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Long-term trends in economic and environmental efficiency of EU agriculture: A DEA-Malmquist approach

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Abstract: Enhancing economic and environmental efficiency is a fundamental objective shared by all European economic sectors, with agriculture being a particular area of focus. In this study, economic and environmental efficiency are considered in parallel and compared in terms of their long-term development. From an economic perspective, the classical production factors of labour, capital and land are compared with economic production output. The environmental perspective of the study focuses on greenhouse gases and acidifying gases, with the investigation based on data from Eurostat from 2009 to 2020. Due to constraints regarding the availability of data , the study encompassed 22 EU countries. The findings indicate that Greece, Spain, the Netherlands and Poland demonstrate high levels of economic efficiency, while Ireland and Finland exhibit notable enhancements in this regard. Low economic efficiency scores are evident in Latvia and Austria, where substantial catching-up processes are observable. With respect to ecological efficiency, Greece, Spain and Italy have been found to be dominant, as have Finland, Sweden and Slovakia. Ireland, Luxembourg and Poland have lower ecological efficiency scores, but only Ireland shows signs of convergence. The present study seeks to minimise the impact of volatility and dispersion with a view to providing valid long-term trends for the purpose of benchmarking efforts and r policy decisions.

Keywords: air emissions; capital; labour; land; Malmquist index; sustainability

Efficiency is widely regarded as one of the most fundamental concepts in economics and can be described as the search for the best relationship between the resources used and the results achieved. In the contemporary era of increasing globalisation and limited resources, the analysis of efficiency at various levels, ranging from individual companies to entire economies or their sectors, is becoming increasingly significant. In addition to economic efficiency, i.e. the optimal utilisation of financial, material or human resources, environmental efficiency is also gaining relevance. The objective is twofold: firstly, to integrate economic prosperity with the conservation of natural resources and, secondly, to minimise adverse environmental impacts. These aspects of efficiency can be analysed as partial-factor productivity or multifactor productivity (total productivity). The present study employs both of these approaches. These issues have long been the focus of extensive research in the agricultural sector, with detailed comparisons being made between European countries and others.

The economic perspective of efficiency clearly demonstrates that economic success is contingent on the resources involved. The aforementioned resources are

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frequently represented by the classical factors of production, namely labour, capital and land. The efficient use of labour, frequently referred to as labour productivity, and its differences or convergence between nations have been analysed by several scholars. For instance, Sharma et al. (1990), Gutierrez (2002), Cuerva (2012), Takács (2014), Martín-Retortillo and Pinilla (2015), and Giannakis and Bruggeman (2018) have provided valuable insights into this subject. The relationship between economic success and invested capital relates to the issue of profitability, which has been analysed for the European agricultural sector, for example by Petrick and Kloss (2012), Takács (2014), Beyer and Hinke (2020), Kryszak et al. (2021), and Martinho (2022). As demonstrated in the works of Sharma et al. (1990), Cherlet et al. (2013), and Smędzik-Ambroży and Majchrzak (2017), aspects of efficiency related to land use, also discussed as land productivity, have been the subject of scholarly investigation.

Other studies, including those by Čechura et al. (2014), Baráth and Fertő (2017), and Kijek et al. (2019), have examined the multifactorial interaction of such production factors in European agriculture. This concept is referred to as total factor productivity (TFP), a term which can be applied in different forms (Kryszak et al. 2023). In this context, one approach to measuring efficiency and its changes in the case of multiple inputs or outputs is Data Envelopment Analysis (DEA) and the related concept of the Malmquist index (MI), which will be presented in more detail later. These two tools are extensively utilised in the domain of agricultural efficiency research (Coelli and Rao 2005; Suzigan et al. 2020; Kryszak et al. 2023) and will be employed in this study as well.

In addition to conventional economic perspectives, the concept of ecological efficiency, alternatively termed eco-efficiency or environmental efficiency, has become increasingly important in recent years. This concept establishes a correlation between economic prosperity and the environmental impacts caused (Ehrenfeld 2005). The impacts of these phenomena are multifaceted and have been the focus of research in various fields, including the European agricultural context. For instance, DEA models have been utilised in studies including those by Bartová et al. (2018), Rybaczewska-Błażejowska and Gierulski (2018), Czyżewski et al. (2021), and Pishgar-Komleh et al. (2021).

DEA is well suited to comparing efficiency across countries using multiple inputs and outputs without requiring a specific production function. MI complements this by enabling the measurement of changes in efficiency over time. A combination of these two methods provides a robust framework for assessing both the level and dynamics of agricultural efficiency.

