*Applied Economic Perspectives and Policy*

WILEY | AAEA Agricultural & Applied Economics Association

SUBMITTED ARTICLE OPEN ACCESS

# Sustainable Productivity Growth in Agriculture: The Role of Shifts in R&D Investments and Technology

Zuzana Smeets Křístková[1,2] | Michiel van Dijk[1] | Robert M'Barek[3] | Hans van Meijl[1,4] | Tomas Ratinger[5]

[1]Wageningen Social and Economic Research, The Hague, BM, the Netherlands | [2]Czech University of Life Sciences in Prague, Praha 6, Czech Republic | [3]European Commission, Joint Research Centre (JRC), Sevilla, Spain | [4]Agricultural Economics and Rural Policy Group, Wageningen University, Wageningen, the Netherlands | [5]Technology Centre of the Czech Academy of Sciences, Praha 6-Bubeneč, Czechia

**Correspondence:** Zuzana Smeets Křístková (zuzana.kristkova@wur.nl)

**Received:** 1 May 2025 | **Revised:** 8 February 2026 | **Accepted:** 23 March 2026

## ABSTRACT

The objective of the paper is to evaluate the long-term prospects of sustainable productivity growth linked to plausible assumptions on public agricultural R&D investments as the key productivity driver. Second, it investigates the role of changing R&D focus from yield maximization to input saving technologies (fertilizers and pesticides). The projections using CGE model MAGNET identify China, India and Brazil as regions with high productivity growth from agricultural R&D while Sub-Saharan Africa regions will struggle with low productivity growth rates and substantial increase in GHG emissions. Overall, GHG emissions are projected to grow more than agricultural output. However it is found that sustainable agricultural productivity growth could become feasible under the reorientation of R&D programs in high income countries (with use of chemical inputs declining as much as 30%) where these policies can make an important contribution to sustainability while food security concerns are limited and spillover effects in terms of higher food prices are low.

## 1 | Introduction

In an unprecedented call to address the challenge of feeding the world, more than 150 Nobel and World Food Prize Laureates plea for a reprioritization of agricultural Research & Development (R&D) to increase agricultural productivity (World Food Price Foundation 2025). The authors list climate change, soil erosion and land degradation, biodiversity loss, water shortages, conflict, and policies that restrict innovation as key drivers impacting negatively crop productivity (World Food Price Foundation 2025). This call for an R&D action reflects the concerns that the current agricultural model is not sustainable—it does not prevent hunger and malnutrition and contributes to the degradation of the environment, while being at the same time the sector mostly exposed to climate change.

The latest OECD-FAO (2025) Agricultural Outlook (2025–2034) shows that agricultural productivity must improve significantly to address global food security challenges. While rising incomes in middle-income countries will increase the demand for animal-source products, addressing the urgent need to eradicate under-nourishment and reduce greenhouse gas emissions, improvements in agricultural productivity are essential. While historically, about three-quarters of the growth in global agricultural output has come from increasing total factor productivity (TFP) (Heisey and Fuglie 2018), the rate of agricultural productivity growth has slowed down in the last decade (Fuglie et al. 2024). This is related to the declining rate of public agricultural R&D spending in high-income countries (Dehmer et al. 2019; Heisey and Fuglie 2018; Fuglie 2016).

Latest research on the US finds that up to $434 billion would be needed from 2021 to 2050 in addition to the current baseline R&D investment in agriculture of about $5 billion per year to offset anthropogenic climate change (Ortiz-Bobea et al. 2025). In the case of the EU, the investment gap has been estimated at EUR 62 billion for 2022 (European Commission and EIB 2023). As explained by Heisey and Fuglie (2018) and Fuglie (2016),





*Applied Economic Perspectives and Policy,* 2026; 48:984–1004
https://doi.org/10.1002/aepp.70069

several reforms of agricultural research infrastructure resulted in a reduced reliance on public sector, shifting towards private R&D (Heisey and Fuglie 2018; Fuglie 2016). The new trend is that developing countries are replacing high income countries in the dynamics of public agricultural R&D spending (Fuglie et al. 2024). It is therefore plausible to expect that in the longer-run, knowledge and productivity hotspots will be shifting geographically from high income countries to other regions of the world resulting in new market equilibria on commodity and input markets with implications on food security and agricultural sustainability. Yet, some regions, such as the European Union (EU), are envisaging a new strategic approach to R&D, with the main objective to improve competitiveness, that is, boost productivity growth, while achieving also goals on climate neutrality (EC 2025a, 2025b).

Urged by the critical environmental state of the planet (e.g., IPCC 2023; IPBES 2019), there is a shifting focus of R&D programs from productivity maximization to conservation of environmental resources and sustainability (Muscio and Sisto 2020; Paroda 2018; Guo 2018). Traditionally, the main goal of public agricultural R&D systems was to promote high yield varieties using breeding methods. However, in line with the reprioritization of agricultural R&D, several promising technologies are being developed with the aim of improving agricultural sustainability. Decision support systems, AI, and big data can save the use of fertilizers and pesticides by providing real time information on the input needs, the accuracy of input application and thus optimize decision support processes. Robotics and autonomous agricultural vehicles can substitute for both manual labor and eliminate the use of pesticide use. Biotechnologies such as CRISPR achieve higher disease resistance and better adaptation to climate change which also leads to the reduced use of fertilizer and pesticide inputs (Ahado et al. 2024). Additionally, the adoption of organic farming on larger scale also implies a reduced use of environmentally sensitive inputs such as pesticides and chemical fertilizers.

In view of the changing shifts in R&D priorities, R&D investments may not maintain similar productivity effects in the longer run as they did in the past. This also implies that the empirically quantified impacts of historical agricultural R&D investments on productivity (see Alston et al. 2000) may no longer be valid for projecting productivity in the future. Increasing the role of private R&D may put pressure on reducing research lags in agriculture, which are typically assumed to span up to 50 years following the extensive literature of Alston and Huffman[1] (as explored in Jin et al. 2024). Furthermore, the sustainability focus of R&D programs may change the direction of technical change from neutral (following the "Griliches"-style TFP accounting, see also Van Meijl and Van Tongeren 1999) to saving specific environmentally intensive inputs. A transition to non-Hicks-neutral progress, with rapid advancements concentrated in capital-rich nations, was recently also observed in an empirical paper of Sheng (2025). The redefinition of agricultural productivity (Bureau and Jesus 2022) has important implications for food security and sustainability which are not sufficiently explored in the literature.

This paper addresses the uncertainties regarding the role of changing R&D landscape in future productivity growth, food security and sustainability. Most of the existing studies have considered agricultural R&D investments as a solution of reducing hunger and improving food security (Smeets-Křístková et al. 2017; Rosegrant et al. 2017; Laborde et al. 2020; Chichaibelu et al. 2021), without taking into account the implications on sustainability. While questions arise to the plausibility of achieving both sustainable and productive agriculture (Coomes et al. 2018), policies in the EU[2] and other initiatives[3] are setting up frameworks for a competitive agri-food sector functioning within planetary boundaries. Without explicitly taking into account R&D investments as productivity drivers, Villoria (2019) argues that TFP will not be sufficient to avoid further land expansion particularly in the zones with high biodiversity scores given the future population and GDP projections. The skepticism is explained by the "*Jevons paradox*" where higher TFP growth produces a rebound effect in the form of higher production and increased land demand (Valin et al. 2013; Villoria 2019). In the studies where R&D investments are explicitly considered (Fuglie, Ray, et al. 2022; Fuglie, Wiebe, et al. 2022; Baldos et al. 2020), R&D investments showed positive linkages to agricultural sustainability but only weakly. Moreover, the studies are based on the application of partial equilibrium (PE) models, where technological progress is proxied by yield growth neglecting other productivity components.

This paper provides a comprehensive approach to assessing the role of public agricultural R&D investments in productivity growth, using a global general equilibrium (CGE) model (MAGNET Woltjer et al. 2014). The paper first identifies the expected knowledge and productivity hotspots in the longer run maintaining the recent trends in public agricultural R&D spending and assesses the prospects of future sustainable growth in agriculture. Second, this paper also investigates the role of changing R&D focus from yield maximization to input saving technologies (fertilizers and pesticides) and contributes thus to the existing gap in the literature as none of the previous studies to our knowledge relate the aggregate R&D investments to the promising set of technologies[4] and considers possible changes in parameters guiding the R&D driven technological progress. This form of sensitivity analysis sheds light on several aspects of sustainable productivity growth: (i) what are the implications of new input saving technologies on food security and sustainability, (ii) how reliable are our ex-ante projections when we do not reflect the newest technology developments in the modeling framework, (iii) how environmental objectives can be most efficiently supported by R&D. The contribution of this paper is thus to stimulate wider discussion on several content as well as methodological aspects of assessing agricultural sustainability and highlight the role of research policy in it.

## 2 | Methods

### 2.1 | International Public R&D Statistics

The main source for public agricultural R&D statistics used in this paper was the WUR-ERS Global Research on Agriculture: Personnel & Expenditures (GRAPE) dataset, which contains harmonized data on public agricultural R&D expenditures for 190 countries, broadly covering the period 1960–2022 (Van Dijk et al. 2025). The definition of public agricultural R&D

investment in GRAPE is consistent with that of the Frascati Manual (2015), which defines public R&D as the total of R&D undertaken within two performing sectors: government (e.g., local, state and national institutions) and higher education (e.g., universities and related research institutes). To measure R&D, GRAPE uses the socio-economic objective classification, which allocates R&D expenditures according to their primary intended social or economic purpose, in this case the sum of primary agriculture, fishery and forestry research.

We complemented the GRAPE dataset with global information on total public R&D expenditures, split by governmental, higher education, and private non-profit sectors. Data was taken from EUROSTAT (2022), OECD (2022a, 2022b), and UNESCO (2022).

To make the data from the various sources comparable, we converted all values to constant USD 2017 PPP values using GDP deflators and PPP conversion factors from World Bank (2021), harmonized the definition of public agricultural R&D and imputed missing data (see van Dijk et al. 2025).

### 2.2 | Building Knowledge Stocks From Agricultural R&D Investments

One of the objectives of investing in agricultural R&D is to increase agricultural productivity, for instance by creating new or improved inputs and outputs or by developing new knowledge to combine inputs more efficiently. R&D spending contributes to the expansion of current knowledge, which can be regarded as a capital stock that grows with each new investment and diminishes when knowledge becomes obsolete (Alston et al. 1995). The expansion of the current agricultural knowledge stock will only translate into higher production and productivity if it is actually utilized, that is, if research results are adopted by farmers and other actors in the sector. The adoption rate of agricultural technologies depends on a wide number of factors, including relative prices of inputs and outputs, farm size and availability, and quality of extension services (Feder and Umali 1993).

It takes time before research spending results in useful knowledge. A review of econometric studies on the rates of return to agricultural investment found R&D expenditure lags in the range of 10–30 years (Alston et al. 2010). The reason for the lag between R&D investment and knowledge generation is related to the different phases that characterize knowledge creation and diffusion (Alston et al. 2010; Fuglie 2018). In the initial research phase, the new technology is still being developed (e.g., the time needed to breed a new crop variety) and therefore R&D investment makes only a limited contribution to the useful knowledge stock. In the next phase, the new technology disseminates and is further improved, ending by a peak in the adoption rate when the contribution of R&D to knowledge is at its maximum. In the final phase, the technology and associated knowledge starts to become obsolete, eventually ending with complete replacement by a new technology.

