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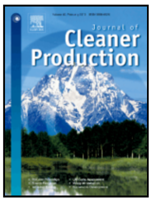

Exploring environmental efficiency of the European agricultural sector in the use of mineral fertilizers

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ABSTRACT

This study analyzes the environmental efficiency of the agricultural sector regarding the use of mineral fertilizers in the period 2001 2012 for a group of European countries. Specifically, efficiency is assessed through a dynamic Data Envelopment Analysis methodology. This method aims to analyze temporal efficiency changes through the estimation of Malmquist indexes with increasing and decreasing temporal windows. Findings show that most countries register efficiency advances in the periods 2002 2003 and 2007 2008. Specific countries, such as Belgium-Luxembourg, Denmark, Netherlands, Sweden and United Kingdom, register persistently higher values of the estimated Malmquist indexes. This study contributes to the existing literature by assessing country-specific efficiency paths, as well as by identifying best-performing countries from which lessons can be learnt. A brief review of main measures taken by a selected group of benchmark countries is offered.

1. Introduction

Agriculture constitutes an economic sector which provides multiple benefits, such as food security and ecosystem services. This sector also generates negative externalities, such as water and land deterioration due to agrochemical pollution (Adegbeye et al., 2020). The use of agrochemical inputs (e.g., fertilizers, pesticides, pharmaceuticals) has been intensified over recent decades to increase production in response to a variety of market (e.g., commodity prices) and policy (e.g., subsidies) factors. This input intensification constitutes the main source of agricultural pollution in the environment, and affects land, water, and air (Shah et al., 2019). In the case of the EU, the total nitrogen input into river basins reached 80 million tons (average for 1985 2005), whereby the largest share was diffuse pollution from agricultural activities (La Notte et al., 2017). Due to this type of pollution, many aquatic ecosystems in Europe are eutrophic or at high risk of eutrophication. This incurs the most significant external costs from farming and implies elevated costs for EU countries that strive to meet the long-term chemical and ecological status in water bodies required by EU legislation (EEA, 2018). It is estimated that the environmental, economic (as a consequence of the impact to other industries), and social cost of agro-fertilization pollution exceeds billions of dollars annually in OECD countries (OECD, 2017). Regarding the achievement of the Sustainable Development Goals (SDGs), addressing the sustainable use of mineral fertilizers constitutes a key factor for SDG2 Sustainable Agriculture which requires to address those agricultural activities which put significant pressures on the environment; and SDG 6, which aims to ensure availability and sustainable management of water for the whole population (Ezbakhe, 2018).

Research and policy efforts to minimize the use of mineral fertilizers have largely focused on technical solutions and on the use of command & control (e.g., regulations) and economic instruments (e.g., environmental taxes, individual incentives). In the EU context, regulatory and individual-incentive schemes have been the main policy instruments implemented for the minimization of environmental costs arising from the use of agro-fertilizers. The Nitrates Directive (1991), the Water Framework Directive (2000), and the cross-compliance requirements of the Common Agricultural Policy (CAP) (2014 2020) constitute good examples. Agricultural land uses occupy more than half of the EU territory and the environment is, in turn, potentially affected by the intense use of mineral fertilizers (e.g., nitrates, phosphorus, and potassium). In fact, the use of mineral fertilizers in agriculture constitutes the main source of nitrogen and phosphorus in European water bodies, and represents more than 50% of total discharge (EEA, 2012). As a result, more than 90% of the River Basin Management Plans (RBMPs) assessed in 2012 indicated that the intensive use of mineral fertilizers by agriculture puts

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significant pressure on water resources in Europe (EC, 2019a). Sutton et al. (2011) estimate the cost of damage associated to the use of nitrogen fertilizers as being up to 320 thousand million euros annually in the EU, which significantly exceeds the estimated economic benefit of its use (80 thousand million euros). Though the efforts made by the EU authorities and Member States (MS) in the development of legal and policy measures to reduce the use of mineral fertilizers have led to a reduction in total nitrogen inputs of 15% since the 1980s, there is still room for potential reductions (EEA, 2018).

Several recent studies have striven to evaluate environmental efficiency for different measures of performance in the agricultural sector (Vlontzos and Pardalos, 2017). Nevertheless, and to the best of our knowledge, no study has assessed the evolution of environmental efficiency in the use of mineral fertilizers in agriculture for a wide group of European countries, nor has explored the use of dynamic Data Envelopment Analysis (DEA) window techniques. The analysis carried out in this work aims to achieve a twofold objective. Firstly, the analysis of the efficiency paths followed by a significant group of EU countries in the period 2001 2012 to assess the effectivity of measures taken to reduce intensity use of mineral fertilizers by the agricultural sector without compromising agricultural output. Secondly, the identification of the best-performing countries in terms of advances in reducing the use of mineral fertilizers. Main management initiatives and policy measures taken by identified benchmark countries are described with the aim to offer valuable information to less efficient countries.

This study aims to achieve these objectives by carrying out a dynamic assessment analysis of the environmental efficiency of the agricultural sector for a representative group of 21 EU countries. The DEA analysis presented allows us to assess the capacity of these countries in minimizing fertilizer-use intensity without reducing their agricultural output capacity from a dynamic window approach, thereby enabling temporal efficiency trends to be assessed in the medium and long term. The analysis identifies which countries present reductions in fertilizer use while maintaining or even increasing the value of agricultural output. Findings offer valuable information for policy- and decision-making regarding the management of fertilizer use by the agricultural sector in the EU and worldwide.

The rest of the paper is structured as follows. The following section offers a general overview of policy and environmental aspects associated to the use of mineral fertilization in the EU context. Section 3 explains the methodology and data used in this study. Subsequently, Section 4 shows and discusses the results and Section 5 offers some policy guidelines based on the measures taken by a group of identified benchmark countries. Finally, several concluding remarks are given.

2. Mineral fertilization, policy aspects, and environmental impact in the EU context

Environmental concerns about the negative environmental externalities associated to the use of mineral fertilizers have increased in recent decades in the EU, leading to a growing set of regulations and policies aimed to minimize environmental damage caused by the excessive use of fertilizers by the agricultural sector. Among these, the CAP (2014 2020) recognizes the adverse environmental impacts of practices that include an intensive use of fertilizers, and prioritizes the more sustainable management of fertilizers through a set of policy instruments, such as cross-compliance measures, the implementation of green direct payments, and rural development support measures tailored to promote best nutrient management practices (BNMPs). The recent EU circular economy package prioritizes agriculture-related initiatives with significant potential to improve resource-use sustainability, including water reuse, the revised EU regulation on fertilizers, and food waste (EC, 2019b). EU climate policies have also set priorities for the reduction of greenhouse gas emissions from agricultural land use and for the promotion of sustainable manure management and of a reduction of mineral fertilizers (EC, 2017a).