In accordance with the title and the preceding literature review, the present study focuses on the agricultural sector of several EU countries and analyses both economic and environmental efficiency aspects. The utilisation of a singular data source, namely the European Statistical Office (Eurostat), guarantees a considerable degree of reliability and comparability amongst the countries examined. The measurement of average levels of economic and environmental efficiency is conducted for each country across two equally spaced sub-periods of six years. The analysis employs MI to decompose changes in efficiency between these sub-periods for each country into two components: the effects of technological progress (frontier shift) and individual improvements relative to best practice (catch-up). The results obtained from this study provide valuable information for the purpose of benchmarking and offer a foundation for further research. The present study makes a significant contribution to previous research in several ways. Primarily, it combines critical economic and environmental aspects, thereby encapsulating recent developments for a broad spectrum of 22 EU countries. The present study serves to update previous findings and offers new insights that partly diverge from earlier results. By distinguishing between economic and environmental efficiency, it is possible to compare the extent of their changes for each country.

MATERIAL AND METHODS

Analytical framework. The present study analyses long-term developments in the economic and environmental efficiency of agriculture across 22 EU countries. A two-step approach is employed, integrating DEA and MI to capture both static efficiency and dynamic changes in productivity over time.

DEA facilitates the comparison of relative efficiency among decision-making units (DMUs) based on multiple inputs and outputs. The methodology employed is a non-parametric linear programming method first introduced by Farrell (1957) and subsequently formalised by Charnes et al. (1978), the purpose of which is to measure relative technical efficiency. In this study, an output-oriented DEA model is employed operating under the assumption of constant returns to scale (CRS). This assumption is deemed suitable for national-level comparisons, where it is presumed that scale inefficiencies are negligible (Coelli and Rao 2005). The technical efficiency (TE) scores range from

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0 to 1, with scores of 1 indicating full efficiency relative to the best-practice frontier.

The MI extends this framework by assessing changes over time (Malmquist 1953; Caves et al. 1982; Färe et al. 1992, 1994). This approach utilises distance functions to compare the performance of dynamic multi-period units (DMUs) across two distinct time periods. The MI is computed as the geometric mean of two productivity indices, thereby decomposing the change in efficiency into two components: Firstly, a catch-up effect (change in technical efficiency) measures changes relative to the frontier. Secondly, the frontier shift effect demonstrates technological progress in the optimal practice. The presence of values of MI, in addition to those of the catch-up and frontier shift effects, that exceed 1, is indicative of enhancements. The complete methodology is outlined in Supplementary 1, which includes the mathematical details.

Modelling and data source. The present study evaluates agricultural efficiency and its long-term changes from both economic and environmental perspectives. In order to maintain clarity and methodological transparency, these two perspectives are modelled separately, with each model using its own set of inputs but the same measure of output (Gross Value Added). While the majority of preceding studies have concentrated on either economic or environmental efficiency, this study combines both perspectives within a unified framework. By modelling them separately yet in a comparable manner, it is possible to make specific assessments of each dimension, as well as to make a direct comparison between them.

The economic model establishes a correlation between the output of the agricultural sector and the input factors of classical production theory (Chambers 1988): labour, capital and land. This approach is widely accepted in the analysis of agricultural efficiency (Coelli et al. 2005; Čechura et al. 2014; Kijek et al. 2019). Output is regarded as the economic success achieved, and is measured by Gross Value Added (GVA) (Eurostat 2024a). In order to avoid the occurrence of distortions due to divergent prices, chain-linked volumes are employed in order to establish prices for the year 2015. Labour input is measured in hours worked (Eurostat 2024b), thus minimising distortions from national differences in contractual working time. The invested capital is represented by the amount of fixed assets (Eurostat 2024c), also measured in chain-linked volumes referring to prices of 2015 to exclude inflation. The measurement of land is derived from the utilised agricultural area (UAA), which is expressed in hectares and aggregated across all farm sizes within each country (Eurostat 2024d).

The environmental model utilises emissions of greenhouse gases and acidifying gases as input proxies for ecological resource consumption, as outlined by Eurostat (2024e), drawing upon the methodologies established by Halkos and Petrou (2019). Greenhouse gases (GHG), including CO_2, N_2O, CH_4, HFC, PFC, SF_6, and NF_3, are expressed in CO_2 equivalents in order to quantify the global warming potential. This approach enables the aggregation of various agricultural aspects, including but not limited to energy consumption and methane emissions from animals, thereby providing a comprehensive assessment. The expression of acidifying gases, such as SOX, NOX and NH_3, is made in SO_2 equivalents. This is done in order to capture various acidifying effects that have been observed, for example, as a result of fertilisers or manure. The two environmental inputs under considerations are designed to capture key ecological impacts arising from both livestock and crop production with reference to climate change and acidification. These two environmental challenges are considered to be of particular significance in the context of modern agriculture (Gołasa et al. 2021; Zamanian et al. 2024). Other ecological aspects, such as energy use, fertilisers and pesticides, were excluded to avoid redundancy and potential double counting. GVA is employed as the output in order to ensure comparability with the economic model. This selection is consistent with the literature and balances theoretical relevance and cross-country data comparability (Czyżewski et al. 2021; Pishgar-Komleh et al. 2021). The reliability of the findings is ensured by sourcing all variables from the Eurostat database for the agriculture, forestry and fishing sector (Sector A) according to the NACE classification (Eurostat 2008).