A number of approaches have been used in the literature to model the agricultural R&D lag structure as described above. The two most common are the trapezoid curve (Huffman and Evenson 2006) and the gamma distribution (Alston et al. 2010) to weight the contribution of R&D investment and calculate the knowledge stock. Here we used the latter approach as it generates a smooth pattern and is also able to replicate the trapezoid-shaped weights with the appropriate selection of parameters. It can be formalized as follows:

$$RDS_t = \sum_{k=0}^{L} \beta_k RDI_{t-k} \tag{1}$$

where $RDS$ is the knowledge stock in year $t$, which is calculated by weighting all past R&D expenditures $RDI_{t-k}$ over the period $t-k$, which is equal to the total lag length $L$, using different weights $\beta_k$ for each year $k$. The weights $\beta_k$ are calculated using a gamma distribution:

$$\beta_k = \frac{(k-g+1)^{\frac{\delta}{1-\delta}} \lambda^{k-g}}{\sum_{k=0}^{L} (k-g+1)^{\frac{\delta}{1-\delta}} \lambda^{k-g}}; \quad \sum_{k=0}^{L} \beta_k = 1 \tag{2}$$

where $g$ is the gestation lag before R&D investment starts to have an impact on productivity, and $\delta$ $(0 \leq \delta \leq 0)$ and $\lambda$ $(0 \leq \lambda \leq 0)$ are parameters that determine the shape of the gamma distribution. It is common to assume a gestation lag of $g = 0$ because most used combinations of $\delta$ and $\lambda$ result in weights that are very close to zero for small values of $k$.

Figure 1 depicts the different R&D lag structures, corresponding with different values of $\delta$ and $\lambda$ that are representative for different country groups (as shown in Table 1). One line illustrates an R&D life span of 35 years ($\delta = 0.8$ and $\lambda = 0.7$), where full impact is only realized 35 years after the first investment. Another line ($\delta = 0.80$ and $\lambda = 0.5$) shows an R&D lag structure of only 15 years, resulting in a peak effect in 5 years. Long R&D structures are often used to model the diffusion of fundamental research that takes long to mature and has a deep impact on agricultural productivity, whereas short time periods are considered more appropriate for research that supports the adaption of existing technologies to new environments and conditions (Fuglie 2018).

### 2.3 | Modeling Agricultural R&D Investments, Productivity and Sustainability in One Consistent Framework

We apply the Modular Applied GeNeral Equilibrium Tool (MAGNET) which is a recursive dynamic, multi-regional, multi-commodity CGE model, covering the entire global economy (Woltjer and Kuiper 2012). As with other CGE models, MAGNET explicitly represents the economic linkages across the sectors of each national economy. It is built upon the GTAP (Global Trade Analysis Project) model (Hertel 1997) and has been widely used for policy analysis (Van Meijl et al. 2024; Gatto et al. 2023; Smeets Křístková et al. 2025; Kuiper and Cui 2021; Doelman et al. 2019). MAGNET is a well-established model in the modeling inventory and knowledge management system of the European Commission for analyzing policy scenarios

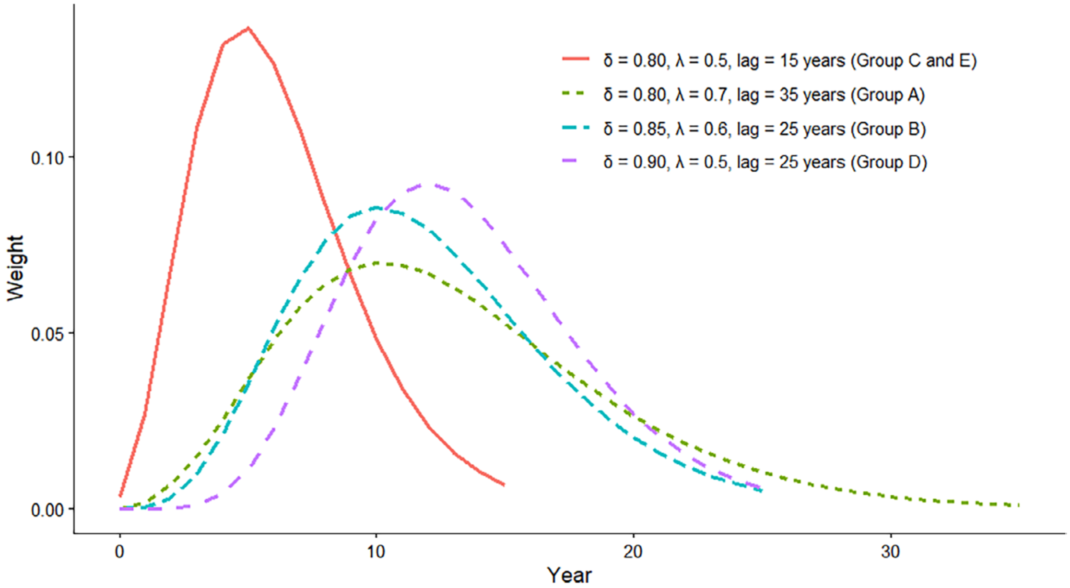



**FIGURE 1** | Alternative lag structures to calculate the knowledge stock.

**TABLE 1** | Parameters to calculate the agricultural knowledge stock for five country groups.

| Group | Country | Lag | Lambda | Delta | Elasticity |
|---|---|---|---|---|---|
| A | USA, Australia and New Zealand | 35 | 0.7 | 0.80 | 0.30 |
| B | Europe | 25 | 0.6 | 0.85 | 0.25 |
| C | China | 15 | 0.5 | 0.80 | 0.20 |
| D | Latin America | 25 | 0.5 | 0.90 | 0.25 |
| E | Asia, Pacific and Africa | 15 | 0.5 | 0.80 | 0.15 |

(European Commission 2024). The MAGNET model is modular in nature and extends the GTAP model through the addition of a number of policy-relevant modules.

In this study we apply version 10.1 of the GTAP database with a coverage of 140 regions, 57 sectors and 8 production factors including natural resources, oil and gas. The database includes detailed information on production, gross bilateral trade flows, transport costs and trade protection data for a 2014 benchmark year. Additional agricultural and bioeconomy sectors have been further split from the original GTAP database, resulting in the total of 113 sectors and 127 commodities in the disaggregated MAGNET database (see Table A1 for list of aggregated commodity groups). Similarly, as for the commodity aggregation, individual GTAP countries were aggregated into 14 regional blocks as visualized in Figure 2 (see Table A2 for regional aggregation mappings).

In this paper we apply a specifically built extension of MAGNET model that allows to model public agricultural R&D investments in a consistent framework (Smeets-Křístková et al. 2017; Smeets Křístková et al. 2016; Smeets Křístková et al. 2025; Jin et al. 2024). Agricultural R&D impacts the economy both in short and in the long term (Figure 3). In the short-term, agricultural R&D investments stimulate both the demand side of the economy as part of the governmental expenditures and the supply side of the economy requiring resources needed in the research process (in terms of labor costs, materials and capital). Disaggregating R&D sector in the Social Accounting Matrix (a data framework used in a CGE model) is a necessary step here to model the supply-side linkages of R&D investments. Capturing both the demand side (i.e., "who pays for the R&D investments") and the supply side of R&D ("how is R&D made") is an important contribution of the CGE approach. Nevertheless, it should be admitted that the short-term macroeconomic effects of agricultural R&D policies are rather limited as agricultural R&D represents only a small share of total R&D expenditures in the economy.[5]

More important are the long-term effects of agricultural R&D investments. As explained in the chapter 2.2, agricultural innovation requires long research time, up to 30–50 years, before it is fully reflected in productivity, a phenomenon called "slow magic". Following this evidence, in MAGNET model, agricultural R&D investments are converted to R&D stocks ($RDS_{t,i}$) using parameters from gamma distribution $\beta_{k,i}$ (see Equation 1) which are parametrized for different types of R&D lag structures as visualized in Figure 1. We assumed a long R&D life span for USA, Canada and New Zealand (35 years) and the EU and other high-income countries (25 years), and a shorter structure for low-income countries in Asia, Africa and Latin America (both 15 years), see Table 1.

To introduce Equation (1) in MAGNET, it needs to be linearized to be in line with the Gempack General Equilibrium Modeling software (Equation 3):

$$0.01 * RDS_{t,i} * rds_{t,i} = \text{if}\left\{t > 1, \left[\Delta RDS0_{t,i} + 0.01 * RDt_{t,i} * rdt_{t,i}\right]\right\} + \text{if}\left\{t = 1, \Delta RDS0_{t,i}\right\} \quad (3)$$