Advances in the abatement of pollution in the soil and water resources from mineral fertilizers have been achieved in recent years due to these EU policies. Nevertheless, this trend is not uniform across all EU member states and results remain unsatisfactory (EEA, 2018). Regarding the pollution of water resources from mineral fertilizers, the first cycle of River Basin Management Plans (RBMP) concluded that only 43% of surface-water bodies had achieved good ecological status (EC, 2007), and 90% of river basin districts (RBDs) are significantly affected by challenges posed by mineral fertilizer pollution. These figures have not registered a significant improvement in the monitoring of second-cycle RBMPs (EC, 2019a). As highlighted by the European Commission (EC) and the European Environment Agency (EEA), the fact that the first and second RBMPs have not been on track to reduce the use of mineral fertilizers may put at risk the long-term environmental targets set by EU legislation (EC, 2019), and may also limit the integration of water measures in the CAP architecture (EEA, 2018). Coherence in implementing the EU agriculture policy regarding fertilization management still constitutes a major challenge for EU authorities. While certain countries are successfully making progress in the reduction of fertilizer use by the agricultural sector, others are making only limited progress. This is clearly shown by the analysis carried out in this study. Although the CAP Pillar I cross-compliance requirements specify that funding must be either directly focused on fertilizer-use minimization (e.g., that based on the Nitrates Directive and on the establishment of specific standards of the good agricultural and environmental condition of land (GAEC) to protect land and water resources from pollution) or indirectly focused (such as that which defines landscape features that provide ecological services), the reduction of fertilization pressures on the environment still remains a priority within the EU context. To this end, the new Green Direct Payment is expected to serve as a reinvigorating instrument to maximize the CAP environmental performance regarding this issue (EU, 2013), and to serve as a complement to Pillar II of the CAP (Rural Development). This instrument promotes activities aimed at guaranteeing the sustainable management of natural resources by containing specific priorities focused on the minimization of agrochemicals (such as priority 4 for the restoration and preservation of ecosystems related to agriculture). Despite these efforts, the EEA warns that concentrations of nitrogen per hectare, as a result of excess mineral fertilization, still represent a serious threat in many regions of the EU, especially in those of central and western Europe (EEA, 2010).

This unsatisfactory fulfillment of the environmental objectives regarding the use of fertilizers by agriculture can be explained as being due to a set of challenges that have yet to be adequately addressed by the EU and its MS (EEA, 2018): a) Diffuse and multi-actor characterization of this type of pollution; b) Lack of coordination between the multiple administrations involved (i.e., national, regional, and sectoral) for the development of cost-effective measures in Nitrates Action Programs without compromising agricultural sector viability; c) Insufficient information available on the measures to minimize fertilizer use in line with the environmental and sustainability objectives as set out by EU legislation and the specific characteristics of each MS (such as fertilization planning, farmers awareness, decision support systems for precision farming, reinforcing monitoring, and inspection systems); and d) Existing gaps in knowledge and innovation among EU countries and regions on innovative techniques for the increase of efficiency in the use of mineral fertilizers. All these challenges require significantly more available information regarding innovative initiatives, effectiveness of measures, and multi-agent and multi-administration coordination. This study aims to contribute in this respect by providing information on the best-performing EU countries in terms of minimizing fertilizer-use intensity without compromising output capacity.

Specifically, this study assesses the environmental performance for a set of European countries in the period 2001 2012 by using an advanced DEA dynamic approach. The countries in our analyzed sample include Austria (AT), Belgium-Luxembourg (BE-LU), Bulgaria (BG), Cyprus (CY), Denmark (DK), Finland (FI), France (FR), Germany (DE), Greece (HE), Hungary (HU), Ireland (IE), Italy (IT), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Spain (ES), Sweden (SE), and the United Kingdom (UK). Norway, as a member of the European Economic Area (EEA) agreement, despite not being subject to CAP funds and requirements, is obliged to transpose all environmental acts (including the Nitrates Directive and WFD) into national laws, and is also compelled to achieve EU environmental objectives, as monitored by the EEA and the EC.

3. Method and data

3.1. Method

DEA methods have been recently used to evaluate environmental efficiency of the agricultural sector. The study of Gutierrez et al. (2017) analyses efficiency patterns of conventional and organic rain-fed cereals in Spain. In the EU context, Kocisova (2015) applies a DEA approach to estimate relative productive efficiency patterns and the study of Moutinho et al. (2017) analyses the environmental efficiency of the agricultural sector in terms of greenhouse gas emissions for 26 EU countries. Similarly, Vlontzos and Pardalos (2017) uses a dynamic DEA method to quantify the environmental efficiency of EU countries primary sectors taking into account greenhouse gas emissions as an undesirable output. In the case of Latin America, the study of Moreno-Moreno et al. (2017) analyses natural and managerial efficiency patterns of the agricultural sector for a representative group of countries.

The methodology applied in this study is based on a dynamic DEA optimization approach that models the functional production relationship between specified input and output variables to assess the relative efficiency for a sample of decision-making units (DMUs). In our specific case, these DMUs are our sampled countries. The proposed DEA optimization model assesses the capacity of these countries with regard to achieving a reduction in fertilizer-use intensity (considered as an undesirable output to be minimized in the optimization model), while increasing, or at least maintaining, agricultural production (considered as a desirable output to be maximized in the model). In the recent DEA literature, the concept of managerial disposability or managerial efficiency illustrates the capacity of a DMU to optimize several outputs on a simultaneous basis (e.g., increasing or at least maintaining desirable outputs while minimizing undesirable outputs), while inputs are at least maintained or increased (Expósito and Velasco, 2018). The analysis carried out in this study analyzes this type of efficiency, which is defined as unified managerial efficiency (UME). Input and output variables are described in detail in the following subsection. The multiple optimization problem (with desirable and undesirable outputs) is usually achieved through the introduction of innovation into the way that inputs are used to obtain outputs, thereby allowing undesirable outputs to be reduced while still augmenting (or at least maintaining) desirable outputs (Sueyoshi and Goto, 2011). This method also enables inter-period changes in relative efficiency to be assessed through Malmquist Indexes (MI) (Sueyoshi et al., 2017). These indexes are estimated for alternative time periods or temporal windows , which help us to evaluate changes and trends in the medium and in the long term. This methodology permits the dynamic assessment of the capacity of each country to achieve specified objectives, in comparison with the remaining countries. Alternative methodologies for the assessment of production efficiency, such as regression analysis, stochastic frontier analysis, and the use of synthetic efficiency ratios, seldom consider the intrinsic input-output relationships and their dynamic changes as do DEA methods, nor do they often rely on pre-set assumptions about relative weights and parameters (such as in regression analysis), which may lead to misleading findings (Expósito et al., 2017). A detailed description of the DEA optimization problem used in this study is offered in the methodological appendix.

