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How will global agriculture and food security respond to future socioeconomic shocks?*

Geraldo Bueno Martha Junior[1]
Cícero Zanetti de Lima[2]

ABSTRACT

The demand and supply-side drivers connected to the "Shared Socioeconomic Pathways" (SSPs) will impact future agriculture. Assessing the projected impacts of those drivers on regional and global agriculture requires approaches that goes beyond the traditional biophysical science methods and tools. The present work uses a static partial equilibrium model for global agriculture that incorporates into the analysis the effects of economic responses to scarcity affecting regional and global agricultural production and land use. By 2050, agricultural output will expand, but at different rates depending on the region and on the SSP-productivity scenario. Yield gains will consolidate as a major driver, but cropland expansion will still play an important role, especially in Sub-Saharan Africa. The SSP1 (Sustainability), a fast technological development scenario, offers a promising perspective to increase global agricultural output and reduce pressures for cropland expansion. Under SSP1 scenario, food insecurity would drop the most, to 2.8% of world population by 2050. Achieving the Sustainability scenario will require an articulated global effort to strengthening agricultural R&D expenditures accompanied by a well-designed strategy to translate science into problem-solving knowledge and technologies that could be successfully transferred and adopted by farmers to boost productivity gains over the next three decades.

Index terms: agricultural R&D, agricultural policy, agricultural yield, food security, land use, Shared Socioeconomic Pathways (SSP).

Ideias centrais

- Agricultural output increases will vary with region and SSP-productivity scenarios.
- Yield gains will be a major driver, but cropland expansion will still play a role.
- The geography of agricultural production will be affected by SSP--productivity scenarios.
- The Sustainability (SSP1) scenario should be pursued to reduce food insecurity.
- The SSP1 scenario requires R&D expenditures to be set as a global priority.

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Como a agricultura e segurança alimentar global responderão aos futuros choques socioeconômicos?

RESUMO

Os *drivers* da demanda e da oferta conectados aos "Caminhos Socioeconômicos Compartilhados" (SSP, no inglês) irão impactar a agricultura do futuro. A avaliação dos impactos desses *drivers* requer abordagens que vão além dos métodos e instrumentos tradicionais das ciências biofísicas. O presente trabalho utiliza um modelo de equilíbrio parcial estático para a agricultura global que incorpora na análise os efeitos das respostas econômicas à escassez que afetam a produção agrícola regional e global e o uso da terra. Até 2050, a produção agrícola se expandirá a taxas diferentes dependendo da região e cenário. Os ganhos de produtividade consolidar-se-ão como um dos principais *drivers*. O cenário SSP1 ("Sustentabilidade"), de rápido desenvolvimento tecnológico, oferece perspectiva promissora para aumentar a produção agrícola global e reduzir a pressão para expansão de área. No cenário SSP1, a insegurança alimentar cairá de maneira mais acentuada, para 2,8% da população mundial em 2050. Alcançar esse cenário

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[1] Embrapa Digital Agriculture, Campinas, SP, Brazil / Graduate Program, Institute of Economics (CEA), Universidade de Campinas (Unicamp), Campinas, SP, Brazil. E-mail: geraldo.martha@embrapa.br.

[2] São Paulo School of Economics, Fundação Getúlio Vargas, Agribusiness Studies Center, São Paulo, SP, Brazil. E-mail: cicero.lima@fgv.br.

Sustentabilidade exigirá um esforço global articulado para fortalecer as despesas em P&D agropecuário, acompanhado de uma estratégia bem desenhada para traduzir ciência em conhecimentos e em tecnologias capazes de resolver problemas que possam ser transferidos e adotados exitosamente pelos proprietários rurais de maneira a alavancar os ganhos de produtividade ao longo das próximas três décadas.

Termos para indexação: P&D agropecuário, política agrícola, produtividade agrícola, segurança alimentar, uso da terra, Caminhos Socioeconômicos Compartilhados (SSP).

INTRODUCTION

Food systems are facing multiple challenges to ensure food security and nutrition for a growing and more affluent population and to support the livelihoods of farmers and other stakeholders in food value chains, and, more broadly, in the bioeconomy (Fanzo et al., 2018; Giller et al., 2021; Von Braun et al., 2021; Martha Júnior & Lopes, 2023). These challenges gain complexity as they require increasing agricultural output in an environmentally sustainable way, from local to global scales (Hertel & Baldos, 2016; Giller et al., 2021; OECD, 2021; Kerr et al., 2022; McKinsey & Company, 2022; FAO, 2023d; World Bank, 2023). Such transformations of food systems are further pressured by a context increasingly jeopardized by the new realities imposed by climate change (Zilli et al., 2020; Fróna et al., 2021; Jägermeyr et al., 2021; Masson-Delmotte et al., 2021; Barrett et al., 2023; Nugroho et al., 2023).

A central question to policy makers and practitioners is how to explore possible futures in the planning process related to long-run agricultural production, land use, food security, and climate change as those socioeconomic drivers evolve (Timmer et al., 1983; El-Chichakli et al., 2016; Schmitz et al., 2022; Martha Júnior & Lopes, 2023). A framework consisting of five "Shared Socioeconomic Pathways" (SSPs) was designed to provide insights on possible futures that could shape future socioeconomic developments as they might unfold if there are no explicit additional policies and measures to limit climate forcing or to enhance adaptive capacity (O'Neill et al., 2014, 2017; Riahi et al., 2017). From a demand-side perspective, population and per capita income are two important shifters of the agricultural demand curve (Hertel & Baldos, 2016; Béné et al., 2019). Therefore, the direction and magnitude of changes of those socioeconomic drivers could alleviate or aggravate the challenges presented to future agriculture and food security. From a supply-side perspective, increasing agricultural productivity (Alston, 2010; Pardey et al., 2016; Fuglie, 2018b), despite the unpredictable and challenging production environment that is very likely to emerge because of climate change pressures (Masson-Delmotte et al., 2021), will ultimately determine how successful nutritional and economic goals can be achieved (Baldos & Hertel, 2014; Fanzo et al., 2018).

Assessing the projected impacts of demand and supply-side drivers on regional and global agriculture requires approaches that goes beyond the traditional biophysical science methods and tools. It is necessary to further incorporate into the analysis the effects of economic responses to scarcity affecting regional and global agricultural production and land use (Hertel, 2018). This study aims to bridge that gap by using the SIMPLE model ("Simplified International Model of Prices, Land Use and the Environment") (Hertel & Baldos, 2016), Brazil's version (SIMPLE-BR), which has the world disaggregated into 17 regions and was calibrated and validated against historical data to have Brazil as an individual region (Lima et al., 2022).

We investigate the impacts of both demand- and supply-side shocks on future developments of SSPs. We explore some of the key issues that will be presented to agriculture, food security, and land use: how could demand and supply-side shocks associated with the SSPs impact the endogenous responses of global agriculture in the horizon up to 2050? What would be the likely effects on food security? What perspectives emerge to science-policy interfaces because of those SSPs-productivity scenarios? We first investigate how demand-side drivers associated with different SSPs scenarios could impact agriculture's response. Then, we explore how changing productivity growth rates (i.e. the supply-side) – a medium to long-run outcome of agricultural research and development (R&D) expenditures (Fuglie, 2018b) –, as affected by SSP scenarios' narratives, could alter previous responses to demand-side shocks. Finaly, we present a few challenges and opportunities from a science-policy perspective.

