WORLD AGRICULTURAL RESOURCES AND FOOD SECURITY

International Food Security

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Assessing the Impact of Agricultural R&D Investments on Long-Term Projections of Food Security

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Abstract
The purpose of this chapter is to analyze the impact of public agricultural Research and Development (R&D) investments on agricultural productivity and long-term food security to derive policy recommendations. The methodological approach is based on the application of the state-of-the art Computable General Equilibrium (CGE) model to R&D. By endogenizing R&D in global CGE models, it is possible to assess the impact of different public R&D policies on the food availability and food access of food security. This study found that R&D investments bring positive effects on the food access dimension of food security, particularly in places such as Sub-Saharan Africa where prices are expected to grow significantly by 2050, as agricultural land becomes scarcer and more expensive. Doubling the R&D intensity would soften the land constraints and substantially decelerate food prices, thus preventing the deterioration of living standards of rural households and leading to a gain in daily caloric consumption. The impact of alternative agricultural R&D policies on the various dimensions of food security has not been analyzed using a CGE framework, which enables capturing both the benefits and costs from R&D investments. Modeling the dynamic accumulation of R&D stocks makes it possible to analyze the effects of R&D on food security over time.

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1. Introduction

There are various challenges for reaching long-term sustainable agricultural production and food security. On the one hand, there are increased demand pressures resulting from ongoing population growth, improvements in living standards in developing countries, and increased demand from nonfood sources (e.g., renewable energy sources). On the other hand, there are constraints on the production side due to climate change, limited agricultural land, and reduced agricultural labor. The Food and Agricultural Organization of the United Nations (FAO, 1996) estimates that food production will need to be increased by 60% to feed a global population of approximately 9 billion people in 2050. Around 80% of the projected growth will have to come from intensification, predominantly an increase in agricultural yields through better use of inputs (Alexandratos & Bruinsma, 2012).

Agricultural research and development (R&D) investments represent a possible solution for the food-security challenge, especially in developing countries where cereal yields are still well below the global average level. Continuous investments in R&D are important from the perspective of all four food-security dimensions, namely food availability, accessibility, utilization, and stability (FAO, 1996). The *availability* dimension of food security is associated with the physical supply of food. According to various scholars (Alston, Andersen, James, & Pardey, 2009; Avila & Evenson, 2010; Fuglie, 2012; Pardey & Beddow, 2013), investments in R&D are important drivers of agricultural productivity and food availability. R&D investments in better seeds and varieties during the Green Revolution resulted in lower agricultural prices, which contributed positively to the *accessibility* dimension of food security. By increasing agricultural productivity, the corresponding farmer income gains can translate into better nutrition, gains in dietary diversity, and improved health that affect positively the *utilization* and *stability* dimensions of food security.

Despite the key role of R&D investments when improving the dimensions of food security, only a few global model studies have explicitly assessed the impact of R&D investment on food security (Baldos, Hertel, & Fuglie, 2015; Dietrich, Schmitz, Lotze-Campen, Popp, & Miller, 2014; Hoddinot, Rosegrant, & Torero, 2012). These studies used partial equilibrium (PE) models such as International Model for Policy Analysis of

Agricultural Commodities and Trade (IMPACT) and Model of Agricultural Production and its Impact on the Environment (MAgPIE) that can simulate the agricultural sector but cannot address the impact of agricultural R&D investment on the wider, global economy (for instance through lower prices of agricultural commodities). Therefore, we use a computable general equilibrium (CGE) model to analyze food security.

The objective of this chapter is to provide projections of agricultural production, food prices, and other food-security indicators toward 2050 with alternative scenarios of R&D investments. In the baseline scenario, R&D investments follow a constant share in agricultural gross domestic product (GDP). In the policy simulations, the impact of doubling and tripling shares of R&D investments in agricultural GDP on food security in targeted developing countries is analyzed, with the major focus on the regions of Sub-Saharan Africa, South Asia, and Latin America. The results are contrasted with a scenario in which land productivity follows an exogenous trend, thus with no R&D investments.