3.2. Data

The principal challenge of DEA studies relies on the quality of data. Information on agricultural variables remains generally scarce and incomplete for long time-series. In our specific case, the output and input data used in the proposed DEA analytical framework has been obtained from the Food and Agriculture Organization of the United Nations database (FAOSTAT, 2019) and covers the period 2001 2012. This information source constitutes a significant advance in terms of data accuracy and reliability. The dataset employed includes information on agricultural inputs and outputs for 21 European countries, although Belgium and Luxembourg are jointly treated as a single DMU due to their size. Three input variables have been included: 1) Labour (in thousands of people): total of the economically active population engaged in the agricultural sector (without including livestock); 2) Cultivated land (in thousands of hectares): includes temporary crops, pastures, permanent crops, and excludes land under trees grown for wood or timber; and 3) Crop capital stock (in thousands of constant 2005 US dollars): includes plantation crops (i.e., trees yielding repeated products, such as vines and fruit trees), land development and irrigation work, flood control structures, equipment and machinery (capital associated to livestock production is not included). Two output indicators have been used. On the one hand, a desirable output is to be maximized as much as possible in the proposed analytical framework as given by the value of gross agricultural production (livestock and animal products not included) in in thousands of constant 2005 US dollars. On the other hand, an undesirable output is represented by the intensity of use of mineral fertilizer consumption per output unit. Specifically, this output measures the quantity of nitrogen (N), phosphorus (P), and potassium (K) in metric tons per generated unit of agricultural output (in thousands of constant US dollars). The use of intensity ratios enables heterogeneity to be reduced in the spatial extent of different DMUs (countries), thus alleviating border effects. The use of a ratio per unit of output (instead of the traditional ratio per hectare of land) facilitates the comparative analysis of different crop mixes between countries, since intensive high-value crops use a higher quantity of fertilizers per hectare than other less intensive crops (e.g., vegetables vs cereals). In this respect, the significant differences in the economic value of the generated outputs help to minimize ratio disparities that arise from the difference in crop mixes across countries.

Descriptive statistics (average values and standard deviations in parentheses) of input and output variables used in this research are shown in Table 1. As can be observed, there is high heterogeneity between countries (largely due to the variation in size of their agricultural sectors), which discourages the comparison of efficiency scores, but not the assessment and comparison of efficiency temporal trends through the estimation of MIs. As presented in the previous section, this constitutes our main interest.

Table 1
Descriptive statistics of input and output variables (2001 2012).

	Inputs			Outputs	
	Capital	Labour	Land	Production	Fertilization intensity
AT	11,906 (230.95)	166 (21.01)	1447 (13.45)	1,859,235 (133,726.61)	0.10 (0.02)
BE-LU	2645 (71.86)	69 (7.86)	925 (9.49)	2,606,363 (148,127.52)	0.19 (0.02)
BG	4414 (878.84)	569 (192.56)	3452 (164.82)	2,077,674 (288,350.53)	0.09 (0.03)
CY	972 (65.93)	34 (3.74)	136 (19.27)	163,914 (33,887.57)	0.09 (0.02)
DE	63,724 (4353.79)	793 (131.11)	12,068 (44.45)	13,789,142 (886,485.77)	0.18 (0.02)
DK	7178 (363.18)	88 (12.78)	2364 (88.86)	1,906,952 (84,544.45)	0.15 (0.02)
ES	67,946 (1963.75)	1149 (125.15)	17,619 (398.80)	20,913,623 (1,513,131.53)	0.09 (0.02)
FI	10,289 (301.97)	115 (16.85)	2238 (26.65)	747,336 (48,940.52)	0.34 (0.05)
FR	64,453 (778.0)	694 (116.66)	19,509 (103.48)	22,039,563 (1,040,659.93)	0.17 (0.02)
HE	18,336 (1040.33)	711 (70.79)	3609 (258.97)	6,551,689 (713,001.76)	0.06 (0.01)
HU	9979 (280.50)	509 (102.96)	4742 (101.88)	3,842,023 (580,991.45)	0.13 (0.03)
IE	6278 (312.56)	157 (7.09)	1120 (65.88)	581,472 (51,298.64)	0.93 (0.11)
IT	75,801 (2755.69)	999 (153.10)	10,155 (688.33)	21,142,785 (1,293,042.41)	0.06 (0.02)
NL	5198 (235.34)	235 (21.39)	1054 (81.18)	3,791,891 (189,064.11)	0.09 (0.02)
NO	7373 (233.08)	96 (7.91)	857 (24.78)	286,580 (23,595.20)	0.60 (0.09)
PL	70,914 (5317.20)	2268 (156.78)	12,738 (927.66)	10,493,136 (684,133.42)	0.16 (0.02)
PT	11,329 (705.95)	585 (63.19)	2075 (241.89)	2,261,877 (119,036.04)	0.08 (0.02)
RO	35,550 (468.43)	2508 (463,87)	9522 (271.43)	5,883,668 (960,449.64)	0.09 (0.02)
SE	8955 (164.87)	126 (11.62)	2659 (30.83)	1,138,589 (62,421.10)	0.22 (0.02)
UK	26,571 (241.89)	495 (20.39)	5958 (163.36)	6,471,228 (323,683.57)	0.25 (0.03)

Source: Authors' own based upon FAOSTAT data.

Fig. 1 shows the evolution of agricultural production and fertilizer-use intensity (as measured by the quantity of N, P, and K in metric tons per generated unit of agricultural output in constant US dollars) for our group of countries in the period 2001 2012. Indexes with base year 2001 have been obtained for both variables: production and fertilization intensity. As previously discussed, although agricultural output has been very stable in real terms during this period, an erratic trend in reduction in the fertilization intensity can be observed up to 2008 (probably influenced by the global economic crisis). From that year onwards, the fertilizer intensity index registers an increasing trend. Nevertheless, as it is discussed in subsequent sections, high heterogeneity is observed depending on the EU country considered.