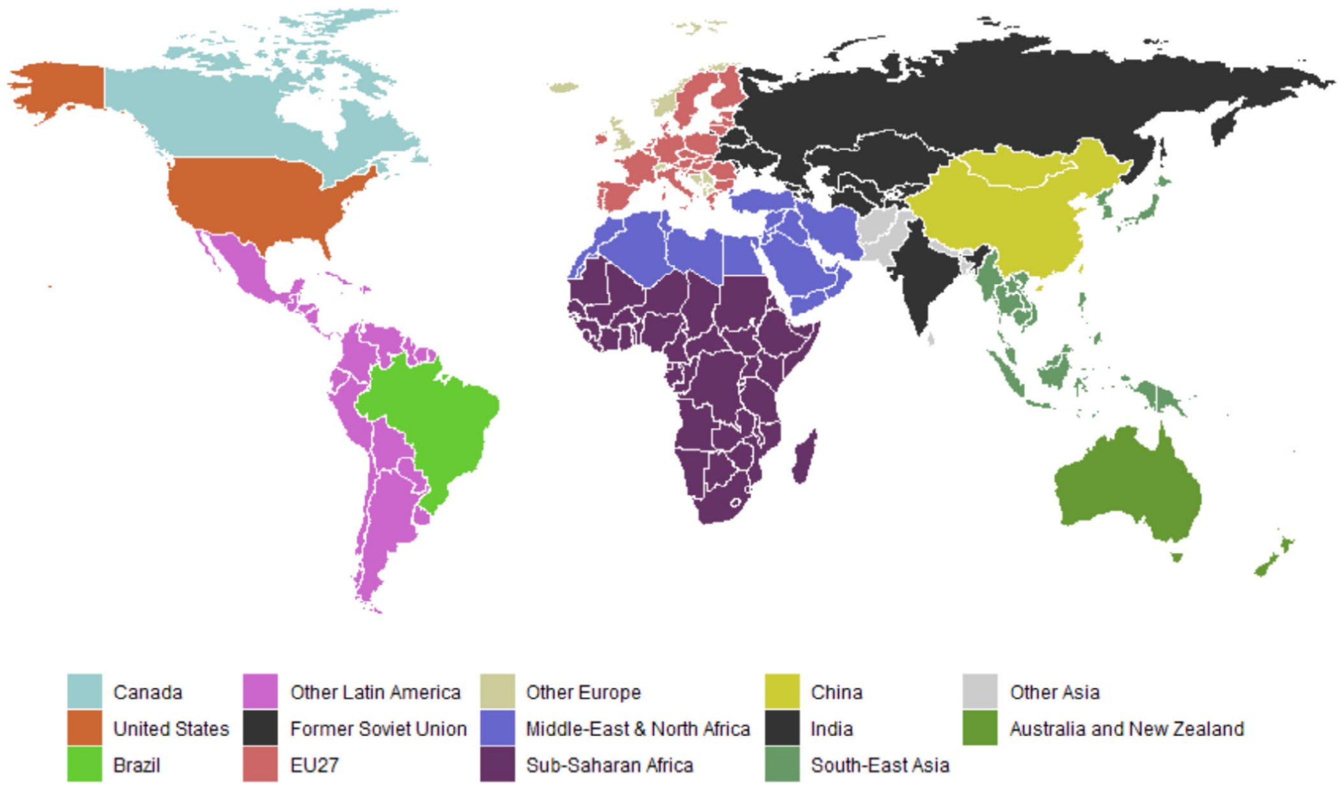



**FIGURE 2** | MAGNET regional aggregation applied in this paper.

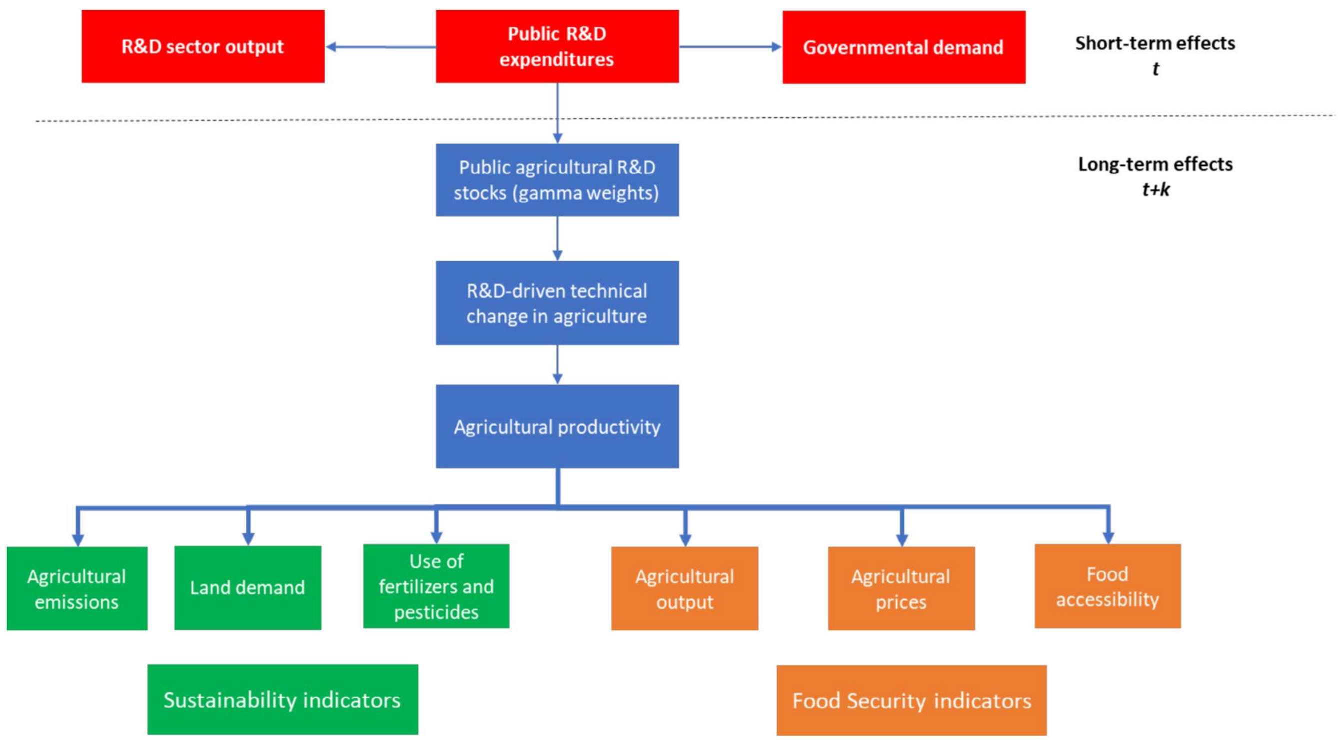



**FIGURE 3** | Modeling Public agricultural R&D investments in MAGNET.

where $RDS_{t,i}$ are R&D stocks in period $t$ and country $i$ in levels, $rds_{t,i}$ is a related variable in percentage change, $RDt_{t,i}$ is a fraction of R&D investments in the current period that contributes to the R&D stocks in current period and $rdt_{t,i}$ is the corresponding percentage change variable. Equation (3) thus shows that the absolute change in public agricultural R&D stock (left hand-side) consists of a fraction of R&D stocks that are "predetermined" $\Delta RDS0_{t,i}$, that is, R&D investments from periods $t$-$k$ that remain productive in period $t$ and a fraction of R&D stocks that are determined within the current solution period from R&D investments. The conditional statement in this equation ensures that in the first solution period, which usually refers to a period with

R&D stocks observed historically (such as period 2014–2020), R&D stocks follow historical trend.

Only when R&D investments are cumulated to become R&D stocks, productivity effects can be realized, which once again reminds that benefits of current R&D policies are only seen in the longer term. The translation of R&D stock to productivity in MAGNET, variable $af\_RD_{t,i}$, is determined by R&D elasticity parameter $\delta_{RD,i}$ (Equation 4):

$$af\_RD_{t,i} = \delta_{RD,i} * rdst_{t,i} \tag{4}$$

where $af\_RD_{t,i}$ represents aggregated R&D driven technological progress in agriculture in period $t$ and country $i$, $rdst_{t,i}$ represents growth of public agricultural R&D stocks and $\delta_{RD,i}$ is the R&D elasticity. While the lag structures of R&D knowledge formation differ for agricultural and industrial innovation, the R&D elasticities that convert cumulated R&D stocks to agricultural productivity are rather comparable. They are usually centered around 0.2%–0.3% with higher values for countries where basic research prevails (high income countries) and lower values for countries where domestic R&D has rather extension character such as in developing countries (see Hall et al. 2009 for R&D returns in general and Alston et al. 2008 for agricultural R&D). Based on these characteristics, R&D elasticities in MAGNET were set to 0.15% for developing to 0.3% for high income countries (Table 1).

In the last step of R&D-productivity accounting in MAGNET, R&D productivity component enters aggregate productivity equation (Equation 5) for $afa_{t,e,j,i}$. Input augmenting technical change $afa_{t,e,j,i}$ is a 3-dimensional variable, defined over for input $e$, sector $j$, and country $i$ and is an important component of production technology in the CES production function. MAGNET has a rather complex equation for technical change with several exogenous variables which are included but not always in use, allowing the possibility to be activated in cases of specific sector, input or commodity shocks in productivity. In a simplified way, the equation for input-augmenting technical change in MAGNET reads as:

$$afa_{t,e,j,i} = ASCALE_{t,e,i,j} \cdot aknreg_{t,i} + DUM_{TCe,j,i} \cdot af\_RD_{t,i} + DUM\_LAND_j \cdot aland_{t,j,r} \tag{5}$$

where $aknreg_{t,i}$ refers to an economy-wide factor augmenting technical change obtained as a residual when targeting expected GDP growth. By multiplying with the $ASCALE_{e,j,i}$ coefficient, the macroeconomic productivity growth is distributed over the production sectors. This results in productivity growth rates that are sector and input-specific. This is the main source of labor productivity growth in agriculture in MAGNET.

The second component is the R&D-driven productivity growth $afa\_RD_{j,i}$ affecting specifically the productivity in agricultural sector (see Equation 4). In the default version, it is assumed that productivity growth is "neutral", that is, all production factors (labor, capital and land) benefit equally from R&D driven technical change and this is applied for all agricultural sectors homogenously (Hicks 1932, cited in Barro and Sala-i-Martin 2004). In the sensitivity analysis, the attribution of productivity growth to individual inputs is changed in line with the considered technology scenario. This is guided by 0–1 dummy coefficient $DUM_{TCe,j,i}$ defined for input $e$, sector $j$ and country $i$ allowing to flexibly change assumptions on the direction of technical change.

The remaining component $aland_{i,r,}$ contains other possible productivity sources in agriculture, for instance related to irrigation or climate change-specific yield shocks. The coefficient $DUM\_I\_LAND_j$ ensures only land-using sectors are considered for this source of productivity growth.

Agricultural productivity growth is linked to several indicators in MAGNET both from the food security and sustainability domains. Concerning food security, higher productivity increases output volume and reduces market prices, affecting positively food availability and in general also food access or food affordability. As food affordability embeds a price of the food basket component and an income component, it might be under pressure for workers in agriculture in case of labor-saving technical change with products with an inelastic demand in case of segmented labor markets (Van Meijl et al. 2020). Concerning environmental sustainability, agricultural productivity can reduce greenhouse gas (GHG) emissions in agriculture when directed to lower use of fuel inputs, fertilizers and if it favors production of less emission-intensive agricultural sectors. However, because of Jevons' paradox, emissions can still increase due to increase of agricultural output as product prices decline (Gatto et al. 2023). Concerning land demand, higher land productivity will save land input and reduce land-related emissions. But also, here due to the Jevons paradox the benefits might be lower than expected as lower prices lead to more food and also non-food demand. The general equilibrium effects result in land demand changes which are not only driven by productivity but also by trade (as shown empirically in Villoria 2019). Furthermore, agricultural productivity can affect the use of sensitive inputs such as fertilizers and pesticides, but it depends on the direction of technical change to which extent these savings become important, which is further explored in the sensitivity analysis of this paper.

## 2.4 | Definition of Baseline and R&D Scenarios

In the last decade, CGE models have established themselves importantly in the field of long-term projections based on foresight studies, such as those of the Shared Socioeconomic Pathways (SSPs) (Riahi et al. 2017). SSPs are scenarios of possible socioeconomic futures to explore the implications of climate change. They comprise five different narratives of the world's future with quantified drivers of population, economic activity, urbanization, and income inequality (O'Neill et al. 2017). CGE models are used to implement the set of SSP scenarios or alternative foresight scenarios to provide long-term projections of economic development (Van Meijl et al. 2020; Doelman et al. 2019).

The SSP projections were also used to construct the MAGNET baseline (Table 2). The SSP2 trajectory, that is, a middle-of-the-road assumption is used for GDP and population growth. Under this trajectory, GDP growth and population growth in the world are facing medium-level challenges and the growth varies quite

**TABLE 2** | Baseline drivers and assumptions.

| | Description |
|---|---|
| Macroeconomic drivers | Population growth: SSP2—Medium variant |
| | GDP growth: SSP2 scenario |
| Sectoral productivity drivers | Land productivity: Endogenously based on R&D investments ("tfp"-effect of cumulated agricultural R&D investments is assumed in baseline) |
| | Feed efficiency improvements in livestock sectors: 1%–2% p.a. based on the IMAGE model – an ecological-environmental model framework developed by the Netherlands Environmental Assessment Agency |
| Policy assumptions | CO2 prices in the European Union (a gradual increase from $30/ton to over $110/ton in 2050) |
| | Public agricultural R&D investment growth follows either the historical growth rates in the past two decades (HR) or follows constant R&D intensity (*ConstRD*). |

significantly across regions. Sectoral productivity drivers assume feed efficiency improvements based on the IMAGE model and exogenous land productivity drivers are replaced by endogenous productivity rates based on agricultural R&D investments.

Alternative R&D scenarios are needed to address the issue of uncertainty on the future trends in public agricultural R&D investments. The default baseline scenario (**Baseline_HR**) assumes that countries keep up with the historical growth rates of R&D spending from the period of 1990–2010. In some cases where countries exhibited excessive growth rates of R&D investments such as China (7%) or India (6%), we corrected the future growth rates downwards (similar assumptions have been applied in Fuglie, Ray, et al. 2022; Fuglie, Wiebe, et al. 2022). The applied rates range from 0% in high-income countries to 4% in China and India and 3% globally. Alternatively, countries can follow a pattern of a constant R&D intensity (**Baseline_ConstRD**), which assumes that R&D expenditures follow a constant share of agricultural GDP (see Table A3 on the comparison of the R&D growth rates). The latter baseline scenario (Baseline_ConstRD) therefore takes into account possible reductions in investments as agricultural GDP declines while the former scenario (Baseline_HR) decouples R&D spending patterns from agricultural performance. Given that the latter scenario is more conservative with endogenous R&D investment growth rates of between 1%–2% annually, the scenario using historical R&D growth rate (Baseline_HR) is used as a default baseline scenario, which already implies that the projections are based on rather optimistic views on future R&D spendings (no projected declines of R&D investment growth are considered).