2. *Methodology*

2.1. The MAGNET model

In this case, we use an extended variant of the Global Trade Analysis Project (GTAP) model (Hertel & Hertel, 1997) known as the Modular Applied GeNeral Equilibrium Tool (MAGNET) (Woltjer et al., 2014). MAGNET is a neoclassical recursive dynamic multisector, multiregion CGE model that has been widely used to simulate the impacts of agricultural, trade, land use, and biofuel policies on global economic development (Banse, Van Meijl, Tabeau, & Woltjer, 2008; Francois, Van Meijl, & Van Tongeren, 2005; Nelson et al., 2014a, 2014b; Nowicki et al., 2009; Van Meijl, Van Rheenen, Tabeau, & Eickhout, 2006). MAGNET includes an improved treatment of agricultural sectors (such as the endogenous land supply curve), agricultural policy, and biofuel policy. On the consumption side, a dynamic CDE expenditure function is implemented that allows for changes in income elasticities when purchasing power parity (PPP)-corrected real GDP per capita changes. Segmentation and imperfect mobility between agricultural and nonagricultural labor and capital are introduced in the modeling of factor markets.

For the analysis in this chapter, MAGNET uses GTAP database version 8, final release (Narayanan, Aguiar, & McDougall, 2013) which contains data on the input-output structure for 140 countries for base year 2007. To conduct the analysis, we aggregate the data to 25 production sectors, from which 11 are primary agricultural sectors and 21 are regions (Appendix).

2.2. Incorporation of R&D-driven technical change

We focus on public agricultural R&D targeted to major improvements of seeds and varieties in the style of the Green Revolution. In other words, we assume that public agricultural R&D is responsible for biological technical change in line with the reasoning of Piesse, Shimpeffeling, and Thirtle (2011). Although one might argue that public R&D comprises a larger category than just land-oriented research, investment in improving crop varieties is still the key focus of publically funded research. We propose a global empirically based approach to link R&D with productivity coefficients applying the function of constant elasticity of substitution (CES) production structures in a global modeling framework. Besides being empirically based, the advantage of linking public R&D to productivity coefficients is that the agricultural sector benefits "freely" from the public R&D sector, while the government pays for all expenditures (increased governmental consumption is reflected in reduced savings to the rest of the economy). Thus, the public goods component of agricultural R&D is well captured. The alternative and more common approach in the CGE literature is to include knowledge as a new production factor resulting from cumulative R&D efforts. In this way, knowledge is embedded in producers' cost minimization, meaning that agricultural producers have to pay for investing in R&D which is more appropriate for modeling private R&D effects.

In line with our assumptions, a separate R&D sector was disaggregated from the public services sector in the social accounting matrix (SAM), the basic data structure of CGE models that reflects all market transactions in an economy. A simple procedure of applying the share of public R&D expenditures in the value of the output of public services was applied to all cost components. This means that the public R&D sector employs the same share of skilled and unskilled labor as other public services. Various data sources were compiled to derive the value of public R&D expenditures for all 140 regions (Smeets Kristkova, Van Dijk, & Van Meijl, 2016). All values were converted to 2007 US dollars to homogenize with values of other variables in SAM.

Following the empirical evidence on the specific shape of knowledge stocks distribution over time, a gamma distribution function was incorporated in MAGNET for building R&D stocks from public R&D expenditures. In line with the evidence in the literature, regions were grouped into six vintage groups. R&D investments in high-income regions such as the United States exhibit the longest lags corresponding to the nature of the research (basic research prevails). On the other hand, developing regions are allocated to vintage groups with shorter lags due to the more adaptive nature of research (Table 1). Similarly, the elasticity values vary with the vintage groups and generally follow the pattern that the longer the R&D distribution lag is, the higher the return and the elasticity of technical

Table 1. Parameters of the gamma distribution function of R&D stock accumulation per vintage group

Group	Typical Regions	Max Lag (*y*)	Peak (*y*)	RD Elasticity	Exo Rate
A	United States (Alston et al., 2009)	35	10	0.35	1
B	Australia (Sheng, Gray, & Mullen, 2011); New Zealand (Hall & Scobie, 2006)	35	10	0.35	1
C	EU-15 and other high income (Thirtle, Piesse, & Schimmelpfenning, 2008)	25	10	0.20	1
D	EU-12 and Russian Federation (Ratinger & Kristkova, 2015)	15	3	0.15	1
E	Latin America (Bervejillo, Alson, & Tumber, 2012)	15	5	0.15	1
F	Asia Pacific and Africa (Alene & Coulibalyl, 2009; Nin Pratt & Fan, 2009)	15	5	0.20	1

change with respect to R&D (the lags and obtained elasticities from neutral and factor-biased studies are comparable).