The present study focuses on 22 EU countries with complete datasets. Bulgaria, Croatia, Cyprus and Portugal do not report several parts of the data described above to Eurostat and thus had to be excluded from this study. Additionally, Malta's agricultural sector is characterised by its small size and notable deviations from standard parameters. Given that DEA is based on comparable units, Malta was excluded to avoid biased benchmarks, as similarly done by Czyżewski et al. (2021). The profound impact of Malta's outlier positioning on comparative analyses is evident in the works of Bartová et al. (2018), Pishgar-Komleh et al. (2021), and Rybaczewska-Błażejowska and Gierulski (2018), who did not exclude this country. Given that the remaining 22 EU countries in this study collectively account for more than 96%

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of the EU's total GVA, it can be assumed that the results reflect a representative sample.

The analysis is constrained by the availability of data, which limits its scope to the period between 2009 and 2020. In order to reduce the volatility of the data and highlight structural changes, this period is divided into two sub-periods: 2009–2014 and 2015–2020. The averaging of values across each six-year interval serves to minimise the influence of outliers and short-term fluctuations. In order to perform a more robust evaluation of temporal change, these sub-periods are compared as they align with two distinct phases of the EUs Common Agricultural Policy (CAP). The initial sub-period encompasses the concluding years of the 2007–2013 CAP programming period, during which traditional income support and rural development priorities were reflected. Conversely, the second sub-period commenced following the 2013 CAP reform, which was implemented from 2015 onwards. This reform introduced significant changes, including the introduction of the greening payments, heightened environmental conditionality, and an augmented emphasis on climate-smart agriculture and sustainability objectives (Anania and d'Andrea 2015; Sotte and Arcuri 2025). These institutional shifts may influence both economic and environmental performance in agriculture, thereby providing a rationale for conducting a comparative analysis. The aforementioned changes are captured using DEA efficiency scores and Malmquist indices, applying the procedures described in Electronic Supplementary Material 1 (ESM) for each country and sub-period, not annually. The calculations were performed using the DEAP software (v. 2.1).

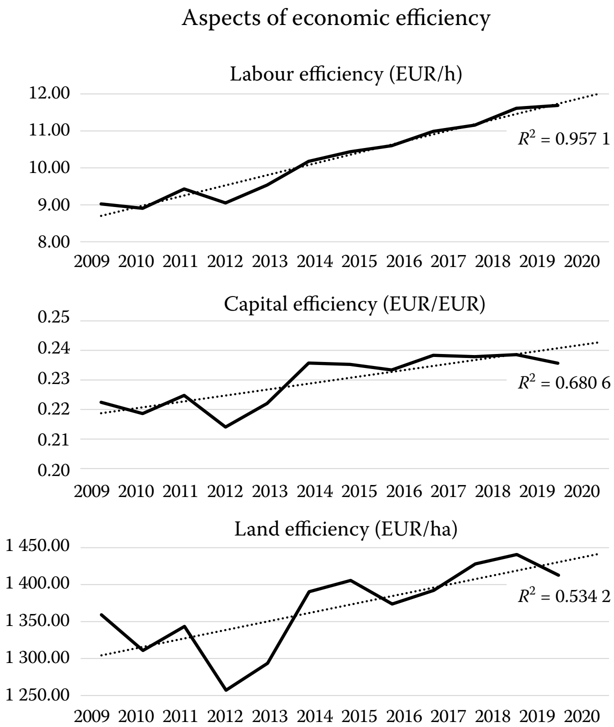
RESULTS AND DISCUSSION

Increasing partial efficiency is defined as the achievement of higher results, measured in terms of GVA, per unit of economic and environmental resources utilised. An examination of the aggregate sample, encompassing the data of all 22 countries, substantiates this assertion. As illustrated in Figure 1, the efficiency trends are delineated for the economic factors of labour, capital and land, in addition to the environmental perspective of greenhouse-gas and acidifying-gas emissions.

Linear regression analysis, based on ordinary least squares, indicates positive slopes with high coefficients of determination, suggesting an increasing efficiency of the specific factors.

However, it should be noted that these general trends vary considerably between the countries analysed, as elaborated below. The DEA and Malmquist indices are utilised to evaluate and compare efficiency changes between the two sub-periods for each country analysed.