To reflect the shift in focus of R&D programs towards sustainability, this paper focuses on the input saving technologies applied in the high-income countries where potential shifts in the direction of R&D-driven technical change in agriculture are expected in line with the sustainability focus advocated in the new policies (scenario **Input_Saving_HighIncome**). Implementing the input saving technology in MAGNET assumes that all R&D productivity improvements are directed to fertilizer and chemical inputs (other inputs and classical production factors do not benefit from productivity growth). For instance, nitrogen-fixing bacteria can significantly cut fertilizer costs and improve sustainability, supporting adoption by both small and large farms (Ahado et al. 2025). Low-risk pesticides based on double-stranded RNA (Broothaerts et al. 2021; Dalakouras et al. 2024) are also examples of promising technologies developed to save specific inputs, deviating thus from the assumption of neutral technical change. Although the conditions for adopting the new technologies are better in high-income countries (where also stringent environmental regulations persist, see Reinhardt (2023) or Wimmer and Dakpo (2023)), as a mean of sensitivity analysis, an additional scenario was produced where it is assumed that the adoption is global (**Input_Saving_all**).

## 3 | Results

### 3.1 | Knowledge Hotspots and Agricultural Productivity Towards 2050

R&D stock projections based on the assumptions in the Baseline_HR scenario show that in the long term, 45% of global knowledge stocks would be concentrated in China, up from 26% in 2020 (Figure 4), while the role of the USA and EU would decline to 5% and 10%, respectively (despite the increasing trend of R&D stocks in both regions). Rapid Chinese takeover as a knowledge leader in agricultural R&D is also in line with a substantial shift in the geography of total (not only agricultural) R&D towards Asia advocated by Dehmer et al. (2019). They suggest that in the medium to long term, the global R&D landscape is expected to change significantly in favor of the Asian countries, resulting in a growing gap between the world's scientific leaders and "laggers". This prospect can be thus also expected in the case of agricultural R&D unless other countries significantly change their spending patterns.

With these projected R&D stocks, productivity growth rates are expected to be between 0.3% and 0.5% globally, with overperforming regions such as China, India as well as Brazil (Figure 5) while USA and Canada lagging behind due to a recent slow-down in R&D investments. The picture becomes more optimistic when other productivity drivers such as economy-wide technical change (i.e., general-purpose technologies that expand the overall productivity frontier of the economy) are factored in (see Equation 5), in which case total productivity growth

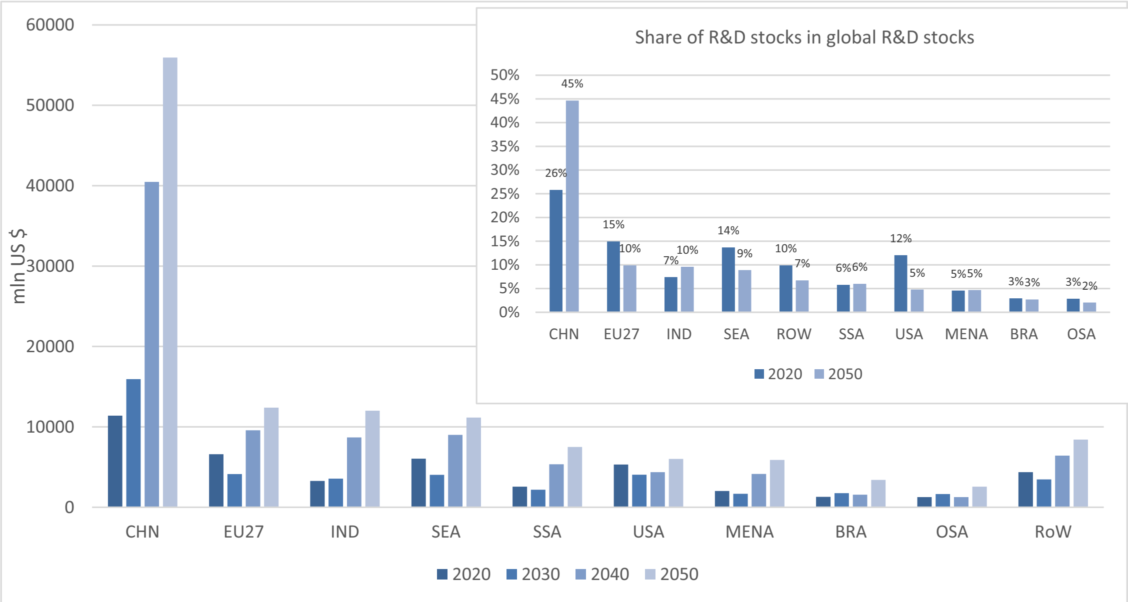



**FIGURE 4** | Expected public agricultural R&D stocks per aggregated region (million US $) and share in total.

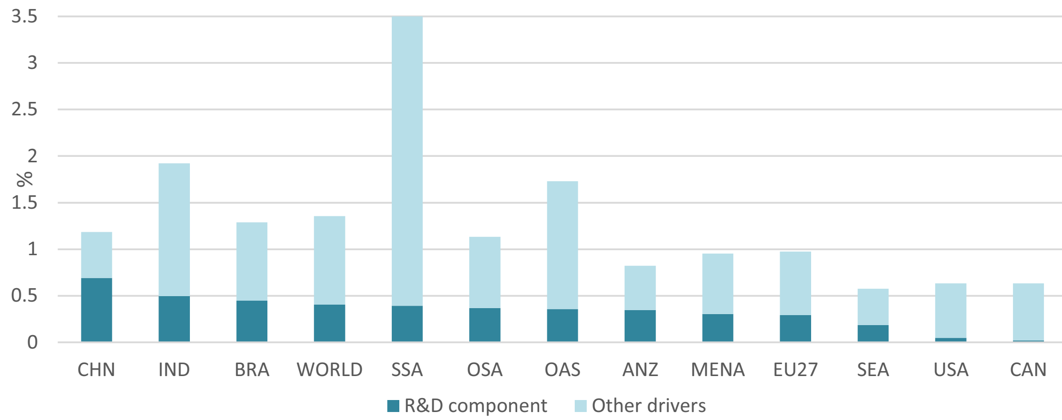



**FIGURE 5** | Annual growth of total and R&D driven technical change in agriculture 2020–2050.

amounts to 1.5% annually on global level. Particularly in Sub-Saharan Africa, the reliance on other drivers to keep up with the expected macroeconomic growth is necessary. From the economic growth perspective, countries with lower capital-output ratios are attaining higher economic and productivity growth compared to high income economies. This is also the case of Sub-Saharan Africa. In this context, the role of general purpose technologies to drive productivity in agriculture is much higher than for instance in the EU economies which already operate close to the technological frontier. The role of agricultural R&D in total agricultural productivity growth thus appears more relevant here.

## 3.2 | Prospects of Sustainable Productivity Growth Under Current R&D Paradigm

Figure 6 reports sustainability indicators that are based on the R&D stocks and productivity rates reported in the previous section. While global agricultural output is expected to grow by about 46% between 2020 and 2050, emissions in agriculture will grow by more than 50%. Given that total land that will be used for agricultural cultivation is expected to grow by 11%, it is clear that emissions per hectare will be increasing as well as per unit of agricultural output. This growth will also require higher use of environmentally sensitive inputs ("FF inputs[6]") such as fertilizer and pesticides. The region level detail shows that the unsustainable results are driven largely by Sub-Saharan Africa, where output will increase by 100%, requiring a 144% increase in emissions. This is driven mostly by output related emissions from cattle production, as well as by the direction of technical change in agriculture, with overly high reliance on economy-wide productivity growth and less on own agricultural R&D, which would increase productivity of land. The share of Sub-Saharan Africa's agricultural emissions in global emissions is expected to rise from 13% to 26% (upper right corner of Figure 6). On the other hand, Brazil, with a similar increase in agricultural output (100%), will require "only" a 50% increase in emissions, suggesting a much more sustainable path of agricultural expansion.

There are several reasons that explain why Brazil and in general Latin America's productivity growth will be more sustainable. First, the productivity growth is expected to rely more on land and capital saving technical change from agricultural R&D. The share of capital in value added in Brazil is rather high (65%), which creates comparative advantage for capital-intensive agricultural sectors (such as oils sector). Second, the production mix will be shifting more towards crops with lower environmental footprint compared to Sub-Saharan Africa, where meat sectors will grow quicker. In India, production growth would be on par with emissions (40%) and would classify India as the second largest polluter of GHG emissions by 2050. While China would become the third largest polluter, agricultural output would grow almost twice as fast as emission growth, which also suggests a more sustainable growth path. Countries like the EU and USA will see only moderate increase in agricultural production (about 20% increase), but for the EU27, the emission increase is comparably smaller than for USA (6% vs. 19% resp.), which is also driven by the higher share of cattle production in the production mix. In any case, both blocks of countries will contribute only by a small share in global emissions in 2050.

Table 3 provides the results on aggregated level with additional sustainability indices. Emissions per hectare are expected to grow in all regions, which is also related to growth of output per hectare. On the other hand, per dollar of agricultural production, the emissions will decline in all regions except for Sub-Saharan Africa. The efficiency of use of sensitive inputs will be the highest in Latin America where the additional use of inputs will bring the highest increase in agricultural production volume.

The persistent growth in agricultural emissions suggests that the path to a sustainable global agricultural production is challenging. This is confirmed when plotting agricultural productivity growth and emissions (Figure 7). Globally we can observe an upward sloping curve, suggesting that higher agricultural productivity levels are associated with higher emissions (and similarly for land use change). At the same time, we can see that the path is different across the regions, which has a degressive character for Sub-Saharan Africa and progressive character for high-income countries. In Sub-Saharan Africa, this suggests that increasing productivity leads at first in faster increase in emissions but after

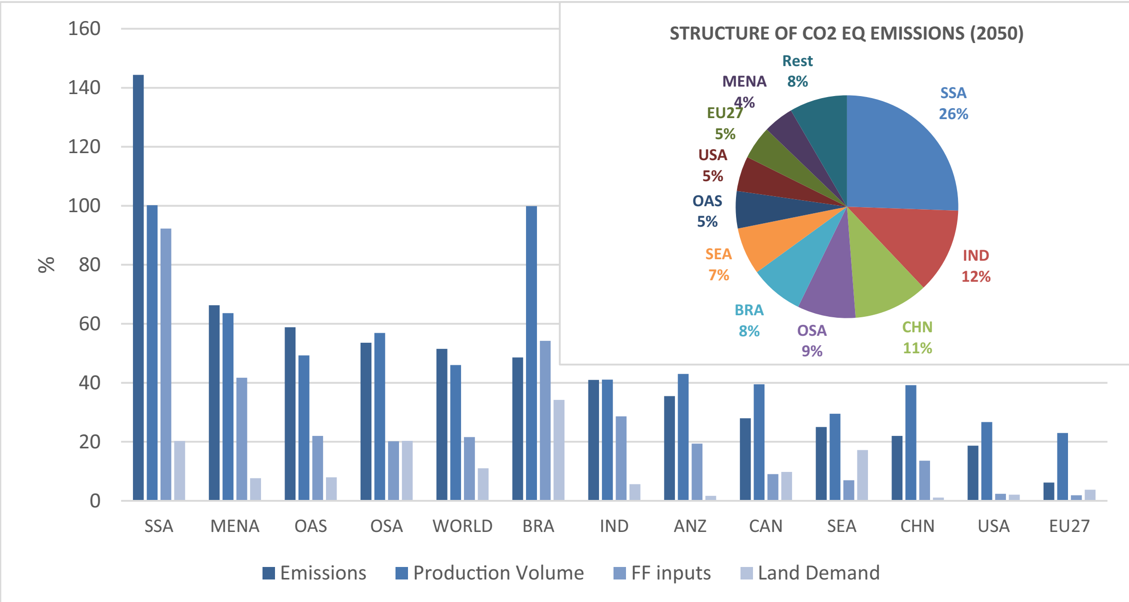



**FIGURE 6** | Projections of sustainability indicators (2020%–2050%).

**TABLE 3** | Growth rates of sustainability indicators (2020%–2050%).

| | Emissions | Production volume | Land demand | FF inputs | Emissions per hectare | Emissions per $ of production | Production per $ of FF input |
|---|---|---|---|---|---|---|---|
| High_ Income | 18 | 26 | 3 | 4 | 16 | −8 | 23 |
| Asia | 34 | 38 | 5 | 14 | 29 | −5 | 24 |
| Latin_ America | 51 | 75 | 26 | 43 | 26 | −24 | 32 |
| SSA | 144 | 100 | 20 | 92 | 124 | 44 | 8 |
| WORLD | 52 | 46 | 11 | 22 | 40 | 6 | 24 |