The growth of the cumulated R&D stocks from the gamma distribution is linked to the land-augmenting technical change as shown in the following equation:

$$\text{aland\_agg}_t = \text{aland}_{exo} + \text{deltaRD} * \text{gr\_rdstock}_t \quad (1)$$

where aland $\_agg_t$ represents the annual growth of the aggregate land-augmenting technical change parameter that enters the CES production function, deltaRD is the elasticity of aland_agg with respect to R&D stock growth (values are reported in Table 1), and rdstock_t is the annual growth rate of domestic R&D stocks. Given that public agricultural R&D stocks are not the only productivity driver, we also consider an exogenous productivity component aland_{exo} that is set to the rate of 1% annually and homogenously across all regions. The 1% rate of exogenous increase is the constant factor of a regression analysis of aggregate yield on R&D stocks. We assume that it captures the increase in land productivity caused by other drivers such as private agricultural and nonagricultural R&D, advances in human capital, etc.

2.3. Definition of scenarios

To develop the baseline scenarios, we use the Shared Socioeconomic Pathways #2 (SSP2), the so-called Middle of the Road scenario (reflects a business-as-usual future), to assess the impact of global climate change (Kriegler et al., 2012; O'Neill et al., 2012, 2014). SSPs are a set of plausible and alternative assumptions that describe potential future socioeconomic developments like GDP and population growth in the absence of climate policies or climate change up to the year 2050.

Besides population and GDP, choices must be made regarding the mechanism of governmental R&D spending. It is generally expected that governments follow a constant agricultural research intensity ratio, being considered as a "norm for reinvestment in the agricultural sector related to size of the agricultural sector" (Beintema & Elliot, 2009, p. 12). However, in some cases, imposing a constant share of agricultural R&D in agricultural GDP does not reflect the research capacity and the expansion of governmental spending. When comparing historical growth rates of R&D investments (2007−2010) with simulation growth rates based on constant R&D shares, large deviations are found, particularly for countries such as China and India. As highlighted in Pardey, Alston, and Chan-Kang (2013), China and India have enjoyed considerably high growth rates of public R&D investments that far outpace the growth of their domestic agricultural sectors. To account for these inconsistencies, regions were grouped into three categories (Table 2). The first category is represented by regions, such as the European Union (EU), where it is plausible to expect that future R&D investments follow a constant share in agricultural GDP. The second group is represented by regions, such as the Middle East, where R&D investments in agriculture are driven mostly by governmental budget growth fueled by oil revenues rather than by domestic agricultural sector. The third group is represented by regions, such as China and India, where R&D expenditures might be either heavily underestimated or excessively overrated into the future, so a mixed solution is chosen that resembles best R&D historical growth rates.

By applying the three different R&D mechanisms, baseline projections of agricultural productivity and food security are obtained. However, in many developing regions, particularly Sub-Saharan Africa and Asia, the existing agricultural R&D intensity ratios are well below those of developed regions (0.5% vs. 2.5%); various R&D strategy documents call for doubling the amount of R&D investments in Africa (Beintema & Elliott,

Table 2. Drivers of public agricultural R&D investment in MAGNET

R&D Mechanism	Regions	
Public agricultural R&D growth follows agricultural GDP growth	Canada	West Africa
	United States	Rest of Eastern Europe
	Central America	Rest of Western Europe
	Brazil	South Africa
	Rest of South America	Rest of South Asia
	East Africa	EU-16
	Oceania	EU-12
Public agriculture R&D growth follows government budget growth	North Africa	High-income Asia
	Middle East	Southeast Asia
Mixed approach (50% agricultural GDP and 50% government budget)	India	China

Table 3. Shares of agricultural R&D investments in real agricultural GDP

R&D/Agricultural GDP	RDbase (%)	2× RDshare (%)	3× RDshare (%)
Central America	1.0	2.0	2.9
Brazil	1.7	3.3	5.0
Rest of South America	1.0	2.0	2.9
West Africa	0.5	1.0	1.5
South Africa	1.3	2.6	3.9
Rest of South Asia	0.4	0.8	1.2
East Africa	0.8	1.6	2.4
High-income countries	4.6	4.6	4.6