METHODS

SIMPLE-BR model

We used the SIMPLE-BR model (e.g. the “Simplified International Model of Prices, Land Use and the Environment”), a version of the SIMPLE model (Hertel & Baldos, 2016) that was further calibrated and validated against historical data to have Brazil as an individual region in the world (Lima et al., 2022). For simplicity, a single agricultural sector, which uses land and non-land (labor, capital, etc.) inputs, is used. Because of SIMPLE’s low complexity, it requires few assumptions and parameters to allow a fast generation of multiple analyses and results that can be easily reproduced, besides the necessary transparency to evaluate the results (Hertel & Baldos, 2016). The SIMPLE model is a multi-regional, static partial equilibrium model for global agriculture, whereas the Brazilian version has 17 economic regions in the world (Lima et al., 2022). This study considered the 2017–2050 period.

SIMPLE is the simplest possible framework for studying the key factors shaping long-run demand and supply for agricultural output, land use, and crop price (Hertel & Baldos, 2016). The long-run changes in agricultural land use and price are mediated by the three margins of economic response to scarcity (Hertel & Baldos, 2016; Hertel, 2018): the price elasticity of demand for agricultural products, the response of yields to higher commodity prices (intensive margin of supply response), and the extensive margin of supply response (area response to commodity prices).

In each region of the model, consumers demand four major groups of commodities (crops, livestock, processed food, and biofuels). Crops can be consumed directly or indirectly through the demands for livestock products and food industry. An increase in the efficiency of livestock and food industry sectors, which use crops in their production, could impact the global demand for crops, as well as the need for new cropland (Hertel & Baldos, 2016).

Regional demand is driven by population, per capita income, and biofuel use mandates (all exogenous to the model), and prices (that are endogenous to the model). Per capita consumption responds to prices and per capita income. Changes in these drivers are weighted by the own-price elasticity and the income elasticity of demand (Hertel & Baldos, 2016). The demand for processed food responds to prices and income, becoming less sensitive as per capita income increases (Muhammad et al., 2011). Higher income allows diet diversification. Thus, for lower per capita income levels, the relative share of livestock and processed foods in the diet is smaller. Demand for these products may be altered by technological progress in these sectors. This dynamic is introduced into the model by allowing the price and income elasticities of demand for each commodity to fluctuate with changes in per capita income based on linear regression estimates between per capita income and the respective elasticities (Hertel & Baldos, 2016).

Global crop production is determined by the sum of the supply of each individual region in the model. Each region has different land endowments and productivity levels and produces an “aggregate commodity crop” using land and non-land inputs. Crop production has four potential uses: direct consumption (crop) and indirect consumption as feed for the livestock sector, food processing, and as biomass for biofuel production. Inputs other than crop are used for production in both the livestock and processed food sectors. The substitution between crop and other inputs (except crop) in these sectors are mediated through specific parameters. In the specific case of livestock production, it is expected that a reduction in crop price, an input to livestock production, may result in an intensification in the use of feed per unit of livestock production (Hertel & Baldos, 2016).

Production is subject to constant returns to scale and uses “Constant Elasticity of Substitution” (CES) functions. Long-term changes in land use and agricultural prices are mediated by margins of economic response to scarcity. The supply of land for crops is price sensitive, thus a decrease (increase) in land rent implies in an expansion (decline) effect of land supply, i.e. the extensive margin. Cropland response varies regionally. In addition, the forces shaping land supply reflect the factors that limit the availability of land for agriculture. For example, the land elasticity parameter may be altered to reflect a scenario in which regional restrictions to land use are required. In addition, the change in agricultural productivity influences the demand for land (Hertel & Baldos, 2016).

A specific parameter determines the substitution possibilities between land and non-land inputs. Increasing the values of this elasticity strengthens the intensive margin of response of crop supply. The substitution of “non-land” inputs (fertilizers, machinery, labor etc.) for “land” in crop production enables the endogenous intensification of agricultural production, allowing productivity growth to occur even in the absence of technological change and scarcity of resources. The SIMPLE-BR model also allows exogenous variations in agricultural productivity, for example, as a result of (dis) investments in agricultural R&D, policies, or climate change (Fuglie et al., 2022; Lima et al., 2022).

The long-run equilibrium is reached when the global crop supply equals the global crop demand, in which there is only one equilibrium price. A “segmented markets” approach, as used in this study, allows consumers and producers to face both global and domestic crop prices. In these cases, the substitution between local and global crops is possible, and the average crop price of producers and consumers depend on these prices (Hertel & Baldos, 2016).

Data

The main source of data in SIMPLE-BR is the FAOSTAT database (FAO, 2023a), in our case built for the base-year 2017. This year was chosen following the earlier work of Hertel & Baldos (2016), which provides initial calibration and validation for the SIMPLE model, and also because the Brazilian version of the model was calibrated and validated considering the 2000–2017 period (Lima et al., 2022). The SIMPLE model is flexible enough to connect new datasets or to change the reference year. Typical data includes income, population, cropland, agricultural output, and prices. Consumption expenditure data and the amount of crop feedstock used at regional level by the biofuel sector were taken from GTAP database (GTAP, 2023). The resulting shares of the crop utilization data were used to split the remaining corn-equivalent crop quantities across each income region and across different uses (e.g., food, feed, and raw materials for processed food). Crop use calculations incorporated indirect use, e.g. crops used as intermediate input for livestock production and processed foods. The global crop price from the value and corn-equivalent quantity data of crop were then determined.

Food security data relies mainly on data published by Food and Agriculture Organization of the United Nations (FAO, 2023b). In the case of Brazil, it was additionally used Brazilian Institute of Geography and Statistics (IBGE) official statistics for the country (PNAD and POF). SIMPLE’s nutrition module uses country-level data, such as average per capita dietary energy intake, the share of food in total energy intake, and food quantities to compute the average dietary energy content of crops, livestock and processed food aggregates consumed in each region. The distribution of dietary energy consumption within each region is considered, allowing the calculation of headcount and average depth of caloric malnutrition. Then, the food caloric content is linked to per capita income, capturing the shifts in the composition of food (Baldos & Hertel, 2014).

Demand and supply-side shocks

The five SSPs are: SSP1 “Sustainability”, with low challenges for mitigation (resource efficiency) and adaptation (rapid development); SSP2 “Middle of the Road”, presenting medium challenges to mitigation and adaptation; SSP3 “regional rivalry”, a scenario with high challenges for mitigation (regionalized energy / land policies) and adaptation (slow development); SSP4 “Inequality”, in which

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there are low challenges for mitigation (global high tech economy), but high challenges for adaptation (regional low tech economies); and SSP5 "Fossil-fueled Development", presenting high challenges for mitigation (resource / fossil fuel intensive) and low challenges for adaptation (rapid development) (O'Neill et al., 2014, 2017, 2020; Riahi et al., 2017). These basic global SSPs scenarios serve as a starting point for developing (semi-)extended versions of SSPs, involving qualitative and quantitative approaches, and intended to present more details for regional and sectoral applications (Palazzo et al., 2017; Mitter et al., 2020; O'Neill et al., 2020; Lehtonen et al., 2021).

In this work, the demand-side shocks for each region and for each SSP scenario represented variations in population and in per capita income. Our baseline considers the SSP2 scenario ("Middle of the Road"). For these scenarios, a unique total factor productivity (TFP) shock, based on a model of agricultural R&D expenditures and knowledge capital accumulation to simulate the baseline evolution in regional TFP (Fuglie, 2018b), was adopted.