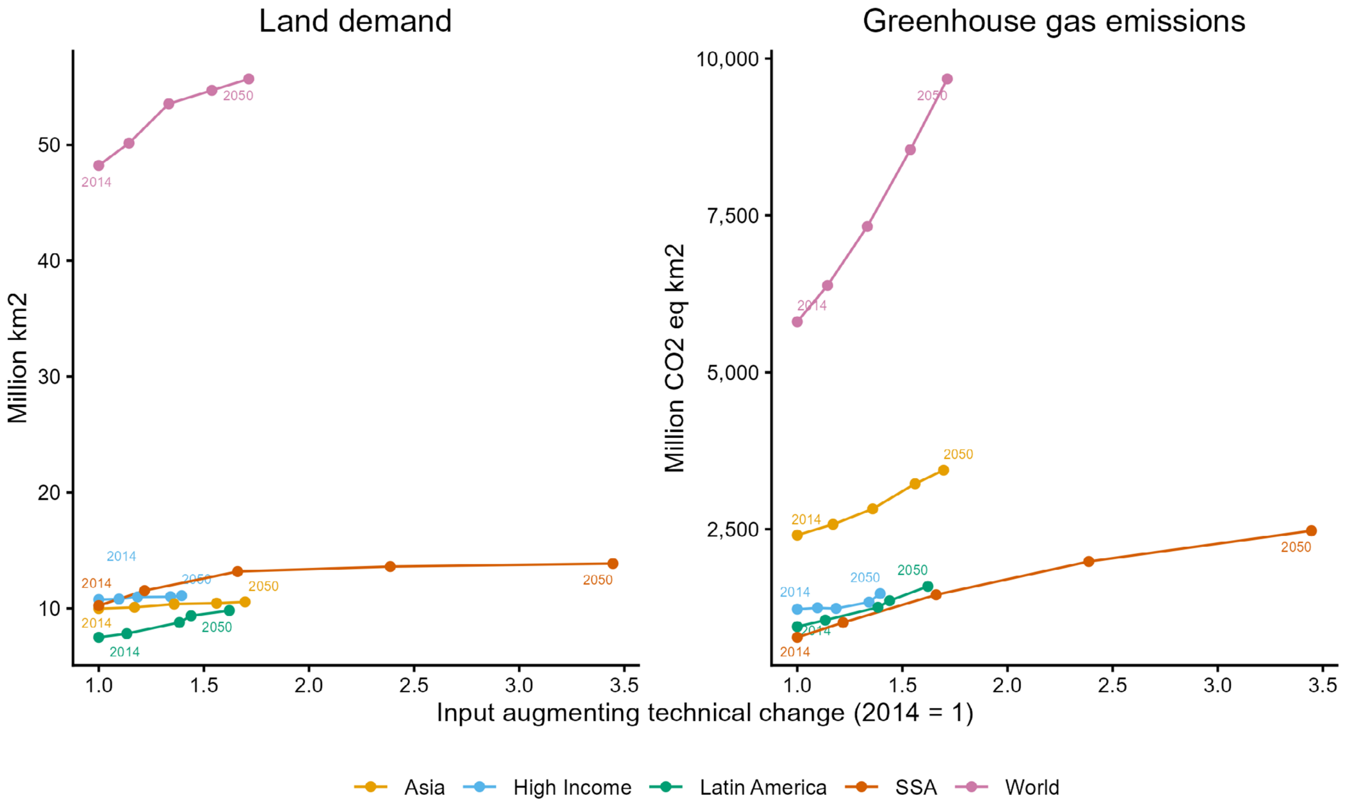



**FIGURE 7** | (a, b) Plotting Agricultural Emissions and land demand with agricultural productivity (selected regions).

reaching a threshold, growth of emissions slows down. This is even more evident when replacing emissions by land demand—after reaching productivity growth threshold, land demand grows slowly. On the other hand, for high-income countries, which exhibit smaller productivity growth than the Global South region, the initial growth of emissions and land demand is slow but after reaching a threshold it grows quickly. These different pathways are related to the land supply asymptote—that is, availability of agricultural land. In Sub-Saharan Africa, the initial land availability allows to increase output quickly but approaching the land asymptote limit, land becomes very scarce leading to slow down of output and emissions. At that point other regions such as the high-income countries respond with more progressive growth of emissions to address the shortage of land in Sub-Saharan Africa.

Still, the openness for investing in R&D matters at least for the speed of how emissions and land demand react to increasing productivity (see Figure A1). In the alternative baseline scenario, which assumes a more pessimistic R&D investment growth rate (Baseline_ConstRD), the curve is steeper compared to the default version. This suggests that higher R&D spending reduces the growth of emissions and land use, but there is no shift in the slope, meaning that under the current R&D productivity model, productivity growth is not expected to be sustainable in the future.

### 3.3 | Shifting the Direction of R&D-Driven Technical Change With Input Saving Technologies

Given the rather pessimistic views on future sustainability growth, the question is to which extent ongoing changes in R&D programs can affect future agricultural sustainability and potential trade-offs with food security. Figure 8 reports the impacts of the input saving technology (**Input_Saving_HighIncome**) implemented in high income countries compared to the default baseline scenario HR in 2050. The emission impacts are quite notable, particularly in Australia, New Zealand, and the EU (−15%), and the use of chemical inputs goes down by −30%. This is however accompanied by a 15% increase in producer prices in these regions which spills over to the rest of the world, causing an increase in agricultural prices of about 3% in the remaining countries.

If the changes in the direction of technical change are considered globally the costs largely outweigh the benefits (this is an extreme scenario that is included for illustration to understand the potential impact of R&D reorientation towards environmental sustainability on a global scale). The emission decline would be reduced by more than 10 percentage points (by 40% instead of 52%) but with accompanying significant increases in producer prices and also more rapid land expansion (see Table A4 for more detailed results). The shifts towards agricultural sustainability would also have important implications on labor markets. This is because any R&D policy that redirects technical change from labor saving to saving other inputs results in higher labor demand. In agriculture, this leads mainly to an increase in wages of unskilled labor (particularly in the case of the **Input_Saving_all** scenario which assumes global change in technology). However, the potentially higher incomes of agricultural households would be compensated by a faster increase in food prices, leaving thus agricultural households with a worse situation than under the baseline status-quo.

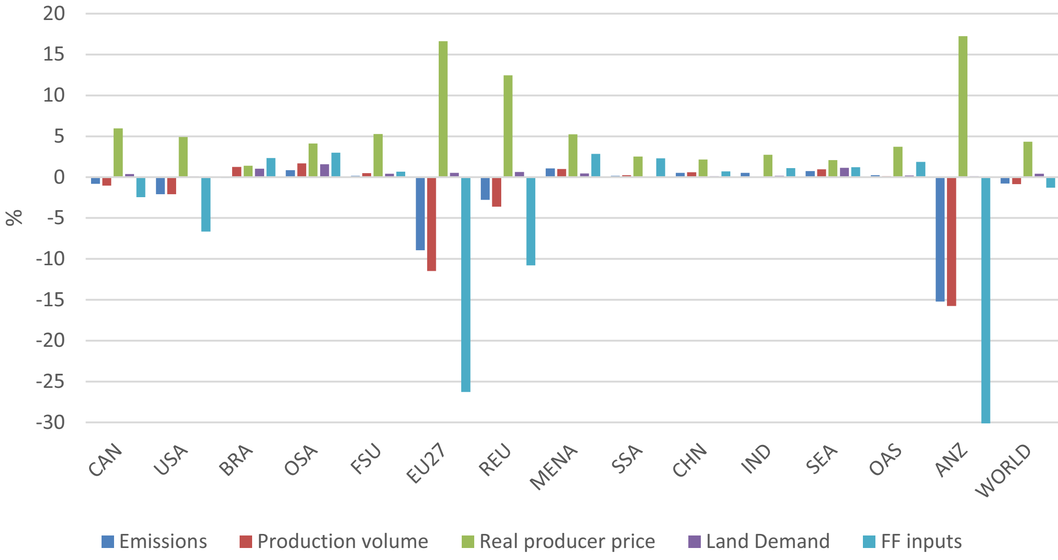



**FIGURE 8** | Impacts of **Input_Saving_HighIncome** scenario (% Change difference from Baseline_HR scenario).

It can be concluded that the alternative technologies lead to lower growth of emissions but at the cost of higher agricultural prices and lower production volume. Nonetheless, if these technologies are adopted only in case of high-income countries, global sustainability impacts are moderate as high-income countries' potential to reduce global environmental footprint (based on emissions and land use change) is rather limited.

Zooming into the EU27 where the considered changes in direction of technical change are supported by concrete policies, it is found that if R&D investments are directed to input saving technologies productivity growth would become sustainable (Figure 9) as additional increase in productivity would be achieved without further increasing emissions (at least within reasonable bounds). On the other hand, there could be a trade-off between emissions and land use where lower use of inputs would be compensated by higher use of land. This is the case of organic farming which requires higher use of land for nitrogen fixation. However, new biotechnologies might reach the reduction of environmentally sensitive input use without additional land, so there may be less of a harmful impact on land use change.

Figure 10 further shows that changing the direction of technical change to save fertilizer and chemical inputs away from traditional production factors could have potentially negative repercussions on EU crop production (particularly crops, fruits, and vegetables) and growth of producer prices.

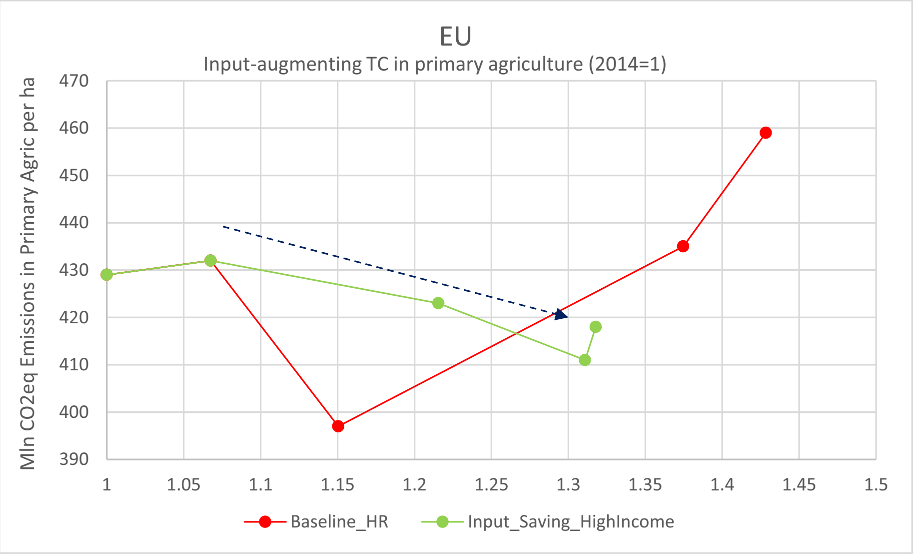
## 4 | Discussion

The modeling exercise in this article supports the view that sustainable productivity growth could be a feasible prospect for high-income countries if R&D programs significantly change their focus.

