Peng *et al. Agricultural and Food Economics* (2024) 12:31
https://doi.org/10.1186/s40100-024-00321-x

Agricultural and Food Economics

RESEARCH **Open Access**

Structural dynamics and sustainability in the agricultural sector: the case of the European Union

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Abstract

This paper seeks to draw a research agenda for unveiling the underlying bottlenecks and possibilities for improving the agricultural total factor productivity in the European Union (EU). To this aim, the paper first surveys the key challenges for the modern agricultural economy. Then, the case of the EU is discussed by looking at the convergence in the partial productivity indicators (including the GHG emission) and growth efficiency that relate to the gap in the total factor productivity growth. The results suggest that the EU member states exhibited growth inefficiency (i.e., a gap in the total factor productivity growth) of 5–9% on average during 2004–2021. The paper also discusses the possibilities to utilize the production theory for assessing the pathways towards improvements in the productivity and sustainability of the EU agriculture.

Keywords: Agriculture, Productivity, Sustainability, Production theory, Decomposition

Introduction

The agricultural sector has seen a number of transformations across the world. The major directions prevailing the current agricultural policies worldwide include the quest for sustainability, ensuring rural livelihoods, and maintaining food security (OECD/FAO 2021; Erenstein et al. 2021; International Food Policy Research Institute 2022). Circularity has also appeared as an important task for economy, including the agricultural sector (Koval et al. 2023). The support policies have been adopted to promote these objectives in major economies, including the USA, the European Union, and China, among others.

In order to respond to the key challenges that have emerged in the last decade, the agricultural sector requires a plethora of policy measures. These may seek to improve the production technologies, managerial procedures, viability of rural communities, and increase resilience of the farms. On the other side, the changes in demand have been noticed due to changes in diets and lifestyle. Thus, the dynamic situation in agricultural sector requires proper modelling frameworks.

The measurement of the productivity and its potential gains constitutes one of the key questions for devising and realizing effective agricultural policies. Indeed, the same applies to the economy in general. Therefore, it is important to develop robust methods and models that would be able to capture the changers in the underlying production technology and assess the existing practices.

The issues of sustainability have been stressed in numerous national and international strategies. The EU has adopted the European Green Deal and strategy From Farm to Fork (Schebesta and Candel 2020; Siddi 2020). These strategies relate to the Common Agricultural Policy that is a key strategy for shaping the agricultural sector of the EU. At the international scale, the Sustainable Development Goals have been adopted by the United Nations. These policy-oriented goals require proper indicators for operationalizing them and the associated policy measures (Hák et al. 2016).

The developing countries have also strived to implement agricultural reforms and boost their productivity levels so as to ensure food security. Among other examples, the case of China is interesting as it has seen various agricultural reforms in the past 2 decades. These, to a certain extent, resemble the policy shifts in the new EU member states. Indeed, China has shifted to net agricultural subsidization after eliminating agricultural taxes in 2004 (Huang and Yang 2017; Huang 2022). This has improved the situation and motivation of farmers along with changes in the output levels and structure. Also, the different policy schemes addressed the acquisition of inputs. The changes in the use of the inputs have resulted in the corresponding dynamics in the greenhouse gas emission. These issues have been analysed by, e.g., Shen et al. (2018).

The productivity and efficiency measures have been revised in order to account for environmental effects caused by the farming systems. Alem (2023) applied stochastic frontier analysis to gauge the green TFP in Norwegian dairy farms. Barath et al. (2024) used data envelopment analysis to assess the eco-efficiency of Hungarian farms. Baráth and Fertő (2024) analysed the effect of ecologisation on the TFP of Hungarian farms by applying the stochastic frontier analysis.

This study seeks to identify the key processes and phenomena shaping the agricultural (total factor) productivity in the EU countries and assess possibilities for its growth using the frontier approach. This allows to link the experience of the EU and other countries to identify the most promising agricultural development paths and the associated policy measures. The research relies on the principles of the production economics that are supplemented by the sustainability approach. The aggregate data are used to provide stylized facts on the shifts in the (environmental) production technology and growth efficiency for the EU countries. Note that growth efficiency relates to the total factor performance gap. The dynamic data envelopment analysis approach provides new insights in the TFP growth potential in the EU agriculture. We then provide a discussion on the further research prospects using the production approach that would allow to identify the means to improve agricultural (total factor) productivity.

Literature review

The economic systems involve multiple stakeholders that are linked via the factor and product markets. In these markets, price information acts as a major signal of the supply and demand shifts. The regions of the world are often linked by the global markets, including the agri-food markets. As agriculture contributes to 3% of the global GDP and to more than 25% of GDP in least developed countries (World Bank 2023), the international linkages are important in terms of the (eventual) convergence among the economies. Therefore, focusing on such major agricultural producer as the European Union may provide insights into the possibilities for sustainable development and welfare gains for the whole world.

This review focuses on interrelated topics of (mega-)trends and challenges relevant to modern agricultural systems. These are of crucial importance for the livelihood of the increasing population on the global scale. As the resource scarcity limits the production scale, the price levels and well-being are affected. Also, the technological progress in agricultural sector may decrease the requirements for the material and human input thereby allowing for an increase in the production scale without further pressure on the resource markets. Thus, it is important to assess the major challenges and trends prevailing in agriculture in particular and resource use in general.

(Mega-)trends in agriculture

Agricultural sector comprises the three major blocks: producers, consumers, and agri-food markets. The processing sector is also involved in the production of the agri-food products. Therefore, the current debate on the modernization of the agricultural sector with respect to the increasing and evolving needs of the society needs to be discussed from different perspectives. In this section, we overview the major problems and avenues for research relevant to different blocks as discussed above.

The economic, social, and environmental concerns have been raised in the context of agriculture. The agricultural systems develop in the rural areas which makes the social component especially important. Accordingly, it is necessary to develop tools that allow relevant stakeholders to track progress achieved along dimensions of sustainable agricultural development (Latruffe et al. 2016).

The low input agricultural practices may be applied to reduce the input requirements and environmental impact of the agricultural production. An increase in the sustainability can be achieved through the proper development of the low input agricultural systems that ensure climate-smart approach is followed. A study on examples of the low input agriculture was prepared by Sarkar et al. (2020).

By using the advanced technologies such as drones, sensors, and GPS, the farmers are able to generate and exploit more precise and comprehensive data in order to optimize the farming practices. Precision agriculture aims to reduce the waste on water, fertilizer, and pesticides; improve yields and quality of corps; further to increase the profits for farmers; and create new opportunities of selling and developing the agricultural technologies. All these benefit crop management, resource allocation, and yields which lead to cost savings and environmental benefits. Shin et al. (2023) discussed development of the precision agriculture.

There has been an increasing interest in locally sourced organically produced food, suggested as a model of sustainable consumption for a range of economic, social, and environmental reasons (Sefayang 2006; Stagl 2002). Organic farming avoids the use of synthetic fertilizers and pesticides, which renders a reduced environmental impact as measured by biodiversity, soil erosion, and water quality. Organic farming also may improve public health creating serious effects for the whole economy. The increasing demand for organic and locally produced food has created opportunities for small-scale farmers and food producers who can cater to this niche market. Under the Farm to Fork strategy, the European Commission has set a target of 'at least 25% of the EU's agricultural land under organic farming and a significant increase in organic aquaculture by 2030' (European Commission 2023).

The increasing population requires expansion of agricultural production (Alexandratos and Bruinsma 2012; Tilman et al. 2002; Green et al. 2005). At the same time, food waste and loss remain a serious problem with 1.3 billion tons of food production being lost or wasted annually (FAO 2011). Vertical farming allows producing agri-food products by stacking the crops or livestock in vertical systems (Banerjee and Adenaeuer 2014). Vertical farming as the trend involves growing crops in indoor, vertically stacked layers that are gaining popularity as a way to produce food in urban areas and in areas with limited access to arable land. By using this pesticide-free method of farming, 98% less water and 99% of space utilized (Eden Green Technology 2023). This allows to minimize the resource use and environmental impact.

Consolidation of the agricultural industry is creating economies of scale and driving efficiency gains as large agribusinesses acquire smaller farms and businesses. The research on the linkages between farm size and productivity has been addressed in a number of studies relying on quantitative approaches (Huan et al. 2022; Wang et al. 2022; Čechura et al. 2022).

The increasing scale of agricultural production does not necessarily imply that family farms get larger. The growth of rural proletarianization has been observed in some countries with recent links to the global agricultural markets (Martinez Valle 2017). Burawoy (2013) and Polanyi (2000) addressed the link between mercantilization of land and peasant agriculture.