In the second experiment, it was investigated how changing productivity growth rates, according to SSP scenarios' narratives, could alter the previous endogenous responses of regional and global agriculture to demand-side shocks: (a) high TFP growth rates in SSP1 and SSP5 scenarios, represented by the observed TFP growth rates averages between the years 2000 and 2016 (USDA, 2022); (b) low TFP growth rates in SSP3 (i.e. assumed to be 70% of the projected figures in the SSP2, baseline scenario); (c) asymmetric TFP growth rates in SSP4 scenario, i.e. high productivity growth rates for China and rich countries, and low productivity growth rates for Brazil and other developing countries. In all of these cases the TFP growth rates were estimated using Fuglie's model.

RESULTS

SSPs scenarios: demand-side shocks

Table 1 depicts the effects of demand-side shocks in the horizon until 2050 by keeping the supply (productivity) response constant across SSP scenarios (i.e. TFP growth follows its projected baseline trend for each region). In the next three decades, it is expected that agricultural output will increase in all regions and SSP scenarios. The projected impacts on cropland will vary by region and scenario.

Globally, cropland is expected to increase 2.1% across scenarios (i.e. 33.5 million hectares, ha) by 2050. Most of that net cropland expansion is projected to occur in Sub-Saharan Africa ("SSA"), in which cropland increase is likely to vary from 16% (SSP1 ~ SSP5, 37 million ha) to 26% (SSP3, 60 million ha) relative to 2017 levels. In the next decades, cropland is projected to decrease in the regions "China", the European Union ("EU"), and the United States of America ("USA"), ranging from -8.3% to -10.3% in China (-11.2 to -13.5 million ha), -0.3% to -0.9% in the EU (-0.3 to -1 million ha), and -1.9% to -3.1% in the USA (-3.1 to -5.1 million ha). The cropland declines in China, in the USA, and in the EU represent, on average across SSP scenarios, 17 million ha.

In Brazil, cropland is projected to increase in all scenarios, varying from 4.4% (SSP4) to 9.3% (SSP3) by 2050, despite the prospects for sizable improvements in yield levels, i.e. from 77% to 78% across the five SSPs scenarios. Such cropland increase in Brazil represents a demand for an extra area of 3 million ha to 6 million ha, which may be made available by further intensifying livestock production (Martha Jr. et al., 2012) that is carried out in approximately 154 million ha of cultivated pastures (MAPBIOMAS, 2023). An estimated 4% increase in the productivity of these pastoral systems would free up the necessary area to accommodate projected cropland expansion in the country in the next three decades.

Table 1. Projected responses to demand-side shocks in selected regions, per percentage change (%), during the period of 2017 to 2050.

	Brazil	China	USA	EU	SSA	World
			Output			
SSP1[1]	84.7	19.9	27.8	39.2	58.2	44.2
SSP2 (baseline)	91.2	22.2	30.3	41.8	71.8	49.4
SSP3	94.4	24.0	28.0	38.4	83.4	52.5
SSP4	84.6	17.1	27.2	37.7	78.7	45.5
SSP5	88.9	19.9	32.7	45.3	57.9	46.3
			Cropland			
SSP1	4.5	-9.3	-3.1	-0.8	16.0	0.8
SSP2 (baseline)	7.7	-8.7	-2.5	-0.6	21.2	2.7
SSP3	9.3	-8.3	-3.0	-0.9	25.5	3.7
SSP4	4.4	-10.0	-3.2	-0.9	23.8	2.0
SSP5	6.6	-9.3	-1.9	-0.3	15.9	1.5
			Yield			
SSP1	76.8	32.1	31.8	40.3	36.4	43.0
SSP2 (baseline)	77.5	33.9	33.6	42.6	41.7	45.5
SSP3	77.8	35.1	32.0	39.6	46.1	47.0
SSP4	76.8	30.0	31.4	39.0	44.4	42.7
SSP5	77.3	32.2	35.3	45.7	36.3	44.1
			Price			
SSP1	-41.0	-53.3	-35.2	-36.2	4.1	-34.4
SSP2 (baseline)	-39.4	-52.4	-34.0	-35.2	11.2	-32.5
SSP3	-38.7	-51.8	-35.0	-36.5	17.1	-32.1
SSP4	-41.0	-54.3	-35.4	-36.8	14.7	-33.9
SSP5	-40.0	-53.3	-33.0	-33.9	3.9	-32.8

[1] SSP1, Sustainability; SSP2, Middle of the Road; SSP3, Regional Rivalry; SSP4, Inequality; SSP5, Fossil-fueled Development.

The projected yield responses in China, the USA, the EU, SSA, and in the world (i.e. 30% to 46% across scenarios and regions) is roughly half of the yield response expected for Brazilian agriculture. Average global food prices are expected to be 33% lower by 2050 compared to 2017 levels. The exception stands for SSA, in which equilibrium real crop prices are projected to increase from 3.9% (SSP5) to 17.1% (SSP3) (Table 1).

SSPs scenarios: demand- and supply-side shocks (a global perspective)

A more accurate representation of future developments in regional and global agriculture must additionally consider the projected effects from a supply-side perspective, leading to scenarios with different SSP-TFP combinations. When the supply-side shocks are considered in addition to the demand-side shocks (Table 2), global agricultural output, as an average across SSP scenarios, would be increased by 15 p.p.. Considering each person consumes 500 kg of corn-equivalent in each year (Connor et al., 2011), that extra response would imply that 147 million people could be additionally fed each year in the 2017–2050 period.

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Table 2. Projected responses in global agricultural to supply (productivity) plus demand (population and per capita income) shocks[(1)].

	Output	Cropland	Prices
		World agriculture. p.p.	
SSP1[(2)]	33.3	-6.7	-23.1
SSP2 (baseline)	0.0	0.0	0.0
SSP3	-6.6	2.7	11.5
SSP4	14.1	-2.9	-7.3
SSP5	33.5	-6.8	-23.8
average across SSPs	14.9	-2.7	-8.6

[(1)]Differences relative to demand-side shocks only (Table 1). [(2)]SSP1, sustainability; SSP2, middle of the road; SSP3, regional rivalry; SSP4, inequality; SSP5, fossil-fueled development.

Across the SSPs scenarios, the most expressive differences between the two experiments were observed in the SSP1 and SSP5 (high TFP growth rates) scenarios – on average, a 33 p.p. difference (Table 2). Compared to previous SSP1's demand-side shock (Table 1), that extra agricultural output in the future expressed by a SSP1-high TFP growth combination (Table 2) indicates that, potentially, 330 million more people could be additionally fed each year in the 2017–2050 period given the improvement in productivity gains (again, considering that each person consumes 500 kg of corn-equivalent in each year). Agricultural output in SSP3 is projected to decrease by 6.6 p.p., and the response in SSP4 is projected to be intermediate (14 p.p.). Taking the worst-case scenario, i.e. a future of "Rivalry" (SSP3-low TFP growth), the resulting decrease in agricultural output would lead to 65 million less people being potentially fed each year due to decreased productivity gains.

From a land-use change perspective, an average across scenarios reveals that 43 million ha would be potentially spared from cultivation, since instead of a net expansion of 33.5 million ha (demand-side shocks only) relative to the base year 2017, a retraction of 9.4 million ha is expected under combined SSPs-TFP shocks. Again, the differences across the possible SSP scenarios are evident. In a world represented by the SSP3 scenario, cropland would need to be expanded in 41.5 million ha relative to 2017. In contrast, 105 million ha would be spared from cultivation if productivity levels climb up to the high TFP growth rates as projected for SSP1 scenario.