Economic perspective. As illustrated in Table 1, the development of the partial efficiency measures for the



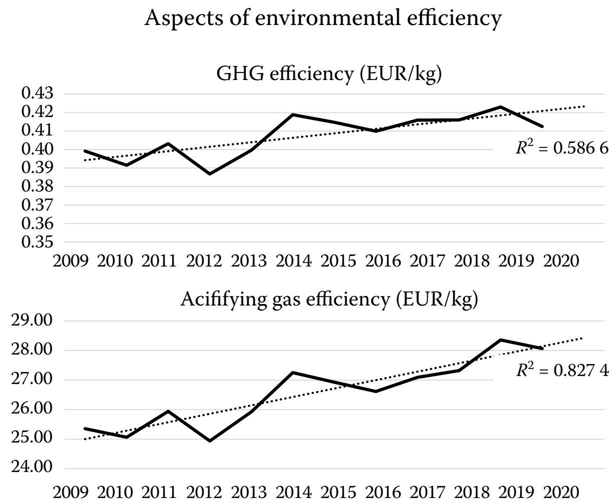


Figure 1. The partial developments of economic and environmental efficiency across the entire sample
Source: Own processing based on Eurostat data

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Table 1. Partial analysis of economic efficiency

Country	Labour efficiency			Capital efficiency			Land efficiency		
	09–14 (EUR/h)	15–20 (EUR/h)	growth (%)	09–14 (EUR/EUR)	15–20 (EUR/EUR)	growth (%)	09–14 (EUR/ha)	15–20 (EUR/ha)	growth (%)
Belgium	18.28	17.69	–3.2	0.30	0.27	–9.6*	1 767.78	1 792.40	1.4
Czechia	10.79	13.15	21.9*	0.29	0.30	1.3	1 005.50	1 165.33	15.9*
Denmark	22.93	24.07	5.0	0.08	0.09	6.5	922.65	866.63	–6.1
Germany	18.66	19.18	2.8	0.14	0.13	–6.5	1 356.07	1 259.92	–7.1
Estonia	10.49	11.56	10.3	0.26	0.20	–24.2**	515.91	474.99	–7.9
Ireland	6.99	10.48	49.8**	0.19	0.26	40.7**	423.32	619.48	46.3**
Greece	5.55	6.05	9.1	0.41	0.46	11.0*	2 230.06	2 386.11	7.0
Spain	18.24	20.65	13.2*	0.56	0.55	–1.6	1 274.72	1 539.08	20.7*
France	18.07	19.81	9.7*	0.27	0.29	9.0	1 204.17	1 227.08	1.9
Italy	13.74	13.72	–0.2	0.19	0.22	14.5**	2 773.96	2 865.55	3.3
Latvia	5.51	6.43	16.7**	0.09	0.11	24.2**	469.05	523.55	11.6*
Lithuania	5.05	6.40	26.9*	0.25	0.21	–16.7**	417.32	420.24	0.7
Luxembourg	20.98	21.53	2.7	0.06	0.05	–16.9	921.84	928.52	0.7
Hungary	7.33	9.10	24.2*	0.19	0.22	18.8	762.79	873.62	14.5
Netherlands	30.21	33.24	10.0**	0.24	0.25	4.8	6 273.51	7 484.66	19.3**
Austria	8.15	10.13	24.3**	0.08	0.09	4.3	1 351.35	1 711.29	26.6**
Poland	2.96	3.18	7.6**	0.59	0.55	–7.4*	840.22	711.59	–15.3**
Romania	1.65	2.73	65.6**	0.36	0.30	–17.0	653.35	818.74	25.3*
Slovenia	4.71	5.80	23.0**	0.24	0.28	15.9**	1 617.01	1 913.36	18.3*
Slovakia	10.57	13.72	29.7*	0.14	0.16	11.3	702.97	979.77	39.4*
Finland	19.60	26.31	34.2**	0.22	0.26	18.9**	2 016.86	2 446.10	21.3*
Sweden	19.57	22.97	17.3**	0.12	0.13	10.6*	1 747.27	2 007.57	14.9**
Weight. mean	9.35	11.08	18.4**	0.223	0.237	6.1**	1 325.80	1 408.85	6.3*
(weighted by)	(the volume of worked hours)			(the volume of fixed assets)			(the volume of used land)		
SD	7.51	8.04	7.1	0.14	0.13	–4.9	1 224.81	1 452.31	18.6

* and **significance at 0.05 and 0.01 levels, respectively
Source: Own processing based on Eurostat data

classical factors of production (labour, capital and land) and their relative changes (growth) for each country in the sample is demonstrated. The analysis indicates that labour efficiency is either increasing or remaining stable across all the countries under consideration. However, capital efficiency frequently exhibits a decline, often attributable to substantial increases in invested capital. The increasing labour efficiency, when considered in conjunction with the decreasing capital efficiency, suggests a persistent substitution of machines for human labour. With the exception of Denmark, Germany, Estonia and Poland, an increase in land efficiency was observed across all other countries. Ireland has demonstrated the most significant advancements in all facets of economic efficiency. The data underlying these changes in the sub-measures of efficiency are described in more detail in Table S1 (Electronic Supplementary Material, ESM). As indicated by rising weighted averages, there is a general increase in efficiency. However, rising standard deviations of labour and land efficiency do not indicate convergence. The significance of these changes is indicated by an asterisk (*) in relation to the *P*-values of a *t*-test, which should be interpreted with caution due to the limited number of years.

