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Long-Term Scenarios for Sub-Saharan Africa's Agro-Food Markets with Varying Population, Income, and Crop Productivity Trends

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This study develops long-term scenarios combining trends in population numbers, incomes, and crop productivity for Sub-Saharan Africa (SSA) up to 2050 by using a recursive-dynamic version of the GTAP general equilibrium model. Results suggest that crop productivity will have a major impact on cropland expansion in SSA, giving potentially available cropland the role of a buffer that could smooth differences between future production outcomes. Another inherent smoothing factor will be countervailing trends in population and income growth that will diminish future differences in food commodity consumption per capita and limit the impact of African trends in the rest of the world.

Key words: cropland expansion, food availability, global economic modeling, socioeconomic trends

Introduction

According to the UN Population Division (2017), the population of Sub-Saharan Africa (SSA) is projected to more than double from today's levels to above 2 billion in 2050. This future population is also very likely to enjoy significantly higher disposable income than today. Consequently, SSA's agricultural sector would have to almost triple its production in the coming decades (van Ittersum et al., 2016) to meet the additional demand for food, feed, fuel, and other purposes of crop biomass, requiring both an expansion of cropland area and a catch-up in crop yields (Alexandratos and Bruinsma, 2012).

Crop area productivity in SSA is low and its growth has been slower than in most parts of the world (Figure 1), while production increases resulted mainly from crop area expansion (Figure 2). These diverging demographic and crop productivity trends suggest that future developments in SSA's agro-food markets are likely to differ substantially from those in the rest of the world. The numerous outlook exercises that discuss the problem of meeting future food demand with sufficient supply (see Le Mouël and Forslund, 2017, for an extensive review) do so mostly from a global balance perspective and hardly address these issues specific to SSA. Indeed, research specifically aimed at SSA's role in future global markets has been scarce so far. An exception is Sulser et al. (2015), who investigate the impact of expected climate change on Africa by 2030 and 2050 using the IMPACT global partial equilibrium model for agricultural commodity markets, an approach which does not consider macroeconomic repercussions.

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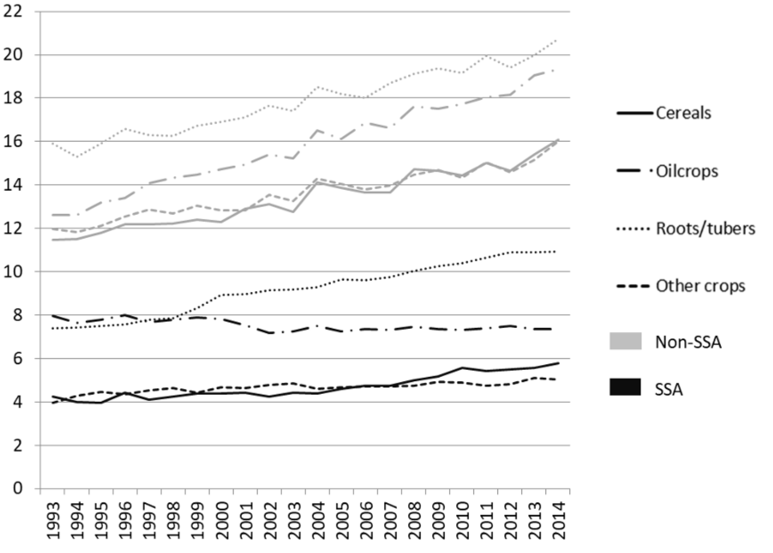

Figure 1. Development of Crop Energy Yields for Major Cultivar Groups in Sub-Saharan Africa (SSA) and the Rest of the World (Non-SSA) (millions kCal/ha), 1993–2014

Source: Food and Agriculture Organization of the United Nations (2017).

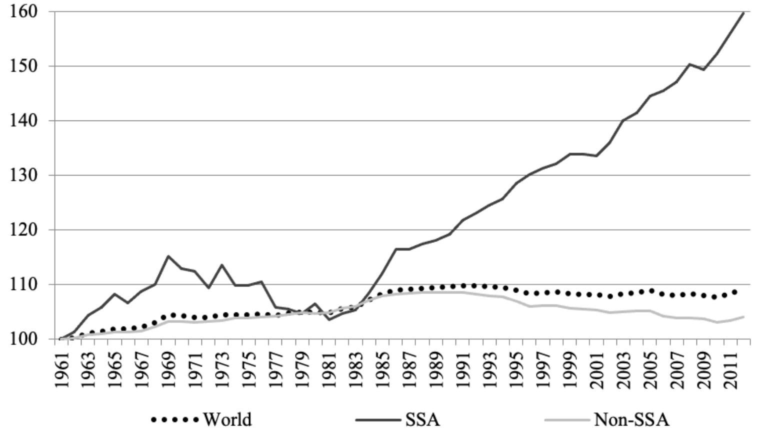

Figure 2. Index of Arable Land in Sub-Saharan Africa (SSA), Non-SSA, and World (1961 = 100), 1961–2012

Source: Food and Agriculture Organization of the United Nations (2017).

Currently, more than 20% of SSA's cereal demand has to be imported (Food and Agriculture Organization of the United Nations, 2017). This share is likely to increase due to sluggish yield growth and the fact that reserves of now uncultivated but potentially available cropland in SSA are still large, albeit not unlimited (Chamberlin, Jayne, and Headey, 2014). Indeed, despite a 60% increase in total arable land use in the last 50 years in SSA (Figure 2),[1] its rapid population growth decreased arable land per person by more than half. Of the selected major world regions, only North America's land use per person dropped faster than SSA's since 1990, and SSA's land-to-inhabitant ratio is now the second lowest after densely populated Asia. Even the steep 26% increase of land use in SSA since 1990 could not prevent a sharp decrease of cropland available per inhabitant.

[1] In FAO terminology, area under "arable land" accounts for all cropland that is used for annual crops, fodder, or rotational fallow. In the following, "arable land" and "cropland" are used synonymously.

Table 1. Land with Rainfed Crop Production Potential for Sub-Saharan Africa (SSA) and Non-SSA) (million ha)

	Non-SSA			SSA		
	Million ha	Percentage of Suitable Land	Percentage of Global Total	Million ha	Percentage of Suitable Land	Percentage of Global Total
Suitable land	3,422	–	76.1	1,073	–	23.9
Total cropland	1,077	31.5	85.5	183	17.1	14.5
Gross reserve	2,345	68.5	72.5	890	82.9	27.5
Prohibited use[a]	1,386	40.5	76.0	438	40.8	24.0
Net reserve	959	28.0	68.0	452	42.1	32.0

Notes: [a]Includes forests and protected areas.
Source: GAEZ v3.0 in Fischer et al. (2012).