2009). The impact of these policy targets on food security is investigated in two additional policy scenarios. The overview of all the scenarios modeled in MAGNET is provided below:

- RDbase: In this scenario, land-augmenting technical change grows according to the growth of domestic R&D stock accumulated from R&D investments using the above described mechanisms and assuming an additional exogenous productivity component of 1% annually.
- 2× RDshare: In this scenario, the share of R&D expenditures in agricultural GDP is doubled in targeted developing countries (Table 3). This is particularly relevant for Sub-Saharan Africa where the R&D intensity ratios have actually decreased rather than increased.
- 3× RDshare: Given that doubling R&D shares might still be far from the R&D intensities of high-income countries, in this scenario, the share of R&D expenditures in agricultural GDP is increased threefold. All Sub-Saharan African regions will have R&D intensities higher than 1% in this scenario.
- EXO scenario: In this scenario, land-augmenting technical change is determined only exogenously, assuming a uniform annual growth rate of 1%. The results of this scenario provide a contrafactual case that allows assessing the impact of additional R&D investments on food security against the case when productivity is solely driven by an exogenous growth rate of 1% annually.

3. *Results*

The first analyzed indicator is land productivity, expressed as land-augmenting technical change (*aland*) that directly reflects the impact of alternative R&D policies. Figure 1 displays the annual growth rates of *aland* with alternative R&D scenarios and the EXO scenario. This exercise enables one to assess the contribution of the R&D investments to land-augmenting technical change compared to the exogenous rates. On the world level, baseline R&D investments would increase growth of land productivity by 0.3 percentage point. The effects are comparable across

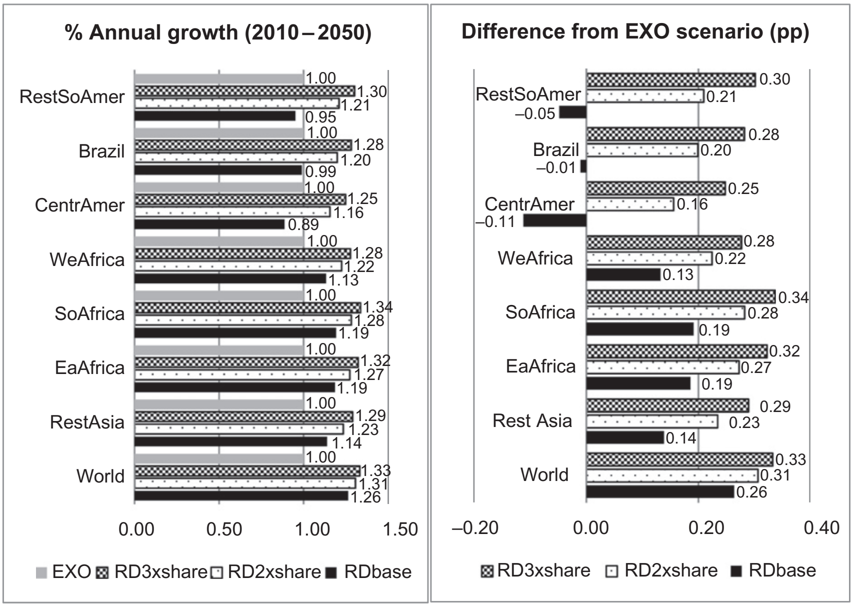

Fig. 1. ***Annual growth of land-augmenting technical change (2010–2050).*** **Source*: Authors.***

the regions. Tripling shares of R&D investment would boost annual land productivity to be one-third of a percentage point higher than the exogenous growth rate. In Sub-Saharan Africa, this would represent a 70% increase of productivity in 2050 compared to 2010 (this would be a substantial productivity boost). Interestingly, growth rates of land productivity in South America would be below 1% annually and comparably lower than the world average if agricultural research intensity were to stay unchanged. This is a result of a deceleration of the R&D stocks accumulation that would occur after 2030. Boosting R&D shares in agricultural GDP would bring important contributions to agricultural productivity in this region.