The purchase prices may also vary depending on the farm size. Such phenomena further increase the speed of consolidation. The differences in the average farm size still exist among major agricultural producers. For instance, US and China stand at the two ends of spectrum with the former relying on large farms, whereas relatively small land plots are exploited in China. The European Union farming has been struggling to find the optimal farm size with some of the support measures encouraging family farming and other being related to the scale of farm and, thus, indirectly pushing the consolidation forwards.

The degree of consolidation is also related to the farm organization. The private (family) farms obviously tend to be smaller and better integrated into rural communities. Appel and Balmann (2023) looked into the interaction among neighbouring farms through the lens of consolidation. As for the corporate farms, they are less important in the sense of the lifestyle maintenance but purely oriented towards production and profit generation. Obviously, such organizations are larger than the family farms are.

Challenges for agriculture

The changes in the production mode have rendered serious shifts in the structure and size of the society. This has attracted concerns in regard to the resources needed to sustain the growing population ever since Malthus (1798). The warning of Malthus subsided as the increasing productivity allowed to produce more from a given level of inputs. However, intensification of production (including agricultural production) has caused undesirable outcomes in the sense of environmental degradation (UNDP 2012).

The effects of population growth and food security were related by Egide et al. (2023). Indeed, population growth is less important for developed economies. However, it affects the agri-food markets globally.

There have been economic growth models adapted to the environmental problems (Niu et al. 2022). In agricultural domain, limited resources such as land, water, and fertilizer can constrain the growth of output and productivity. The neoclassic growth model of Solow explained the economic growth in terms of the factor inputs (capital and labour) and technology. Thus, an increase in output may be realized by increasing the use of the factor inputs and/or technological progress. The revised 'environmental' Solow model includes natural resources (depletable) and land (limited but not depletable). Using the theory, we can analyse the impact of resource constrains on economic growth. Also, such undesirable outputs as greenhouse gas emission may also be included as an environmental input into such models. Milani (2023) presented an outline of the environmental Solow model along with the comparative statics. Guilló and Magalhães (2023) included labour, capital, and GHG emission in their formulation of the Solow model. Therefore, economic growth should be analysed alongside the environmental considerations.

Consumers (especially those in the developed economies) exhibit a shift in their preferences towards more sustainable (ways of producing) food. This implies that certain premia consumers are willing to pay for sustainable food (Katare et al. 2023). Annunziata and Vecchio (2016) argued that local origin can be one of the determinants when choosing organic food. Labelling is important to convey the message of sustainability of agri-food products (Katare et al. 2023).

Excessive use of the natural resources may induce environmental degradation. Braussman and Bretscheger (2018) discussed the maintenance of the land quality in the presence of the intensive farming practices that rely on (excessive) use of chemical fertilizers and pesticides. Environmental degradation is also caused by deforestation that further contributes to soil erosion (Mirzabaev et al. 2023) and reduced biodiversity. Lanz et al. (2018) discussed the linkages between agricultural productivity and pressures on biodiversity. Environmental degradation impacts agricultural production in the long run as the ecosystem services diminish and further increase in the input requirements are needed. Such trends lead to a decline in the income and decreased sustainability in general (Barbier and Hochard 2018; Nkonya et al. 2016). Among different inputs required to sustain the agricultural output amid the environmental degradation, family labour input appeared as a highly affected one (Barbier and Hochard 2019). In addition, environmental degradation may have a wider socioeconomic income through reduced food availability.

The increasing use of fossil fuels and adverse environmental effects of economic activities have contributed to climate change (Aghbashlo et al. 2022; Dembedza et al. 2022). Climate change is likely to negatively affect agricultural productivity (Delincé et al. 2015). The energy systems are also affected by climate change (Pathak 2023). Biological processes are also affected by the climate change, e.g. the increasing spread of pathogens (Galanakis 2023).

The climate change has a double effect on the modelling of the economic activities. On the one hand, such models as the environmental Solow growth model take the environmental effects into consideration. On the other hand, the climate change may increase the volatility of the business environment. This is especially topical for the agri-food sector where changes in the weather may reduce the yields and create turmoil in the global markets. The footprint approach is another important direction to consider the impacts of the food systems on the environment and resources (Kong et al. 2022; Haller 2022).

The international markets for agri-food products are affected by supply chain disruptions that occur due to unforeseen events. For instance, the agri-food markets were affected by reduced supply from Russia and Ukraine in 2022/23 (OECD 2023). The study of Ben and Bilali (2022) identified short- and long-term impacts of the Russian-Ukrainian war on global food security.

The outbreaks of diseases have long been known to affect the agri-food markets. However, disruptions of an unprecedented scale had come into effect due to the COVID-19 outbreak. The impact of the lockdowns related to COVID-19 can be illustrated by the fact that the global demand for electricity fell by more than 20% in 2020 (Alam et al. 2023). As for the agricultural sector, mixed impacts of the COVID-19 pandemic were noticed (Gray 2020; Beckman and Countryman 2021). The supply chains were disturbed causing the increasing shortages and price levels of the agricultural inputs and, sometimes, a decline in the demand for the agricultural products. On the other hand, the increase in the market prices was observed due to supply chain disruptions in the commodity markets (e.g. in the corn sector). Thus, the net effect of the pandemic developments varied across the agricultural sectors.

The agricultural production also should be constrained by reasonable limits to the intensification. The mode of production needs to be adapted so as to minimize the risks of zoonoses that have become a threat of a threatening scale (Baker et al. 2022). Thus, the assessment of agricultural development and productivity relates to multiple issues that relate to both supply and demand side and have external and internal impacts from the viewpoint of agricultural sector.

Methodological preliminaries

The research relies on the theory of production economics. The production economics combine a set of theories and tools that allow describing the underlying production possibilities along with the best practice. The best practice operation is usually defined as the production frontier (or a surface in case multiple inputs/outputs are involved). The principles of the production economics were outlined in such fundamental references as Chambers (1988) or Ferguson (2008). The theoretical foundations need to be implemented empirically to obtain the measures of efficiency and productivity that are of the key interest. The use of the distance functions and measures of efficiency has been described by, e.g. Orea and Zofío (2017).

The non-parametric approach allows modelling the production technology without restrictive assumptions on the behaviour of the error term (that would be present in the regression model). The non-parametric approach can be implemented by means of the data envelopment analysis or deterministic parametric frontiers both of which rely on the linear programming. Thus, the non-parametric approach is easier to implement and allows imposing the desirable economic axioms. The use of the non-parametric production

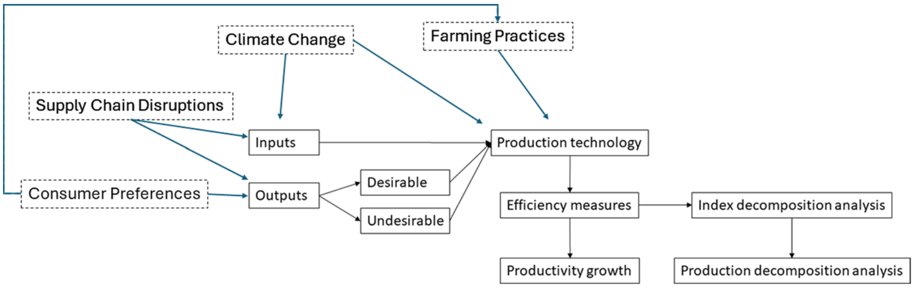

Fig. 1 The key blocks of the research framework on efficiency and productivity growth in agriculture amid the topical concerns

technology and efficiency measures for the analysis of agricultural activities amid the topical concerns identified in the preceding section is presented in Fig. 1.

As shown in Fig. 1, the input and output variables are used to construct the production technology. This technology also contains its boundary, i.e. the efficiency frontier. Thus, the measures of efficiency can be recovered. The measures of efficiency can be measured against the production frontiers based on the different time periods. This allows assessing the productivity growth over time (including efficiency change and technology change). The inclusion of additional techniques can further enhance the analysis. In this thesis, we seek to use the index decomposition analysis along the efficiency measurement that allows for the production-theoretic decomposition analysis.