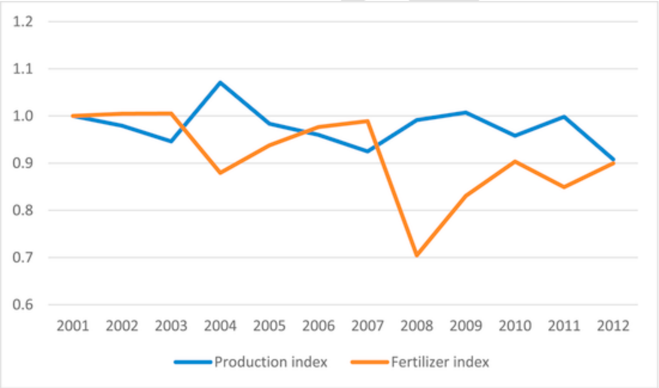

Fig. 1. Evolution of production and fertilizer-use indexes for the EU countries.

4. Results

Our proposed DEA model allows relative managerial efficiency scores (UME in our DEA model) to be estimated for each country in the analyzed period 2001 2012. Based upon the estimated relative efficiency scores for each country, the dynamic evolution of these efficiency estimates has been analyzed through the estimation of MIs for various temporal windows. In fact, three alternative estimations have been used not only to maximize the information extracted from estimated MIs, but also to test the robustness of our findings. The first estimation (Fig. 2) focuses on estimated MIs with increasing temporal windows, from two-period (2001 2002; T = 2) to twelve-period windows (2001 2012; T = 12). This analysis determines the years during which significant advances were made by our sampled countries as described by positive changes in the estimated MIs while subsequent years are added to the temporal window. The second estimation (Table 2 and Fig. 3) are based on the estimation of MIs for four-year windows (2001 2004; 2005 2008; 2009 2012). This estimation enables additional information focused on specific sub-periods to be offered. These sub-periods have been selected based on significant policy events, such as the EU WFD implementation in 2001 and the 2003 CAP reform, and on when significant impulses to manage mineral fertilization should have been made. The third estimation (Table 3) shows estimated MIs with decreasing temporal windows, from a twelve-period (2001 2012) to a one-period window (2011 2012). This is the opposite approach to that of the first analysis, and although estimated MIs do indeed differ, the general trend for each country and the group as a whole should offer similar information. This last analysis aids in the identification of whether the efforts made by the analyzed countries increase in subsequent years, since past years are not taken into account in the MI estimation with decreasing temporal windows. This exercise not only facilitates in the verification of previous findings regarding the identification of benchmark countries, but it also assures robustness in the findings.

Fig. 2 shows the dynamic evolution of MIs with increasing temporal windows for each of our sampled countries. As can be observed, a group of countries composed of BE-LU, NL, UK, and NO have outperformed the remaining countries, by registering significant advances in the estimated efficiency in the periods 2002 2003 (after the implementation of the WFD in 2001; 2003 CAP reform with Single Payment Scheme and cross-compliance requirements) and by maintaining this outperformance during the rest of the period with another significant increase between 2006 and 2008 (previous to the first-cycle RBMPs in the period 2009 2015). Other countries following similar patterns include SE, FI, and DK, although these countries started to outperform the others from 2006 until the end of the period analyzed. Most countries appear to register efficiency advances in the periods 2002 2003 and 2007 2008, though these advances are minor compared to those achieved by BE-LU and NL. Countries such as RO, BG and PT fail to register any significant changes, and show very limited advances in efficiency across the whole period.

Subsequently, MIs with 4-year windows have been estimated for the periods 2001 2004, 2005 2008, and 2009 2012, with the aim to

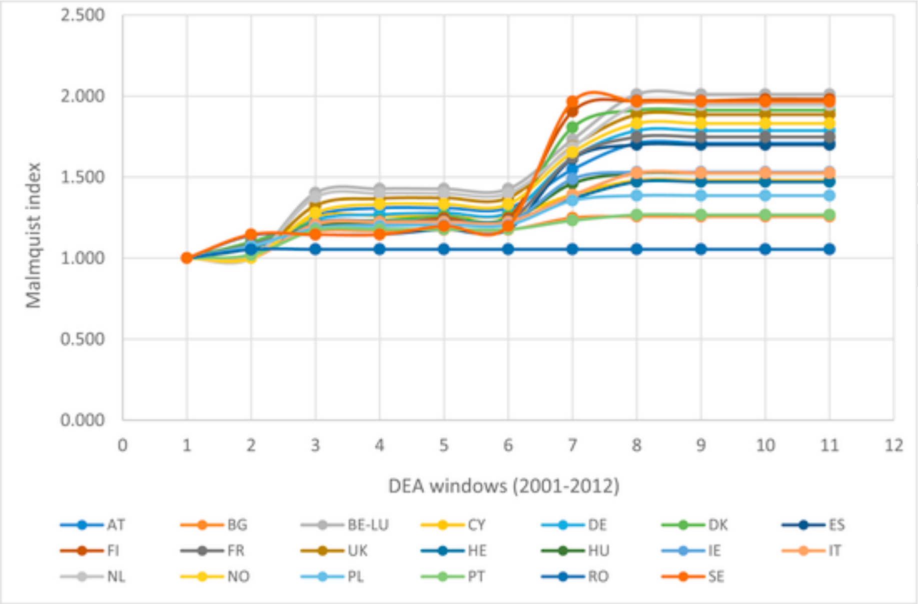

Fig. 2. Malmquist Indexes with increasing windows (2001 2012).

Table 2
Estimated MIs by country and average values (4-year windows).

	2001 04	2005 08	2009 12
AT	**1.259**	1.200	1.004
BG	1.167	1.172	**1.042**
BE-LU	**1.402**	1.212	1.000
CY	**1.250**	1.098	**1.110**
DE	**1.237**	**1.340**	1.000
DK	**1.220**	**1.552**	1.000
ES	1.145	**1.564**	1.000
FI	1.184	**1.712**	1.000
FR	1.192	**1.446**	1.000
UK	**1.324**	1.283	1.000
HE	**1.215**	1.112	**1.075**
HU	1.198	**1.305**	1.000
IE	1.184	1.227	**1.084**
IT	1.210	1.115	1.001
NL	**1.376**	1.201	1.000
NO	**1.279**	1.263	1.004
PL	1.183	1.104	**1.109**
PT	1.172	1.059	**1.122**
RO	1.054	1.004	**1.152**
SE	1.146	**1.819**	1.000
Average	1.220	1.289	1.035
Weighted average	1.205	1.301	1.023

Note: Weighted average upon agricultural production.