Table 2. Share of Major World Regions in Global Cropland (temporary and permanent crops) and Cropland Expansion, 1993–2016

	Share in Global Cropland (%)		Cropland Expansion (%)	
Region	1993	2015	Total Growth 1993–2015	Annual Growth 1993–2015
World	100.0	100.0	3.6	0.2
Australia, New Zealand	3.3	3.1	2.3	0.2
Central and Eastern Asia	12.1	11.5	−3.6	−0.3
Southeast Asia	5.8	7.3	30.5	1.4
South Asia	15.7	15.0	−0.9	−0.1
North America	15.5	12.7	−13.8	−0.8
Latin America and Carib.	9.9	12.3	27.0	1.2
Europe	20.6	18.2	−7.2	−0.4
West Asia and North Africa	6.0	5.9	1.1	0.0
Sub-Saharan Africa (SSA)	11.2	14.0	28.0	1.3
World w/o SSA (Non-SSA)	88.8	86.0	0.5	0.0

Notes: In the case of North America, a major source of the reported cropland decline is the statistical reclassification of areas producing fodder (e.g., alfalfa) into pasture after 2002, while planted crop areas even have grown since then.
Source: Food and Agriculture Organization of the United Nations (2017).

The strong trend in SSA's cropland raises the question about the remaining potential for expansion. Table 1 shows recent global estimations for suitable cropland resources (i.e., suitable for the major food crops and their regional varieties), split into SSA and non-SSA.

The data suggest that, with one-third of global net reserves, SSA still has the potential for more than twice its current cropland use. SSA's gross land reserves—which include forests and protected areas—are almost 5 times above current cropland use. This means that the potential for land expansion in parts of SSA will continue, at least until 2050. Between 1993 and 2015, arable land increased at an average annual rate of 1.25% (see Table 2). When assuming a continuation of this growth (which is plausible, as SSA's farm population growth is also going to continue), SSA would see a further increase in cropland of roughly 55% from 2010 to 2050. That would change the ratio of cropland to net reserve from 183:452 (2010) to 283:352 (2050). But the continent's sufficient land endowment does not preclude the emergence of problematic regional land scarcity in more densely populated countries in Western and Central Africa. Chamberlin, Jayne, and Headey (2014) point out that land abundance is unequally distributed across SSA, with West Africa likely to become severely land constrained even before 2050.

Given these upcoming constraints, delivering sufficient food without increasing pressure on land by means of "sustainable intensification" (Smith, 2013) is high on the agenda for international agricultural research organizations. Godfray et al. (2010), for instance, discuss measures to increase production and use efficiency, which make it jointly possible to feed more than 9 billion people worldwide by 2050 without further agricultural land expansion. van Ittersum et al. (2016) question whether the same holds for SSA (i.e., that it could feed itself by 2050 or later based on its current agricultural land given its population trends). They contend that further substantial crop area expansion would be inevitable even if SSA's large yield gaps for major crops were closed, which is rather unlikely (see again Figure 1). Even if enough food could be produced globally, SSA would further enlarge its food import dependency. Consequently, outlook studies focusing on future global land use report that Africa will experience the largest continental increases of cropland use by the middle of the twenty-first century, despite soaring food imports (e.g., Schmitz et al., 2014; Sulser et al., 2015).

This study strives to systematically explore possible trajectories for the three most crucial driving factors for Africa's biomass market development: population, income, and crop area productivity. For that purpose, we develop long-term scenarios that combine demographic, economic, and agro-technological trends up to 2050 by using a recursive-dynamic version of the Global Trade Analysis Project (GTAP) general equilibrium model. Results focus on cropland use, farm production, food consumption, and imports of food commodities. By comparing results for SSA with those of the rest of the world (non-SSA), we also look at possible changes in the position and role of SSA in global crop biomass markets. The model used for scenario generation is the GTAP-derived recursive dynamic extended model (G-RDEM).[2]

Methodology: Long-Run Projections with a Dynamic General Equilibrium Model

Agriculture still employs a large share of the workforce in SSA and contributes considerably to gross domestic product (GDP), but its role in the overall economy is likely to change considerably in upcoming decades. These long-term interactions between a large agricultural sector and the rest of an economy can be simulated by the use of a computable general equilibrium (CGE) model. G-RDEM is a CGE model specifically developed to generate long-term baselines. It is based on the well-known and tested standard GTAP model (Hertel and Tsigas, 1997), which shares basic features with most other global CGE models. The recursive-dynamic G-RDEM model adds five features especially important to simulate long-run structural change: a demand system with nonlinear Engel curves, endogenous saving rates, differentiated industrial productivity growth, interest payments on foreign debt, and time-varying cost shares for intermediates. G-RDEM is part of the modular and flexible platform CGEBox (Britz and van der Mensbrugghe, 2018) for computable general equilibrium modeling. CGEBox allows us to introduce additional features on top of the mechanisms provided by G-RDEM that are not part of the GTAP standard model but are useful for long-term analysis. To facilitate modernization processes in the agro-food sector, we allow for substitution between intermediate inputs in production, specifically for feed substitution in animal production and for agricultural goods in the food industry. To enable long-term changes in consumer preferences, we replaced the CDE (constant difference in elasticity) demand system used in the GTAP standard model by an implicitly additive demand system, where exponential Engel curves are driven by the utility depending on income. The underlying parameters are estimated on global panel data to cover the relevant income changes during baseline construction. As the commitment terms are generally small relative to given consumption, the Engel curves therefore follow rather closely the changes in marginal budget shares driven by longer-term growth in real per capita GDP.

