD and the share of production in total African production is higher under FT + AD scenario compared to the baseline scenario.

| Region | *Food* scenario | *Export* scenario |
|---|---|---|
| EAC | sugarcane, maize, sweet potato, milk, sunflower, cotton | Sweet potato, beans, chickpea, sheep and goat meat, sunflower, beef |
| ECCAS | cassava, sugarcane, oil palm, maize, groundnut, wheat | sorghum, oil palm, sheep & goat meat, potato, cotton, beans |
| AMU | sugarcane, milk, wheat, potato, maize, barley | wheat, barley, chickpea, poultry eggs, poultry meat, milk |
| ECOWAS | sugarcane, cassava, rice, oil palm, sorghum, soya | cassava, millet, groundnut, oil palm, sheep & goat meat, rice |
| SACU | sugarcane, maize, potato, milk, poultry meat, soya | wheat, milk, maize, sugarcane, pig meat, soya |
| RSouthAf | cassava, sugarcane, maize, sweet potato, rice, milk | beef, milk, sugarcane, cotton, poultry meat, pig meat |
| RCEAf | Potatoe, maize, sugarcane, milk, wheat, sorghum | Barley, chickpea, sorghum, wheat, cassava, beef |
| Egypt | sugarcane, wheat, potato, maize, poultry meat, rice | Potato, poultry eggs, cotton, poultry meat, sorghum, wheat |

Supplementary Table 5. Impact of *Free Trade* and *Agricultural Development* scenarios on intra-African trade volume for crops and livestock products in 2030. Total import or export volume (in 1000 t fm) from or to other African regions and the share of total African imports or exports.

| REGION | Scenario | African crop imports | | African crop exports | | African livestock imports | | African livestock exports | |
|---|---|---|---|---|---|---|---|---|---|
| | | *1000 t* | *share* | *1000 t* | *share* | *1000 t* | *share* | *1000 t* | *share* |
| EAC | Baseline | 3122 | 39% | 498 | 6% | 0 | 0% | 2 | 2% |
| | Free Trade | 22041 | 44% | 3651 | 7% | 61 | 6% | 83 | 8% |
| | AgDev | 2445 | 49% | 434 | 9% | 0 | 0% | 2 | 2% |
| | FT + AD | 13563 | 45% | 3044 | 10% | 54 | 5% | 80 | 7% |
| ECCAS | Baseline | 2345 | 29% | 36 | 0% | 49 | 44% | 0 | 0% |
| | Free Trade | 13719 | 27% | 518 | 1% | 245 | 23% | 7 | 1% |
| | AgDev | 83 | 2% | 106 | 2% | 45 | 38% | 3 | 2% |
| | FT + AD | 682 | 2% | 1522 | 5% | 189 | 17% | 60 | 5% |
| AMU | Baseline | 399 | 5% | 0 | 0% | 0 | 0% | 22 | 20% |
| | Free Trade | 2406 | 5% | 94 | 0% | 180 | 17% | 140 | 13% |
| | AgDev | 469 | 9% | 89 | 2% | 1 | 1% | 28 | 24% |
| | FT + AD | 3491 | 11% | 1302 | 4% | 215 | 19% | 190 | 17% |
| ECOWAS | Baseline | 206 | 3% | 245 | 3% | 33 | 29% | 0 | 0% |
| | Free Trade | 1374 | 3% | 1653 | 3% | 307 | 29% | 23 | 2% |
| | AgDev | 209 | 4% | 546 | 11% | 40 | 34% | 2 | 1% |
| | FT + AD | 1612 | 5% | 4502 | 15% | 362 | 32% | 27 | 2% |
| SACU | Baseline | 137 | 2% | 1493 | 18% | 0 | 0% | 69 | 61% |
| | Free Trade | 319 | 1% | 8047 | 16% | 0 | 0% | 450 | 43% |
| | AgDev | 181 | 4% | 659 | 13% | 0 | 0% | 68 | 57% |
| | FT + AD | 1093 | 4% | 2549 | 8% | 0 | 0% | 437 | 39% |
| RSouthAf | Baseline | 1157 | 14% | 4469 | 55% | 31 | 27% | 6 | 5% |
| | Free Trade | 5187 | 10% | 28421 | 56% | 137 | 13% | 143 | 14% |
| | AgDev | 614 | 12% | 2369 | 47% | 30 | 25% | 6 | 5% |
| | FT + AD | 1661 | 5% | 12379 | 41% | 135 | 12% | 165 | 15% |
| RCEAf | Baseline | 670 | 8% | 47 | 1% | 0 | 0% | 8 | 7% |
| | Free Trade | 5075 | 10% | 451 | 1% | 82 | 8% | 122 | 12% |
| | AgDev | 905 | 18% | 160 | 3% | 0 | 0% | 5 | 5% |
| | FT + AD | 6103 | 20% | 1581 | 5% | 114 | 10% | 90 | 8% |
| EgyptReg | Baseline | 53 | 1% | 1300 | 16% | 0 | 0% | 7 | 6% |
| | Free Trade | 327 | 1% | 7613 | 15% | 31 | 3% | 74 | 7% |
| | AgDev | 93 | 2% | 637 | 13% | 2 | 2% | 6 | 5% |
| | FT + AD | 2163 | 7% | 3489 | 11% | 55 | 5% | 74 | 7% |