identify performance differences between our sampled countries between these three temporal sub-periods (Fig. 3 and Table 2). Simple and weighted (by value of agricultural production) average values are also shown in Table 2. With a significant positive performance over the average performance (average and weighted average MI) during the first period compared to the subsequent periods, the following countries need to be highlighted: AT, BE-LU, CY, DE, DK, UK, HE, NL, and NO (Table 2), whereby BE-LU, UK, and NL constitute the countries with the best performance (as shown by the estimated MIs). This group of countries could be identified as the leading group, since they attain significant results at the beginning of the period. On the other hand, countries such as DE, DK, ES, FI, FR, HU, and SE register significantly higher MI values during the sub-period 2005 2008. MIs estimated for the third sub-period clearly show that most countries have made little effort to improve their performance, as reflected by the very low values. During this period, countries such as CY, PL, PT, and RO have registered the highest MI values. In summary, estimated MI values for the three periods clearly show a decreasing trend, which shows the decreasing performance delivered by our group of countries as a whole. This trend can be seen with higher clarity in Fig. 4. Fig. 3 helps to describe the differences between the countries in our group. While MIs for the period 2009 2012 register no significant differences between countries (grey columns), estimated indexes for the first two sub-periods differ considerably depending on the country considered (blue and orange columns). This finding can be explained by the lack of coordination within countries when implementing measures to minimize the use of mineral fertilizers and prevent environmental pollution, as is discussed further in the following section. A common finding for most countries is that efforts to reduce fertilizer-use intensity are low or inexistent (1 values) during the most recent (period 2009 2012).

Table 3 shows the estimated MIs with decreasing temporal windows, from T = 12 (2001 2012) to T = 2 (2011 2012). This approach, despite differing from that with increasing temporal windows (Fig. 2) since estimated MI values differ between these two approaches, offers complementary information to that obtained from previous steps. In this respect, the average capacity of our group of countries to minimize fertilizer-use intensity, while maximizing (or at least maintaining) crop production values, is reduced during the period analyzed, as shown by the clear decreasing trend of average values, for both simple and weighted average values (as shown in the last two rows in Table 3 and Fig. 4). The highest values of estimated MIs are registered for temporal windows T = 12, T = 11, T = 10, and T = 6 (Table 3). These values show that, between 2001 and 2003, and also during 2006 2007, countries made significant advances in addressing the challenge of reducing fertilizer-use intensity. It is worth noting efforts performed by BE-LU, DE, DK, FI, UK, NL, NO, and SE, which register persistently higher values of MIs over the average values for MIs between T = 12 and T = 6. Other countries, such as AT, ES, and FR, despite not having outperformed persistently for many years, register improvements over average MIs for several years. Countries such as CY, HE, IE, IT, POL, POT, and

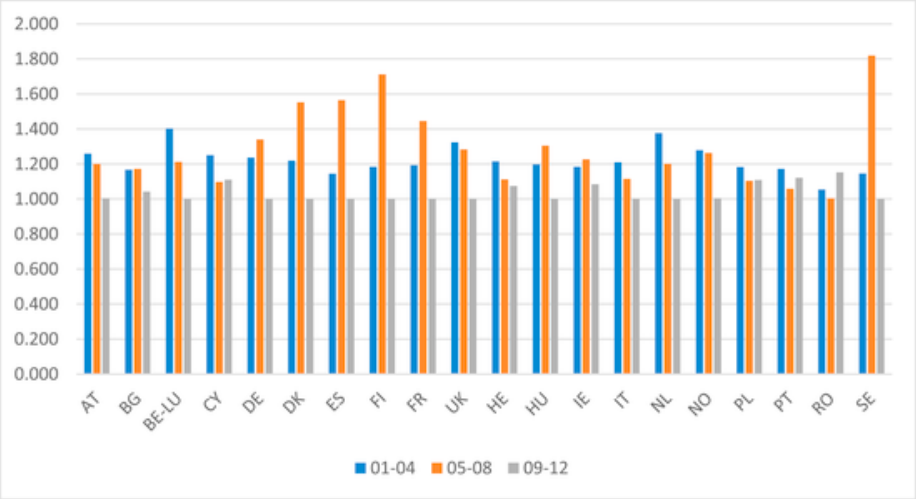

Fig. 3. Estimated MIs by country (4-year windows).

Table 3
Estimated MIs with decreasing windows (2001 2012).

	T = 12	T = 11	T = 10	T = 9	T = 8	T = 7	T = 6	T = 5	T = 4	T = 3	T = 2
	01 12	02 12	03 12	04 12	05 12	06 12	07 12	08 12	09 12	10 12	11 12
AT	**1.709**	**1.820**	**1.947**	1.364	1.333	**1.577**	1.623	**1.145**	1.004	**1.118**	1.000
BG	1.257	1.359	1.174	1.109	1.184	1.209	1.574	1.012	1.042	1.069	1.000
BE-LU	**2.011**	**2.142**	**2.107**	**1.430**	**1.408**	**1.704**	**1.724**	**1.161**	1.000	**1.154**	1.000
CY	1.479	1.633	1.567	1.187	1.163	1.293	1.555	1.029	**1.110**	1.061	1.000
DE	**1.787**	**1.900**	**1.841**	**1.473**	**1.467**	**1.587**	**1.629**	**1.096**	1.000	1.082	1.000
DK	**1.913**	**2.002**	**1.813**	**1.641**	**1.638**	**1.635**	**1.735**	**1.066**	1.000	1.082	1.000
ES	**1.700**	1.728	1.473	**1.638**	**1.627**	1.451	**1.685**	1.013	1.000	1.082	1.000
FI	**1.981**	**2.040**	**1.864**	**1.800**	**1.753**	**1.676**	**1.803**	1.024	1.000	1.082	1.000
FR	**1.748**	**1.821**	1.630	**1.542**	**1.543**	**1.533**	1.610	1.057	1.000	1.082	1.000
UK	**1.886**	**2.047**	**2.006**	**1.455**	**1.430**	**1.638**	**1.675**	**1.116**	1.000	1.082	1.000
HE	1.471	1.581	1.525	1.208	1.195	1.340	1.519	1.052	**1.075**	1.069	1.000
HU	1.524	1.645	1.531	1.382	1.374	1.446	1.612	1.046	1.000	1.076	1.000
IE	1.531	1.621	1.501	1.327	1.272	1.338	1.553	1.037	**1.084**	1.062	1.000
IT	1.526	1.610	1.647	1.251	1.222	1.369	1.524	**1.117**	1.001	**1.102**	1.000
NL	**1.945**	**2.062**	**2.020**	**1.404**	**1.385**	**1.657**	**1.667**	**1.150**	1.000	**1.141**	1.000
NO	**1.831**	**1.897**	**1.957**	**1.479**	**1.403**	**1.638**	**1.666**	**1.111**	1.004	1.081	1.000
PL	1.386	1.493	1.348	1.163	1.140	1.229	1.549	1.028	**1.109**	1.060	1.000
PT	1.267	1.439	1.306	1.095	1.096	1.177	1.543	1.021	**1.122**	1.060	1.000
RO	1.054	1.229	1.033	1.000	1.004	1.020	1.541	1.001	**1.152**	1.049	1.000
SE	**1.966**	**2.023**	**1.716**	**1.851**	**1.819**	**1.641**	**1.807**	1.000	1.000	1.082	1.000
Average	1.649	1.755	1.650	1.390	1.373	1.458	1.630	1.064	1.035	1.084	1.000
Weighted Average	1.637	1.729	1.614	1.403	1.390	1.445	1.607	1.066	1.023	1.084	1.000

RO register certain improvements (above-average values) at the end of the period (mainly during T4 and T5 periods).