Environmental production technology can be established to link the inputs, outputs, and undesirable outputs. Let $x_{t,ik}$, $y_{t,jk}$, and $z_{t,lk}$ denote the input, output, and undesirable output quantities for period, t respectively. The number of inputs, outputs, and undesirable outputs is I, J, and K , respectively. The dynamic DEA model proposed by Sengupta (2002) takes the following form in the input-orientation:

$$\begin{aligned}
&\min_{\lambda,\phi} \phi \\
&\text{s.t.} \\
&\sum_{k=1}^{K} \lambda_k \frac{x_{t,ik}}{x_{t-1,ik}} \leq \frac{x_{t,ik'}}{x_{t-1,ik}}, \quad i = 1, 2, ..., I, \\
&\sum_{k=1}^{K} \lambda_k \frac{y_{t,jk}}{y_{t-1,jk}} \geq \frac{y_{t,jk'}}{y_{t-1,jk}}, \quad j = 1, 2, ..., J, \\
&\sum_{k=1}^{K} \lambda_k \frac{z_{t,lk}}{z_{t-1,lk}} \leq \frac{z_{t,lk'}}{z_{t-1,lk}}, \quad l = 1, 2, ..., L, \\
&\lambda_k \geq 0, \quad k = 1, 2, ..., K
\end{aligned} \tag{1}$$

Let the efficient input quantities for periods t and $t-1$ for observation $k\prime$ be denoted as $x^*_{t,ik\prime}$ and $x^*_{t-1,ik\prime}$. The growth efficiency scores rendered by the dynamic DEA indeed correspond to the ratio of the observed TFP growth rate compared to the optimal one (Sahoo et al. 2012):

$$\text{TFPG}_{k'} = \frac{\left(y_{t,jk'}/x_{t,ik'}\right)/\left(y_{t-1,jk'}/x_{t-1,ik'}\right)}{\left(y_{t,jk'}/x^*_{t,ik'}\right)/\left(y_{t-1,jk'}/x^*_{t-1,ik'}\right)} = \frac{x^*_{t,ik'}/x^*_{t-1,ik'}}{x_{t,ik'}/x_{t-1,ik'}} = \phi^*_{k'}, \tag{2}$$

where $\phi^*_{k'}$ is the growth efficiency that solves Eq. 1 for $k\prime$. This illustration applies to a two-dimensional case; yet, it can also be generalized to higher dimensions.

The empirical research deals with the growth efficiency in the EU counties. The data on the EU-27 countries come from the Eurostat database, and the period covered is 2004–2021. The economic activity is measured in terms of the total agricultural output taken from the Economic Accounts for Agriculture. It is measured in PPS of 2015 at the producer prices. The labour input is taken from agricultural labour input statistics and is measured in Annual Work Units (AWUs). The land input is measured as the main area (in hectares) provided by the crop production statistics.

Results

In this section, we focus on the structural changes in the EU agriculture. The country-level data from Eurostat are used for the analysis. The results shed light on the topical issues in the EU agriculture that reward further analysis by means of the production and productivity analysis.

Agricultural output in the EU

The production of agricultural sector increased in the EU countries (excluding the UK and including Croatia) by some 5.1% over 2004–2022 (Table 1). The growth rates varied across the countries. The highest growth rates were observed for the new EU Member States that accessed in 2004. These include the Baltic States, where growth in the agricultural output exceeding 60% was noted. These countries have seen serious transformations in their agricultural sectors due to transition towards the market economy and, subsequently, accession to the EU with incoming investments via the support payments.

The decline in the agricultural output (measured in real terms) was noted for Romania, Bulgaria, Hungary, Slovakia, Malta, Slovenia, France, Croatia, Italy, and Greece. As one can note, these countries include both developed and emerging economies. For the emerging economies, the transition from the planned economy and subsequent agricultural reforms may have had a prolonged impact. For the developed economies, the transition in the energy structure may have taken the place with less attractive agricultural sector being abandoned among changes in the support schemes and urbanization.

The relative importance of the EU Member States in the agricultural production varied during 2004–2022 due to uneven growth in the agricultural output as discussed above. The highest increase in the share of the agricultural output was observed for Poland as its share in the EU agricultural output went from 8% in 2004 up to 10.4% in 2022. The second highest increase in the share of the agricultural output was noted for Spain as it went from 10.8% up to 12.4%. The other countries showed change of less than 1 p.p. with the highest changes observed for Lithuania, the Netherlands, and Ireland. Thus, both the large and small economies enjoyed the increasing importance in the EU agricultural production.

The steepest decline in the share of the agricultural output generated in the EU was noted for Italy (from 14.1% down to 12.6%), Romania (form 8.3% down to 6.9%), and France (form 16.4% down to 15.1%). These results suggest that the importance of the largest agricultural-producing countries tended to decline in the EU. This can be explained by increasing competition for the agricultural inputs, leading to loss in the competitive advantage in these economies. As for the case of Romania, a general decline in the agricultural output played an effect. These results indicate that there have been

Table 1 Agricultural output (in PPS) in the EU Member States, 2004 and 2022

Country	Output, million PPS			Share, %		
	2004	2022	Growth, %	2004	2022	Change, p.p
EU-27	415,423	436,635	5.1	100	100	
Belgium	7015	8227	17.3	1.7	1.9	0.20
Bulgaria	9863	8584	− 13.0	2.4	2.0	− 0.41
Czechia	7081	7967	12.5	1.7	1.8	0.12
Denmark	7208	8825	22.4	1.7	2.0	0.29
Germany	50,895	51,225	0.6	12.3	11.7	− 0.52
Estonia	811	1298	60.1	0.2	0.3	0.10
Ireland	6239	8144	30.5	1.5	1.9	0.36
Greece	14,158	13,998	− 1.1	3.4	3.2	− 0.20
Spain	44,957	54,206	20.6	10.8	12.4	1.59
France	68,113	65,829	− 3.4	16.4	15.1	− 1.32
Croatia	3552	3212	− 9.6	0.9	0.7	− 0.12
Italy	58,547	54,981	− 6.1	14.1	12.6	− 1.50
Cyprus	1237	753	− 39.1	0.3	0.2	− 0.13
Latvia	1180	2115	79.3	0.3	0.5	0.20
Lithuania	2700	4886	81.0	0.7	1.1	0.47
Luxembourg	324	384	18.4	0.1	0.1	0.01
Hungary	13,969	11,406	− 18.3	3.4	2.6	− 0.75
Malta	217	141	− 35.2	0.1	0.0	− 0.02
Netherlands	22,100	25,107	13.6	5.3	5.8	0.43
Austria	6015	6905	14.8	1.4	1.6	0.13
Poland	33,404	45,551	36.4	8.0	10.4	2.39
Portugal	8869	10,212	15.1	2.1	2.3	0.20
Romania	34,678	30,128	− 13.1	8.3	6.9	− 1.45
Slovenia	1635	1503	− 8.1	0.4	0.3	− 0.05
Slovakia	3312	2946	− 11.1	0.8	0.7	− 0.12
Finland	3067	3090	0.8	0.7	0.7	− 0.03
Sweden	4277	5013	17.2	1.0	1.1	0.12

Data source: Eurostat, output of the agricultural 'industry'; data for 2005 are used for Croatia

structural changes in the agricultural production in the EU with both small and large, developed and emerging economies being affected in various directions. Therefore, it is important to ascertain if the discussed changes in the agricultural production have led to an improved welfare. The measurement of the welfare and its change remains an issue to be solved by choosing proper methodologies.

Agricultural inputs in the EU

Up to now, the discussion has focused on the agricultural output. The agricultural production also requires agricultural inputs that include primary inputs and intermediate ones. The primary inputs remain available for the future use after a cycle of agricultural production process (e.g. land, labour force, and capital) and intermediate ones (e.g. seeds, fertilizers, and pesticides). These inputs can be used in varying quantities and proportions. This gives raise to the issue of the resource productivity and, eventually, efficiency in the agricultural sector.

The early attempts to address the issue of the agricultural productivity across countries can be traced back to Hayami and Ruttan (1970) who applied econometric approach to infer on the underlying causes of the productivity disparities at the country-level. The theory of induced innovation played a key role in explaining the demand for institutional innovations through the prism of the resource endowments (Ruttan and Hayami, 1984). A more recent study by Fuglie (2018) yet again revisited the question of the productivity differential in the agricultural sector. Thus, the resource use and productivity need to be discussed to identify the major bottlenecks and possibilities for the EU agriculture.

Primary inputs

Labour is one of the key inputs in the agricultural production technology. To take into account the partial employment in the agricultural sector, the labour input is measured in the Annual Work Units (AWUs) that correspond to 1800 h of working time; yet, a single person cannot represent more than one AWU irrespectively of his workload. The data for agricultural input in the EU are presented in Table 2.