These variations underscore the significance of both internal innovation and the dissemination of best practices. For instance, the Netherlands' consistently high efficiency is likely linked to its intensive use of precision farming and capital investments (OECD 2015), while Ireland's large improvement points to successful

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structural and technological reforms supported by advisory services and policy innovation (Läpple and Thorne 2019). Such cases serve to emphasise the importance of benchmarking and targeted policy learning across the EU.

As illustrated in Table 2, the results of the DEA analysis are presented from a multifactorial economic perspective. This analysis offers efficiency scores (TE) for the average levels of the two sub-periods. In addition, an analysis of their changes is provided using the Malmquist index. It is evident that the peer countries which define the efficient frontier of the economic perspective are consistently Greece, Spain, the Netherlands and Poland. It can be hypothesised that, given Finland's achievement of a high efficiency score for the period 2015 to 2020, geographical location within Europe is not the primary factor influencing economic efficiency in agriculture. A substantial frontier shift, driven by technological advancement, contributes to improvements in economic efficiency for almost all countries, with the largest impact in the Netherlands. However, the individual changes in relation to the current frontier (catch-up) vary considerably. It is noteworthy that Ireland, Finland and Slovakia have exhibited the most substantial increases in economic efficiency, while Lithuania and Romania have demonstrated the most significant declines. It is evident that countries such as the Netherlands, Spain, Greece, and Poland have demonstrated a consistent ability to delineate the efficient frontier. In contrast, Ireland, Finland, and Slovakia have exhibited notable catch-up effects, signifying the presence of untapped efficiency potential. Conversely, Romania, Latvia and Lithuania display relatively low technical efficiency and limited progress, suggesting the presence of structural challenges or delayed modernisation. The presence of low technical efficiency scores and limited catch-up performance can be interpreted as indicators of efficiency reserves, thus highlighting a potential for improvements.

The high economic efficiency scores of the Netherlands, Greece and Spain, in conjunction with the low

Table 2. Multifactorial analysis of economic efficiency

Country	Economic efficiency		Catch-up	Frontier shift	MI^{econ}
	09–14 (TE^{econ})	15–20 (TE^{econ})			
Belgium	0.872	0.753	0.864	1.094	0.944
Czechia	0.660	0.653	0.989	1.107	1.095
Denmark	0.758	0.722	0.953	1.101	1.049
Germany	0.617	0.576	0.933	1.090	1.017
Estonia	0.544	0.489	0.899	1.091	0.980
Ireland	0.371	0.499	1.344	1.093	1.469
Greece	1.000	1.000	1.000	1.088	1.088
Spain	1.000	1.000	1.000	1.046	1.046
France	0.797	0.804	1.008	1.086	1.095
Italy	0.719	0.744	1.035	1.076	1.114
Latvia	0.252	0.277	1.097	1.088	1.193
Lithuania	0.439	0.375	0.854	0.978	0.835
Luxembourg	0.694	0.648	0.933	1.101	1.027
Hungary	0.459	0.486	1.060	1.104	1.170
Netherlands	1.000	1.000	1.000	1.128	1.128
Austria	0.327	0.331	1.012	1.073	1.086
Poland	1.000	1.000	1.000	0.930	0.930
Romania	0.633	0.555	0.876	1.005	0.880
Slovenia	0.671	0.728	1.084	1.085	1.176
Slovakia	0.452	0.507	1.123	1.083	1.216
Finland	0.769	0.904	1.175	1.079	1.269
Sweden	0.649	0.690	1.064	1.101	1.171

MI – Malmquist index; TE – technical efficiency

Source: Own processing based on Eurostat data

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score of Latvia, corroborate the conclusions of Bartová et al. (2018) and Kijek et al. (2019). This is not the case for the high economic efficiency of Poland and its substantial increase for Ireland, as demonstrated by the present analysis. The observed discrepancies may be attributable to two factors. Firstly, the more recent data of this study may be indicative of recent trends. Secondly, the divergent operationalisation of economic factors may be a contributing factor to the observed discrepancies.

In addition to the economic aspects of efficiency, which are based on the classical production factors of labour, capital and land, the environmental perspective is becoming increasingly important and is the subject of the following section.

Environmental perspective. The environmental impacts of agriculture are multifaceted and varied in nature. The present study examines two significant aspects of air pollution: namely, greenhouse gas emissions and acidifying gas emissions. Both types of emissions involve different chemicals, which are converted into CO_2 equivalents or SO_2 equivalents, respectively, in order to quantify an aggregated impact on climate change and acidification of the natural environment. As these emissions reduce the available budgets before critical tipping points are reached, they are considered a consumption of ecological resources or an input factor in the DEA (Halkos and Petrou 2019). The partial efficiency measures delineated in Table 3 establish the euro amount in terms of GVA in relation to one kilogramme of these aggregated emissions.