Supplementary Table 6. Impact of *Free Trade* and *Agricultural Development* scenarios on Trade Intensity Index (TII) for intra-African exports and imports in 2030. Calculation of TII adjusted from Bouët et al. [21]. TII for exports is calculated as the ratio of the share of Africa as destination of total exports of an African region to the share of Africa as a destination in total world exports, similarly for TII on imports. A TII value larger than 1 indicates a large intra-African trade intensity compared to trade with the rest of the world.

| Region | Crop imports | | | | Crop exports | | | |
|---|---|---|---|---|---|---|---|---|
| | Baseline | Free Trade | AgDev | FT + AD | Baseline | Free Trade | AgDev | FT + AD |
| EAC | 5.83 | 10.02 | 4.99 | 10.16 | 1.46 | 3.43 | 1.25 | 3.82 |
| ECCAS | 6.46 | 9.71 | 0.59 | 2.94 | 0.26 | 2.03 | 0.51 | 3.37 |
| AMU | 0.21 | 0.63 | 0.30 | 1.42 | 0.02 | 1.87 | 1.04 | 4.40 |
| ECOWAS | 0.10 | 0.35 | 0.13 | 0.64 | 0.36 | 1.55 | 0.52 | 2.57 |
| SACU | 0.41 | 0.47 | 0.74 | 2.57 | 0.44 | 1.53 | 0.24 | 0.79 |
| RSouthAf | 5.06 | 7.62 | 3.08 | 4.86 | 2.20 | 3.85 | 1.63 | 3.88 |
| RCEAf | 0.85 | 2.80 | 1.22 | 4.74 | 0.24 | 1.49 | 0.64 | 3.16 |
| Egypt | 0.03 | 0.11 | 0.05 | 0.80 | 1.54 | 3.32 | 1.12 | 3.20 |

| Region | Livestock imports | | | | Livestock exports | | | |
|---|---|---|---|---|---|---|---|---|
| | Baseline | Free Trade | AgDev | FT + AD | Baseline | Free Trade | AgDev | FT + AD |
| EAC | 0.00 | 28.29 | 0.00 | 24.40 | 4.92 | 6.06 | 2.92 | 5.99 |
| ECCAS | 8.53 | 10.17 | 7.91 | 8.51 | 2.29 | 5.72 | 5.62 | 6.13 |
| AMU | 0.00 | 2.15 | 0.05 | 2.34 | 2.80 | 4.67 | 2.24 | 4.80 |
| ECOWAS | 2.50 | 5.92 | 2.62 | 6.13 | 0.00 | 6.06 | 6.55 | 6.18 |
| SACU | 0.00 | 0.00 | 0.00 | 0.00 | 2.45 | 4.89 | 2.42 | 4.91 |
| RSouthAf | 18.72 | 17.31 | 18.57 | 17.14 | 1.12 | 5.18 | 0.91 | 5.14 |
| RCEAf | 0.00 | 11.13 | 0.00 | 12.91 | 4.11 | 5.87 | 3.72 | 5.91 |
| Egypt | 0.00 | 1.52 | 0.38 | 2.42 | 0.57 | 3.26 | 0.54 | 3.20 |

Supplementary Table 7. Impact of *Free Trade* and *Agricultural Development* scenarios on agricultural trade balance of African regions for 2000 – 2050 in GLOBIOM. The trade balance is calculated as the total value of agricultural exports (domestic market price exporter x export volume) minus the total value of agricultural imports (domestic market price importer x import volume) for each region's agricultural trade flows with Africa and the rest of the world (in million 2000 USD). Given that our modelling framework does not cover all major African export commodities (i.e. not coffee, cocoa, tea and horticultural produce), the trade balances should be interpreted in terms of the relative differences across scenarios, rather than the absolute trend.