The baseline projections presented in the paper show that China,[7] India, and Brazil would see the most rapid productivity growth from R&D investments, with the EU and USA lagging behind. In the case of Sub-Saharan Africa, there is much higher reliance on economy-wide productivity growth as the role of domestic agricultural R&D will remain low. Latin America stands out as a region where additional agricultural R&D investments are highly effective as they support the expansion of agricultural production under comparatively lower environmental costs in terms of GHG emissions and use of environmentally sensitive inputs.

From the environmental sustainability point of view, it is rather desirable that productivity "hotspots" are moving away from high income countries which contribute relatively little to emissions growth to countries with higher environmental footprint. Despite this, future projections seem rather pessimistic as global emissions growth will exceed agricultural output growth, which is in line with Villoria's main conclusions. One of the reasons is that Sub-Saharan Africa, as one of the future biggest polluters, is not expected to make a leap forward in productivity. Another reason is Jevon's paradox—our analysis showed that higher productivity growth is associated with higher emissions and land demand growth (although the curvature of this relationship differs per region), and increasing the amount of R&D investments will only slow down the growth of emissions but not revert it.

By conducting a sensitivity analysis, it is found that sustainable agricultural productivity growth could become feasible under the reorientation of R&D programs. However, this only holds for high income countries where these policies can make an important contribution to sustainability while food security concerns are limited and spillover effects in terms of higher food prices are low. Adopting such technologies globally would jeopardize livelihoods of agricultural households, with emission savings resulting mostly from output contraction rather than from sustainable practices and shifting comparative advantage again back to high income countries. This is in line with Wimmer and Dakpo (2023) who argue that policy instruments aiming at increasing productivity should be tailored to the specific needs of individual countries due to the heterogeneity of production conditions and different productivity drivers. Our results also imply that technologies directed solely on saving environmentally



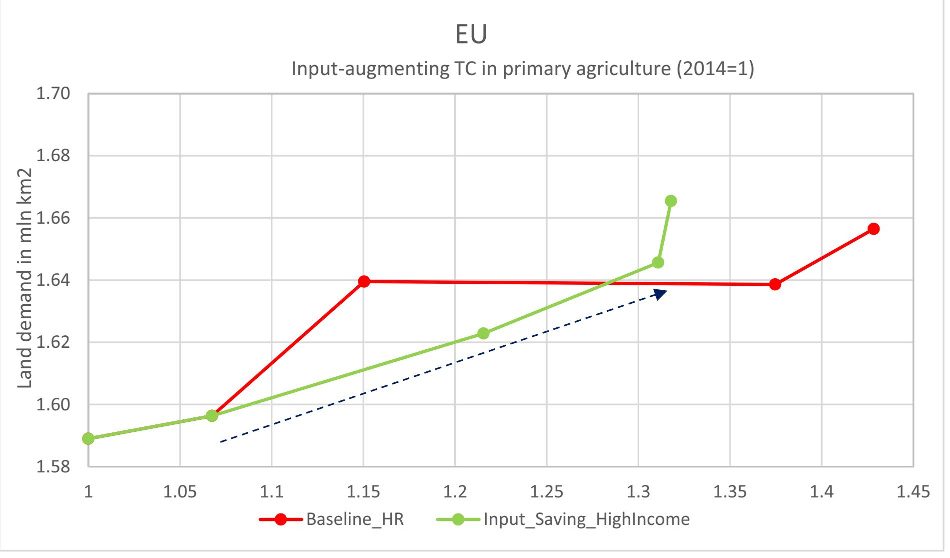




**FIGURE 9** | (a, b) Plotting Agricultural Emissions and land demand with agricultural productivity (selected regions) under input saving technology—case of the EU.

sensitive inputs are not the right solution for achieving sustainability in food production. As cited in Reinhardt (2023), the digital transformation is the "best hope" for bridging the gap between productivity and sustainability. Removing barriers for innovation and supporting the drivers of adoption should be the priority for policy makers. Revitalizing R&D and physical capital investment in agriculture are the essential drivers of adoption of capital-embodied technologies (Sheng 2025).

One of the research questions was to investigate how reliable our modeling approaches are if they are based on assumptions that neglect the "greening" aspects of new R&D in agricultural technologies. Our results show that if these technologies are adopted locally, which would be the recommendation, the differences on global level are not crucial. In general, we should expect more optimistic emission projections coming out of the ex-ante economic models but more pessimistic food price projections as well as higher growth of unskilled labor wages. In case of a global shift in agricultural technology and productivity—a case when technologies stop having traditional productivity impacts—more drastic deviations from the usual baselines would be expected. This also shows that even though agricultural R&D is only one of the components of aggregate productivity growth, it still matters importantly for food security and sustainability impacts.

The presented modeling framework, due to lack of a comprehensive dataset, omits private agricultural R&D, which is an important contributor to productivity growth in high-income countries. It also does not reflect the possibility of productivity growth via international R&D spillovers for which empirical evidence exists in the macroeconomic and industrial literature (based on the seminal work of Coe and Helpman 1995, who were the first authors that considered the role of foreign R&D spillovers and Van Meijl and Van Tongeren (1999, 1998), who applied it in a CGE analysis). The lack of empirical evidence for agricultural R&D, international knowledge spillovers and sustainability constrains its implementation in the economic models like MAGNET but would be an interesting area for further research. A starting point is to identify mechanisms how knowledge spreads across the world and bilateral trade flows enable these linkages but need to be supplemented

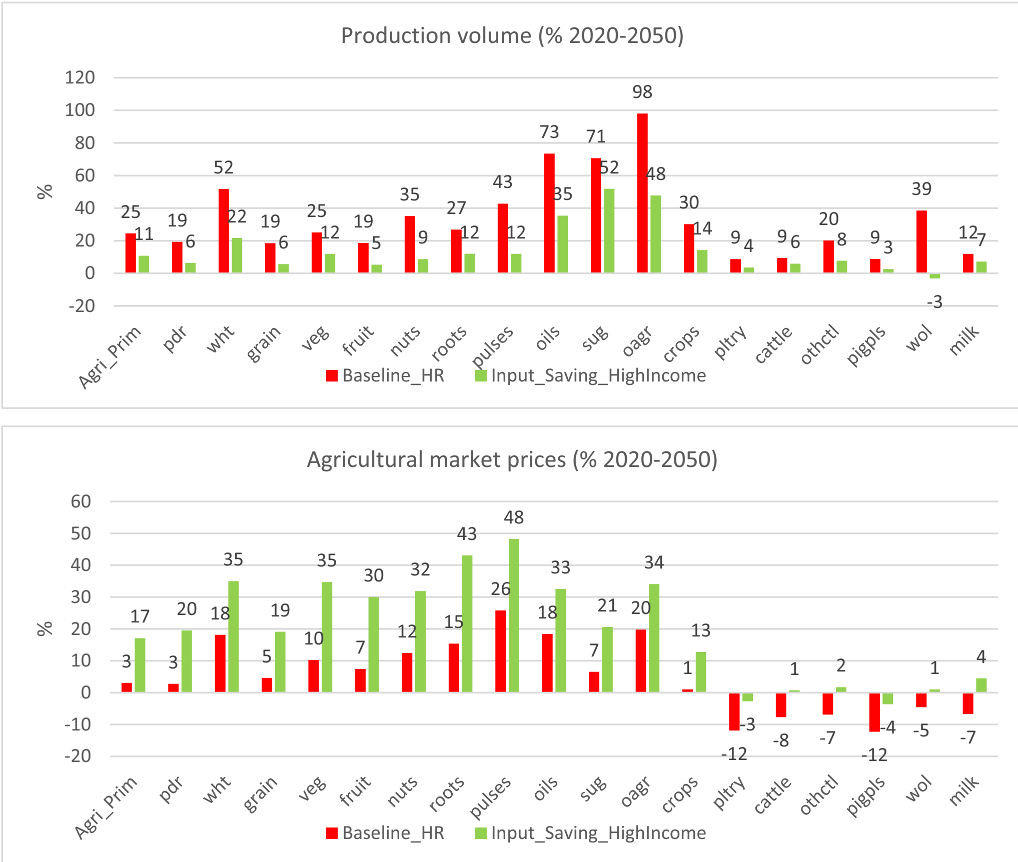



**FIGURE 10** | Agricultural production and prices growth in 2020–2050 period in the EU. *Note:* For abbreviations of the agricultural commodities, see Table A1.

with the absorption capacity of countries. Furthermore, the analysis focuses only on a limited number of indicators for environmental sustainability which are GHG emissions and land use change. The emissions in the MAGNET model are partially linked to output as for example for methane in the animal sectors, and partially linked to emission-intensive inputs such as fertilizers and fossil fuels, but MAGNET does not capture sufficiently impacts on other environmental indicators such as biodiversity, ammonia leaching or the use of high-risk pesticides.

It is also important to highlight that the obtained modeling results are based on the assumptions that trade regimes follow the established WTO rules and the regional free trade agreements. Current political discussions on trade barriers, taxes and other deviations towards protectionism would alter the terms of trade relations and possibly also lead to different projection results. Although not explicitly considered in this modeling framework, the level of trade openness also facilitates international knowledge and innovation transfer, which could also be jeopardized and lead to lower welfare, should the world economic system switch towards protectionism (see, e.g., Van Meijl and Van Tongeren 2004).

## 5 | Conclusion

Sustainable productivity growth could be a feasible prospect for high-income countries if R&D programs significantly change their focus. These insights are supported by sensitivity analysis with assumed changes in productivity parameters. However, new empirical evidence is needed to quantify the impact of promising technologies on productivity and make thus the parameters backed up by evidence. The results might imply that there are conflicting goals as productivity growth is not necessarily compatible with environmental sustainability, at least under the currently used technological possibilities. Not applying and further investing in technologies to foster environmental sustainability and fully employing productivity growth at the current technological possibilities may jeopardize food security. Simulation approaches like this can bring insights into the optimal allocation of different technologies across the regions and production systems. In concrete it would be interesting to design a certain mix of technologies that balance productivity and sustainability respecting the regional characteristics and endowment limits.

Another important aspect is the role of agriculture within the wide macroeconomic framework. The importance of economy-wide technological progress is extremely important also for agriculture and food security, particularly in Sub-Saharan Africa where several countries are expected to undergo rapid economic growth which can only be facilitated by high technological progress. This implies that economic models that estimate future productivity growth in agriculture without taking into account technological spillovers from the rest of the economy may provide biased projections.

Science clearly articulates the urgent need to address the challenge of feeding the world through an increase of agricultural productivity (World Food Price Foundation 2025). The 2030 world's agenda for Sustainable Development features science, technology, and innovation as a key leverage to reach several agrifood systems-related SDG targets addressing technology (FAO 2026). The global agenda for sustainable development (the food security and environmental targets) is accompanied by a global R&D infrastructure and research partnerships that focus on yield improvement, climate resilience, and pest/disease management, namely FAO, IFAD, and CGIAR. Flanked by this global coordination, the European Union, for instance, has launched in the last years several initiatives to improve the development of technologies and productivity (EU's Life Sciences Strategy, Bioeconomy Strategy, Biotech Act). For the new Multi-annual financial framework from 2028, the European Commission (2025b) proposes to almost double the budget for research and innovation.

Global and regional initiatives addressing the investment gap in agricultural R&D are under development, but probably not yet sufficient in size and orientation.