An important question that arises when inspecting the evolution of land-augmenting technical change is how these developments are translated in agricultural and food production. Figure 2 shows the annual growth rates of agrifood production and the differences from the EXO scenario. On the world level, it seems that R&D investments provide little contribution to the quantity of agrifood production; however, the regional effects are more noticeable. Particularly in West Africa, tripling the share of R&D investments could improve the availability of food by 0.34 percentage point annually, or 40% more over the total period. Important effects of R&D on food availability are found in the case of South America, except for Brazil, where R&D policy would have negligible effects on food production.

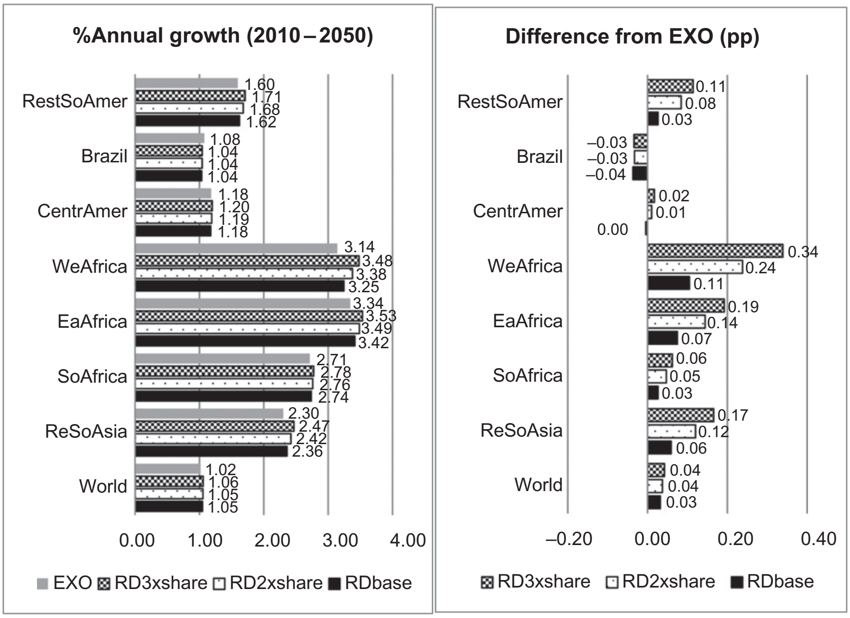

Fig. 2. Annual growth of agrifood production volume (2010–2050).
Source*: Authors.*

The availability of food is only one of the indicators of food security. It is also important to assess economic access to food in future projections. Figure 3 shows that the world agrifood prices might decline by about 0.5% annually, which reflects a gradual decline of prices in most regions of the world. Conversely, agrifood prices in regions such as Sub-Saharan Africa will continue rising. In the absence of any R&D investments and assuming an autonomous 1% yield growth, agrifood prices might grow between 0.85% and 1.7% annually. The increase in prices will be driven by the limited availability of land. For land-scarce regions such as Sub-Saharan Africa situated on the steep part of the land supply curve, further increases in agricultural demand would have little effect on supplied agricultural quantity but would have a substantial effect on both land and agrifood prices. Conversely, for land-abundant countries situated at the flat part of the land supply curve, the impact on land prices is limited.

The impact of R&D investments on reducing food prices is notable. Although agrifood prices will still face an increase, any additional R&D investments will substantially decelerate price inflation. In the case of tripling R&D shares, annual food prices would decelerate growth by 0.9 percentage point. Also, although food production would be unaffected by R&D investments in Brazil, prices would decline and therefore the positive effects of food security in South America are mostly observed in the food access dimension.