Table 2 Agricultural labour input in the EU, 2004 and 2022

Country	Labour force, 1000 AWU			Share, %			Share of hired labour, %		
	2004	2022	Growth, %	2004	2022	Change, p.p	2004	2022	Change, p.p
EU-27	12,474.6	7752.9	− 37.9	100	100.0		19.9	29.8	10.0
Belgium	71.9	52.3	− 27.3	0.58	0.7	0.1	15.2	24.1	8.9
Bulgaria	712.4	152.7	− 78.6	5.71	2.0	− 3.7	11.6	44.8	33.2
Czechia	144.9	94.8	− 34.6	1.16	1.2	0.1	83.2	70.2	− 13.0
Denmark	66.9	48.6	− 27.3	0.54	0.6	0.1	36.1	63.8	27.7
Germany	592.0	465.0	− 21.5	4.75	6.0	1.3	35.3	46.0	10.7
Estonia	38.3	16.5	− 56.9	0.31	0.2	− 0.1	38.4	64.7	26.3
Ireland	160.0	156.9	− 1.9	1.28	2.0	0.7	8.9	12.1	3.1
Greece	613.4	328.8	− 46.4	4.92	4.2	− 0.7	19.4	18.1	− 1.3
Spain	1032.2	850.3	− 17.6	8.27	11.0	2.7	38.7	51.7	13.0
France	930.0	697.2	− 25.0	7.46	9.0	1.5	30.7	41.3	10.6
Croatia	228.0	172.1	− 24.5	1.83	2.2	0.4	6.1	8.7	2.6
Italy	1299.4	1019.0	− 21.6	10.4	13.1	2.7	24.4	33.5	9.1
Cyprus	30.4	18.9	− 37.8	0.24	0.2	0.0	22.7	42.1	19.4
Latvia	139.5	62.6	− 55.1	1.12	0.8	− 0.3	14.0	34.2	20.2
Lithuania	165.4	120.4	− 27.2	1.33	1.6	0.2	20.9	28.1	7.2
Luxembourg	4.0	3.5	− 10.6	0.03	0.0	0.0	15.7	31.2	15.5
Hungary	553.8	311.7	− 43.7	4.44	4.0	− 0.4	23.0	35.9	12.9
Malta	4.3	5.4	25.6	0.03	0.1	0.0	7.0	5.6	− 1.4
Netherlands	166.9	156.7	− 6.1	1.34	2.0	0.7	41.5	48.0	6.5
Austria	151.4	121.4	− 19.8	1.21	1.6	0.4	9.1	17.5	8.4
Poland	2279.4	1427.7	− 37.4	18.3	18.4	0.1	5.9	9.7	3.9
Portugal	380.8	223.1	− 41.4	3.05	2.9	− 0.2	20.9	38.7	17.8
Romania	2336.0	1015.0	− 56.5	18.7	13.1	− 5.6	11.4	16.7	5.4
Slovenia	90.2	72.9	− 19.1	0.72	0.9	0.2	8.7	6.1	− 2.6
Slovakia	105.4	38.6	− 63.4	0.84	0.5	− 0.3	63.5	76.4	12.9
Finland	101.3	63.9	− 36.9	0.81	0.8	0.0	17.5	27.8	10.4
Sweden	76.8	57.0	− 25.8	0.62	0.7	0.1	29.7	44.3	14.6

Data source: Eurostat; data for 2005 are used for Croatia

On average, the agricultural labour force declines in the EU over 2004–2022. The total EU agricultural labour input declined from 12.5 million AWU in 2004 down to just 7.8 million AWU in 2022. This is obviously related to depopulation of the rural areas in the EU and loss of the attractiveness of the agribusiness. Also, the consolidation of farms has led to a decreasing labour input demand in the EU. Looking at individual countries, the steepest decline exceeding 50% of the labour force in 2004 was observed for Bulgaria, Estonia, Latvia, Romania, and Slovakia. Greece also showed a decline of 46%. The most stable level of the labour input was maintained in Ireland (− 19%) and the Netherlands (− 6.1%). Indeed, these countries have become a popular destination for the agricultural workers from the new EU Member States, especially those that showed the steepest decline in the agricultural labour force.

The spatial distribution of the EU agricultural labour force has obviously been altered during 2004–2022. Greece, Spain, and Italy appeared as the countries with the highest gain in the structure of the EU agricultural labour. Indeed, these countries are also large agricultural producers with substantial labour shares.

The changes in the agricultural labour input are also related to the changing business models in the sector. This can be revealed by looking at the dynamics in the hired labour share within the total agricultural labour force. At the EU-level, the share of the hired agricultural labour force increased from 19.9% up to 29.8% during 2004–2022. This marks a departure from family farming towards corporate farming. This has social, economic, and environmental impacts. Also, such transition is uneven across the EU countries. They also differ in the levels of the hired labour force. The lowest share of the hired labour force is observed for Croatia, Malta, Austria, Slovenia, and Poland. The countries show a single-digit shares of the hired labour force suggesting that small family-run farms prevail there. Slovenia also showed a decline in the share of the hired labour. The highest share of the hired agricultural labour force is noted for Czechia the Netherlands and Slovakia where more than 50% of the labour force is hired. Denmark and Estonia provide a case where a shift form family-run farms to those based on the hired labour has occurred as the share went from less than 40% up to more than 60% during 2004–2033. As regards the changes in the share of the hired labour, the steepest increase was observed for Bulgaria and Latvia, besides the aforementioned cases of Denmark and Estonia. The steepest decline was posted for Czechia where the share of the hired agricultural labour went form 83.2% down to 70.2 during 2004–2022. Thus, the decisions to embark on different farming models requiring family or hired labour emerged across the EU Member States with prevailing direction of the increasing farm size and, thus, share of the hired labour.

The gains in agricultural labour productivity are the key measure to secure the increasing welfare of farmers who comprise significant share of the rural population. The data on the agricultural labour productivity in the EU are provided in Table 3. The increasing human capital quality in the agricultural sector may help to increase the agricultural labour productivity and, eventually, income.

The highest labour productivity is observed in Denmark and the Netherlands (more than 100 thousand PPS per AWU). Belgium, Germany, and Luxembourg have also joined the ranks of such countries within the period of 2004–2022. At the other end of spectrum, the lowest values were noted for such countries as Bulgaria, Latvia, Lithuania,

Table 3 Labour productivity in the EU agriculture (1000 PPS/AWU), 2004 and 2022

Country	2004	2022	Growth, %
EU-27	33.3	56.3	69.1
Belgium	97.6	157.3	61.2
Bulgaria	13.8	56.2	306.1
Czechia	48.9	84.1	72.0
Denmark	107.7	181.4	68.4
Germany	86.0	110.2	28.1
Estonia	21.2	78.7	271.3
Ireland	39.0	51.9	33.1
Greece	23.1	42.6	84.5
Spain	43.6	63.7	46.4
France	73.2	94.4	28.9
Croatia	15.6	18.7	19.8
Italy	45.1	54.0	19.8
Cyprus	40.7	39.8	− 2.2
Latvia	8.5	33.8	299.4
Lithuania	16.3	40.6	148.7
Luxembourg	82.1	108.7	32.4
Hungary	25.2	36.6	45.1
Malta	50.5	26.1	− 48.4
Netherlands	132.5	160.2	20.9
Austria	39.7	56.9	43.2
Poland	14.7	31.9	117.7
Portugal	23.3	45.8	96.5
Romania	14.8	29.7	100.0
Slovenia	18.1	20.6	13.7
Slovakia	31.4	76.3	142.9
Finland	30.3	48.3	59.6
Sweden	55.7	88.0	58.0

Poland, and Slovenia in 2004. These countries improved their agricultural labour productivity during 2004–2022; yet, the lowest gains were observed for Slovenia. Bulgaria can be considered as the country with the highest growth in the agricultural labour productivity over 2004–2022 which can also be attributed to a steep decline in the agricultural labour force. Estonia and Latvia showed high growth in the labour productivity of 271% and 299%, respectively. Thus, a catching up process has been in place in the EU agriculture in the sense of the agricultural labour productivity. At the EU-level, the agricultural labour productivity went up from 33.3 thousand PPS/AWU up to 56.3 thousand PPS/AWU during 2004–022 which corresponds to a 69% increase.