### Acknowledgments

Funding was provided by the European Commission's Joint Research Centre (on the technical development of the agricultural R&D database), and the Horizon Europe 101060075 BRIGHTSPACE project (Designing a Roadmap for Effective and Sustainable Strategies for Assessing and Addressing the Challenges of EU Agriculture to Navigate within a Safe and Just Operating Space) (https://brightspace-project.eu/).

### Funding

This work was supported by HORIZON EUROPE Framework Programme, 101060075; Joint Research Centre in Seville, Spain.

### Conflicts of Interest

The authors declare no conflicts of interest.


### Data Availability Statement

MAGNET database is not available publicly, it is based on GTAP database which is not public (fees apply). The newly built public agricultural R&D database may be available upon request.

### Endnotes

[1] R&D in agriculture might take 5–10 years before the variety is adopted, due to time spent on experimental trials and regulatory approvals. After the variety is adopted, farmers have to learn how to produce it, and consumers have to accept the new product innovation on the market. Therefore, the peak of benefits only comes 15–25 years evolving pests or diseases (Alston et al. 2008).

[2] European Commission (2025a): A Vision for Agriculture and Food Shaping together an attractive farming and agri-food sector for future generations, https://agriculture.ec.europa.eu/vision-agriculture-food_en.

[3] The Coalition on Sustainable Productivity Growth for Food Security and Resource Conservation (SPG Coalition) was launched in 2021 at the United Nation's Food Systems Summit: https://www.usda.gov/oce/sustainability/spg-coalition and promotes a holistic approach to productivity growth that considers impacts and trade-offs among multiple objectives such as food security and nutrition, resource conservation, climate change mitigation and others.

[4] Although in Mason-D'Croz et al. (2019) the authors explicitly consider several investment strategies such as agricultural R&D, irrigated area, water and soil management, they assume that higher investments in agricultural R&D will reduce yield gaps, following thus the typical productivity-oriented R&D paradigm.

[5] Globally, the share of public agricultural R&D expenditures in total public R&D expenditures is less than 10% (about 6% in the EU). However, in some specific countries such as the Sub-Saharan Africa, the share can be as high as 76% (MAGNET R&D database) suggesting that the short-term macro effects are more pronounced in this region.

[6] Inspired by the EU's Farm to Fork strategy which specifically targets the use of fertilizers and pesticides (Wesseler 2022).

[7] The results are in line with Dehmer et al. (2019) who projects a rapid take-over of China as a knowledge leader.

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## Appendix A

**TABLE A1** | Aggregate commodity groups in the MAGNET model.

| Order | Group | Description | Order | Group | Description |
|---|---|---|---|---|---|
| 1 | pdr | Paddy rice | 33 | res | Residue sector |
| 2 | wht | Wheat | 34 | biod | Biodiesel |
| 3 | grain | Cereal grains nec | 35 | biog | Biogasoline |
| 4 | oils | Oil seeds | 36 | ftfuel | Fisher-Tropsch 2nd gen biofuel |
| 5 | sug | Sugar cane, sugar beet | 37 | eth | Ethanol 2nd gen biofuels |
| 6 | hort | Vegetables, fruit, nuts | 38 | gas | Gas |
| 7 | crops | Crops nec | 39 | coa | Coal |
| 8 | oagr | Other agriculture | 40 | ely | Electricity |
| 9 | cattle | cattle sector | 41 | ely_c | Electricity from coal |
| 10 | othctl | sheep, goats, horses | 42 | ely_g | Electricity from gas |
| 11 | pltry | poultry sector | 43 | ely_n | Electricity from nuclear |
| 12 | wol | Wool, silk-worm cocoons | 44 | ely_h | Electricity from hydro |
| 13 | pigpls | Pig and other animal product | 45 | ely_w | Electricity from wind and solar |
| 14 | milk | Raw milk | 46 | bioe | Bioelectricity 2nd gen |
| 15 | bfmt | beef meat | 47 | pla | Polylactic acid bioplastics |
| 16 | othcmt | Meat: other cattle, sheep, goats, horse | 48 | pe | Polyethylene bioplastics |
| 17 | pulmt | poultry meat | 49 | bfchem | Traditional bioplastics |
| 18 | othmt | Other meat product nec | 50 | lsug | Ligno sugar |
| 19 | dairy | Dairy products | 51 | othcrp | Chemical, rubber, plastic prods |
| 20 | sugar | Sugar and molasses | 52 | fert | Fertilizer |
| 21 | cvol | Crude vegetable oil | 53 | f_chem | Mixed fossil biochemical sector |
| 22 | vol | Vegetable oils and fats | 54 | mvh | Motor vehicles and parts |
| 23 | pcr | Processed rice | 55 | cons | Construction |
| 24 | ofd | Processed food | 56 | othind | Other industry |
| 25 | feed | Animal feed | 57 | pel | Pellet sector |
| 26 | wfish | Wild fish | 58 | gas_dist | Gas manufacture, distribution |
| 27 | aqcltr | Aquaculture | 59 | trans | Transport sector |
| 28 | fishp | Fish processing | 60 | pubedu | Public service & education |
| 29 | frs | Forestry | 61 | ser | Services |
| 30 | plan | Plantation | 62 | ddgs | Biogasoline byproduct |
| 31 | c_oil | Crude oil | 63 | oilcake | Oil cake byproduct of cvol |
| 32 | petro | Petroleum, coal products | 64 | fishm | Fish meal |

*Source:* authors.

**TABLE A2** | MAGNET regional aggregation applied in this paper.

| GTAP code | Description | Magnet group | Description | GTAP code | Description | Magnet group | Description |
|---|---|---|---|---|---|---|---|
| aus | Australia | ANZ | Australia and New Zealand | mlt | Malta | EU27 | EU27 |
| nzl | New Zealand | ANZ | Australia and New Zealand | nld | Netherlands | EU27 | EU27 |
| xoc | Rest of Oceania | SEA | South-East Asia | pol | Poland | EU27 | EU27 |
| chn | China | CHN | China | prt | Portugal | EU27 | EU27 |
| hkg | Hong Kong | CHN | China | rou | Romania | EU27 | EU27 |
| jpn | Japan | SEA | South-East Asia | svk | Slovakia | EU27 | EU27 |
| kor | Korea | SEA | South-East Asia | svn | Slovenia | EU27 | EU27 |
| mng | Mongolia | CHN | China | esp | Spain | EU27 | EU27 |
| twn | Taiwan | CHN | China | swe | Sweden | EU27 | EU27 |
| xea | Rest of East Asia | SEA | South-East Asia | gbr | United Kingdom | REU | Other Europe |
| brn | Brunei Darussalam | SEA | South-East Asia | che | Switzerland | REU | Other Europe |
| khm | Cambodia | SEA | South-East Asia | nor | Norway | REU | Other Europe |
| idn | Indonesia | SEA | South-East Asia | xef | Rest of EFTA | REU | Other Europe |
| lao | Lao People's Dem Rep | SEA | South-East Asia | alb | Albania | REU | Other Europe |
| mys | Malaysia | SEA | South-East Asia | blr | Belarus | FSU | Former Soviet Union |
| phl | Philippines | SEA | South-East Asia | rus | Russian Federation | FSU | Former Soviet Union |
| sgp | Singapore | SEA | South-East Asia | ukr | Ukraine | FSU | Former Soviet Union |
| tha | Thailand | SEA | South-East Asia | xee | Rest of Eastern Europe | FSU | Former Soviet Union |
| vnm | Viet Nam | SEA | South-East Asia | xer | Rest of Europe | REU | Other Europe |
| xse | Rest of Southeast Asia | SEA | South-East Asia | kaz | Kazakhstan | FSU | Former Soviet Union |
| bgd | Bangladesh | OAS | Other Asia | kgz | Kyrgyztan | FSU | Former Soviet Union |
| ind | India | IND | India | tjk | Tajikistan | FSU | Former Soviet Union |
| npl | Nepal | OAS | Other Asia | xsu | Rest of Former Soviet Union | FSU | Former Soviet Union |
| pak | Pakistan | OAS | Other Asia | arm | Armenia | FSU | Former Soviet Union |
| lka | Sri Lanka | OAS | Other Asia | aze | Azerbaijan | FSU | Former Soviet Union |
| xsa | Rest of South Asia | OAS | Other Asia | geo | Georgia | FSU | Former Soviet Union |
| can | Canada | CAN | Canada | bhr | Bahrain | MENA | Middle-East & North Africa |
| usa | United States of America | USA | United States | irn | Iran Islamic Republic of | MENA | Middle-East & North Africa |
| mex | Mexico | OSA | Other Latin America | isr | Israel | MENA | Middle-East & North Africa |
| xna | Rest of North America | USA | United States | jor | Jordan | MENA | Middle-East & North Africa |
| arg | Argentina | OSA | Other Latin America | kwt | Kuwait | MENA | Middle-East & North Africa |
| bol | Bolivia | OSA | Other Latin America | omn | Oman | MENA | Middle-East & North Africa |

(Continues)

TABLE A2 | (Continued)

| GTAP code | Description | Magnet group | Description | GTAP code | Description | Magnet group | Description |
|---|---|---|---|---|---|---|---|
| bra | Brazil | BRA | Brazil | qat | Qatar | MENA | Middle-East & North Africa |
| chl | Chile | OSA | Other Latin America | sau | Saudi Arabia | MENA | Middle-East & North Africa |
| col | Colombia | OSA | Other Latin America | tur | Turkey | MENA | Middle-East & North Africa |
| ecu | Ecuador | OSA | Other Latin America | are | United Arab Emirates | MENA | Middle-East & North Africa |
| pry | Paraguay | OSA | Other Latin America | xws | Rest of Western Asia | MENA | Middle-East & North Africa |
| per | Peru | OSA | Other Latin America | egy | Egypt | MENA | Middle-East & North Africa |
| ury | Uruguay | OSA | Other Latin America | mar | Morocco | MENA | Middle-East & North Africa |
| ven | Venezuela | OSA | Other Latin America | tun | Tunisia | MENA | Middle-East & North Africa |
| xsm | Rest of South America | OSA | Other Latin America | xnf | Rest of North Africa | MENA | Middle-East & North Africa |
| cri | Costa Rica | OSA | Other Latin America | ben | Benin | SSA | Sub-Saharan Africa |
| gtm | Guatemala | OSA | Other Latin America | bfa | Burkina Faso | SSA | Sub-Saharan Africa |
| hnd | Honduras | OSA | Other Latin America | cmr | Cameroon | SSA | Sub-Saharan Africa |
| nic | Nicaragua | OSA | Other Latin America | civ | Cote d'Ivoire | SSA | Sub-Saharan Africa |
| pan | Panama | OSA | Other Latin America | gha | Ghana | SSA | Sub-Saharan Africa |
| slv | El Salvador | OSA | Other Latin America | gin | Guinea | SSA | Sub-Saharan Africa |
| xca | Rest of Central America | OSA | Other Latin America | nga | Nigeria | SSA | Sub-Saharan Africa |
| dom | Dominican Republic | OSA | Other Latin America | sen | Senegal | SSA | Sub-Saharan Africa |
| jam | Jamaica | OSA | Other Latin America | tgo | Togo | SSA | Sub-Saharan Africa |
| pri | Puerto Rico | OSA | Other Latin America | xwf | Rest of Western Africa | SSA | Sub-Saharan Africa |
| tto | Trinidad and Tobago | OSA | Other Latin America | xcf | Central Africa | SSA | Sub-Saharan Africa |
| xcb | Caribbean | OSA | Other Latin America | xac | South Central Africa | SSA | Sub-Saharan Africa |
| aut | Austria | EU27 | EU27 | eth | Ethiopia | SSA | Sub-Saharan Africa |
| bel | Belgium | EU27 | EU27 | ken | Kenya | SSA | Sub-Saharan Africa |
| bgr | Bulgaria | EU27 | EU27 | mdg | Madagascar | SSA | Sub-Saharan Africa |
| hrv | Croatia | EU27 | EU27 | mwi | Malawi | SSA | Sub-Saharan Africa |
| cyp | Cyprus | EU27 | EU27 | mus | Mauritius | SSA | Sub-Saharan Africa |