The strong performance of Finland and Slovakia in environmental efficiency, particularly in terms of frontier

Table 3. Partial analysis of environmental efficiency

Country	Greenhouse gas efficiency			Acidifying gas efficiency		
	09–14 (EUR/kg CO_2)	15–20 (EUR/kg CO_2)	growth (%)	09–14 (EUR/kg SO_2)	15–20 (EUR/kg SO_2)	growth (%)
Belgium	0.22	0.22	–0.2	17.73	19.05	7.4
Czechia	0.39	0.43	10.3	25.75	27.68	7.5
Denmark	0.18	0.17	–1.4	14.74	14.63	–0.7
Germany	0.33	0.30	–9.0	18.10	17.23	–4.8
Estonia	0.30	0.30	0.2	21.28	23.01	8.1
Ireland	0.09	0.12	35.0**	7.69	10.41	35.3**
Greece	0.65	0.76	17.8*	47.58	54.01	13.5*
Spain	0.60	0.65	8.4*	27.00	29.41	8.9*
France	0.36	0.37	3.6	24.07	25.38	5.4
Italy	0.79	0.79	0.3	44.13	46.35	5.0
Latvia	0.31	0.32	1.0	25.23	27.14	7.6
Lithuania	0.25	0.25	2.2	14.81	15.57	5.2
Luxembourg	0.17	0.16	–7.4	10.06	9.62	–4.3
Hungary	0.50	0.48	–3.7	27.60	28.88	4.6
Netherlands	0.39	0.45	13.7**	43.67	51.00	16.8**
Austria	0.47	0.50	5.8*	30.06	31.27	4.0
Poland	0.21	0.20	–7.7*	15.53	14.80	–4.7
Romania	0.34	0.39	12.2	22.92	27.29	19.0
Slovenia	0.36	0.41	13.6*	19.72	23.38	18.5*
Slovakia	0.65	0.81	24.5	35.05	42.35	20.8
Finland	0.53	0.62	16.8**	60.27	78.71	30.6**
Sweden	0.54	0.67	22.7**	46.58	55.58	19.3**
Weight. mean	0.40	0.42	3.9*	25.75	27.40	6.4**
(weighted by)	(the volume of GHG emissions)			(the volume of acidifying gas emissions)		
SD	0.18	0.21	18.0	13.36	16.99	27.2

* and **significance at 0.05 and 0.01 levels, respectively; GHG – greenhouse gases

Source: Own processing based on Eurostat data

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shift and catch-up, is indicative of the effective integration of sustainability-oriented practices. Conversely, the persistent low environmental efficiency observed in Poland and Luxembourg calls for deeper alignment with EU's climate and resource targets.

These findings imply that there is no universal trade-off between economic and environmental efficiency. It is evident that countries such as Finland and Ireland have demonstrated that progress in both domains is indeed attainable when supported by coherent policy frameworks and technological progress. The CAP reform from 2015 onwards may have contributed to this alignment in several cases.

In the majority of cases, greenhouse gas efficiency and acidifying gas efficiency demonstrate an increase, signifying a reduction in pollution relative to GVA. However, the aggregate enhancement in this ratio for all 22 countries is not substantial and appears to be insufficient to meet the EU's environmental objectives. Some countries, including Belgium, Denmark, Germany, Luxembourg, Hungary and Poland, are experiencing a decline in both greenhouse gas efficiency and acidifying gas efficiency.

In addition to these partial aspects of environmental efficiency, Table 4 presents the results of the DEA and the MI for both groups of emissions combined.

During the initial sub-period (2009–2014), Italy and Finland demonstrated the highest levels of efficiency, while Greece, Slovakia and Finland demonstrated full efficiency during the subsequent sub-period (2015–2020). The geographical diversity of these countries, which are spread across Europe, serves as a testament to the fact that efficiency is not solely attributed to regional advantages. This finding suggests the possibility of attaining analogous outcomes across all European countries. It is evident that all countries in the sample contribute to technological progress, as evidenced by the frontier shift measures, which are greater than 1 in all cases. However, a significant number of countries have a catch-up measure that is considerably less than one, indicating