SSPs scenarios: demand and supply-side shocks (a regional perspective)

In the next three decades, world agriculture is expected to expand, but at different rates depending on the region and on the SSP-TFP scenario considered. Yield gains will be a major driver explaining agricultural output increases, but cropland expansion is expected to still play an important role in production, especially in SSA (Table 3). Globally, regional equilibrium prices are projected to fall between 21% and 58% in the 2017–2050 period, indicating consumers are likely to benefit while farmers are expected to experience further pressures to cope with declining prices.

The conditions projected for the SSP3 ("Regional Rivalry") scenario largely reflect a country's inability to sustain R&D expenditures, triggering lower TFP growth rates over the medium to the long run. As shown in Table 3, the future reflected by the SSP3 scenario challenges the most both China and the aggregate of global agriculture (output expands the least and cropland expansion is at its highest). In SSA, agricultural output expansion reaches 87% in the SSP3 scenario, requiring cropland to increase 30% in the period. For all the regions (Table 3), cropland and equilibrium prices are at their maximum projected values at SSP3, while food insecurity would be reduced the least under this SSP3 scenario (Table 4) – i.e., approximately 5% of the world population would still face food insecurity by 2050.

Table 3. Projected responses to supply and demand-side shocks in selected regions, per percentage change (%), during the period of 2017 to 2050[(1)].

	Brazil	China	USA	EU	SSA	World
			Output			
SSP1[(2)]	160.9	89.2	18.2	28.4	41.2	77.5
SSP2 (baseline)	94.2	22.2	30.1	41.6	71.6	49.4
SSP3	71.6	16.8	25.7	33.3	86.9	45.9
SSP4	31.1	103.2	49.2	65.1	60.5	59.6
SSP5	166.6	90.0	22.6	33.9	40.9	79.8
	Brazil	China	USA	EU	SSA	World
			Cropland			
SSP1	-3.8	-14.9	-9.9	-3.7	4.0	-5.9
SSP2 (baseline)	8.2	-8.7	-2.5	-0.6	21.1	2.6
SSP3	13.0	-6.5	-0.9	-0.1	30.1	6.4
SSP4	-11.1	-12.8	-3.0	-0.7	19.9	-0.9
SSP5	-1.9	-14.7	-8.8	-3.2	3.8	-5.3
	Brazil	China	USA	EU	SSA	World
			Yield			
SSP1	171.2	122.2	31.1	33.4	35.8	88.6
SSP2 (baseline)	79.5	33.8	33.5	42.4	41.7	45.6
SSP3	51.9	24.9	26.8	33.5	43.7	37.2
SSP4	47.5	133.1	53.9	66.3	33.8	61.0
SSP5	171.8	122.8	34.5	38.3	35.7	89.8

[(1)] By 2050, global real equilibrium prices are expected to decline in all SSP scenarios: SSP1, -58%; SSP2, -33%; SSP3, -21%; SSP4, -41%; and SSP5, -57%. [(2)]SSP1, Sustainability; SSP2, Middle of the Road; SSP3, Regional Rivalry; SSP4, Inequality; SSP5, Fossil-fueled Development.

Table 4. Major drivers explaining food insecurity changes in the 2017–2050 period.

	Total change	Share of malnutrition	Contribution of population	Contribution relative to population (Index = 100)		
	(malnutrition count. million)	(% global population)	(million)	Per capita income	Biofuels	TFP[(1)]
SSP1[(2)]	-348.3	2.8	137.4	-15.0	0.6	-243.0
SSP2	-225.8	3.8	266.1	-9.7	0.2	-60.0
SSP3	-82.2	4.9	459.5	-4.5	0.1	-21.2
SSP4	-216.4	4.0	314.3	-7.1	0.2	-46.8
SSP5	-307.3	3.2	133.0	8.5	0.6	-258.2

[(1)] TFP, total factor productivity. [(2)]SSP1, Sustainability; SSP2, Middle of the Road; SSP3, Regional Rivalry; SSP4, Inequality; SSP5, Fossil-fueled Development.

Brazilian agriculture is expected to be severely impacted in the futures projected for SSP3 and SSP4 scenarios, indicating the country would failure to sustain a rapid technological development strategy. Farm productivity is largely the main driver explaining output growth in Brazil, irrespective of the SSP scenario. However, in the SSP3 scenario (low TFP growth), despite of the approximately 8.3 million ha of cropland expansion, only 76% of the output level projected for the baseline scenario SSP2 would be achieved. The situation deteriorates further in the “world” represented in the SSP4 scenario (with a low TFP growth rate), in which Brazilian agricultural output is projected to be 63 p.p. lower than the levels expected for SSP2. In contrast, a strong focus on technological development and productivity gains in Brazilian agriculture would result in the greatest output by 2050, i.e. 161% (SSP1, “Sustainability”) to 167% (SSP5, “Fossil-fueled Development”) higher than in 2017.

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The SSP1 and SSP5 scenarios perform better and are comparable in yields and output responses for global agriculture. However, agricultural output is projected to expand faster for SSP4 scenario in China, the USA, and the EU (Table 3). Nevertheless, considering each person consumes 500 kg of corn-equivalent in each year (Connor et al., 2011), by pursuing the SSP4 scenario as a global strategy, instead of the SSP1 scenario, it would imply in a reduced amount of food that could otherwise feed 177 million people per year. From a land-use change perspective, 78 million ha of cropland would be additionally needed in SSP4 in comparison to SSP1 scenario. Furthermore, the SSP1 scenario is also the most aggressive one in reducing global food insecurity (Table 4), that could drop from 7.9% to 2.8% of global population in the 2017–2050 period. However, it is worth of noting that although increased agricultural productivity and output are necessary conditions to reduce food and nutritional insecurity and hunger, such advances are not sufficient conditions to solve the problem. It is necessary to jointly design and implement strategies to allow the expansion of income and access to food by the most vulnerable population, in order to verify effective advances towards ending hunger and malnutrition by 2030, e.g. the United Nations' Sustainable Development Goal 2 (SDG-2).

Our modeling results showed the different demand and supply-side scenarios will also impact the geography of agricultural production in the future, with outcomes being influenced by regional vulnerability and different combinations of demand and supply-side shocks. Developed regions are likely to have their share in global food output decreased by 2050. However, since these regions are more resilient, they tend to be the least affected by the different SSP-TFP scenarios (Table 5). Brazil and Southern Asia are projected to have their share in global food output increased irrespective of the scenario, but the absolute outcome depends on the scenario. Brazil is the most vulnerable region to variations in SSP-TFP scenarios, whereas Southern Asia vulnerability to SSP-TFP scenarios is projected to be intermediate among developed regions and Brazil (Table 5).

Table 5. Resilience in agricultural output response (% change) as a result of different supply and demand-side shocks, in the 2017–2050 period.