| REGION | Scenario | Agricultural trade balance (Mln. 2000 USD) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 |
| EAC | Baseline | -2 864 | -5 887 | -7 058 | -8 574 | -10 243 | -11 954 |
| | Free Trade | -2 864 | -5 887 | -7 058 | -14 190 | -17 399 | -20 809 |
| | AgDev | -2 864 | -5 887 | -7 058 | -6 920 | -8 320 | -9 439 |
| | FT + AD | -2 864 | -5 887 | -7 058 | -8 933 | -10 531 | -11 467 |
| ECCAS | Baseline | -2 646 | -7 789 | -8 125 | -9 207 | -10 342 | -11 719 |
| | Free Trade | -2 646 | -7 789 | -8 125 | -14 563 | -17 090 | -20 000 |
| | AgDev | -2 646 | -7 789 | -8 125 | -4 562 | -5 027 | -4 886 |
| | FT + AD | -2 646 | -7 789 | -8 125 | -3 951 | -4 403 | -4 081 |
| AMU | Baseline | -14 482 | -25 389 | -26 624 | -29 340 | -32 007 | -34 638 |
| | Free Trade | -14 482 | -25 389 | -26 624 | -29 766 | -32 636 | -35 318 |
| | AgDev | -14 482 | -25 389 | -26 624 | -21 434 | -21 007 | -20 670 |
| | FT + AD | -14 482 | -25 389 | -26 624 | -21 409 | -21 253 | -21 314 |
| ECOWAS | Baseline | -9 580 | -21 737 | -25 690 | -31 017 | -35 770 | -41 083 |
| | Free Trade | -9 580 | -21 737 | -25 690 | -30 706 | -35 761 | -40 799 |
| | AgDev | -9 580 | -21 737 | -25 690 | -23 742 | -28 214 | -29 036 |
| | FT + AD | -9 580 | -21 737 | -25 690 | -23 430 | -28 119 | -27 916 |
| SACU | Baseline | -538 | -3 329 | -2 925 | -2 497 | -2 175 | -1 603 |
| | Free Trade | -538 | -3 329 | -2 925 | -1 063 | -410 | 600 |
| | AgDev | -538 | -3 329 | -2 925 | -1 107 | -224 | 634 |
| | FT + AD | -538 | -3 329 | -2 925 | -451 | 684 | 1 900 |
| RSouthAf | Baseline | -37 | -982 | -211 | -1 049 | -1 452 | -1 738 |
| | Free Trade | -37 | -982 | -211 | 5 168 | 5 931 | 7 400 |
| | AgDev | -37 | -982 | -211 | -1 517 | -2 043 | -3 402 |
| | FT + AD | -37 | -982 | -211 | 675 | 250 | -859 |
| RCEAf | Baseline | -2 276 | -4 880 | -13 283 | -13 180 | -14 008 | -14 273 |
| | Free Trade | -2 276 | -4 880 | -13 283 | -14 590 | -16 181 | -17 124 |
| | AgDev | -2 276 | -4 880 | -13 283 | -11 230 | -10 547 | -9 962 |
| | FT + AD | -2 276 | -4 880 | -13 283 | -11 090 | -11 505 | -11 827 |
| EgyptReg | Baseline | -6 065 | -12 540 | -15 405 | -19 219 | -22 802 | -26 426 |
| | Free Trade | -6 065 | -12 540 | -15 405 | -18 831 | -22 354 | -25 802 |
| | AgDev | -6 065 | -12 540 | -15 405 | -18 848 | -22 001 | -25 185 |
| | FT + AD | -6 065 | -12 540 | -15 405 | -18 609 | -21 812 | -25 131 |

Supplementary Table 8. Determinants of extensive margin in agricultural trade. Probit regression at level of the 39 economic regions and 18 + 6 crop and livestock products in primary equivalent in GLOBIOM. Trade in volume with representative 5 year average for each time period.