In order to identify the major trends underlying the development of the agricultural labour productivity in the EU, the average value and the coefficient of variation (relative standard deviation) are presented in Fig. 2. Obviously, the average agricultural labour productivity followed a steadily upward trend. The EU Member States also converged in the sense of the agricultural labour productivity if measured by the coefficient of variation. The coefficient of variation tended to increase during the 2004–2007; yet, it showed a clearly negative trend afterwards indicating a convergence in the agricultural labour productivity.

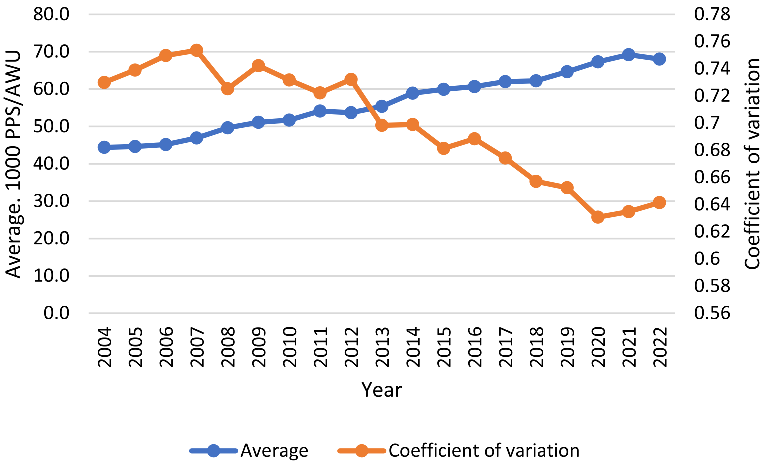

Fig. 2 The average labour productivity and its coefficient of variation in the EU, 2004–2022

The results suggest that the agricultural labour increased in the EU agriculture during 2004–2022. These changes were not even across the countries, indicating that some of them were less successful in adopting the modern farming practices. Also, the share of the hired labour differs considerably across the countries indicating the prevalence of different farming models. The analysis of the performance gaps is needed to address the different levels of the agricultural labour productivity in the EU.

Land is mostly important for the crop farming. However, it also produces feed for animals that are also an important input in the livestock farming. The utilized agricultural area has seen challenges stemming from the urbanization in the EU. The dynamics in the land area in the EU are shown in Table 4.

At the EU-level, the total utilized agricultural land area declined by some 4%. However, some countries, especially, the new EU Member States, showed a steep increase in the utilized agricultural area. The notable examples include Estonia, Croatia, Latvia, and Greece, where the increase exceeded 20% over 2004–2021. These countries are highly dependent on the support payments under the CAP and these payments have stimulated the scale of farming there. As a result of such changes, the structure of the land utilized for agricultural production has also changed in the EU. France, German, Romania, and Italy show the highest decline in the share of the agricultural land. At the other end of spectrum, Poland and Spain exhibit the highest increase in the share of the utilized agricultural land at the EU level.

Land productivity can be analysed in order to measure the returns of the landowners who are farmers in most cases. The partial measure of the land productivity is shown in Table 5. At the EU level, there has been a growth of 14.2% in the land productivity. However, the growth rates for this indicator are highly variant across the EU Member States. The highest growth is observed for Austria, Latvia, Spain, and Poland, where land productivity grew by more than 40% over 2004–2021. Croatia and Greece posted the steepest decline in the land productivity. Note that such countries as Estonia, Latvia, and Lithuania managed to increase their land productivity amid significant increase in the utilized agricultural area. Therefore, the different countries

Table 4 Agricultural land input in the EU, 2004 and 2021

Country	Utilized agricultural area, 1000 ha			Share, %		
	2004	2021	Growth, %	2004	2021	Change, p.p
EU-27	168,733	161,223	− 4	100	100	
Belgium	1394	1368	− 2	0.58	0.7	0.2
Bulgaria	5331	5047	− 5	5.71	2	− 0.3
Czechia	3631	3530	− 3	1.16	1.2	0.1
Denmark	2664	2618	− 2	0.54	0.6	0.2
Germany	17,020	16,592	− 3	4.75	6	− 0.5
Estonia	792	987	25	0.31	0.2	0.1
Ireland	4305	4337	1	1.28	2	0.3
Greece	4022	5137	28	4.92	4.2	− 0.4
Spain	25,972	24,420	− 6	8.27	11	2.3
France	29,633	28,898	− 2	7.46	9	− 2.0
Croatia	1176	1476	26	1.83	2.2	− 0.1
Italy	14,965	12,987	− 13	10.4	13.1	− 1.8
Cyprus	155	123	− 20	0.24	0.2	− 0.1
Latvia	1642	1970	20	1.12	0.8	0.2
Lithuania	2604	2937	13	1.33	1.6	0.4
Luxembourg	128	133	4	0.03	0	0.0
Hungary	5862	5049	− 14	4.44	4	− 0.3
Malta	10	11	5	0.03	0.1	0.0
Netherlands	1926	1812	− 6	1.34	2	0.4
Austria	3368	2602	− 23	1.21	1.6	0.1
Poland	16,301	14,522	− 11	18.3	18.4	1.8
Portugal	3870	3980	3	3.05	2.9	0.3
Romania	14,130	13,079	− 7	18.7	13.1	− 0.5
Slovenia	491	479	− 2	0.72	0.9	− 0.1
Slovakia	1935	1856	− 4	0.84	0.5	− 0.1
Finland	2253	2268	1	0.81	0.8	− 0.1
Sweden	3153	3003	− 5	0.62	0.7	0.0

have taken different trends in the land productivity growth that may be related to changes in the output-mix and integration in the agri-food markets.

The convergence among the EU countries in the sense of the land productivity is further analysed by considering the coefficient of variation and the average value of the relevant indicator (Fig. 3). The average land productivity tended to increase and rebound during 2004–2010 with a slightly upward trend thereafter. The coefficient of variation kept declining with a rather small slope indicating a relatively slow convergence among the EU Member States in the sense of land productivity.

These finding imply that the EU Member States need to optimize the land use in agriculture. The adjustments in the CAP support measures may be important in encouraging or discouraging specific land use types. The differences in the land productivity and its growth imply the need for analysis of the productivity differential.

Intermediate inputs

Intermediate consumption is related to farming intensity. As intermediate consumption becomes more intensive, higher yields can be expected. However, the use of the

Table 5 Land productivity in the EU agriculture (1000 PPS/ha), 2004 and 2021

Country	2004	2021	Growth, %
EU-27	2.5	2.8	14.2
Belgium	5.0	6.2	23.5
Bulgaria	1.9	1.8	− 0.3
Czechia	1.9	2.3	17.3
Denmark	2.7	3.3	23.1
Germany	3.0	3.2	7.5
Estonia	1.0	1.3	22.3
Ireland	1.4	1.9	29.6
Greece	3.5	2.7	− 24.3
Spain	1.7	2.4	40.7
France	2.3	2.3	− 1.7
Croatia	3.0	2.3	− 22.8
Italy	3.9	4.3	9.3
Cyprus	8.0	6.3	− 20.6
Latvia	0.7	1.1	46.9
Lithuania	1.0	1.6	51.1
Luxembourg	2.5	3.0	19.8
Hungary	2.4	2.8	16.4
Malta	21.3	13.2	− 38.1
Netherlands	11.5	14.2	23.8
Austria	1.8	2.7	49.6
Poland	2.0	3.1	49.5
Portugal	2.3	2.7	18.8
Romania	2.5	2.7	11.4
Slovenia	3.3	3.2	− 5.2
Slovakia	1.7	1.8	3.4
Finland	1.4	1.4	0.9
Sweden	1.4	1.6	18.3

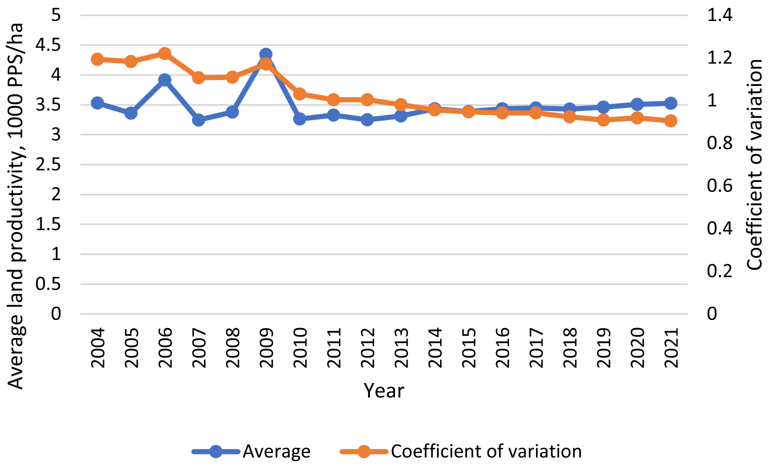

Fig. 3 The average land productivity and its coefficient of variation in the EU, 2004–2021

intermediate inputs depends on the selling prices of the agricultural products, and sometimes, low intensity agriculture is maintained along with low yields (subsistence farming). The relevant statistics for the EU agriculture are presented in Table 6.