Regions of the model[(1)]	Worst result/scenario		Best result/scenario		Range[(2)] (p.p.)
Eastern Europe	-22.6	SSP4[(3)]	102.8	SSP5	125.4
Northern Africa	25.9	SSP4	92.3	SSP5	66.5
Sub-Saharan Africa	40.9	SSP5	86.9	SSP3	46.0
South America	26.1	SSP1	108.3	SSP2	82.2
Brazil	31.1	SSP4	166.6	SSP5	135.5
Australia and New Zealand	-3.2	SSP1	35.8	SSP2	39.0
European Union and the United Kingdom	28.4	SSP1	65.1	SSP4	36.7
Southern Asia	66.3	SSP4	131.2	SSP4	64.8
Central America and the Caribbean	22.0	SSP1	101.9	SSP2	79.8
Southern Africa	13.5	SSP1	58.5	SSP2	44.9
Southeastern Asia	24.6	SSP4	86.2	SSP5	61.5
Canada	-5.1	SSP1	43.1	SSP2	48.2
United States of America	18.2	SSP1	49.2	SSP4	31.0
China	16.8	SSP3	103.2	SSP4	86.4
Middle East	29.0	SSP4	84.3	SSP5	55.3
Japan and Korea	1.8	SSP3	14.6	SSP5	12.8
Central Asia	39.0	SSP5	74.7	SSP3	35.7
World	45.9	SSP3	79.8	SSP5	33.9

[(1)]A full description of the regions of the model is available at Lima et al. (2022). [(2)]Range, considering the five scenarios of SSP yield for each region. [(3)]SSP1, Sustainability; SSP2, Middle of the Road; SSP3, Regional Rivalry; SSP4, Inequality; SSP5, Fossil-fueled Development. The higher the resilience, the lower is the range value.

DISCUSSION

Demand and supply-side drivers will affect the endogenous responses of both regional and global agriculture and food security outcomes. When only demand responses are considered, economic margins of response to scarcity are not fully represented and the impacts on land use, for example, are exacerbated (Hertel, 2018), as can be seen in the results presented in Table 2. When supply-side shocks were simultaneously considered, global cropland variation was reduced by 2.7 p.p. relative to the only demand-side shocks. Agricultural output is ultimately the result of intensive (productivity) and extensive (land) margins. Decreases in the former necessarily requires increases in the later to sustain a given agricultural output level to meet demand. Conversely, if productivity is sustained at higher levels, it is possible to decrease the pressures on natural resources (Martha Jr. et al., 2012; Hertel et al., 2014; Villoria, 2019) with a likely reduction in greenhouse gases emissions associated with land-use changes (Lobell et al., 2013; Deconinck & Toyama, 2022).

In the long run, R&D expenditures fueling technological innovations are major drivers explaining the increase of agricultural productivity and output (Pardey et al., 2016; Fuglie, 2018b; Martha Jr. & Alves, 2018; Fuglie et al., 2022; Lima et al., 2022). When demand and supply forces are jointly evaluated, compared to the situation in which only demand-side shocks are considered, it is possible to investigate, for example, the likely effects of a weakened R&D strategy, leading to a slower than expected technological development pace in SSP1 or SSP5 narratives. Conversely, such comparisons allow exploring the possible impacts of unanticipated improvements in R&D efforts in the "worlds" represented by SSP3 and SSP4 scenarios (Table 2; for a regional perspective, compare results in Tables 1 and 3).

Future agriculture and food security outcomes will be further jeopardized by the increasing challenges imposed by climate change (Zilli et al., 2020; Fróna et al., 2021; Jägermeyr et al., 2021; Masson-Delmotte et al., 2021). In fact, the growth rate in crop yield (output per area harvested) has been already compromised by human-induced warming in the past 50 years (IPCC, 2022), and the rate of growth in cropland productivity has been maintained because of increases in land use intensity, which refers to the average number of harvests per year (Fuglie, 2018a). Recent agricultural outlooks are already projecting a worrying decrease in yield growth rates for the next decade (Brasil, 2022; OECD-FAO…, 2022), as compared to figures estimated from historical time-series (USDA, 2022). Our results further indicate that these challenges presented to agricultural output increase, decreased cropland expansion, and strengthened food security are likely to be more severe in the worlds represented by "Regional Rivalry" (SSP3 scenario) and "Inequality" (SSP4 scenario) (Tables 3 and 5).

Furthermore, when farmers are exposed to an unknown environment of production, such as the one foreseen with the advancement of climate change (Zilli et al., 2020; Fróna et al., 2021; Jägermeyr et al., 2021), their previous technological knowledge is of limited use (Alves, 1987). Previous farmers' experience is more suitable for an environment that is not changing, or that is changing very slowly (Alves, 1987). Ultimately, climate-related impacts are context-specific but expected to be higher in environments that are already hot and have limited socio-economic and institutional resources for adaptation (Godde et al., 2021). The lower resilience in agricultural output response across regions, under different supply and demand-side shocks, supports this assertive. The difference in agricultural output response between the worst and the best scenarios are generally higher than 40 p.p. for developing regions of the model and lower than that threshold for developed regions (Table 5). In addition, it is plausible to assume that famers in temperate regions will eventually benefit from knowledge and technologies already developed for agriculture in the tropics. Farmers in the tropics, however, will need to further develop knowledge and technologies to cope with a new and challenging environment of production.

Given the lag of decades between investments in research and the realization of the associated full benefits (Alston, 2010; Fuglie, 2018b), sustaining R&D expenditures at higher levels over the

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short to medium terms are strategic to increase agricultural TFP in the long run (Fuglie, 2018b; Lima et al., 2022). In other words, farmers will not be able to sustain high levels of productivity unless they are backed by and compromised with a solid science-based approach (Alves, 1987). In this context, a grand challenge to public and private decision-makers is to avoid failures to sustain a rapid technological development and adoption over the medium to the long-run (Martha Jr. & Alves, 2018). Technological progress and innovations must advance at least at rates equivalent to the pace at which those negative pressing changes imposed by climate change are established in the production environment, allowing agricultural output to increase largely based on yield gains and improved resource-use efficiency, coupled with reduced pressures to expand cropland (Embrapa, 2014).

CONCLUDING REMARKS

The SSP1 "Sustainability" scenario could deliver an increased agricultural output, coupled with improved food security and environmental benefits (Tables 3 and 4). However, such possible future will not come for free, nor it will be a "natural decision", as it will not always be the superior approach, and its regional performance is scenario-dependent (Tables 3, 4, and 5). Supply shocks to global agricultural production and its supply chains, such as the ones resulting from covid-19 and the on-going war between Ukraine and Russia (FAO, 2023c; Laber et al., 2023), impose further challenges to future outcomes for regional and global agriculture.

From a policy perspective, a successful sustainability path will probably need to identify and implement small loss - big gain strategies (DeFries et al., 2004), and permit enough flexibility to buffer against unexpected supply shocks without compromising long-term goals. Furthermore, a resilient sustainability path will strongly depend on an articulated global effort to strengthening agricultural R&D expenditures accompanied by a well-designed strategy to translate science into problem-solving knowledge and technologies that could be successfully transferred to and adopted by farmers to boost productivity gains over the next three decades. Actionable steps for such hopeful SSP1 future must set R&D expenditures as a priority across regions (Alston, 2010; Pardey et al., 2016; Fuglie, 2018b) to sustain a challenging weighted average productivity growth rate in global agricultural around 2.4% per year up to 2050. Political support to such strengthened research approach is likely to increase if R&D efforts are communicated to stakeholders from a real-world perspective of great challenges and opportunities to agricultural value chains. Barriers to technology adoption must be continuously identified, monitored, and alleviated to avoid impairing the innovation process (Beddow et al., 2014; Martha Jr. & Alves, 2018). However, it would be naive to think that supply responses alone would suffice to ensure regional and global food security. In addition to increased agricultural output, ending hunger and malnutrition by 2030 (SDG-2) requires other joint approaches to effectively succeed, such as increased incomes and an improved access to food.