(Continues)

**TABLE A2** | (Continued)

| GTAP code | Description | Magnet group | Description | GTAP code | Description | Magnet group | Description |
|---|---|---|---|---|---|---|---|
| cze | Czech Republic | EU27 | EU27 | moz | Mozambique | SSA | Sub-Saharan Africa |
| dnk | Denmark | EU27 | EU27 | rwa | Rwanda | SSA | Sub-Saharan Africa |
| est | Estonia | EU27 | EU27 | tza | Tanzania | SSA | Sub-Saharan Africa |
| fin | Finland | EU27 | EU27 | uga | Uganda | SSA | Sub-Saharan Africa |
| fra | France | EU27 | EU27 | zmb | Zambia | SSA | Sub-Saharan Africa |
| deu | Germany | EU27 | EU27 | zwe | Zimbabwe | SSA | Sub-Saharan Africa |
| grc | Greece | EU27 | EU27 | xec | Rest of Eastern Africa | SSA | Sub-Saharan Africa |
| hun | Hungary | EU27 | EU27 | bwa | Botswana | SSA | Sub-Saharan Africa |
| irl | Ireland | EU27 | EU27 | nam | Namibia | SSA | Sub-Saharan Africa |
| ita | Italy | EU27 | EU27 | zaf | South Africa | SSA | Sub-Saharan Africa |
| lva | Latvia | EU27 | EU27 | xsc | Rest of South African Customs | SSA | Sub-Saharan Africa |
| ltu | Lithuania | EU27 | EU27 | xtw | Rest of the World | ANZ | Australia and New Zealand |
| lux | Luxembourg | EU27 | EU27 | | | | |

*Note:* Details on GTAP country aggregation are found at: https://www.gtap.agecon.purdue.edu/databases/regions.aspx?Version=12.211.

**TABLE A3** | Projected growth rates of R&D spending in the R&D scenarios.

| | 1990–2020 | 2020–2050 HR | 2020–2050 RDIN |
|---|---|---|---|
| 1 CAN | 0.6% | 0.3% | 1.5% |
| 2 USA | 0.4% | 1.7% | 0.7% |
| 3 BRA | 4.0% | 3.2% | 2.3% |
| 4 OSA | 2.8% | 2.5% | 1.4% |
| 5 FSU | 2.4% | 3.4% | 0.5% |
| 6 EU27 | 1.8% | 2.2% | 0.7% |
| 7 REU | 1.1% | 0.6% | 0.7% |
| 8 MENA | 3.6% | 3.4% | 1.5% |
| 9 SSA | 3.2% | 3.3% | 2.2% |
| 10 CHN | 6.5% | 4.4% | 0.8% |
| 11 IND | 5.7% | 4.2% | 1.2% |
| 12 SEA | 1.9% | 2.0% | 1.0% |
| 13 OAS | 3.2% | 3.2% | 1.8% |
| 14 ANZ | 2.5% | 1.1% | 1.5% |
| Total | 3.1% | 3.3% | 1.1% |

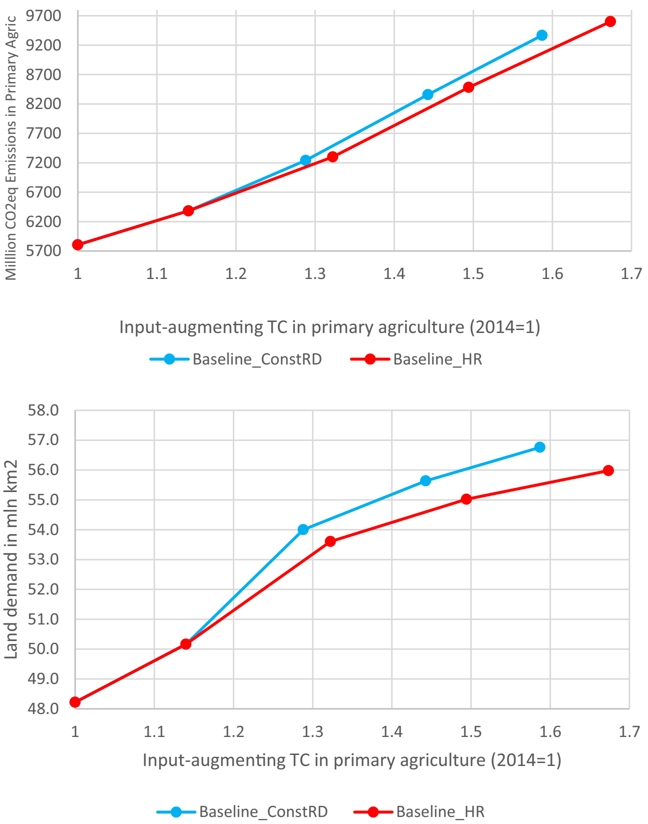


**FIGURE A1** | Plotting global emissions and global land demand with input-augmenting technical change in agriculture (Baseline_HR and Baseline_ConsRD).

**TABLE A4** | Growth rates of sustainability and food security indicators (2020%–2050%) under varying R&D scenarios.

| | Emissions | | | Production volume | | | Real producer price | | | Land demand | | | FF inputs | | | Consumer Food Prices | | | Wages UnSk labour | | | Wages Sk labour | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | HR | IS_HI | IS_ all | HR | IS_ HI | IS_ all | HR | IS_HI | IS_all | HR | IS_HI | IS_all | HR | IS_HI | IS_all | HR | IS_HI | IS_all | HR | IS_HI | IS_all | HR | IS_HI | IS_all |
| CAN | 28.0 | 26.9 | 31.4 | 39.5 | 38.1 | 41.4 | 19.8 | 26.9 | 64.4 | 9.8 | 10.2 | 11.9 | 9.1 | 6.4 | 12.8 | −10.9 | −9.8 | −4.7 | 12.9 | 13.7 | 16.1 | 13.2 | 14.0 | 16.7 |
| USA | 18.7 | 16.2 | 18.5 | 26.7 | 24.1 | 26.4 | 14.0 | 19.6 | 44.6 | 2.1 | 2.2 | 2.7 | 2.4 | −4.4 | −3.8 | −9.1 | −7.8 | −2.1 | 4.8 | 6.1 | 9.2 | 4.4 | 5.6 | 8.8 |
| BRA | 48.6 | 48.5 | 37.7 | 99.9 | 102.4 | 83.4 | −36.3 | −35.5 | −16.3 | 34.2 | 35.6 | 45.5 | 54.2 | 57.8 | 21.4 | −2.0 | 0.1 | 13.2 | 121.8 | 128.9 | 168.6 | 121.6 | 128.6 | 166.6 |
| OSA | 53.6 | 54.9 | 43.0 | 56.9 | 59.6 | 46.8 | −13.0 | −9.5 | 24.5 | 20.3 | 22.3 | 29.7 | 20.2 | 23.8 | 1.0 | −5.3 | −3.8 | 8.0 | 48.4 | 52.1 | 69.2 | 53.6 | 57.2 | 73.6 |
| FSU | 12.8 | 13.0 | 4.0 | 21.1 | 21.7 | 11.6 | −3.0 | 2.1 | 41.3 | 2.4 | 2.8 | 4.2 | −1.0 | −0.3 | −22.1 | −7.3 | −5.4 | 10.0 | 54.3 | 56.3 | 70.5 | 57.8 | 59.7 | 71.1 |
| EU27 | 6.2 | −3.3 | 4.1 | 23.0 | 8.9 | 21.2 | −11.7 | 3.0 | 27.8 | 3.8 | 4.3 | 5.6 | 1.9 | −24.9 | −9.9 | 4.4 | 9.2 | 17.9 | 63.6 | 68.8 | 93.1 | 64.2 | 67.9 | 93.9 |
| REU | 12.5 | 9.4 | 13.9 | 20.3 | 16.0 | 20.9 | −11.7 | −0.8 | 18.6 | 2.4 | 3.0 | 4.4 | −6.3 | −16.4 | −11.4 | 6.9 | 10.5 | 17.5 | 46.8 | 52.5 | 61.0 | 47.0 | 52.7 | 61.5 |
| MENA | 66.3 | 68.1 | 57.8 | 63.6 | 65.2 | 53.0 | −10.2 | −5.5 | 34.9 | 7.7 | 8.2 | 10.1 | 41.7 | 45.8 | 30.9 | 0.3 | 3.5 | 27.5 | 37.2 | 39.2 | 52.4 | 40.7 | 42.6 | 55.0 |
| SSA | 144.4 | 144.8 | 125.8 | 100.2 | 100.6 | 77.7 | 54.8 | 58.7 | 185.9 | 20.3 | 20.3 | 21.3 | 92.3 | 96.7 | 143.4 | 57.6 | 60.8 | 155.0 | −20.9 | −20.6 | −16.3 | −6.2 | −5.9 | −0.8 |
| CHN | 22.0 | 22.6 | 3.8 | 39.2 | 40.1 | 14.5 | 18.1 | 20.6 | 125.4 | 1.1 | 1.2 | 3.1 | 13.6 | 14.4 | −30.5 | −11.7 | −10.8 | 23.7 | 116.3 | 117.6 | 141.9 | 100.6 | 101.7 | 121.2 |
| IND | 41.0 | 41.8 | 26.1 | 41.1 | 41.0 | 21.4 | 49.8 | 53.9 | 164.8 | 5.7 | 5.8 | 7.9 | 28.6 | 30.0 | 21.9 | 20.0 | 22.6 | 98.7 | 16.7 | 16.6 | 22.2 | 20.6 | 20.5 | 25.6 |
| SEA | 25.0 | 25.9 | 25.5 | 29.5 | 30.8 | 31.7 | 5.5 | 7.7 | 39.1 | 17.2 | 18.5 | 29.4 | 7.0 | 8.3 | 3.4 | 0.6 | 1.7 | 14.9 | 47.5 | 49.0 | 64.8 | 49.0 | 50.5 | 64.6 |
| OAS | 58.8 | 59.2 | 50.5 | 49.3 | 49.5 | 33.3 | 92.4 | 99.5 | 214.8 | 8.0 | 8.2 | 10.0 | 22.0 | 24.3 | 38.1 | 49.1 | 52.7 | 111.0 | 3.8 | 3.6 | 1.3 | 17.1 | 16.8 | 11.9 |
| ANZ | 35.5 | 14.9 | 17.3 | 43.0 | 20.5 | 24.5 | −4.4 | 12.1 | 49.3 | 1.7 | 1.8 | 2.7 | 19.4 | −16.6 | −12.2 | 2.4 | 6.5 | 17.2 | 13.8 | 16.8 | 22.8 | 13.7 | 16.7 | 22.7 |
| WORLD | 51.5 | 50.3 | 40.4 | 46.0 | 44.8 | 32.8 | 15.0 | 20.0 | 87.4 | 11.1 | 11.5 | 14.2 | 21.6 | 20.0 | 0.3 | 3.4 | 5.8 | 31.7 | 64.1 | 66.0 | 83.4 | 42.6 | 44.8 | 57.9 |

*Note:* Indicators are reported for primary agricultural sector, except for consumer food prices which also include food processing commodities.
Abbreviations: HR = Baseline_HR (default scenario based on Historical R&D growth rates); IS_all = Input_Saving_All scenario; IS_HI = Input_Saving_HighIncome scenario.