| | Dependent variable: new trade in period [t+1] (1) or not (0) from exporter i to importer j in product k | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2000 (t) – 2010 (t+1) | | | | 2006 (t) – 2016 (t+1) | | | | | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| Tariff$_t$ (ijk) | -0.00002**<br>(0.00001) | -0.00001**<br>(0.00001) | -0.00002***<br>(0.00001) | -0.00002***<br>(0.00001) | | | | | | |
| ΔTariff (ijk) | -0.00000<br>(0.00001) | -0.00000<br>(0.00001) | -0.00001<br>(0.00001) | -0.00001<br>(0.00001) | | | | | | |
| Log(Distance) (ij) | -0.025***<br>(0.003) | -0.007**<br>(0.003) | -0.019***<br>(0.003) | -0.019***<br>(0.003) | -0.031***<br>(0.002) | -0.027***<br>(0.003) | -0.028***<br>(0.003) | -0.026***<br>(0.003) | -0.026***<br>(0.003) | -0.027***<br>(0.003) |
| Δ Log(GDP) (i) | 0.074***<br>(0.008) | 0.087***<br>(0.008) | 0.070***<br>(0.007) | 0.068***<br>(0.007) | -0.006<br>(0.009) | -0.006<br>(0.009) | -0.009<br>(0.007) | -0.022***<br>(0.008) | -0.023***<br>(0.008) | -0.037***<br>(0.008) |
| Dummy FTA$_t$ (ij) | | 0.053***<br>(0.012) | 0.014*<br>(0.008) | 0.016*<br>(0.009) | | | | | | |
| Dummy entry into FTA in [t+1] (ij) | | 0.010<br>(0.007) | -0.001<br>(0.006) | 0.002<br>(0.006) | | | | | | |
| Trade intensity$_t$ (ij) | | 0.280***<br>(0.037) | 0.240***<br>(0.035) | 0.230***<br>(0.035) | | 0.100***<br>(0.038) | 0.110***<br>(0.036) | 0.120***<br>(0.036) | 0.120***<br>(0.036) | 0.120***<br>(0.036) |
| Exporter experience$_t$ (ik) | | | 0.006***<br>(0.0002) | 0.006***<br>(0.0002) | | | 0.004***<br>(0.0002) | 0.004***<br>(0.0002) | 0.004***<br>(0.0002) | 0.005***<br>(0.0002) |
| Δ Export cost (i) | | | -0.001**<br>(0.0005) | -0.008***<br>(0.002) | | | | | | |
| Export cost$_t$ (i) | | | | 0.001***<br>(0.0004) | | | | | | |
| Δ Export cost* Export cost$_t$ (i) | | | | 0.0004***<br>(0.0001) | | | | | | |
| Δ Log(TFI) (i) | | | | | | | -0.002<br>(0.012) | -0.110**<br>(0.050) | -0.082<br>(0.051) | 0.001<br>(0.052) |
| Dummy TFIt (i) < 1.5 | | | | | | | | 0.012***<br>(0.004) | 0.012***<br>(0.004) | 0.008*<br>(0.004) |
| Δ Log(TFI) * Dummy TFI$_t$ (i) < 1.5 | | | | | | | | 0.086*<br>(0.052) | 0.065<br>(0.052) | 0.005<br>(0.052) |
| Δ Log(CUST) (i) | | | | | | | | | 0.025**<br>(0.012) | -0.044*<br>(0.024) |
| Dummy CUST$_t$ (i) < 4 | | | | | | | | | | 0.024***<br>(0.004) |
| Δ Log(CUST) * Dummy CUST$_t$ (i) < 4 | | | | | | | | | | 0.052*<br>(0.027) |
| Observations | 20,949 | 20,949 | 20,949 | 20,949 | 19,243 | 19,243 | 19,243 | 19,243 | 19,243 | 19,243 |
| Log Likelihood | -3,993 | -3,945 | -3,500 | -3,484 | -2,993 | -2,989 | -2,697 | -2,655 | -2,655 | -2,606 |
| Pr > Chi2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Note: *p<0.1; **p<0.05; ***p<0.01

Product and Importer Fixed Effects included. New trade flows smaller than 1000 ton dropped from the sample.

Δ: change in variable over time ([t+1] – [t]).