The resulting CGE model is used here to generate different long-term baselines by letting it replicate exogenously given paths of economic development as depicted by changes in real GDP and population. These projections emerge from the Shared Socioeconomic Pathways (SSPs) as implemented by the International Institute for Applied Systems Analysis (IIASA) (van Vuuren et al., 2017). The main aim of the application of the CGE model is to provide a consistent and

[2] See Britz and Roson (2019) for an extensive explanation and discussion.

plausible global decomposition of given macroeconomic and population projections with regard to industrial and demand composition. Our focus on biomass production and use implies to maintain the full detail for agriculture and food processing available in the latest GTAP 9 database (Aguiar, Narayanan, and McDougall, 2016), which provides a snapshot of the global economy in 2011 for 140 countries or regions and 57 sectors. We choose to aggregate to 10 global regions, of which one is SSA, but keep full sectoral detail.[3] Further, we carefully model changes at the intensive margin in agriculture (i.e., yield developments) and at the extensive margin (i.e., land expansion), as discussed in the following sections.

A distinctive feature of the scenarios presented in this study is the use of fixed trajectories of crop area productivity (i.e., crop yields) over the 40-year simulation period. The fixed crop productivity trajectories are used to clearly separate the effects of the varying pace of technological change on markets from other factors and were obtained by precalculating linear trends of crop area productivity and imposing these on the relation between crop output and cropland factor use in the model. As crop area productivity is an implicit endogenous variable in the standard version of G-RDEM, fixing it requires that an otherwise fixed parameter (model coefficient) of the same dimensionality had to be turned into an adjusting variable to keep the model square. The suitable choice is land-specific technical change, which adjusts endogenously for each region, crop, and simulation period. The derivation of the crop yield trajectories is explained in more detail in the section on scenarios. Finally, this study uses the GTAP-AEZ database (Lee et al., 2005) and module to simulate agricultural production on the spatial scale of agro-ecological zones (AEZ) within each model region, using real hectares as units for crop area.

Modeling and Parameterization of Cropland Expansion in G-RDEM

Table 2 summarizes cropland expansion in major world regions since the beginning of the 1990s. For most world regions, cropland has not been observed to expand significantly in recent decades. Reasons for that are restrictions to land conversion (most effective in high-income countries) but also an exhaustion of land reserves such as in most arid and semi-arid regions. Exceptions to this global trend of stagnating cropland growth are Southeast Asia, Latin America, and Sub-Saharan Africa, which have all expanded their cropland by a bit more than one-quarter since 1993. However, expansion in Latin America and Southeast Asia was compensated by declining cropland in North America, Europe, and Eastern Asia, which results in an only marginal increase of 0.51% in cropland for non-SSA between 1993 and 2016.

The approach chosen for shifting production factor supply in general (labor, capital, land) is a central characteristic of any dynamic CGE model. In the case of G-RDEM, while labor supply is assumed to grow with population, the growth of the capital endowment employed in various sectors is dynamically governed by the price of capital and investment processes. Similar to capital, available cropland is not automatically growing with population, as growth in cropland is constrained by potentially available cropland, the latter being either natural land-cover forms such as forest or savanna or land already under agricultural use, such as pasture. In the model version applied for this study, supply of land is governed by an elasticity reacting to land shadow prices. In an attempt to extrapolate cropland expansion in the different GTAP regions from recent decades (see Table 2) up to 2050 for the baseline scenario, this elasticity was set to 0.25 for world regions with higher cropland expansion pressure (SSA, Latin America, South Asia, and Southeast Asia), and to 0.05 for all other regions. Available land can then be substituted among different use categories depending on relative land rents, as shown in Figure 3, with ω denoting the elasticity of substitution in factor demand. The elasticities for substitution between pasture and cropland were again chosen higher

[3] The sectoral aggregation of the employed model version contains the following cropping activities: wheat, rice, maize, "other cereals," "vegetables, fruits and nuts," oilseeds, sugar crops, plant-based fibers, and "other crops." The GTAP database does not provide a detailed distinction between African staple and cash crops, which limits the scope for analyzing, for example, food-versus cash crop–centered strategies for food security.

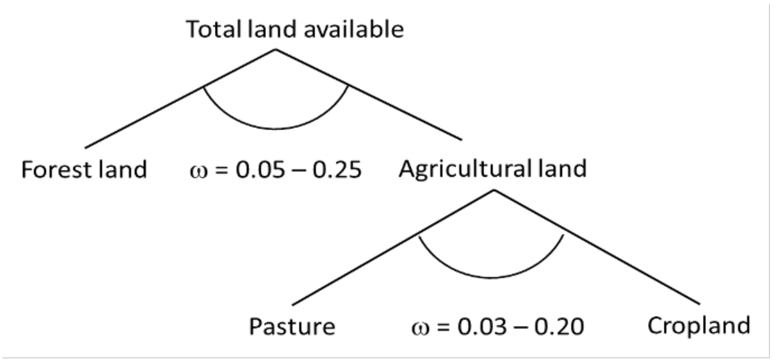

Figure 3. Nesting Scheme of Substitution Possibilities in Land Use for Biomass Production, with Applied Substitution Elasticity Values (*ω*)

(0.2) for SSA, South Asia, Southeast Asia, and Latin America, while kept at 0.03 for all other world regions. The numbers attached to the different elasticities were chosen such that prevailing trends in land use categories for the involved world regions were largely continued in the baseline scenario. As regional land use trends appear to be relatively stable over several decades, land supply elasticies were kept constant over the simulation period.

Scenario Design

The simulated scenarios are characterized by trend variations in the socio-economic (population and GDP growth) and crop productivity dimensions. Three socio-economic baseline scenarios with predefined population and economic income trajectories are created, which are then shocked with three different crop biomass productivity trajectories.

Socioeconomic Trends

Population and economic growth trends driving our recursive-dynamic model were mainly borrowed from the IIASA SSP scenario database (International Institute for Applied Systems Analysis, 2016) which provides a quantitative framework for the IPCC's Shared Socioeconomic Pathway narratives. Additionally, recently updated population projections for SSA were adopted from Food and Agriculture Organization of the United Nations (2017). While non-SSA regions are assumed to follow the SSP2 ("middle-of-the-road") pathway throughout all scenarios, SSA's development is varied between SSP2, SSP1 ("sustainability"), and SSP3 ("fragmented world"), as illustrated by Figure 4. Under the assumptions of SSP1, global as well as regional population growth would be lower and economic growth higher than under SSP2, while the opposite would be the case for SSP3, which is why SSP1 is referred to as an optimistic and SSP3 a pessimistic scenario regarding human development.