As a final thought, bringing increased insights into regional and sectoral SSP perspectives are welcome (Riahi et al., 2017) and necessary to better support the decision-making process, because the different regions of the world, or the economic sectors, may respond quite distinctly to the different shocks associated with the SSPs futures, for example, by revealing different impacts on land-use changes or food security matters (Popp et al., 2017; Mora et al., 2020; Silva Bezerra et al., 2022). Understanding the interdisciplinary challenges that are relevant to the sustainability of local, regional, and global agriculture toward 2050 is not a trivial task. Science-policy scenarios to support the decision-making process will become more relevant and able to mimic real-world opportunities and challenges when considering possibilities ranging from global to local drivers and impacts, and vice-versa. Future work will benefit if the potential impacts of climate change in relevant supply and demand-side drivers are considered and, additionally, if multi-scale approaches of the sustainability dimensions (social, economic, environmental) are incorporated into the analysis, aiming to provide knowledge and insights tailored to specific contexts.

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REFERENCES

ALSTON, J.M. **The benefits from agricultural research and development, innovation, and productivity growth**. Paris: OECD, 2010. 26p. (OECD Food, Agriculture and Fisheries Papers, n.31). DOI: https://doi.org/10.1787/5km91nfsnkwg-en.

ALVES, E. Mobilizing political support for the Brazilian agricultural research system. In: RUTTAN, V.W.; PRAY, C.E. (Ed.). **Policy for agricultural research**. Boulder: Westview Press, 1987. p.363-376. DOI: https://doi.org/10.1201/9780429301940-16.

BALDOS, U.L.C.; HERTEL, T.W. Global food security in 2050: the role of agricultural productivity and climate change. **The Australian Journal of Agricultural and Resource Economics**, v.58, p.554-570, 2014. DOI: https://doi.org/10.1111/1467-8489.12048.

BARRETT, C.B.; ORTIZ-BOBEA, A.; PHAM, T. Structural transformation, agriculture, climate, and the environment. **Review of Environmental Economics and Policy**, v.17, p.195-216, 2023. DOI: https://doi.org/10.1086/725319.

BEDDOW, J.M.; HURLEY, T.M.; PARDEY, P.G.; ALSTON, J.M. Food security: yield gap. **Encyclopedia of Agriculture and Food Systems**, p.352-365, 2014. DOI: https://doi.org/10.1016/B978-0-444-52512-3.00037-1.

BÉNÉ, C.; PRAGER, S.D.; ACHICANOY, H.A.E.; TORO, P.A.; LAMOTTE, L.; CEDREZ, C.B.; MAPES, B.R. Understanding food systems drivers: a critical review of the literature. **Global Food Security**, v.23, p.149-159, 2019. DOI: https://doi.org/10.1016/j.gfs.2019.04.009.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. **Projeções do Agronegócio 2020-2022 a 2030-2032**. 2022. Available at: <https://www.gov.br/agricultura/pt-br/assuntos/politica-agricola/todas-publicacoes-de-politica-agricola/projecoes-do-agronegocio>. Accessed on: Dec. 11 2023.

CONNOR, D.J.; LOOMIS, R.S.; CASSMAN, K.G. **Crop ecology**: productivity and management in agricultural systems. 2nd ed. Cambridge: Cambridge University Press, 2011. 576p. DOI: https://doi.org/10.1017/CBO9780511974199.

DECONINCK, K.; TOYAMA, L. **Environmental impacts along food supply chains**: methods, findings, and evidence gaps. Paris: OECD, 2022. 47p. (OECD Food, Agriculture and Fisheries Papers, n.185). DOI: https://doi.org/10.1787/48232173-en.

DEFRIES, R.S.; FOLEY, J.A.; ASNER, G.P. Land-use choices: balancing human needs and ecosystem function. **Frontiers in Ecology and the Environment**, v.2, p.249-257, 2004. DOI: https://doi.org/10.1890/1540-9295(2004)002[0249:LCBHNA]2.0.CO;2.

EL-CHICHAKLI, B.; VON BRAUN, J.; LANG, C.; BARBEN, D.; PHILP, J. Policy: five cornerstones of a global bioeconomy. **Nature**, v.535, p.221-223, 2016. DOI: https://doi.org/10.1038/535221a.

EMBRAPA. Empresa Brasileira de Pesquisa Agropecuária. **Visão 2014-2034**: o futuro do desenvolvimento tecnológico da agricultura brasileira. Brasília, 2014. 194p.

FANZO, J.; DAVIS, C.; MCLAREN, R.; CHOUFANI, J. The effect of climate change across food systems: Implications for nutrition outcomes. **Global Food Security**, v.18, p.12-19, 2018. DOI: https://doi.org/10.1016/j.gfs.2018.06.001.

FAO. Food and Agriculture Organization of the United Nations. **Faostat**. Available at: <https://www.fao.org/faostat/en/#home>. Accessed on: Dec. 11 2023a.

FAO. Food and Agriculture Organization of the United Nations. **Faostat**: Suite of Food Security Indicators. Available at: <https://www.fao.org/faostat/en/#data/FS>. Accessed on: Dec. 11 2023b.

FAO. Food and Agriculture Organization of the United Nations. **Guidelines to increase the resilience of agricultural supply chains**. Rome, 2023c. 40p. DOI: https://doi.org/10.4060/cc5481en.

FAO. Food and Agriculture Organization of the United Nations. **The state of food security and nutrition in the world 2023**: urbanization, agrifood system transformation and healthy diets across the rural–urban continuum. Rome, 2023d. 283p. DOI: https://doi.org/10.4060/cc3017en.

FRÓNA, D.; SZENDERÁK, J.; HARANGI-RÁKOS, M. Economic effects of climate change on global agricultural production. **Nature Conservation**, v.44, p.117-139, 2021. DOI: https://doi.org/10.3897/natureconservation.44.64296.

FUGLIE, K.; RAY, S.; BALDOS, U.L.C.; HERTEL, T.W. The R&D cost of climate mitigation in agriculture. **Applied Economic Perspectives and Policy**, v.44, p.1955-1974, 2022. DOI: https://doi.org/10.1002/aepp.13245.

FUGLIE, K.O. Is agricultural productivity slowing? **Global Food Security**, v.17, p.73-83, 2018a. DOI: https://doi.org/10.1016/j.gfs.2018.05.001.

FUGLIE, K.O. R&D capital, R&D spillovers, and productivity growth in world agriculture. **Applied Economic Perspectives and Policy**, v.40, p.421-444, 2018b. DOI: https://doi.org/10.1093/aepp/ppx045.

GILLER, K.E.; DELAUNE, T.; SILVA, J.V.; DESCHEEMAEKER, K.; van de VEN, G.; SCHUT, A.G.T.; van WIJK, G.; HAMMOND, J.; HOCHMAN, Z.; TAULYA, G.; CHIKOWO, R.; NARAYANAN, S.; KISHORE, A.; BRESCIANI, F.; TEIXEIRA, H.M.; ANDERSSON, J.A.; van ITTERSUM, M.K. The future of farming: Who will produce our food? **Food Security**, v.13, p.1073-1099, 2021. DOI: https://doi.org/10.1007/s12571-021-01184-6.

GODDE, C.M.; MASON-D'CROZ, D.; MAYBERRY, D.E.; THORNTON, P.K.; HERRERO, M. Impacts of climate change on the livestock food supply chain; a review of the evidence. **Global Food Security**, v.28, art.100488, 2021. DOI: https://doi.org/10.1016/j.gfs.2020.100488.

GTAP. Global Trade Analysis Project. **GTAP Data Base**. Available at: <https://www.gtap.agecon.purdue.edu/databases/default.asp>. Accessed on: Dec. 11 2023.