At the EU-level, there has been little change in the use of the intermediate inputs (growth of 4.2% over 2004–2022 was observed). However, individual countries how high variation in the intermediate consumption growth. In Estonia, a 99% growth was observed over 2004–2022 indicating that the use of the intermediate inputs has doubled. The decline was observed for certain countries; yet, it is not of the same magnitude as the gains were. The steepest decline is observed for Cyprus (− 65.7%).

The absolute level of the intermediate consumption can be compared to the agricultural output to construct a partial productivity indicator. The results in Table 6 suggest that intermediate consumption productivity was also stagnant in the EU as it increased by a margin of 0.9% during 2004–2022. This suggests that the use of the intermediate inputs rewards more attention in the EU. Notably, Finland, Lithuania, Cyprus, and

Table 6 Intermediate input use and productivity in the EU, 2004 and 2022

Country	Intermediate inputs, million PPS			Intermediate input productivity, factor		
	2004	2022	Growth, %	2004	2022	Growth, %
EU-27	248,645	258,994	4.2	1.67	1.69	0.9
Belgium	7219	5325	− 26.2	0.97	1.54	59.0
Bulgaria	6010	5082	− 15.5	1.64	1.69	2.9
Czechia	5325	5587	4.9	1.33	1.43	7.2
Denmark	5585	5730	2.6	1.29	1.54	19.3
Germany	31,958	32,064	0.3	1.59	1.60	0.3
Estonia	552	1100	99.3	1.47	1.18	− 19.7
Ireland	4124	5272	27.8	1.51	1.54	2.1
Greece	7019	6566	− 6.4	2.02	2.13	5.7
Spain	22,047	26,968	22.3	2.04	2.01	− 1.4
France	42,007	40,408	− 3.8	1.62	1.63	0.5
Croatia	2229	1868	− 16.2	1.59	1.72	7.9
Italy	25,430	25,048	− 1.5	2.30	2.20	− 4.7
Cyprus	1333	457	− 65.7	0.93	1.65	77.7
Latvia	967	1636	69.3	1.22	1.29	5.9
Lithuania	2523	3273	29.7	1.07	1.49	39.5
Luxembourg	225	281	24.8	1.44	1.37	− 5.2
Hungary	9686	8671	− 10.5	1.44	1.32	− 8.8
Malta	110	84	− 23.8	1.97	1.67	− 15.0
Netherlands	14,120	15,608	10.5	1.57	1.61	2.8
Austria	3869	4215	8.9	1.55	1.64	5.4
Poland	23,005	29,458	28.0	1.45	1.55	6.5
Portugal	5047	6709	32.9	1.76	1.52	− 13.4
Romania	17,797	18,129	1.9	1.95	1.66	− 14.7
Slovenia	986	935	− 5.2	1.66	1.61	− 3.0
Slovakia	3051	2522	− 17.4	1.09	1.17	7.6
Finland	3094	2257	− 27.1	0.99	1.37	38.1
Sweden	3325	3742	12.6	1.29	1.34	4.2

Data source: Eurostat; data for 2005 are used for Croatia

Belgium posted steep increase in the intermediate consumption productivity of over 30%. Estonia, Malta, Portugal, and Romania showed decline of more than 10% in the intermediate input productivity.

The EU-level trends in the average intermediate consumption productivity and the associated coefficient of variation are presented in Fig. 4. The average intermediate consumption productivity followed a slightly upward trend during the period of 2004–2022. Indeed, the decline was noted for the endpoints of the period covered. The coefficient of variation slightly decreased during the period covered.

The results suggest that the intermediate consumption productivity requires attention in the EU agriculture as its mean value and coefficient of variation show little change over 2004–2022. Thus, the average level and convergence among the countries did not show desirable trends. As the intermediate inputs are crucial for the agricultural production and sustainable intensification in particular, there is a need to identify the potential for development and address the performance gaps in this area.

Environmental pressures

The European Green Deal has envisaged a decrease in the environmental pressures created by the farming activities. The agricultural sector has not been included in the EU Emission Trading Scheme yet, but concerns over the climate change require adoption of the regulatory mechanisms. Therefore, it is important to analyse the patterns of the GHG emission across the EU Member States in the agricultural sector. The results are summarized in Table 7.

The GHG emission in agriculture went down by 4.4% in the EU during 2004–2022. Most of the countries followed a downward trend in the GHG emission; yet, the exceptions include Bulgaria, Estonia, Ireland, Latvia, Lithuania, Luxembourg, Hungary, Poland, the Netherlands, and Slovenia. Note that most of these countries are the new EU Member States acceded in 2004. The steepest decline in the GHG emission is noted for such large emitters as France (− 10.8%) and Italy (− 8.7%) besides a number of smaller emitters with higher degree of decline and large emitters with shallow decline.

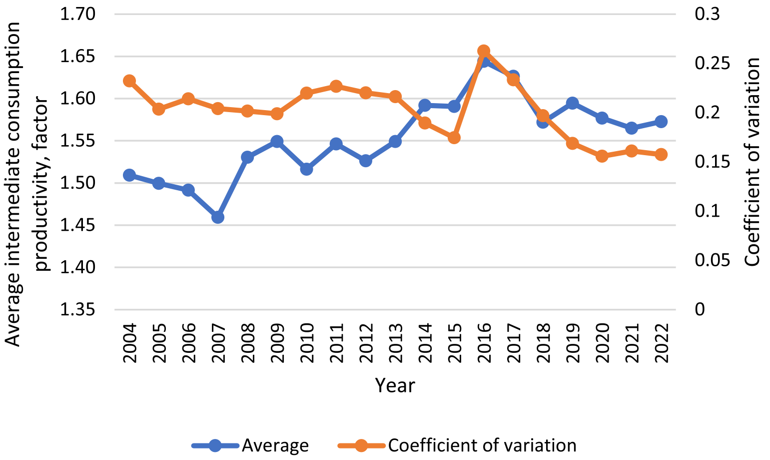

Fig. 4 The average intermediate consumption productivity and its coefficient of variation in the EU, 2004–2022

Table 7 GHG emission related to agricultural sector in the EU, 2004 and 2021

Country	GHG emission, million t			GHG emission productivity, PPS/t		
	2004	**2021**	**Growth, %**	**2004**	**2021**	**Growth, %**
EU-27	477.5	456.3	− 4.4	870	993	14.2
Belgium	12.6	12.3	− 2.6	557	693	24.5
Bulgaria	6.1	6.6	7.7	1609	1409	− 12.4
Czechia	9.2	9.1	− 1.3	770	890	15.5
Denmark	14.9	13.5	− 9.4	485	647	33.5
Germany	65.5	62.7	− 4.4	777	851	9.6
Estonia	1.4	1.8	24.8	563	687	22.0
Ireland	21.7	23.6	8.9	288	345	19.9
Greece	12.4	8.7	− 30.4	1139	1582	38.9
Spain	49.6	46.8	− 5.7	906	1271	40.2
France	87.0	77.6	− 10.8	783	841	7.4
Croatia	4.1	3.5	− 15.7	868	997	14.9
Italy	44.3	40.5	− 8.7	1321	1371	3.8
Cyprus	0.8	0.7	− 5.3	1647	1102	− 33.1
Latvia	2.1	2.8	29.3	550	749	36.3
Lithuania	4.3	4.6	5.9	624	1004	61.0
Luxembourg	0.7	0.7	9.1	491	559	13.9
Hungary	7.7	8.8	14.0	1816	1597	− 12.1
Malta	0.1	0.1	− 5.0	1866	1279	− 31.5
Netherlands	27.7	28.6	3.4	799	900	12.7
Austria	8.4	8.2	− 2.7	715	849	18.7
Poland	44.9	45.5	1.2	743	978	31.6
Portugal	8.7	8.6	− 0.5	1023	1257	22.8
Romania	21.2	20.9	− 1.4	1638	1714	4.6
Slovenia	2.0	2.0	0.6	804	740	− 7.9
Slovakia	3.1	2.8	− 10.6	1054	1170	11.0
Finland	8.0	7.7	− 3.5	384	404	5.3
Sweden	8.8	7.8	− 11.4	485	616	27.2

Data source: Eurostat; energy combustion, agriculture

Smith et al. (2014) provided a survey on the means for mitigating the agricultural GHG emission.