5. Brief discussion and policy guidelines in some benchmark countries

Despite the significant policy and investment efforts made in recent decades in the design and implementation of solutions to tackle diffuse pollution derived from the use of mineral fertilizers in agriculture, their negative environmental externalities have yet to be significantly reduced (Okumah et al., 2019). This delay is mainly due to the special characteristics of this type of pollution (i.e., heterogeneity of pollution sources and pollutants, diffuse nature, invisibility, significant gaps in the knowledge on pollutant dynamics and monitoring), which impede the definition of policy and management instruments (Duckett et al., 2016). As a result, diffuse pollution generated by mineral fertilizers remains a persistent problem in the EU as the main soil pollutant (Malaj et al., 2014), and constitutes a major pressure for more than 40% of Europe's water bodies in rivers and coastal waters, and in one third of groundwater bodies, lakes, and transitional waters (EEA, 2018). According to the UN (2015), this problem is expected to increase in the next few years as a response to the pressure to intensify food production globally due to population growth and economic development. In this context, the need to analyze and research into effective measures for the reduction of fertilizer pollution has become more urgent than ever.

This study has assessed the efficiency paths in the period 2001 2012 for a group of EU countries, which has enabled individual and common trends to be assessed in the EU regarding the reduction in the use of mineral fertilizers in agriculture, and has also enabled the identification of certain best-performing countries from

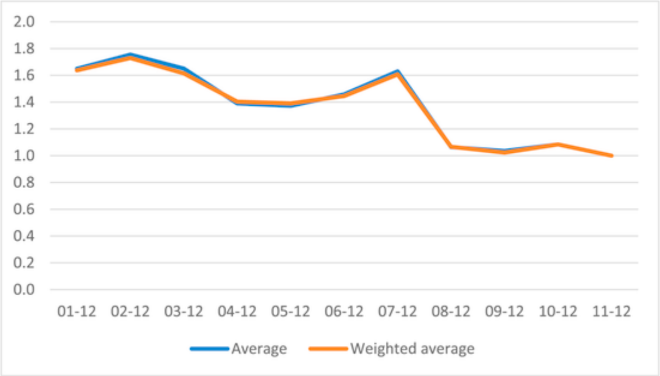

Fig. 4. Average MIs (decreasing temporal windows).

which lessons may be learnt. In the EU, as in the rest of the developed world, the biological maximum of crop yields has been achieved, and no significant additional increases are expected to be gained through the higher intensity of use of mineral fertilizers (Good and Beatty, 2011). On the basis of this reality, the EU aims to develop and coordinate EU agricultural and environmental (e.g., WFD, Nitrates Directive) policies to minimize the negative effects of the use of chemical inputs in agriculture based on the polluter pays and cost recovery principles (Berbel and Expósito, 2018). EU policy has also promoted the implementation of fertilization reduction programs by developing BNMPs, such as those that involve coordinating fertilizer requirements and application methods and rates for particular crops, soils, and soil water status. Though these programs have improved the quality of groundwater, rivers and lakes, results remain insufficient (EC, 2019a). As shown in Fig. 1, the use of mineral fertilizers was reduced in the period 2001 2012, although the decreasing trend observed until 2008 has reverted in recent years. Our findings reveal that a reduced group of countries have significantly outperformed the rest of the countries during the period analyzed. With the aim to offer useful information for policy- and decision-makers, the cases of Belgium-Luxembourg, Denmark, United Kingdom, Netherlands and Sweden are analyzed in greater detail, since they have been identified as benchmark countries from which lessons may be learnt.

5.1. Belgium-Luxembourg

According to the assessment report on the implementation of second-cycle RBMPs (EC, 2019a), Belgium has made significant efforts to guarantee the implementation of the Nitrates Directive and the WFD requirements to reduce the negative environmental impacts of mineral fertilizers. Along these lines, farmers are being instructed on the implementation of BNMPs through Rural Development Programs, and CAP funds are subject to the fulfillment of cross compliance requirements to minimize the use of fertilizers. Basic and supplementary measures for the control of diffuse pollution from agriculture at source are set in all RBDs and general binding rules are applied to nitrate and phosphorus uses. Financing is secured by national and European funds.

In the case of Luxembourg, the current Rural Development Program includes a wide spectrum of voluntary measures, in addition to those of the Nitrate Action Program and the mandatory measures of the national plant protection law. Stricter mandatory measures are largely included in relation to zones used for drinking-water abstraction. Since the first-cycle RBMPs, drinking-water protection measures (e.g., establishment of safeguard zones, buffer zones) have been implemented in five drinking-water protection zones near groundwater bodies, with specific Grand-ducal Regulations for each protection zone. Another seven protection zones are in the process of being designated through regulations, and a further 80 remain provisional designations under technical investigation (to be defined in the third-cycle RBMPs). For surface-water bodies, there is only one relevant protection zone (impoundment reservoir Obersauer Stausee) under the law of 27th May 1961 and the Grand-ducal Regulation of 16th December 2011, which also sets out the measures/restrictions at and around the site. There are a large number of agricultural measures which apply on a nationwide basis: both mandatory and voluntary measures. Mandatory measures include the prohibition of fertilizer application on strips of land along water courses, conditions relating to fertilizer application equipment, creation of additional storage capacity for organic fertilizer, restrictions on livestock numbers, measures related to nitrogen-fixing crops, and prohibition of ploughing on permanent grassland. Supplementary measures mainly include advice programs to farmers regarding voluntary measures and incentives to implement BNMPs.

5.2. Denmark

The Danish case is also worth noting, since the negative impacts of nutrient loads in water bodies have triggered the designation of the whole country as a Nitrate-Vulnerable Zone (Cruz et al., 2019). The most significant measures implemented by Denmark for the reduction of the use of mineral fertilizers follow certain initiatives: 1) Identification of BNMPs adjusted to land and crop differences (such as restricting nitrate applications in autumn, since these are often leached as toxic emissions over winter); 2) Development of legislation outlining specific fertilization inputs and management practices for each crop, including the adjustment of restrictive fertilizer standards to the level of economic optimum and adjustment of no-tillage regulation; 3) Definition of gaps and targets regarding fertilizer applications on a local and regional basis; 4) Implementation of online fertilizer accounts for each farmer, including information on cultivated area and type of crops, fertilizer use and intensity, fertilizer exchange, and stock; 5) Requirement to provide detailed fertilizer budgets before farmers are eligible to receive CAP subsidy payments; 6) Implementation of eco-taxes on agricultural pollutants, such as fertilizers; 7) Financing needs are secured in all RBDs through EU and national funds.