Supplementary Table 9. Data and assumptions for the compilation of international road transport costs in Africa.

| Data | |
|---|---|
| Distance from country $c$ to country $\check{c}$ (km) | GeoDIST CEPII |
| Fuel price for transport between country $c$ to country $\check{c}$ (USD/liter) | GIZ International Fuel Prices average 1998, 2000 and 2002 – average of fuel price in regions that are crossed for trade between exporter $r$ to importer $\check{r}$. |
| Truck parameters for trade from country $c$ to country $\check{c}$: daily fixed cost, profit margin, speed, fuel consumption, other variable costs (tires, maintenance, bribes) | Survey data from Teravaninthorn and Raballand[5]. To obtain bilateral-specific values, we take the average parameter value of all countries that are crossed for trade between exporter $c$ to importer $\check{c}$. |
| **Assumptions** | |
| Border crossing time | Based on average number of country borders to cross between exporter and importer, assuming 24 hours delay per country border crossing[65,66]. Transport route based on road network from African Development Report 2010 (Map 4.4 Major African Corridors)[74]. For example, under these assumptions, EAC has an average border crossing time of 48 hours with RSouthAf, 60 hours with ECCAS and 84 hours with SACU. |
| Other waiting time: delays at weighbridges at roadblocks | 2 days for crossing one regional border, 3 days for crossing 2 regional borders, 4 days for crossing 3 or more regional borders[65,66]. |
| Driver resting time | Driving time x 2[66] |
| Load capacity | 30 ton[65,66] |
| Differentiation across products | Transport cost of livestock products = 2x transport cost of crops. |

Supplementary Table 10. Data and assumptions for the compilation of local trade costs in Africa.

| Data | |
|---|---|
| Average travel time in each homogenous response unit (HRU) to reach closest city with 50,000 inhabitants (hours) | Weiss et al.[4]. We estimate the distance to closest city based on the reported average speed in African regions in Teravaninthron and Raballand[65] and based on an average 60 km/h for countries in the rest of the world. |
| Fuel price (USD/liter) | Average regional price from GIZ International Fuel Prices, average 1998 - 2002 |
| Truck parameters: daily fixed cost, transporter profit margin, speed, fuel consumption, other variable costs (tires, maintenance, bribes) | Regional parameters based on survey data from Teravaninthorn and Raballand[65] and Eberhard-Ruiz and Calabrese[66], e.g.:<br>• Speed: 30 km/h in ECCAS, EAC, RCEAf and ECOWAS; 50 km/h in the other African regions.<br>• Fuel consumption: 65 l per 100 km in ECCAS, 60 l per 100 km in ECOWAS, EAC and RCEAf and 50 l per 100 km in the other African regions.<br>• Trucker profit margin: 109% in ECCAS, 80% in ECOWAS, 66% in RCEAF and EAC, 40% in RSouthAf and 15% in SACU, EgyptReg and AMU.<br>• Uniform value of 60 USD/ton for daily fixed costs for all African countries. |
| Assumptions | |
| “First mile” transport | The first 5 km is transported with small vehicle with low load capacity (50 kg) e.g. motorcycle, pack donkey, … [6] |
| Medium distance transport | In all Sub-Saharan African countries (except South Africa), the first 50 km after first mile transport with pick-up truck with medium load capacity (1.2 ton)[6–8]. |
| Long distance transport | In all Sub-Saharan African countries (except South Africa), the rest of the distance to the closest city of 50,000 inhabitants is travelled through truck with large load capacity (12.5 ton)[7,75]. For countries in Northern Africa and South-Africa, large load capacity truck is assumed for both medium and long distance transport. |
| Driver resting time | Driving time x2[66] |
| Marketing costs (storage, losses, wholesale fees & profit) | 30% mark-up on purchase price (producer price + transport cost), based on reported price transmission between farm gate and wholesale in Ghana in World Development Report 2008[13], composition of wholesale price in Minten and Kyle[12] and ratio between marketing and transport cost in Fafchamps et al.[8]. |
| Differentiation across products | Transport costs of milk x2, transport costs of meat and eggs x4. |

Supplementary Table 11. Validation of GLOBIOM local trade cost in African regions in 2000 with literature and price data. For each Africa region, regionally important products are selected.