The ratio of the agricultural output to the GHG emission in agriculture gives the GHG emission productivity indicator. The differences in the latter indicator are substantial across the EU Member States. While some countries showed the GHG productivity of just 300–400 PPS/t, some other posted values of 1700–1800 PPS/t. Thus, the countries should embark on the spill-over of the best practices to reduce the contribution to the climate change due to the agricultural activities. The highest increase in the GHG emission productivity was observed for Denmark, Greece, Spain, Lithuania, and Poland (more than 30%).

The average value of the GHG emission productivity tended to increase in the EU (Fig. 5). However, the period of 2004–2012 marked fluctuations towards different directions, whereas the later period saw an almost flat trend with slightly positive slope. Therefore, the increase in the GHG emission productivity has ceased and requires further attention.

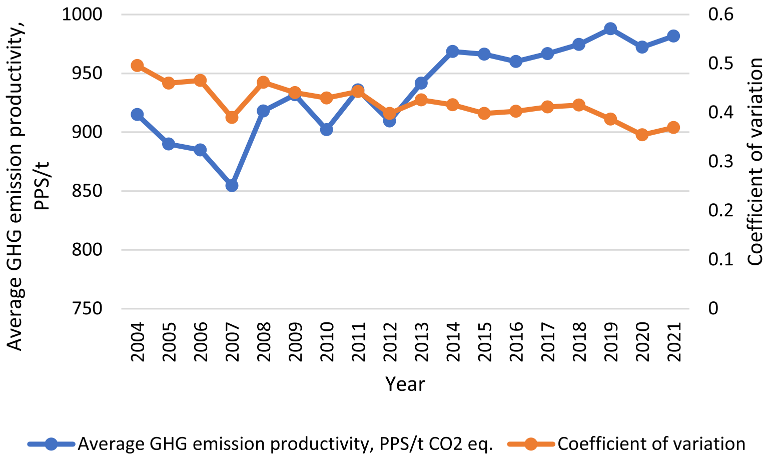

Fig. 5 The average GHG emission productivity and its coefficient of variation in the EU, 2004–2021

The coefficient of variation tended to decline steadily even though the slope was not that steep. This suggests that the EU countries tended to converge in the sense of the GHG emission productivity even though this process was not very fast. Thus, the mitigation of the GHG emission in the EU agriculture is a topical issue for performance analysis.

The discrepancies among the EU Member States in the GHG emission productivity require further attention from the microeconomic viewpoint. Specifically, this indicates that the pricing of such an undesirable output as the GHG emission is not effective in ensuring equal emission intensity across the countries. In this regard, further studies are needed to assess the possible reallocation of the agricultural production and the related GHG emission.

TFP measures

The dynamic DEA proceeds by using the ratios of the data from the current period over those from the previous period. The resulting ratios are then used as the inputs and outputs in the same manner as is the case in the conventional DEA. We assume convex production technology and free disposability. The constant and variable returns to scale are also assumed. The inputs included in the model are labour force, gross fixed capital consumption, land area, intermediate consumption as inputs, and the total agricultural output as an output. The GHG emission is also included in the input set assuming free disposability (Hailu and Veeman 2001). The construction of the underlying variables was discussed above. Thus, the growth efficiency (or the ratio of the observed to the optimal TFP growth) is obtained for the conventional production technology and the environmental production technology.

To check the trends in the TFP growth that may appear due to the previously discussed dynamics in the factor endowments and productivity, we apply the dynamic DEA in Eq. 1. The growth efficiency for a certain year covers the total factor productivity growth over the 2 subsequent years. Thus, data for 2004–2021 are used to construct the growth efficiency scores for 2005–2021.

The weighted mean growth efficiency scores were calculated by using the agricultural output as the weighing factor. The resulting means and coefficients of variation (CVs) are depicted in Fig. 6. As one can note, the growth efficiency remained rather stable over 2004–2021. For 2004–2005 and 2020–2021, the growth efficiency scores of 0.93 and 0.94, respectively, were noted. This implies that the TFP growth rate was lower than the optimal one due to the growth inefficiency. The steepest decline in the growth efficiency was noted in 2007–2008 and 2017–2018. These periods also marked an increasing variability of the growth efficiency across the analysed countries.

The country-level results are provided in Table 8. As one can note, the differences among the country means are rather meagre with the lowest value for France (0.91) and the highest one for Cyprus (0.95). This indicates that the potential increase in TFP growth in case growth efficiency is eradicated. Slightly negative trends are observed for most of the countries. Therefore, the growth inefficiency remains an issue among the EU member states, leading to subdued TFPP growth in agricultural sector.

All in all, the analysis of growth efficiency implies that the TFP growth could be improved by 5–9% depending on the country. This would allow to increase the welfare of the stakeholders associated with the EU agriculture. Further studies are needed to identify the sources and factors of the TFP growth in EU agriculture along with possible changes in the production plans, leading to improved (environmental) productivity. Production analysis based on the frontier approach provides multiple options to embark on such studies.

One can identify certain similarities in the ranking of countries according to TFP efficiency for 2019 as reported by Wimmer and Dakpo (2023) and a comparable measure of growth efficiency in this study as Belgium, Denmark, Estonia, and Sweden are ranked above average in both instances. Note that the measure of TFP efficiency is a transitive one, whereas the growth efficiency is not. Also, the time periods and underlying technologies differ across the two studies.

Agenda for further research

The results presented in the preceding section suggest that the EU countries are still in the process of convergence in the sense of the agricultural (total factor) productivity and its growth. The inclusion of the environmental indicators (e.g. GHG emission) suggests

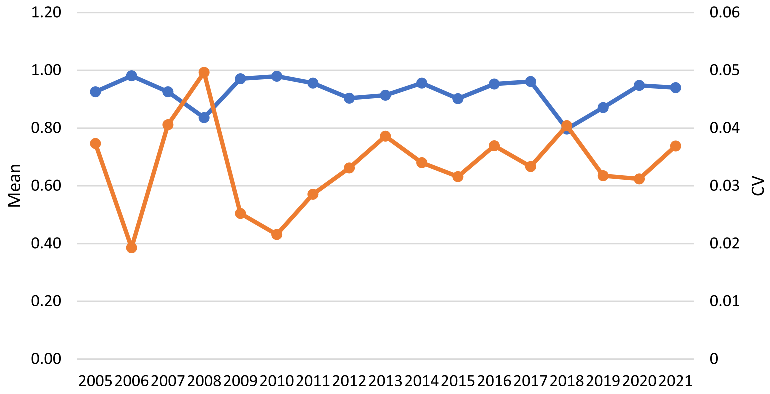

Fig. 6 Average growth efficiency and its coefficient of variation for the EU countries, 2004–2021

Table 8 Average growth efficiency and its trends across the EU countries, 2004–2021

Country	Mean	Trend
France	0.91	− 0.0023
Malta	0.92	− 0.0013
Italy	0.92	− 0.0040
Slovenia	0.92	− 0.0022
Netherlands	0.92	− 0.0026
Portugal	0.92	− 0.0007
Greece	0.92	− 0.0032
Hungary	0.92	− 0.0012
Germany	0.92	0.0001
Austria	0.92	− 0.0029
Sweden	0.93	− 0.0025
Luxembourg	0.93	0.0002
Czechia	0.93	− 0.0020
Ireland	0.93	− 0.0005
Estonia	0.93	− 0.0043
Croatia	0.93	− 0.0015
Finland	0.93	− 0.0018
Denmark	0.93	− 0.0011
Romania	0.93	0.0007
Lithuania	0.93	− 0.0030
Spain	0.93	− 0.0022
Belgium	0.94	− 0.0009
Bulgaria	0.94	− 0.0025
Latvia	0.94	− 0.0051
Poland	0.94	− 0.0039
Slovakia	0.95	− 0.0010
Cyprus	0.95	− 0.0029

that additional facets of the performance may also be revealed due to the differences among the countries. Thus, we outline the future research agenda for the frontier-based benchmarking in the context of the EU agriculture to identify the major challenges for the agricultural policies of the EU form the perspective of the resource utilization and production economics. The environmental pressures are taken into account in lines with the Sustainable Development Goals. The resulting non-parametric framework allows to model the production technology and derive the measures of efficiency and productivity gains.