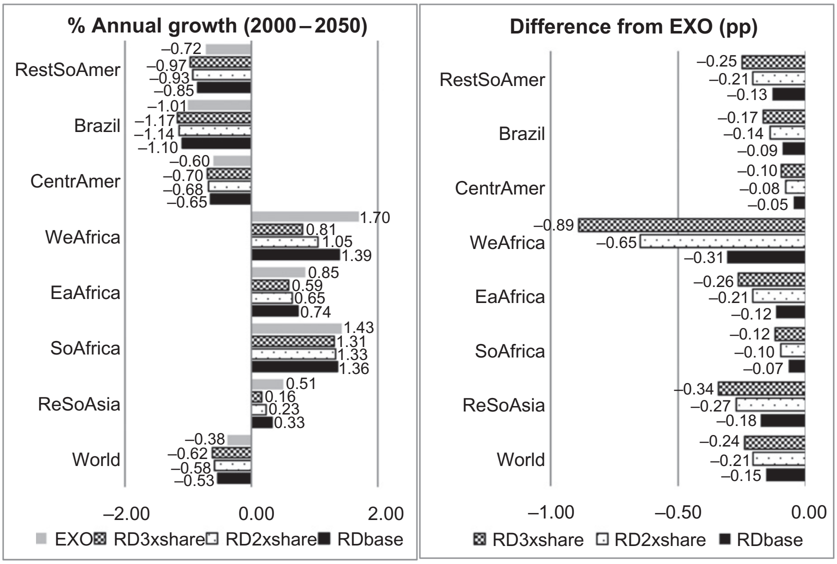

Fig. 3. Annual growth of agrifood prices (2000−2050)*. Source*: Authors.

Growth of food prices is only one of the indicators of food access. It is also important to take into account the purchasing power of households which may vary over time. Rural households that are dependent on agricultural incomes are the most vulnerable. As an appropriate indicator, the ratio of wages of unskilled labor in agriculture to the cereal price index is chosen. Figure 4 compares this ratio between 2010 and 2050. Results show that worldwide, food access by rural households would improve between 150% and 200% depending on the R&D investment scenario. Positive growth in food access is particularly noted in Asia and South America, whereas food access improvements in Sub-Saharan Africa are very moderate. Moreover, in the absence of R&D investments, the purchasing power of West African households dependent on low-skilled labor would decline compared to 2010. Increasing R&D intensity would have important contributions for improving the food access of rural households. The largest contribution of tripling R&D shares is found in East Africa where living standards could grow by 136% compared to 71% under constant R&D intensity. Clearly, these projections estimate a large regional inequality of food access in the future. Two factors play a role in explaining the opening divide in food access. First, there is the growth of food prices in regions such as Sub-Saharan Africa. Second, low wages in the agriculture sector are projected to decline relative to wages in other sectors due to segmented factor markets (i.e., farmers are locked into the agricultural sector). Rural households will be more vulnerable than urban households to future prices.

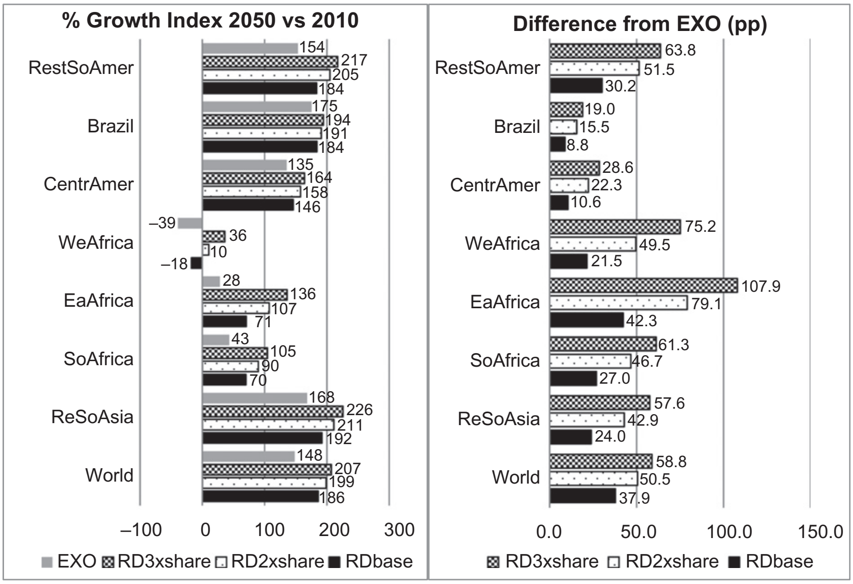

Fig. 4. Ratio of unskilled wages in primary agriculture to cereal price index.* Source*: Authors.

Figure 5 shows how food availability and food access are reflected in total caloric consumption. On the world level, total increase of caloric consumption per day would be about 600–700 kcal which represents an increase from about 2,300 kcal in 2010 to 3,000 kcal in 2050. In Sub-Saharan Africa, the increase in caloric consumption would be more than 1,000 kcal, exceeding average global caloric increase. The right-side of Figure 5 shows how additional R&D investments are translated into excess calories. For East Africa and West Africa, doubling R&D shares would bring a gain of 100–150 kcal per day, and with triple shares, households could consume 200 kcal per day more.