Throughout the scenarios, SSA's average population growth is considerably higher than that in the rest of the world. The populations of those regions that form non-SSA would grow by factors of between 0.9 (East Asia) and 1.5 (North Africa and Middle East), with their combined growth projected to a moderate 18% between 2010 and 2050. In stark contrast, SSA's corresponding population growth is 140% for the same period in the model's baseline scenario, SSP2. While SSA's population accounts for 12.1% of the global total in 2010, it is projected to rise to 22% in 2050 due to a lagged demographic transition (Conley, McCord, and Sachs, 2007). SSA's GDP growth per capita is above non-SSA's for SSP1 and SSP2 but lower for SSP3. According to these average annual growth rates, SSA's per capita GDP would increase by a factor of between 1.4 (SSP3) and 3.4

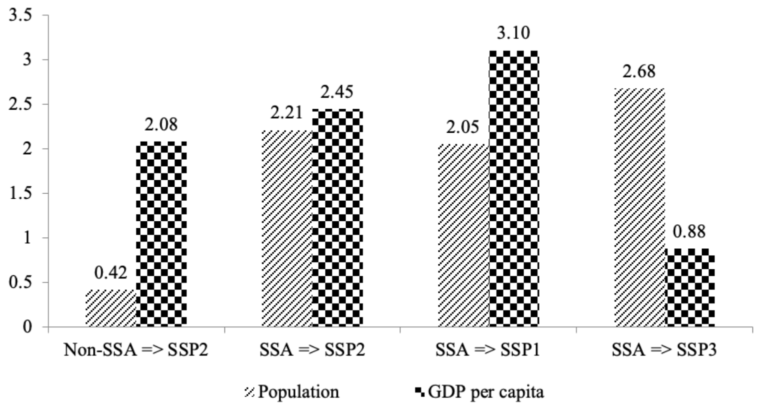

Figure 4. Socioeconomic Trends: Average Annual Growth Rates of Population and Real per Capita GDP, 2010–2050, in Percentage for Sub-Saharan Afria (SSA) and Non-SSA (average across regions for latter)

(SSP1) between 2010 and 2050. Both population and income trends have decreasing growth rates over the simulation period.

Crop Productivity Trends

Energy yields (million Kcal per hectare) were calculated for a broad selection of crops covering more than 98% of global cropland. Data on the yields of each cultivar's harvested commodities (in hectogram per hectare) were obtained from FAOSTAT (Food and Agriculture Organization of the United Nations, 2017). The gross energy contained in these crop commodities was obtained from the FAOSTAT crop consumption database as well as from Feedipedia (http://www.feedipedia.org). Energy yields of crop groups could then be calculated by multiplying physical crop yields with energy content per kilogram. These energy yields were then aggregated to crop groups (cereals, oil crops, roots and tubers, and other important annual and perennial crops) and across all crops. To make these energy yields useful as a driving factor for long-term projections, we calculated linear trends for individual countries, given data availability and plausibility. The linear trends were then converted into percentages of the average 2012–2014 energy yields for each country. The purpose of this conversion into percentages was to create the possibility of applying them to the GTAP baseline relation of crop output to land factor use of the related cropping activity, expressed as USD per USD relation and not in physical units. For simplicity, the resulting area productivity trends were applied to all cropping activities in the GTAP database and thus implicitly also to niche crops that were omitted from the energy yield calculations.

Trends for country groupings were then calculated as averages of all or selected members of the grouping. The average of all member countries is assumed to represent the baseline trend, whereas the average of the "best" or "worst" performing two-thirds of the country groupings was taken as an "optimistic" or "pessimistic" outlook on crop productivity (Figure 5). The results, despite being aggregated across all crops, are diverse across world regions. As it is unlikely that trends based on 2 decades of data would continue on smaller spatial scales until 2050, yield trends were aggregated for two stylized groupings, Sub-Saharan Africa (SSA) and all other countries (non-SSA), for the GTAP simulations, as shown in Figure 5.

For all crops taken together, projected productivity growth is smaller for SSA than for the rest of the world. The difference is particularly large under the pessimistic perspective. As current absolute productivity levels are also significantly lower in SSA, only the combination of an optimistic productivity scenario for SSA with the baseline scenario for non-SSA would facilitate a long-term

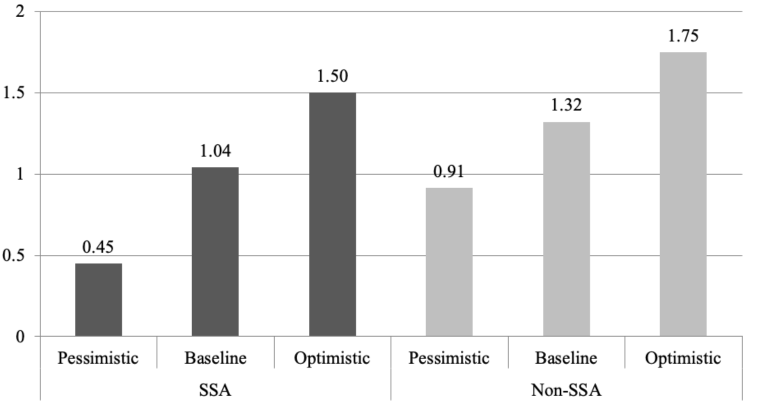

Figure 5. Crop Energy Yield Trends for Sub-Saharan Africa (SSA) and Non-SSA for All Crops Taken Together, Baseline, Pessimistic or Optimistic Trends Based on 1993–2014 (as a percentage of 2012–2014 yield levels)

closure of the gap between SSA's crop productivity and the world average. The absolute magnitude of the projected annual productivity growth is roughly in line with results from Ray et al. (2013), who also point out that this global productivity growth trend would require additional cropland expansion to produce sufficient crops for future global demand. It can therefore be expected that simulations will lead to moderate global cropland expansion, with land expanding most where demand will grow fastest.

Scenarios

In all, we simulated seven scenarios, one baseline and six counterfactual scenarios. Two counterfactual scenarios focus on differences in socioeconomic trends between SSA and the rest of the world, two on differences in crop productivity, and two combine these two dimensions. Even though the shorthands for all scenarios contain the abbreviation SSP, these scenarios are not meant to reflect detailed SSP narratives but only possible consequences of these narratives for population and economic growth. Exogenous crop productivity trends are deliberately not endogenously linked to socioeconomic trends; rather, this study explicitly assumes that progress in cropping technology development and adoption will not happen automatically with economic growth but will require specific impulses and efforts by agricultural policy, as the history of the Green Revolution demonstrates.