HERTEL, T.W. Economic perspectives on land use change and leakage. **Environmental Research Letters**, v.13, art.075012, 2018. DOI: https://doi.org/10.1088/1748-9326/aad2a4.

HERTEL, T.W.; BALDOS, U.L.C. **Global change and the challenges of sustainably feeding a growing planet**. Cham: Springer, 2016. 184p. DOI: https://doi.org/10.1007/978-3-319-22662-0.

HERTEL, T.W.; RAMANKUTTY, N.; BALDOS, U.L.C. Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO_2 emissions. **Proceedings of the National Academy of Sciences**, v.111, p.13799-13804, 2014. DOI: https://doi.org/10.1073/pnas.1403543111.

IPCC. Intergovernmental Panel on Climate Change. **Climate change 2022**: impacts, adaptation, and vulnerability: summary for policymakers. Cambridge: Cambridge University Press, 2022. Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. DOI: https://doi.org/10.1017/9781009325844.001.

JÄGERMEYR, J.; MÜLLER, C.; RUANE, A.C.; ELLIOTT, J.; BALKOVIC, J.; CASTILLO, O.; FAYE, B.; FOSTER, I.; FOLBERTH, C.; FRANKE, J.A.; FUCHS, K.; GUARIN, J.R.; HEINKE, J.; HOOGENBOOM, G.; IIZUMI, T.; JAIN, A.K.; KELLY, D.; KHABAROV, N.; LANGE, S.; LIN, T.-S.; LIU, W.; MIALYK, O.; MINOLI, S.; MOYER, E.J.; OKADA, M.; PHILLIPS, M.; PORTER, C.; RABIN, S.S.; SCHEER, C.; SCHNEIDER, J.M.; SCHYNS, J.F.; SKALSKY, R.; SMERALD, A.; STELLA, T.; STEPHENS, H.; WEBBER, H.; ZABEL, F.; ROSENZWEIG, C. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. **Nature Food**, v.2, p.873-885, 2021. DOI: https://doi.org/10.1038/s43016-021-00400-y.

KERR, R.B.; NAESS, L.O.; ALLEN-O'NEIL, B.; TOTIN, E.; NYANTAKYI-FRIMPONG, H.; RISVOLL, C.; FERRE, M.G.R.; LÓPEZ-I-GELATS, F.; ERIKSEN, S. Interplays between changing biophysical and social dynamics under climate change: Implications for limits to sustainable adaptation in food systems. **Global Change Biology**, v.28, p.3580-3604, 2022. DOI: https://doi.org/10.1111/gcb.16124.

LABER, M.; KLIMEK, P.; BRUCKNER, M.; YANG, L.; THURNER, S. Shock propagation from the Russia–Ukraine conflict on international multilayer food production network determines global food availability. **Nature Food**, v.4, p.508-517, 2023. DOI: https://doi.org/10.1038/s43016-023-00771-4.

LEHTONEN, H.S.; AAKKULA, J.; FRONZEK, S.; HELIN, J.; HILDÉN, M.; HUTTUNEN, S.; KALJONEN, M.; NIEMI, J.; PALOSUO, T.; PIRTTIOJA, N.; RIKKONEN, P.; VARHO, V.; CARTER, T.R. Shared socioeconomic pathways for climate change research in Finland: co-developing extended SSP narratives for agriculture. **Regional Environmental Change**, v.21, art.7, 2021. DOI: https://doi.org/10.1007/s10113-020-01734-2.

LIMA, C.Z. de; MARTHA JR., G.B.; BARIONI, L.G.; BALDOS, U.C.; HERTEL, T.W. Agricultural R&D investments in Brazil: global responses and local spillovers. In: ANNUAL CONFERENCE ON GLOBAL ECONOMIC ANALYSIS, 25., 2022, Virtual Conference. [**Proceedings**]. 2022. p.1-14. Available at: <https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=6679>. Accessed on: Dec. 11 2023.

LOBELL, D.B.; BALDOS, U.L.C.; HERTEL, T.W. Climate adaptation as mitigation: the case of agricultural investments. **Environmental Research Letters**, v.8, art.015012, 2013. DOI: https://doi.org/10.1088/1748-9326/8/1/015012.

MAPBIOMAS. **Projeto MapBiomas – Mapeamento Anual de Cobertura e Uso da Terra no Brasil - Coleção 7**. 2023. Available at: <https://mapbiomas-br-site.s3.amazonaws.com/Fact_Sheet_Coleção_6_Agosto_2021_27082021_OK_ALTA.pdf>. Accessed on: Dec. 11 2023.

MARTHA JR., G.B.; ALVES, E. Brazil's agricultural modernization and Embrapa. In: AMANN, E.; AZZONI, C.R.; BAER, W. (Ed.). **The Oxford handbook of the Brazilian economy**. New York: Oxford University Press, 2018. p.309-337. DOI: https://doi.org/10.1093/oxfordhb/9780190499983.013.15.

MARTHA JR., G.B.; ALVES, E.; CONTINI, E. Land-saving approaches and beef production growth in Brazil. **Agricultural Systems**, v.110, p.173-177, 2012. DOI: https://doi.org/10.1016/j.agsy.2012.03.001.

MARTHA JÚNIOR, G.B.; LOPES, M.A. Charting new sustainable agricultural innovation pathways in Brazil. **Scientia Agricola**, v.80, e20230067, 2023. DOI: https://doi.org/10.1590/1678-992X-2023-0067.

MASSON-DELMOTTE, V.; ZHAI, P.; PIRANI, A.; CONNORS, S.L.; PÉAN, C.; CHEN, Y.; GOLDFARB, L.; GOMIS, M.I.; MATTHEWS, J.B.R.; BERGER, S.; HUANG, M.; YELEKÇI, O.; YU, R.; ZHOU, B.; LONNOY, E.; MAYCOCK, T.K.; WATERFIELD, T.; LEITZELL, K.; CAUD, N. (Ed.). **Climate Change 2021**: the physical science basis: summary for policymakers. Switzerland: IPCC, 2021. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

MCKINSEY & COMPANY. **What is food insecurity**? 2022. Available at: <https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-food-insecurity>. Accessed on: Dec. 11 2023.

MITTER, H.; TECHEN, A.-K.; SINABELL, F.; HELMING, K.; SCHMID, E.; BODIRSKY, B.L.; HOLMAN, I.; KOK, K.; LEHTONEN, H.; LEIP, A.; LE MOUËL, C.; MATHIJS, E.; MEHDI, B.; MITTENZWEI, K.; MORA, O.; ØISTAD, K.; ØYGARDEN, L.; PRIESS, J.A.; REIDSMA, P.; SCHALDACH, R.; SCHÖNHART, M. Shared socio-economic pathways for European agriculture and food systems: the Eur-Agri-SSPs. **Global Environmental Change**, v.65, art.102159, 2020. DOI: https://doi.org/10.1016/j.gloenvcha.2020.102159.

MORA, O.; LE MOUËL, C.; LATTRE-GASQUET, M. de; DONNARS, C.; DUMAS, P.; RÉCHAUCHÈRE, O.; BRUNELLE, T.; MANCERON, **S**.; MARAJO-PETITZON, E.; MOREAU, **C**.; BARZMAN, M.; FORSLUND, A.; MARTY, P. Exploring the future of land use and food security: a new set of global scenarios. PLoS ONE, v.15, e0235597, 2020. DOI: https://doi.org/10.1371/journal.pone.0235597.