Congestion in agricultural production

The congestion in the production has been described by Cooper et al. (2007). In the production context, congestion refers to the technology property of free disposability, i.e. the excessive use of resources or suboptimal production levels may be possible due to the aforementioned assumption. Nevertheless, such situations indicate that the production technology should be redefined taking into account the weak disposability axiom. Therefore, the production possibility set should be assessed based on different economic axioms. Recently, Ren et al. (2021) presented a survey on the measures and applications of the congestion in the production context.

The congestion can also occur in the environmental production technologies where undesirable outputs are generated. The study by Wu et al. (2013) introduced the undesirable outputs in the congestion analysis framework. Sueyoshi and Goto (2016) presented the model for congestion analysis with managerial disposability. Then, Zhou et al. (2017) used the congestion analysis to assess the energy-mix in the APEC countries.

In the case of the EU agriculture, the congestion analysis may be applied to the case of agricultural production. The inclusion of the energy and greenhouse gas emissions as the variables in the production technology allows assessing the congestion of these environmentally sensitive variables. The results would indicate the possible directions for agricultural policies to tackle the potentially existing congestion.

Production-theoretic decomposition of the GHG emission in agriculture

The change in the greenhouse gas emissions is important given the commitments taken by the governments worldwide. Even though the agricultural sector has not been included in the emission reduction targets, yet, the European Green Deal has pointed to the need for sustainability gains in the agricultural sector. The decomposition of the change in the greenhouse gas emission allows identifying the major factors contributing to its dynamics.

The index decomposition analysis has appeared as a prevailing tool for decomposing the changes in emission or other variables of interest (Xu and Ang 2013). The efficiency analysis provides another factor of the emission dynamics, viz. efficiency and technological change. The two approaches have been unified under the umbrella of the production decomposition analysis (or production-theoretic decomposition analysis), PDA. Lin and Du (2014) used the PDA to decompose the energy intensity change. Wang and Zhou (2018) applied the PDA to assess the energy intensity changes across different countries. Wang et al. (2019) used the PDA to describe the carbon emission in Chinese power generation sector.

The production decomposition analysis can be used to decompose the energy-relevant greenhouse emission in the EU agricultural sector. The novel model can be constructed by assuming different technologies (e.g. nonconvexity). This allows to identify the potential policy improvements, leading to reduction in the greenhouse gas emission from the agricultural sector.

Energy intensity in agriculture

The use of energy is important for agricultural production. Especially, certain farming types require high energy inputs to maintain the technological properties (e.g. horticulture and greenhouse farming). Also, subsidies and exemptions are applied for energy inputs. This makes it more relevant to analyse the use of energy. However, looking at the energy use indicators from the single indicator or two indicator perspective may be misleading. Thus, it is important to take the production technology (multiple inputs and outputs) into consideration when calculating energy intensity.

The study by Zaim (2004) called for inclusion of the Data Envelopment Analysis in the assessment of pollution intensity. Then, Zaim et al. (2017) used the non-parametric modelling to construct the energy intensity measure based on the production technology. Then, Zaim and Gazel (2018) applied the novel energy intensity measure for the case of Japan.

As regards the EU agriculture, the modified energy intensity measure can be applied to meaningfully measure the changes in energy intensity across different regions. This is beneficial for shaping the support measures aimed at the energy conservation and efficiency.

Productivity growth and capacity utilization in agriculture

Capacity utilization is an important economic characteristic showing the extent to which fixed factor inputs are utilized. In the absence of the proper amounts of the variable inputs, the fixed inputs may be underused. This results in a decreased production level. The recent crises related to pandemic and military conflicts have stressed the need for ensuring proper levels of production by boosting the capacity utilization (especially, in agricultural sector).

The capacity utilization can be measured in the production technology setting as described by Fare et al. (1989) and Kerstens et al. (2008). The efficiency decomposition (De Borger et al. 2012), different orientations of the model (Cesaroni et al. 2017), and convexity assumptions (Kerstens et al. 2019) have been used to extend the models for the measurement of the capacity utilization. The productivity growth can also take into account the changes in the capacity utilization (De Borger and Kerstens 2000; Kerstens et al. 2022).

In the context of the EU agriculture, the productivity change may be decomposed with respect to capacity utilization (among traditional components of efficiency change and technical change). This will provide insights into how different regions adapt their resources and production volumes to a given technology. The results will be relevant in suggesting the improvements of the agricultural policy in regard to production capacity allocation.

Concluding remarks

The agricultural production has seen multiple shifts recently due to the dynamics in the relative input prices and other internal or external shocks. The induced innovations already discussed in the agricultural economics literature can explain an increasing introduction of machinery and agrochemicals. Currently, the increasing urbanization further pushes the labour and land supply down in the rural areas and requires corresponding business model adjustments. To address these challenges, such solutions as the automatization/robotization, precision farming, and vertical farming have been proposed. These new solutions allow mitigating the labour, land, and agrochemical inputs along with growth in the agricultural output. Such dynamics are possible in the midst of the total factor productivity growth.

The increasing use of the agrochemicals and increasing intensity of the agricultural production have brought about certain concerns over the safety and quality of the agricultural production. The modern information and communication technologies allow for a rapid data exchange that can contribute to creating novel approaches of marketing of agri-food products. Also, consumer experiences and preferences are modelled by modern quantitative approaches to adapt to their taste. Thus, the agricultural product markets need to become competitive monopolistic markets where each product has specific traits making it unique in otherwise saturated market. Of course, such issues are less relevant for the developing countries where food security is still a major concern.

The sustainability goals have been addressed in the recent extensions of the neoclassical economic models. These adjustments represent the global pursuit for climate change mitigation that is supported by considerable public funds. The exogenous Solow growth model can be presented as a typical case where the considerations over the resource scarcity were taken into account though introduction of additional variables and assumptions into the economic production technology. The recent concern over the climate change further modifies these models by switching to emission variables as inputs or undesirable outputs in the economic growth models.

The impacts of pandemics and military conflicts leading to supply chain disruptions once again stressed the fragility of the agri-food supply chains. The need for involving the relevant factors in the models for agricultural sector and resource use has become more obvious. The effects of such disruptions, however, are diverse across the sub-sectors of agriculture. Therefore, the adjustments in the assumptions on the functioning of the agricultural markets are not straightforward.

Further research needs to address the growing concerns over the climate change from two perspectives: First, the environmental impact of the production processes needs to be included in the quantitative models to properly understand the possibilities for optimization. Second, the effects of the climate change need to be modelled. For instance, the increasing risk may be realized due to the climate change which can also be an input in the production model.

The empirical research indicates that the TFP growth gap persisted in the EU member states. This implies that the agricultural TFP growth may increase by 1–9% depending on a country under analysis. The results are rather stable during 2004–2021, indicating that further attention is needed to this issue. The results suggest several directions for research in agricultural production in the EU. The major methodological direction to be followed is the production economics and non-parametric modelling of the production technology. The proposed research agenda involves energy use and the related greenhouse gas emission that are in accordance with the sustainability goals topical for the reforms of the agricultural policy. The efficiency and productivity change measures can be used for the construction of additional indicators representing production and environmental impacts. The empirical findings of the research based on the frontier techniques would be important for offering guidelines for agricultural policy improvements. The comparison of such regions as EU and the US or China may bring novel insights into the theory and practice of agricultural production analysis and agricultural policy.

The research is limited in that we considered aggregate data and non-parametric setting. The TFP gap identified in this study may be supplemented by the TFP growth measures obtained by different means. The use of parametric methods may allow to incorporate additional variables (e.g. contextual variables related to discussed challenges and trends in agriculture). The use of the micro-data would allow to identify more nuanced patterns of efficiency and productivity growth that may differ across regions and farming types.

Acknowledgements
Not applicable.

Author contributions
BP and TB conceptualized the original research idea, designed the methodology, collected the data, and wrote the original draft of the manuscript. RM conducted the investigation, performed the formal analysis, supervised the entire research activity planning and execution and wrote the original draft. GPA dealt with the visualization of the manuscript and wrote the original draft. All authors read and approved the final manuscript.

Funding
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Availability of data and materials
The datasets used and/or analysed for the current study are available on reasonable request to the corresponding author.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 7 November 2023 Revised: 1 July 2024 Accepted: 19 July 2024

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