Baseline Scenario

The base scenario to which all other scenarios are compared contains the SSP2 (business as usual) population and income trends for both SSA and non-SSA-regions. In addition, crop energy yield trends averaged across all crops (enforcing uniform trends for crop groups) for the base period, 1993–2014, are applied (SSP2-Av_Yield). Despite its first-view rigidity, unitary trends across crop categories might be the more realistic long-term outlook, as it is unlikely that crop productivity trends would diverge massively between different crops over several decades.

Socioeconomic Counterfactual Scenarios

These scenarios focus on socioeconomic trends (population and per capita income growth). We run simulations that keep SSP2 trends for non-SSA, while applying SSP1 or SSP3 trends to SSA,

Table 3. Scenario Overview: Combinations of Socioeconomic and Crop Productivity Trends

	Socioeconomic Trends		
Crop productivity trends	**SSP2** (trend population and income growth)	**SSP1** (low pop. growth, high GDP growth)	**SSP3** (high pop. growth, low GDP growth)
Average crop productivity	Baseline	SSP1-Av_Yield	SSP3-Av_Yield
Optimistic crop productivity	SSP2-Opt_Yield	SSP1-Opt_Yield	
Pessimistic crop productivity	SSP2-Pess_Yield		SSP3-Pess_Yield

which results in two scenarios (SSP1-Av_Yield and SSP3-Av_Yield). These scenarios illustrate the increasing socioeconomic weight of SSA in world agricultural markets, which is mainly due to SSA's outstanding population development. The impact of SSA's growing global weight will become apparent when comparing changes by, say, 2020 with those by 2050. Crop productivity trends are kept at averages based on a period from 1993 to 2014 and will not vary with socioeconomic trends.

Counterfactual Scenarios Combining Socioeconomic and Agrotechnological Trends

It is highly plausible that higher economic growth will foster the development and adoption of agricultural technologies that would increase SSA's currently low crop productivity levels. This is reflected in a set of additional scenarios that augment the previously mentioned socioeconomic scenarios with long-term trends of area productivity for all crops combined. This exercise will help to explore SSA's capacity to feed itself for the coming decades. We simulated the following four counterfactual scenarios:

1. The "optimistic" productivity scenario involves higher income growth and smaller population increase (SSP1 scenarios), which are combined with optimistic crop yield trends for SSA (SSP1 Opt_Yield).

2. The "pessimistic" productivity scenario combines the socioeconomic SSP3-scenarios (higher population and lower economic growth with pessimistic crop yield trends for SSA) (SSP3 Pess_Yield).

3. The "yield effort" scenario illustrates the difference a specific effort to increase African crop yields could make. Optimistic yield trends are combined with baseline socioeconomic trends in this scenario (SSP2 Opt_Yield).

4. Finally, a scenario with average socioeconomic trends but pessimistic expectations regarding crop biomass productivity. This scenario would assume that SSA would return to the sluggish crop productivity growth that was characteristic from the 1970s through the 1990s (SSP2 Pess_Yield).

The last two scenarios would be compared to the baseline scenario with the goal of investigating an increasing global market impact of African crop productivity development. Results will focus on SSA's future crop biomass production and import requirements as well as per capita food consumption and crop price changes. Moreover, future global and regional needs for cropland are discussed. Table 3 summarizes the scenarios.

The macroeconomic closure of the model keeps the exchange rates of all model regions fixed to unity and uses them as the regional numeraire, while foreign savings and trade balances adjust over time and due to shocks.

Table 4. Percentage Change in Total Output, All Crops and Cereals, 2010–2050

	All Crops		Cereals	
Scenario	**SSA (%)**	**Non-SSA (%)**	**SSA (%)**	**Non-SSA (%)**
Baseline	119.4	54.2	133.8	62.5
SSP1-Av_Yield	123.9	54.6	138.5	63.2
SSP3-Av_Yield	111.8	53.8	126.5	61.7
SSP2-Opt_Yield	145.5	54.0	160.1	62.3
SSP2-Pess_Yield	84.7	54.4	98.1	62.5
SSP1-Opt_Yield	150.9	54.3	166.3	63.0
SSP3-Pess_Yield	78.9	53.9	93.4	61.5

Table 5. Percentage Change in per Capita Output, All Crops and Cereals, 2010–2050

	All Crops		Cereals	
Scenario	**SSA (%)**	**Non-SSA (%)**	**SSA (%)**	**Non-SSA (%)**
Baseline	−8.6	30.6	−2.6	37.7
SSP1-Av_Yield	−0.7	30.9	5.7	38.2
SSP3-Av_Yield	−26.5	30.3	−21.4	37.0
SSP2-Opt_Yield	2.3	30.4	8.4	37.5
SSP2-Pess_Yield	−23.0	30.8	−17.5	37.7
SSP1-Opt_Yield	11.2	30.7	18.0	38.1
SSP3-Pess_Yield	−37.9	30.4	−32.9	36.9

Results

Starting with crop production, Table 4 shows quantitative changes in the output of crop biomass for SSA and the rest of the world (non-SSA). Results are shown for crop in total and for cereals, which are the most important energy source for food, feed, and bio-based fuels. In the middle-of-the-road baseline scenario, production increases twice as fast in SSA than in the rest of the world, driven by the higher population and income growth projections. In non-SSA, results across all scenarios suggest relatively small effects from changes in SSA on the rest of the world, a feature that repeats itself throughout the analysis. If current cropland expansion trends continue in SSA, a declining share of the additional demand for crop biomass could be produced domestically. SSA's levels of additional crop production in the middle-of-the-road baseline seem to be below those deemed necessary by the previously mentioned studies to match future consumption. Under the purely socioeconomic scenarios, it is interesting to note that SSA would produce more total crop biomass under the SSP1 scenario (low population and high income growth) than under SSP3 (with reversed trends). Higher production and lower population imply that per capita total demand (all uses) would be much higher with higher incomes. Moreover, demand for crops as intermediate inputs into processed food and animal production activities would increase dramatically under more favorable income scenarios. Therefore, combined higher household and intermediate demand for crop commodities would actually overcompensate lower future population numbers under the SSP1-Av_Yield scenario. When crop productivity trends in SSA are varied under the same socioeconomic trends (SSP2-Opt_Yield vs. SSP2-Pess_Yield), production expectedly increases significantly more at higher yield trends. A combination of the two scenario dimensions (SSP1-Opt_Yield vs. SSP3-Pess_Yield) further accentuates the previous results.