MUHAMMAD, A.; SEALE JR., J.L.; MEADE, B.; REGMI, A. **International evidence on food consumption patterns**: an update using 2005 international comparison program data. Washington: ERS, USDA, 2011. 59p. (United States Department of Agriculture. Technical Bulletin, 1929). DOI: https://doi.org/10.2139/ssrn.2114337.

NUGROHO, A.D.; PRASADA, I.Y.; LAKNER, Z. Comparing the effect of climate change on agricultural competitiveness in developing and developed countries. **Journal of Cleaner Production**, v.406, art.137139, 2023. DOI: https://doi.org/10.1016/j.jclepro.2023.137139.

O'NEILL, B.C.; CARTER, T.R.; EBI, K.; HARRISON, P.A.; KEMP-BENEDICT, E.; KOK, K.; KRIEGLER, E.; PRESTON, B.L.; RIAHI, K.; SILLMANN, J.; van RUIJVEN, B.J.; van VUUREN, D.; CARLISLE, D.; CONDE, C.; FUGLESTVEDT, J.; GREEN, C.; HASEGAWA, T.; LEININGER, J.; MONTEITH, S.; PICHS-MADRUGA, R. Achievements and needs for the climate change scenario framework. **Nature Climate Change**, v.10, p.1074-1084, 2020. DOI: https://doi.org/10.1038/s41558-020-00952-0.

O'NEILL, B.C.; KRIEGLER, E.; EBI, K.L.; KEMP-BENEDICT, E.; RIAHI, K.; ROTHMAN, D.S.; van RUIJVEN, B.J.; van VUUREN, D.P.; BIRKMANN, J.; KOK, K.; LEVY, M.; SOLECKI, W. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. **Global Environmental Change**, v.42, p.169-180, 2017. DOI: https://doi.org/10.1016/j.gloenvcha.2015.01.004.

O'NEILL, B.C.; KRIEGLER, E.; RIAHI, K.; EBI, K.L.; HALLEGATTE, S.; CARTER, T.R.; MATHUR, R.; van VUUREN, D.P. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. **Climatic Change**, v.122, p.387-400, 2014. DOI: https://doi.org/10.1007/s10584-013-0905-2.

OECD. Organisation for Economic Co-operation and Development. **Making better policies for food systems**. [Paris], 2021.

OECD-FAO Agricultural Outlook 2022-2031. Paris: OECD, 2022.

PALAZZO, A.; VERVOORT, J.W.; MASON-D'CROZ, D.; RUTTING, L.; HAVLÍK, P.; ISLAM, S.; BAYALA, J.; VALIN, H.; KADI, H.A.K.; THORNTON, P.; ZOUGMORE, R. Linking regional stakeholder scenarios and shared socioeconomic pathways: quantified West African food and climate futures in a global context. **Global Environmental Change**, v.45, p.227-242, 2017. DOI: https://doi.org/10.1016/j.gloenvcha.2016.12.002.

PARDEY, P.G.; CHAN-KANG, C.; DEHMER, S.P.; BEDDOW, J.M. Agricultural R&D is on the move. **Nature**, v.537, p.301-303, 2016. DOI: https://doi.org/10.1038/537301a.

POPP, A.; CALVIN, K.; FUJIMORI, S.; HAVLIK, P.; HUMPENÖDER, F.; STEHFEST, E.; BODIRSKY, B.L.; DIETRICH, J.P.; DOELMANN, J.C.; GUSTI, M.; HASEGAWA, T.; KYLE, P.; OBERSTEINER, M.; TABEAU, A.; TAKAHASHI, K.; VALIN, H.; WALDHOFF, S.; WEINDL, I.; WISE, M.; KRIEGLER, E.; LOTZE-CAMPEN, H.; FRICKO, O.; RIAHI, K.; van VUUREN, D.P. Land-use futures in the shared socio-economic pathways. **Global Environmental Change**, v.42, p.331-345, 2017. DOI: https://doi.org/10.1016/j.gloenvcha.2016.10.002.

RIAHI, K.; van VUUREN, G.P.; KRIEGLER, E.; EDMONDS, J.; O'NEILL, B.C.; FUJIMORI, S.; BAUER, N.; CALVIN, K.; DELLINK, R.; FRICKO, O.; LUTZ, W.; POPP, A.; CUARESMA, J.C.; KC, S.; LEIMBACH, M.; JIANG, L.; KRAM, T.; RAO, S.; EMMERLING, J.; EBI, K.; HASEGAWA, T.; HAVLIK, P.; HUMPENÖDER, F.; DA SILVA, L.A.; SMITH, S.; STEHFEST, S.; BOSETTI, V.; EOM, J.; GERNAAT, D.; MASUI, T.; ROGELJ, J.; STREFLER, J.; DROUET, L.; KREY, V.; LUDERER, G.; HARMSEN, M.; TAKAHASHI, K.; BAUMSTARK, L.; DOELMAN, J.C.; KAINUMA, M.; KLIMONT, Z.; MARANGONI, G.; LOTZE-CAMPEN, H.; OBERSTEINER, M.; TABEAU, A.; TAVONI, M. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. **Global Environmental Change**, v.42, p.153-168, 2017. DOI: https://doi.org/10.1016/j.gloenvcha.2016.05.009.

SCHMITZ, A.; MOSS, C.B.; SCHMITZ, T.G.; van KOOTEN, G.C.; SCHMITZ, H.C. **Agricultural policy, agribusiness, and rent-seeking behaviour**. 3rd ed. London: University of Toronto Press, 2022. 488p.

SILVA BEZERRA, F.G.; VON RANDOW, C.; ASSIS, T.O.; BEZERRA, K.R.A.; TEJADA, G.; CASTRO, A.A.; GOMES, D.M. de P.; AVANCINI, R.; AGUIAR, A.P. New land-use change scenarios for Brazil: refining global SSPs with a regional spatially-explicit allocation model. **PLoS ONE**, v.17, e0256052, 2022. DOI: https://doi.org/10.1371/journal.pone.0256052.

TIMMER, C.P.; FALCON, W.P.; PEARSON, S.R. **Food policy analysis**. Washington: World Bank, 1983. 301p.

USDA. Economic Research Service. **International agricultural productivity**. 2022. Available at: <https://www.ers.usda.gov/data-products/international-agricultural-productivity/>. Accessed on: Dec. 11 2023.

VILLORIA, N.B. Technology spillovers and land use change: empirical evidence from global agriculture. **American Journal of Agricultural Economics**, v.101, p.870-893, 2019. DOI: https://doi.org/10.1093/ajae/aay088.

VON BRAUN, J.; AFSANA, K.; FRESCO, L.O.; HASSAN, M.H.A.; TORERO, M. Food system concepts and definitions for science and political action. **Nature Food**, v.2, p.748-750, 2021. DOI: https://doi.org/10.1007/978-3-031-15703-5_2.

WORLD BANK. **Food Security Update**. Nov. 2023. 25p. Available at: <https://www.worldbank.org/en/topic/agriculture/brief/food-security-update>. Accessed on: Dec. 11 2023.

ZILLI, M.; SCARABELLO, M.; SOTERRONI, A.C.; VALIN, H.; MOSNIER, A.; LECLÈRE, D.; HAVLÍK, P.; KRAXNER, F.; LOPES, M.A.; RAMOS, F.M. The impact of climate change on Brazil's agriculture. **Science of The Total Environment**, v.740, art.139384, 2020. DOI: https://doi.org/10.1016/j.scitotenv.2020.139384.