5.3. United Kingdom

The Catchment Based Approach framework was set up to establish independently-led, voluntary partnerships in each management catchment to engage local communities and encourage wider participation in identifying the local pressures, agreeing priorities, and planning on-going actions to tackle the priorities. Detailed descriptions of Programmes of Measures to tackle diffuse pollution from mineral fertilizers are given in all RBMPs, including the voluntary Countryside Stewardship program whose financial support comes from CAP funding. Supplementary measures for agricultural pollution, mainly based on a voluntary basis, are also implemented in all RBMPs with active assistance to farmers by Catchment authorities, the Environment Agency, and other public and private organizations. In this respect, the government of the United Kingdom has provided upwards of £9m in funding and operational support for projects delivered via Catchment Partnerships with more than 1500 organizations. Although, general binding rules are used in all RBDs, most measures not covered under the Nitrates Directive are on a voluntary basis and receive financial support from a variety of sources, such as Catchment Partnership action funds, Environment Agency Programmes, Water Company Investment programmes (National Environment Programme), and private funds.

5.4. The Netherlands

The Netherlands carried out a very detailed gap analysis, whose results were published in 2013 (Assessment of the effectiveness of the existing measures and identification of which additional measures are needed to close the gap in the implementation of the Nitrates Directive and the WFD). The Dutch government decided to take this ambitious gap analysis in the context of the process of the Delta-approach to intensify efforts towards reducing diffuse pressures in the Netherlands from agriculture. The Deltaplan Agrarisch Waterbeheer is a plan with specific measures to improve pollution from agriculture (e.g., nutrients) via additional measures (to those already foreseen by EU norms). The main objective is not only to define a set of mandatory measures to be fulfilled by all farmers countrywide (e.g., definition of specific BNMPs adapted to specific local and regional conditions), but also to design voluntary supplementary measures (Dalgaard et al., 2014). With the aim to ensure general acceptance and feasibility, this plan has been developed in cooperation with farmers and other social organizations, which guarantees positive outcomes. Sufficient financial resources are secured through Horizon 2020, CAP, structural and cohesion funds and national funds.

Work in this direction is still ongoing and regional analyses are being carried out that will be integrated into a national analysis in 2019. These results will feed into the third RBMPs and in the 7th Nitrates Action program. The latest Nitrates Action programs define safeguard zones surrounding drinking-water protection areas in all RBMPs and state that if water extraction takes places for human consumption, then the whole water body is designated as a protected area. Specific binding rules designed for agrochemical diffuse-pollution abatement in water bodies are established in all RBDs for nitrates, phosphates, and pesticides.

5.5. Sweden

The case of Sweden shares certain similarities with the Austrian and Danish cases, such as the implementation of eco-taxes on fertilizers, the application of general binding rules for nitrates and phosphorus to control diffuse pollution from agriculture in all RBDs, and the requirement for farmers to provide detailed fertilization budgets to obtain access to CAP subsidy payments. Sweden has ensured that the designation of Nitrate-Vulnerable Zones and the revision of Action Programs effectively contribute towards the environmental goals set by EU legislation (e.g., guaranteeing the implementation of safeguards and buffer zones and the set of fertilization load limits). In this direction, the project Focus on nutrients , which was started in 2001, has achieved a reduction of 7.5 kg N/ha on arable farms, and nitrogen transported in rivers has decreased by 20 30% in ten years (Helssten et al., 2017). This project involves 8000 farmers and features voluntary participation, the implementation of farm-specific measures, and follow-up visits to participating farms, which together imply a positive net benefit from advisory services for farmers. Similarly to the Danish case, nutrient balances can be assessed online by the farmers themselves (Nordin and Hojgard, 2016).

These reviewed cases constitute good examples of better mineral fertilization management in the EU context through better coordinated and detailed action programs, the use of specific economic instruments (e.g., environmental taxation, individual incentives), the guarantee of reliability through collaboration with the farming community, and through securing the financial resources required. On the EU scale, the better management of mineral fertilizers should focus on the bigger picture and should develop strategies for the benefit of air, soil, water, climate, and biodiversity. In seems obvious that the wide variety of agricultural practices and fertilizer application rates among EU countries indicates that there is scope for the improvement of fertilizer-use efficiency and for a reduction in its negative environmental effects, without significant reductions of agricultural yields (Van Grinsven et al., 2015). In this respect, a suitable balance between voluntary actions and mandatory measures (and rules) needs to be set up on a European level, through taking into account significant differences in agricultural conditions between countries and regions. The participation of the farming community, together with other social groups, in the design of these measures should be also guaranteed to ensure technical feasibility and general acceptance (Zhang et al., 2018). In 2017, the EC launched an Environmental Implementation Review (EIR) to improve the implementation of environmental policies, including those related to agricultural practices (e.g., precision farming, nutrient management planning) (EC, 2017b). This EIR has been revised in 2019 (EC, 2019c) to offer an opportunity to work on identifying and resolving the gaps in implementation and compliance that exist between agricultural and environmental policies (as it is the case of intensive use of mineral fertilizers by the agricultural sector).

6. Conclusions

This study carries out a dynamic assessment analysis of the environmental efficiency of the agricultural sector for a representative group of 21 European countries. The DEA analysis presented herein assesses the capacity of these countries to minimize fertilizer-use intensity without compromising their agricultural output capacity from a dynamic temporal windows approach, enabling temporal efficiency trends to be assessed in the medium and long term. The analysis shows which countries register reductions in fertilizer use while maintaining or even increasing the value of their agricultural output, thereby enabling the identification of those benchmark countries regarding the management of fertilizer use by the agricultural sector. To this end, the principal measures implemented in several of these identified benchmark countries have been described and discussed. These cases constitute good examples of the best management of mineral fertilization in the EU context through: well-coordinated and detailed action programs; the use of specific economic instruments (e.g., environmental taxation); the guarantee of reliability through collaboration with the farming community; and through securing the required financial resources, among other initiatives. On the EU scale, the better management of mineral fertilizers should focus on the bigger picture and develop strategies for the benefit of air, soil, water, climate, and biodiversity. This study offers valuable information in terms of providing information for policy- and decision-making in the EU, since the high heterogeneity in the application of mineral fertilizers shows that there is scope not only for the improvement of fertilizer-use efficiency, but also for a reduction in its negative environmental impacts. Further research will be focused on analyzing the determinants of the efficiency performance paths identified herein, through testing the significance of certain measures in the countries under analysis, such as resource funding and specific environmental taxation instruments.