It is useful to set total increase of output into perspective of population growth, which is done in Table 5. It turns out that crop output per capita is projected to decrease in the baseline. Clearly positive trends would only be observed under optimistic assumptions for crop productivity and favorable expectations regarding population and economic growth.

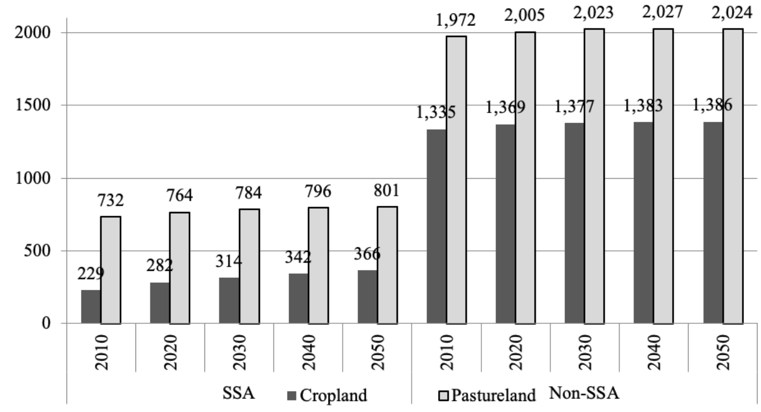

Figure 6. Projected Crop- and Pastureland Expansion for Sub-Saharan Africa (SSA) and the Rest of the World (Non-SSA), 2010–2050, Baseline Scenario (million ha)

Table 6. Percentage Change in Agricultural Areas, All Crops, Cereals, and Pastures, 2010–2050

	All Crops		Cereals		Pastures	
Scenario	**SSA** (%)	**Non-SSA** (%)	**SSA** (%)	**Non-SSA** (%)	**SSA** (%)	**Non-SSA** (%)
Baseline	62.6	6.1	69.7	13.3	9.5	2.7
SSP1-Av_Yield	67.1	6.5	74.9	13.7	7.5	2.8
SSP3-Av_Yield	55.2	5.4	61.5	12.7	14.8	2.4
SSP2-Opt_Yield	60.2	5.9	66.2	13.3	8.8	2.4
SSP2-Pess_Yield	65.5	6.2	74.0	13.3	10.3	2.5
SSP1-Opt_Yield	64.9	6.3	71.7	13.7	6.9	2.6
SSP3-Pess_Yield	58.6	5.5	66.6	12.6	15.8	2.2

The projected expansion of total production can be differentiated into rising area productivity—which is fixed by assumption—and by expanding crop areas. As demand increases will be much larger in SSA than in the rest of the world and productivity levels and growth smaller, as shown previously, production will in large parts have to be achieved by expanding crop areas (Figure 6). Land used for pasture will also expand in SSA but at a much slower pace due to the expectation that increased use of compound feed will diminish the importance of grazing.

Trajectories of agricultural land use are detailed across scenarios in Table 6. SSA's cropland expands by slightly more than 60% until 2050, whereas crop area would only increase by 6% in the rest of the world (non-SSA). Similar to the production results, land use would expand more under an optimistic socioeconomic outlook for SSA (SSP1-Av_Yield) than under a pessimistic one (SSP3-Av_Yield). By contrast, optimistic crop productivity trends (SSP2-Opt_Yield) would save cropland, particularly in comparison to the pessimistic yield trend scenario. Interestingly, cropland use in the rest of the world is more affected by the chosen trend variations in SSA than production. Both in SSA and the rest of the world, cereals grow somewhat slower than noncereal crops such as oil or fiber crops. Pastures remain almost unchanged outside Africa and grow only modestly in SSA. The reason is that grazing livestock in developing countries is increasingly fed with cultivated feed crops, reducing the derived demand for pasture while increasing demand for feed crop area.

Table 7 reports the effect of increasing global demand on crop prices; the quantity and value changes of all individual crop commodities were used to calculate a unified composite crop price index. Generally, real prices of crops are projected to fall on average in non-SSA and are projected to increase by 44% in SSA in the baseline scenario. Prices would also vary considerably in SSA across scenarios: high growth in per capita income but also a pessimistic crop productivity outlook

Table 7. Percentage Change in Composite Output Price for All Cropping Activities, 2010-2050

Scenario	SSA	Non-SSA
Baseline	44.1	−8.0
SSP1-Av_Yield	64.7	−7.6
SSP3-Av_Yield	14.3	−8.3
SSP2-Opt_Yield	27.1	−9.3
SSP2-Pess_Yield	68.2	−8.4
SSP1-Opt_Yield	45.2	−8.9
SSP3-Pess_Yield	31.8	−8.8

Table 8. Composite Price Index for Cropland in 2050 (2010 = 1)

Scenario	SSA	Non-SSA
Baseline	9.22	1.34
SSP1-Av_Yield	11.42	1.39
SSP3-Av_Yield	6.03	1.29
SSP2-Opt_Yield	8.45	1.29
SSP2-Pess_Yield	9.89	1.34
SSP1-Opt_Yield	10.59	1.33
SSP3-Pess_Yield	6.58	1.29

further drive up prices significantly, and vice versa. Price levels in the non-SSA aggregate would scarcely be affected by changes in SSA.

The diverging price trends between SSA and the rest of the world for most cropping activities is caused by increasing overall production costs in Africa or, more specifically, by a cost explosion for African farmland. Table 8 presents changes of a composite cropland price index up to 2050. While cropland prices would modestly increase in real terms outside of SSA, African cropland prices are projected to rise between 6 and almost 12 times compared to their base-year value across scenarios. This is remarkable given the much higher land use flexibility that is *a priori* assumed for SSA by attributing a relatively high land supply elasticity to this region and demonstrates the problems that result from the population-driven hunger for cropland in this world region.

Other major elements of production costs change much less over time. For instance, intermediates and capital for cereals production become 32% and 10% cheaper per unit in the baseline scenario, while labor unit costs increase by 10% until 2050.