| REGION | Commodity | Weighted Avg. Distance to 50K city† (km) | Weighted Avg. local trade cost‡ (2000 USD/ton) | Producer – to – consumer price ratio | VALIDATION Producer – to – wholesale price ratio (survey evidence/FAO data) |
|---|---|---|---|---|---|
| ECOWAS | Maize<br>Rice<br>Poultry meat | 122<br>125<br>137 | 158<br>181<br>601 | 60%<br>66%<br>75% | 64% (Ghana maize,[13]), 81% (Benin agricultural products, [8]; avg. distance 69 km) |
| ECCAS | Maize<br>Cassava<br>Groundnut | 205<br>260<br>254 | 195<br>243<br>276 | 62%<br>50%<br>63% | 41% (Congo Dem. R., [12]; avg. distance: 337 km cassava, 373 km groundnut, 323 km maize) |
| EAC | Maize<br>Cassava | 135<br>155 | 155<br>156 | 58%<br>41% | 40 – 55% (Uganda maize, [76]), 33 – 45% (Uganda cassava, [76]) |
| RCEAf | Maize<br>Wheat<br>Sorghum | 294<br>251<br>181 | 102<br>121<br>102 | 53%<br>74%<br>56% | 63% - 89% (Ethiopia grain market, [77]; avg. distance 177 – 331 km); 79 – 86% (Ethiopia teff, [6]) |
| RSouthAf | Maize<br>Cassava<br>Rice | 207<br>253<br>257 | 121<br>115<br>134 | 60%<br>44%<br>65% | 65% (Malawi domestic agricultural products, [8]; avg. distance 53 km), 76% (Madagascar domestic agricultural products, [8]; avg. distance 39 km) |
| AMU | Maize<br>Wheat | 108<br>108 | 35<br>63 | 90%<br>87% | No validation data available |
| Egypt | Maize<br>Wheat | 296<br>677 | 49<br>64 | 84%<br>84% | No validation data available |
| SACU | Maize<br>Beef | 132<br>234 | 39<br>341 | 81%<br>74% | 82% (South Africa maize, FAO/GIEWS producer to wholesale price, 2000); 50% - 99% (South Africa beef, [78]) |

Supplementary Table 11 (continued). Validation of GLOBIOM local trade cost in rest of the world in 2000 with literature and price data. For rest of the world, regional relevant cereal products with validation data available are shown.

| REGION | Commodity | Weighted Avg. Distance to 50K city[†] (km) | Weighted Avg. local trade cost[‡] (2000 USD/ton) | Producer – to – consumer price ratio | VALIDATION Producer – to – wholesale price ratio (survey evidence/FAO data) |
|---|---|---|---|---|---|
| RussiaReg | Maize | 150 | 35 | 82% | 73% - 100% (FAO/GIEWS producer to wholesale price, maize, range 2005 – 2014); 72% - 84% (FAO/GIEWS producer to wholesale price, 3rd class wheat, range 2005 – 2014) |
| | Wheat | 149 | 29 | 86% | |
| UkraineReg | Maize | 110 | 28 | 66% | 69% (FAO/GIEWS producer to wholesale price, maize, 2000) |
| BrazilReg | Maize | 164 | 27 | 85% | 80% - 110% (FAO/GIEWS producer to wholesale price, maize, range 2014 – 2016) |
| IndiaReg | Wheat | 216 | 47 | 71% | 73% - 104% (FAO/GIEWS producer to wholesale price, wheat, 2000); 53% - 74% (FAO/GIEWS producer to wholesale price, rice, 2000) |
| | Rice | 165 | 40 | 72% | |
| ChinaReg | Maize | 167 | 30 | 85% | 95% - 130% (FAO/GIEWS producer to wholesale price, maize, range 2014 – 2016); 58% - 95% (FAO/GIEWS producer to wholesale price, rice, range 2014 – 2016) |
| | Rice | 159 | 36 | 82% | |

[†] The regional distance to market is the average of the distance to closest city of 50K inhabitants for each supply unit weighted by the base-year production quantity in each supply unit for each commodity.

[‡] The regional local trade cost is the average of the local trade cost across supply units weighted by the base-year production quantity in each supply unit for each commodity. When a region does not produce a certain product in the base-year, a simple average is taken across supply units.

Supplementary Table 12. Assumptions on Africa food value chain stage in 2020 in GLOBIOM. In 2000 all countries and commodities are assumed to be marketed in traditional value chains with 30% marketing margin.

| Stage | Country | Commodity | Source |
|---|---|---|---|
| Modern (10% marketing margin) | Morocco | Poultry meat | [55] |
| Transitional (15% marketing margin) | Zambia | Maize, soya, sugarcane | [57,79] |
| | Zimbabwe | sugarcane | [79] |
| | South Africa | Maize | [80] |
| | Kenya | Maize, beans, sugarcane | [81], MAFAP |
| | Tanzania | Maize | MAFAP |
| | Uganda | Sugarcane | MAFAP |
| | Nigeria | Rice, Maize | [58], MAFAP |
| | Senegal | Rice | [58] |
| Transitional (20% marketing margin) | All other SSA countries | All other | [56] |

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