Table 4. Multifactorial analysis of environmental efficiency

Country	Envir. efficiency 09–14 *(TE^{envir})*	Envir. efficiency 15–20 *(TE^{envir})*	Catch-up	Frontier shift	MI^{envir}
Belgium	0.347	0.312	0.898	1.149	1.032
Czechia	0.547	0.550	1.005	1.083	1.089
Denmark	0.284	0.244	0.862	1.149	0.990
Germany	0.421	0.378	0.898	1.023	0.919
Estonia	0.440	0.406	0.923	1.125	1.039
Ireland	0.147	0.173	1.176	1.150	1.353
Greece	0.963	1.000	1.038	1.122	1.165
Spain	0.764	0.801	1.048	1.034	1.084
France	0.511	0.486	0.952	1.095	1.043
Italy	1.000	0.997	0.997	1.026	1.023
Latvia	0.493	0.446	0.906	1.149	1.040
Lithuania	0.327	0.321	0.981	1.054	1.034
Luxembourg	0.223	0.199	0.892	1.052	0.938
Hungary	0.631	0.608	0.964	1.033	0.996
Netherlands	0.731	0.698	0.955	1.207	1.152
Austria	0.648	0.636	0.981	1.071	1.051
Poland	0.318	0.265	0.833	1.125	0.937
Romania	0.487	0.507	1.042	1.103	1.149
Slovenia	0.461	0.516	1.120	1.023	1.146
Slovakia	0.834	1.000	1.199	1.031	1.236
Finland	1.000	1.000	1.000	1.252	1.252
Sweden	0.887	0.934	1.053	1.151	1.212

MI – Malmquist index

Source: Own processing based on Eurostat data

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that they are lagging behind the technical possibilities and the distance to this frontier is increasing. Ireland demonstrated the highest improvement in environmental efficiency, though this was at a very low level. Finland has demonstrated a notable commitment to technological advancement, evidenced by its substantial contributions to the field. Conversely, Slovakia exhibited the most significant catch-up effect in attaining the efficient frontier. Conversely, Germany, Luxembourg and Poland demonstrated a decline in environmental efficiency with regard to air pollution, a trend that necessitates corrective efforts or policy action.

In their 2018 study, Rybaczewska-Błażejowska and Gierulski (2018) found high environmental efficiency for Finland, Greece and Italy, and low values for Poland and Ireland, considering a wide range of ecological impacts. Conversely, other studies focusing exclusively on GHG emissions as an ecological parameter identified the highest environmental efficiency in Denmark, Belgium and the Netherlands, and the lowest efficiency in Slovakia, Latvia, Lithuania and Estonia (Bartová et al. 2018; Pishgar-Komleh et al. 2021). Therefore, the inclusion of additional acidifying gases, as implemented in this study, aligns the findings more closely with studies encompassing broader environmental impacts. The inclusion of Malta's diminutive agricultural sector renders this country the environmental benchmark in the aforementioned studies.

A final comparison of the changes observed in economic and environmental efficiency combines the results mentioned previously. As illustrated schematically in Figure 2, the economic and environmental Malmquist