Switching to commodity demand, Table 9 lists changes in household consumption per capita between 2010 and 2050 for all items that suitable for food and then for food products of animal origin and other processed food. Not surprisingly, the socioeconomic scenarios have a notably higher impact on domestic commodity use than the crop productivity scenarios. Commodity consumption is predominantly a function of overall economic growth and disposable incomes, which is why insufficient domestic farm productivity in SSA can be partly compensated with higher imports if incomes of agents in the model are sufficiently high. If, on the other hand, income growth per capita is slow, overall future demand for food will be lower, regardless of faster crop productivity growth in SSA, while the latter would rather result in higher crop exports. The scenarios involving pessimistic population and income trends result in the lowest food consumption growth paths (SSP3-Av_Yield and SSP3-Pess_Yield), while slow farm productivity growth (SSP2-Pess_Yield) alone reduces baseline consumption growth to a much lesser extent. Whether decreasing overall food consumption would also mean lower food energy intake is not possible to conclude from the results, as the model's database does not contain separate sectoral quantity and price information. In the baseline the consumption of animal-based food as well as other processed food would grow at much faster rates in SSA as compared to non-SSA and would react sensitively to changes in socioeconomic conditions. Higher or lower crop productivity trajectories, by contrast, have little impact on the

Table 9. Change in per Capita Household Consumption of All Food Items, Animal Products, and Other Processed Food, 2010–2050

	SSA			Non-SSA		
Scenario	All Food Items (%)	Animal Food Products (%)	Other Processed Food (%)	All Food Items (%)	Animal Food Products (%)	Other Processed Food (%)
Baseline	91.7	215.3	195.5	62.9	81.8	63.6
SSP1-Av_Yield	117.8	266.5	250.2	61.6	80.5	62.8
SSP3-Av_Yield	49.5	126.3	109.0	64.8	83.7	65.2
SSP2-Opt_Yield	96.0	209.7	196.3	63.3	82.0	63.9
SSP2-Pess_Yield	83.9	218.8	188.6	62.8	81.4	63.9
SSP1-Opt_Yield	122.3	260.4	251.6	62.1	80.7	63.1
SSP3-Pess_Yield	42.2	128.8	104.5	64.7	83.4	65.5

Notes: "All food items" were aggregated across all GTAP sectors producing raw or processed food commodities. Animal products were aggregated from GTAP sectors producing food of exclusively animal origin (i.e., "cattle, sheep, goats, horses," "other animals," "raw milk," fishery, meat items, and dairy products). Other processed food was aggregated from "food processing," "vegetable oils," "processed rice," and "sugar."

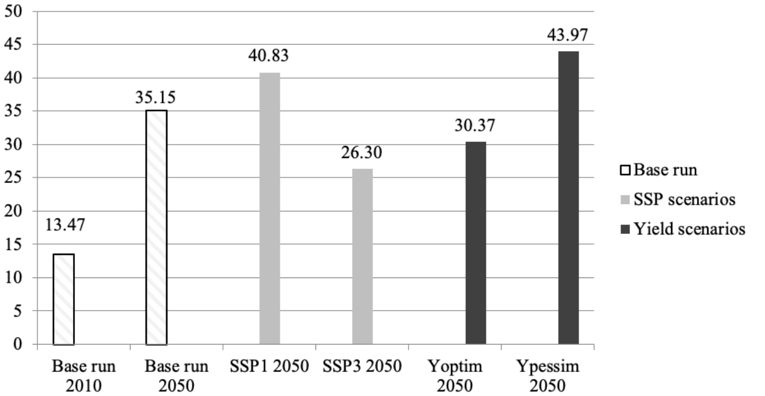

Figure 7. Imports to Sub-Saharan Africa as a Percentage of Domestic Production of Cereals

consumption of higher-value food. Again, regions outside Africa are only affected to a minor extent by changes in SSA across scenarios.

Figure 7 illustrates possible changes in patterns of trade. In the base year, SSA imports moderate shares of food/feed raw commodities such as cereals, but cereal import dependence is set to grow dramatically regardless of the scenario chosen. When comparing baseline results for 2050 with the socioeconomic and crop productivity scenarios, it turns out that import dependence (here defined as the share of imports in production) would grow with higher overall economic growth but be lower under a more optimistic crop productivity outlook. Under the pessimistic crop yield scenario, imports would rise to almost half of domestic production.

Tracing Input–Output Relations in Food Production and Processing

The results reported so far suggest stagnating or declining per capita production of *crops* but at the same time increasing consumption of *food* in SSA. This section attempts to explain this apparent contradiction. The levels and changes of quantitative input use for processed food and feed items are traced for that purpose on a per capita basis. Table 10 starts with an aggregate market balance for cereals (rice, wheat, "other cereals"). While per capita production declines slightly in the baseline, imports increase by a factor of more than 2.5, leading to an increase in total use of 18%. Of the two

Table 10. Per Capita Cereals Market Balance for Sub-Saharan Africa in the Baseline Scenario

	2010	2050	Change Factor
Production	80.0	77.9	0.97
Imports	10.8	27.4	2.54
Exports	1.6	0.4	0.23
Total use	89.2	105.0	1.18
Household consumption	72.4	71.8	0.99
Intermediate demand	16.8	33.1	1.97

Table 11. Sub-Saharan Africa per Capita Processed Food and Compound Feed Output, Use, and Net Imports and Respective Cereals Input Use, Baseline Scenario

	2010	2050	Change Factor
Processed food output	72.1	259.8	3.60
Cereals as inputs in processed food production	5.6	15.9	2.85
Processed food total use	84.2	303.1	3.60
Processed food net imports	12.1	43.3	3.58
Compound feed output	5.1	15.3	2.99
Cereals as inputs in compound feed production	0.3	0.8	2.85
Compound feed total use	5.9	17.6	2.98
Compound feed net imports	0.8	2.3	2.88

Table 12. Sub-Saharan Africa per Capita Compound Feed Market Balance, Baseline Scenario

	2010	2050	Change Factor
Production	5.1	15.3	2.99
Imports	1.2	2.9	2.40
Exports	0.4	0.7	1.75
Total use	5.6	17.2	3.07
Intermediate demand	5.5	17.1	3.11

most important components of cereals use, household consumption stays constant, while the use of cereals as intermediate input doubles. This increasing input use is basically provided by the rising shares of imports in the commodity balance, as shown in Figure 7.

Table 11 then presents two activities that make heavy use of cereals as crucial ingredients of their output. First, processed food production increases by a factor of 3.6 per capita, but this increase is causing a rise in input demand for cereals by a factor of 2.85 only. As the food industry in this model version can substitute inputs, other inputs such as livestock products make up for the decreased cereals share. Another factor that might decrease demand for cereals as an input in food processing could be an increasing import share of processed food, but this does not appear to be the case: food net imports (imports minus exports) increase at the same rate as output and use.