Finally, Figure 6 provides an overview of the costs of R&D policies. In Sub-Saharan Africa, cumulative nominal governmental spending on agricultural R&D reaches between US$2 billion and US$6 billion, depending on the agricultural research intensity. Total R&D spending of Sub-Saharan Africa would represent only 2% of world R&D expenditures (US$260 billion) in the baseline scenario, but would increase to 5% when tripling R&D shares. R&D expenditures in the rest of South Asia would grow from US$1 billion to US$3 billion, whereas in Brazil they would exceed US$20 billion. When these costs are related to additional gains in calories, it is found that obtaining an additional 100 kcal of nutrition per day requires substantially less costs in Africa than in South America. R&D costs per 100 kcal are US$2 billion in South Africa, US$1 billion in

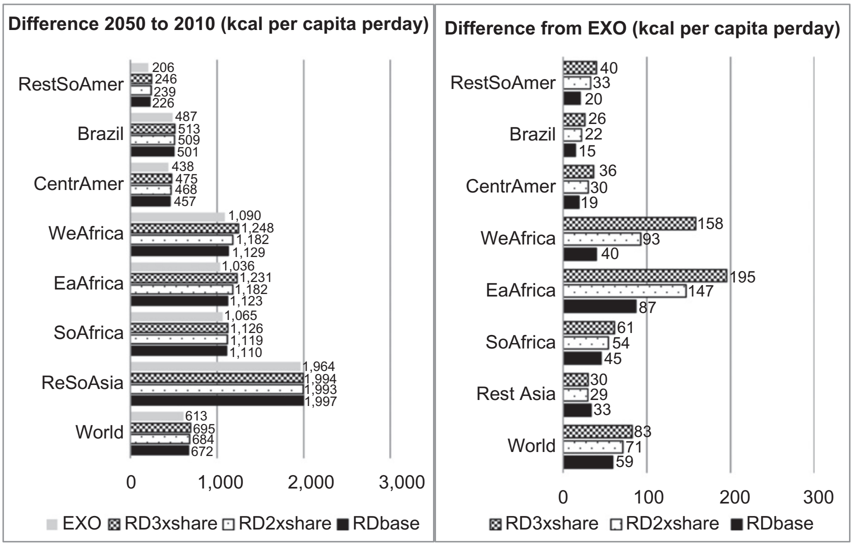

Fig. 5. Absolute increase in total caloric consumption per capita per day.
Source*: Authors.*

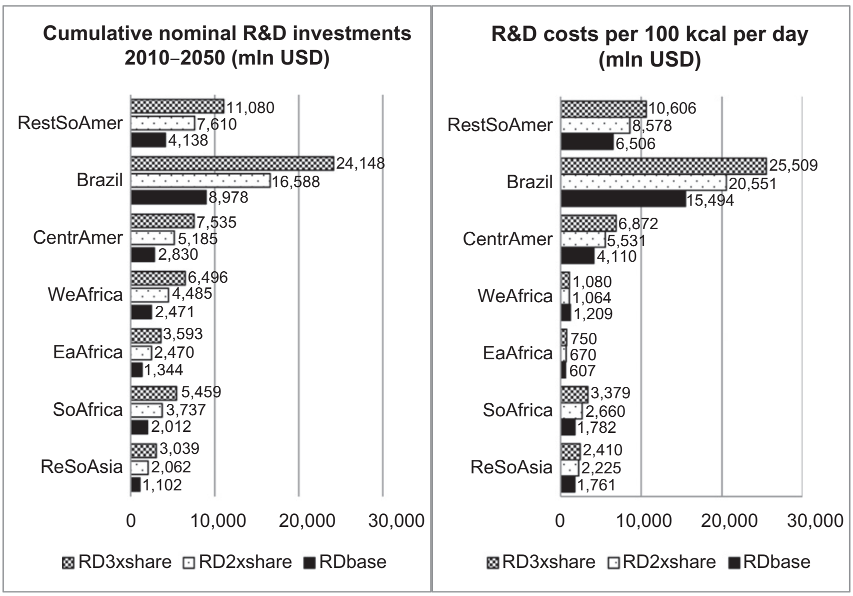

Fig. 6. Cumulative R&D investments and R&D costs per excess calories.
Source*: Authors.*

West Africa, and less than US$1 billion in East Africa, whereas they are between US$15 billion and US$25 billion in South America. It is also interesting to compare the costs of additional caloric consumption across the scenarios. Whereas in South America, R&D costs per gained calorie grow quickly with increasing R&D intensity, they remain almost constant in Sub-Saharan Africa.