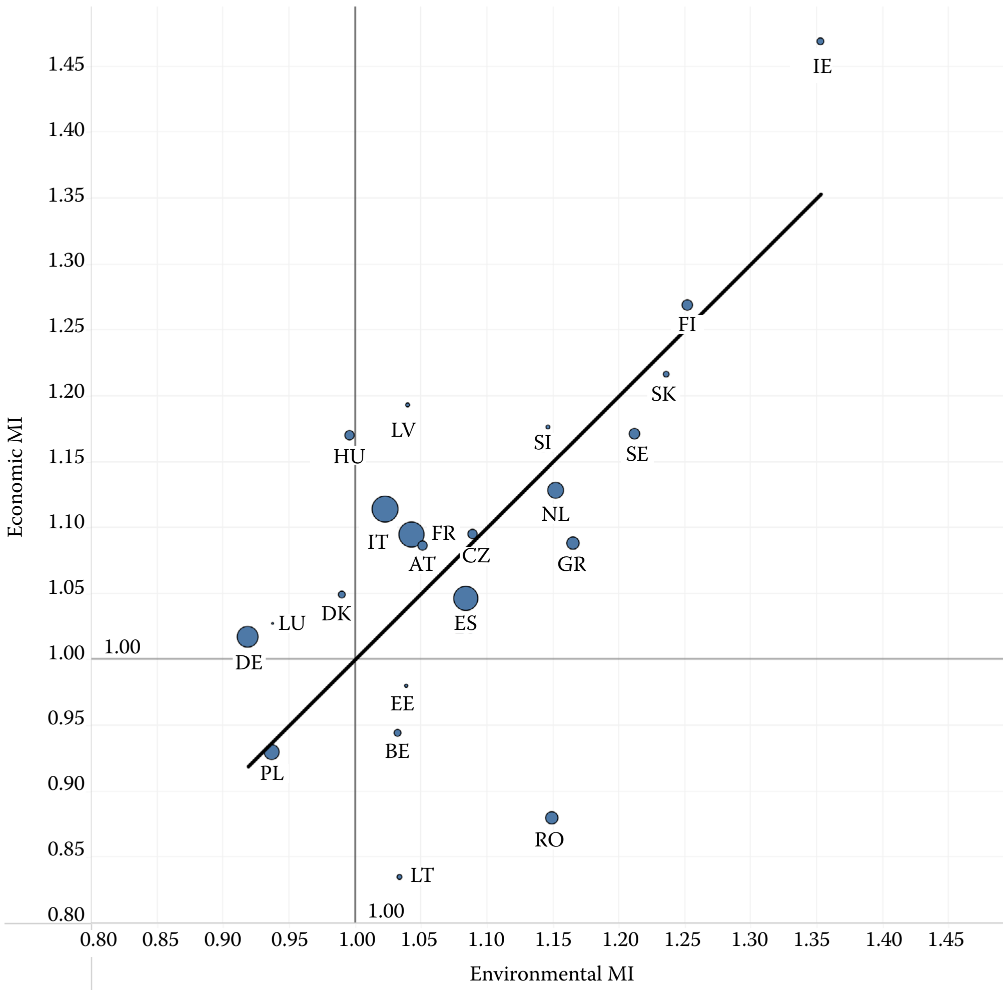

Figure 2. Comparison of changes in economic and environmental efficiency

AT – Austria; BE – Belgium; CZ – Czechia; DE – Germany; DK – Denmark; EE – Estonia; ES – Spain; FI – Finland; FR – France; GR – Greece; HU – Hungary; IE – Ireland; IT – Italy; LT – Lithuania; LU – Luxembourg; LV – Latvia; MI – Malmquist index; NL – Netherlands; PL – Poland; RO – Romania; SI – Slovenia; SK – Slovakia; SE – Sweden

Source: Own processing based on Eurostat data

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indices can be represented in a similar manner. The dimensions of the bubbles are proportionate to the volume of each country's agricultural GVA.

The majority of the countries under consideration demonstrated an enhancement in both economic and environmental efficiency during the period under review. Ireland, Finland and Slovakia demonstrated the most significant progress in both domains, a development that cannot be attributed exclusively to sub-optimal TE levels in the initial sub-period (Tables 2 and 4). Poland continues to demonstrate its pre-eminence in economic efficiency. However, a decline in the second sub-period was observed, a finding that is consistent with the results reported by Marzec and Pisulewski (2019) concerning Polish crop production. A notable weakness for Poland is the decline in environmental efficiency during the observed period. It is recommended that countries such as Romania, Lithuania, Belgium and Estonia prioritise economic progress in the future. Conversely, Germany, Luxembourg, Denmark and notably Hungary have witnessed advancements in economic efficiency, though they have lagged behind in environmental efficiency. The reference line in Figure 2 exhibits a slope of 1, signifying an equilibrium between economic and ecological progress. The absence of any systematic positioning above or below this line suggests that there is no general indication of a dominance of economic progress over environmental progress, as postulated by Hoang and Coelli (2011).

While this study provides valuable insights into the long-term dynamics of efficiency, its findings are limited by the availability of harmonised and comparable environmental indicators across all EU countries. It is recommended that future research efforts focus on refining the environmental assessment by incorporating a more comprehensive set of ecological dimensions. These dimensions should include, but are not limited to, additional relevant emissions, biodiversity loss, and resource depletion. However, the implementation of this approach is contingent upon the availability of reliable and harmonised indicators. Furthermore, the assumption of constant returns to scale and the aggregation of data into two six-year sub-periods, while appropriate for the purpose of comparability, may obscure short-term variability and existing scale effects. Furthermore, it should be noted that the results of the Malmquist decomposition are descriptive in nature and do not undergo statistical significance testing. Nevertheless, the dual approach adopted here already captures major economic and ecological pressures relevant to EU agricultural sustainability, particularly those linked to emissions and land use.

CONCLUSION

The present study provides a dual-perspective assessment of long-term efficiency trends in EU agriculture, combining separate economic and environmental analyses using a DEA-Malmquist framework. The results presented herein indicate that the long-term economic and environmental efficiency of the European agricultural sector is, in general, on the rise. Nevertheless, considerable variations are observed among the countries analysed. The findings suggest that attaining efficient economic and environmental outcomes is feasible across all regions, thereby challenging the notion of any inherent advantage for any specific geographical area (northern, eastern, southern or western countries), including the potential for customised assessment of inputs or outputs. In order to address this issue, it is essential to implement more extensive benchmarking procedures in order to emulate best practices among European countries. This can be facilitated through scientific exchange or legal requirements. The acceptance of unnecessary differences in efficiency across the EU has been demonstrated to result in the inefficient use or waste of economic and environmental resources. This is incompatible with the goal of sustainability. It is imperative that national profit interests and competitive advantages be subordinated to this overarching objective.

A comparison with the results of other studies indicates that the selection and operationalisation of economic and environmental factors have a substantial impact on the outcomes. The high volatility of the results has been addressed here by presenting the long-term development through a comparison of average values from two six-year periods, which correspond to two CAP programming periods. The study demonstrates that adopting a more comprehensive, integrated approach to economic and environmental efficiency can yield valuable insights. The utilisation of standardised data sources and harmonised methodologies is imperative for ensuring the comparability of results and should be prioritised in future research endeavours.

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