Production of compound feed for livestock activities increases by a factor of 3, causing an increased input demand for cereals of almost the same magnitude—cereals are more difficult to substitute in feed production than in food processing, which is a very broad category after all. Compound feed is an example of a processed commodity that by itself is an important production input for higher-value livestock activities (see Table 12). Both production and use of compound feed in SSA is projected to triple per capita, with input use being the only relevant use category. Table 13 shows the two activities, namely grazing livestock and other livestock activities, where the majority of that increasing demand originates. Due to the modernizing of production processes in grazing livestock (more use of complementary feed in addition to grazing and fodder), its demand for compound feed increases much faster than its output. An important driving force for expanding feed use is also the shrinking availability of pastureland in SSA, which is accompanied by increasing

Table 13. Sub-Saharan Africa per Capita Grazing Livestock and Other Livestock Output and Respective Cereals Input Use, Baseline Scenario

	2010	2050	Change Factor
Grazing livestock output	27.0	92.6	3.43
Compound feed as input in grazing livestock production	1.0	5.3	5.51
Other livestock output	17.9	59.8	3.34
Compound feed as input in other livestock production	2.6	6.8	2.61

conflicts between crop farmers and herders (see, e.g., Moritz, 2010). Other livestock outputs (mainly poultry and pigs), on the other hand, are projected to require less compound feed per output thanks to trends toward better feed efficiency.

What makes these results somewhat difficult to appreciate is the fact that a CGE model does not deal with physical quantities but rather with quantity indexes with a price of unity in the base year. As the value of processed food or feed output is much higher than that of its input ingredients (all the more so the more technologically advanced and capital-intensive production processes become), the data generation process of a CGE model makes quantities of higher-value commodities look much greater compared to raw materials than is actually the case.

Summary and Discussion

The inherent assumptions made for this scenario analysis predominantly lead to adaptations in the extent of cropland use. This is in part due to the parameterization of the land supply function which is—based on observed global land use trends of recent decades—assumed to be comparatively elastic in SSA. But while varying crop productivity trends would primarily impact land use and domestic supply of crop raw commodities, the "scarcity effect" of, for instance, a pessimistic crop yield outlook for SSA is shown to diminish somewhat on its way through the food value chains. Factors contributing to this result are increasing imports of raw materials as well as assumptions about technical progress in food production and processing inherent to the baseline scenarios. Therefore, overall consumption and, in particular, food energy intake would likely be less affected than production. This is primarily because all socioeconomic scenarios assume increasing economic growth for SSA, which inevitably requires increasing production efficiency for the economic sectors in the region. Available private incomes will have to increase as well, with the consequence that the capacity of households to buy processed and imported food will grow over the simulation period. As long as incomes grow and cropland can expand, negative food consumption trends will be unlikely.

Another relatively clear result is that the various counterfactual socioeconomic and crop productivity development paths, albeit starkly different from SSA's baseline scenario, seem to have little effect on the rest of the world, a finding that is perhaps most striking when looking at prices for crop outputs. To explain this, it is useful to discuss the socioeconomic and productivity scenarios separately. In any case, it is changing total—and not per capita—supply or demand of crop biomass by SSA that might tip the rest of world out of balance. In the socioeconomic scenarios (which are characterized by a modification of the demand drivers), increased per capita demand by increasing income is partly offset by slower population growth and vice versa, while in the crop productivity scenarios (addressing a supply-side driver), lower productivity is partly compensated by higher cropland expansion and vice versa—and cropland expansion generally works as a buffer for any supply- or demand-side trend deviations as long as there is potential cropland available. It can be concluded that while SSA's global share in population, income, and crop biomass supply and demand will roughly double until the middle of the twenty-first century, the likelihood and scope of SSA to persistently force world markets toward, for example, higher crop prices remains limited.

The interpretation of the simulation results is subject to a number of limitations. Perhaps most importantly, while we deemed it necessary to aggregate results for physical output across sector or commodities to reduce the complexity of model output, aggregating is also problematic in a CGE data framework. Base production *quantities* from the GTAP database are by convention equal to production *values in constant dollars* at a price of 1. They represent the economic value of all inputs used in production and are hardly usable as a food security indicator. For instance, producing one calorie of deep-freeze convenience food requires far more economic inputs (for processing, precooking, air-tight packaging, the cool-chain, etc.) than a calorie of staple foods. When aggregating these quantities across low- and high-value commodities, the latter are over-represented in the aggregate. A pure shift from the cheaper to the more expensive commodity then would suggest an increase in quantitative consumption that actually might not be happening. The problem could be addressed by adding price information to the GTAP database, at least for relatively homogeneous commodities. We therefore recommend viewing such aggregated results as tendencies rather than precise results.

Another methodological challenge is the change of input-output (I/O) coefficients over longer periods. I/O relations are crucial for crops as inputs for food and nonfood production activities, but trends in I/O coefficients are not widely available across sectors and regions. Just fixing I/O relations as a solution may ignore certain forms of technical progress that might be significant in the longer run. The effect of continued technical progress on input-output relations can actually be manifold; it can lead to both higher (when, e.g., higher yields require higher fertilizer use) and lower input requirements (e.g., better energy efficiency of power utilities or the transport sector). Producing processed food from agricultural raw materials should leave I/O relations largely unchanged in the case of, for example, "paddy rice" and "processed rice," but for larger and more indeterminate aggregates such as "processed food," the degree of necessary flexibility with respect to the composition of raw materials used is still an open topic.

The model's regional and sectoral degree of detail was chosen with the objective of treating SSA as one focus region. This approach of course disguises a considerable degree of heterogeneity within the SSA aggregate region. This is specifically relevant in the area of cropland use expansion, where emerging regional scarcity, as for instance in West Africa or the East African highlands, is not posing a hard constraint within the model. While the projected land use expansion of about 60% until 2050 might fit well into SSA's aggregate cropland reserves, regional land scarcity might require specific efforts to improve area productivity in those hotpots to avoid internal migration pressure and conflicts. It would be highly desirable to further endogenize the processes of land use expansion for those world regions where this issue is still highly relevant, such as SSA, but also Latin America and Southeast Asia.

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