4. Conclusions

In this chapter, the projections of food security toward 2050 with alternative R&D policy scenarios were analyzed. By linking R&D investments with land productivity in global CGE models, it is possible to assess the impact of different public R&D policies on food security. Such analysis is particularly important for developing countries where food-security issues are the most pertinent and the share of public R&D expenditures in agricultural GDP is still well below the share in most developed regions.

Concerning the impact of projected R&D investments on agricultural productivity, it was found that tripling the shares of R&D investments in agricultural GDP would boost the annual land-augmenting technical change in Sub-Saharan Africa by 70% in 2050 compared to that of 2010. As for Latin America, stimulating R&D intensity would be important for avoiding a decline of R&D stocks accumulation that is expected to occur after 2030 in a baseline scenario.

With respect to *food availability*, the impact of R&D investments is mostly notable in land-scarce countries such as Sub-Saharan Africa, whereas in land-abundant countries such as Latin America, R&D investments contribute little to the increase of agrifood production. Concerning *food access*, the impact of R&D investments is more pronounced in developing regions. In Sub-Saharan Africa, prices are expected to grow significantly by 2050 due to a high increase in food demand and land scarcity. The additional R&D investments will substantially decelerate food prices in this situation as the land constraint is released by higher yields. In West Africa, food prices would be 30% lower in 2050 than in the case of no R&D investments.

The projections also show that toward 2050, a large regional inequality of food access will be expected. Growth from low wages in agriculture would not adequately compensate for the expected future growth in food prices; this would result in a deterioration of the living standards of rural households dependent on income from agriculture.

With respect to daily caloric consumption, it was found that stimulating R&D investments in Sub-Saharan Africa can bring an additional 200 kcal per capita. Moreover, the R&D costs of additional calories are notably lower in Sub-Saharan Africa compared to Latin America. This points to the problem of current underinvestment in Sub-Saharan Africa, where additional R&D investments keep the benefit-cost ratio constant, as opposed to Latin America, where R&D costs grow quicker than the gain in calories. Stimulating shares of R&D investments in agricultural GDP is a cost-effective policy that can contribute significantly to food security in regions such as Sub-Saharan Africa.

The policy implications following from this chapter are largely directed toward higher support of national R&D investments in the developing regions. As agricultural land becomes more limited, it will be crucial to focus more R&D investments on land-augmenting technologies such as new varieties of crops.

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Appendix: Description of regions, production sectors, and periods applied in MAGNET

Regions	Production Sectors	Periods	
1. Canada	1. pdr[a]	1. p[1]	2007–2010
2. United States	2. wht[a]	2. p[2]	2010–2020
3. Central America	3. grain[a]	3. p[3]	2020–2030
4. Brazil	4. oils[a]	4. p[4]	2030–2040
5. Rest of South America	5. sugar[a]	5. p[5]	2040–2050
6. North Africa	6. hort[a]		
7. West Africa	7. crops[a]		
8. Rest of East Europe	8. cattle[a]		
9. Rest of West Europe	9. pigpoul[a]		
10. South Africa	10. milk[a]		
11. Middle East	11. cmt		
12. India	12. omt		
13. Rest of South Asia	13. dairy		
14. High-income Asia	14. sugar		
15. Southeast Asia	15. vol		
16. East Africa	16. ofd		
17. EU-16	17. fish		
18. EU-12	18. lowind		
19. China	19. oth_ser		
20. Oceania	20. oagr[a]		
21. RussiaStan	21. pub_ser		
	22. highind		
	23. rd		
	24. fossilfuel		
	25. CGDS		
	Total		

Note: Sector description follows GTAP terminology (sector listing: https://www.gtap.agecon.purdue.edu/databases/v9/v9_sectors.asp).