CRediT authorship contribution statement

Alfonso Expósito: Conceptualization, Methodology, Formal analysis, Writing - original draft, Validation, Visualization, Supervision. **Francisco Velasco:** Data curation, Methodology, Software, Writing - review & editing.

Methodological Appendix.

Our DEA optimization problem is described by means of an axiomatic expression, where $X \in R_m^+$ represents the vector of inputs,

$G \in R_s^+$ is the desirable output vector, and $B \in R_h^+$ is the undesirable output vector. These are all column vectors with positive components. The concept of managerial disposability indicates that the analyzed decision-making units (DMUs), or countries in our specific case, may increase or maintain the input vector to decrease the vector of undesirable outputs, for which it needs to use innovative measures (e.g., innovative fertilization practices, such as fertigation and manure management, or other innovative measures in legislation and cooperation among agents for the improvement of the input-output relationship). These measures can be carried out in parallel if it is possible to increase (or at least maintain) the desired output vector. In this respect, our optimization problem can be specified by the following production function:

$$P^m(X) = \left\{ (G,B)\ ; G \le \sum_{j=1}^{n} G_j\,\lambda_j;\ B \ge \sum_{j=1}^{n} B_j\,\lambda_j;\ X \le \sum_{j=1}^{n} X_j\,\lambda_j;\ \lambda_j \ge 0,\ j = 1, \dots n \right\}$$

The DEA window analysis technique was developed by Banker et al. (1984) and Charnes and Cooper (1985), although subsequent developments have been delivered by Charnes et al. (1994) and Sueyoshi et al. (2017), among others. Under this methodology, a window with n x w observations is denoted starting at a time t (1 < t < T) with window width w (1 w< =T-t), where T is the number of periods. In our specific case, n = 20 (number of countries) and T = 13 (years in the period 2000 2012). Although Charnes et al. (1994) suggested a window width of a minimum of 3 4 periods to obtain the best balance of information and stability, this study uses different window widths to test the robustness of the findings. Once the window width is set, relative efficiency scores (unified managerial efficiency (UME) scores) can subsequently be analyzed over a time horizon using the values of the MI (Sueyoshi et al., 2017). In our MI measurement, frontier crossovers of periods have been considered, since outcomes of innovations, implemented to increase the efficiency at reducing undesirable outputs while maintaining/increasing desirable outputs, usually involve a time lag. The MI with frontier crossovers can be specified with the following expression:

$$MI_z^{\mathrm{t-1\&t}} = \sqrt{\frac{UME_z^R}{IUIM_{z\to \mathrm{t-1\&t}}^R}\ \frac{IUIM_{t\to z}^R}{UME_{t\to \mathrm{t-1\&t}}^R}}$$

The components of the specified MI are obtained as follows. The degree of UME_z^R (Unified Managerial Efficiency in the z-th period) regarding de k-th DMU in the z-th period is obtained by:

$$Max\ \xi + \varepsilon_s \left[\sum_{i=1}^{m} R_i^x d_i^{x+} + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b\right]$$

$$s.t. \sum_{j\varepsilon J_z} x_{ijz}\,\lambda_{jz} - d_i^{x+} = x_{ikz}\ ;\ \forall\, k\varepsilon J_z\ ;\ i = 1, \dots, m$$

$$\sum_{j\varepsilon J_z} g_{rjz}\,\lambda_{jz} - d_r^g\ -\ \xi\ g_{rkz} = g_{rkz};\ \forall\, k\varepsilon J_z\ ;\ r = 1, \dots, s$$

$$\sum_{j\varepsilon J_z} b_{fjz}\,\lambda_{jz} + d_f^b\ +\ \xi\ b_{fkz} = b_{fkz};\ \forall\, k\varepsilon J_z\ ;\ f = 1, \dots, h$$

$$\lambda_{jz} \ge 0;\ j = 1, \dots, n; z : \mathit{a\ base\ period}\ ;\ \xi\ \text{Unrestricted};\ d_i^{x+} \ge 0; i = 1, \dots, m$$

$$d_r^g \ge 0; r = 1, \dots, s;\ d_f^b \ge 0;\ f = 1, \dots, h$$

$$UME_z^R = 1 - \left[\xi^* + \varepsilon_s \left(\sum_{i=1}^{m} R_i^x d_i^{x+*} + \sum_{r=1}^{s} R_r^g d_r^{g*} + \sum_{f=1}^{h} R_f^b d_f^{b*}\right)\right]$$

Similarly, the degree of $UEM_{t\to \mathrm{t-1\&t}}^R$ on the k-th DMU in the t-th period (t = z+1, ,T) is obtained by the following model:

$$Max\ \xi + \varepsilon_s \left[\sum_{i=1}^{m} R_i^x d_i^{x+} + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b\right]$$

$$s.t. \sum_{j\varepsilon J_{\mathrm{t-1\&t}}} x_{ij\mathrm{t-1\&t}}\,\lambda_{j\mathrm{t-1\&t}} - d_i^{x+} = x_{ikt}\ ;\ \forall\, k\varepsilon J_t\ ;\ i = 1, \dots, m$$

$$\sum_{j\varepsilon J_{\mathrm{t-1\&t}}} g_{rj\mathrm{t-1\&t}}\,\lambda_{j\mathrm{t-1\&t}} - d_r^g\ -\ \xi\ g_{rkt} = g_{rkt};\ \forall\, k\varepsilon J_t\ ;\ r = 1, \dots, s$$

$$\sum_{j\varepsilon J_{\mathrm{t-1\&t}}} b_{fj\mathrm{t-1\&t}}\,\lambda_{j\mathrm{t-1\&t}} + d_f^b\ +\ \xi\ b_{fkt} = b_{fkt};\ \forall\, k\varepsilon J_t\ ;\ f = 1, \dots, h$$

$$\lambda_{j\mathrm{t-1\&t}} \ge 0;\ j = 1, \dots, n\ \mathit{and\ specific}\ t;\ \xi\ \text{Unrestricted};\ d_i^{x+} \ge 0; i = 1, \dots, m$$

$$d_r^g \ge 0; r = 1, \dots, s;\ d_f^b \ge 0;\ f = 1, \dots, h$$

The degree of $UME_{t\to \mathrm{t-1\&t}}^R$ is measured by:

$$UME_{t\to \mathrm{t-1\&t}}^R = 1 - \left[\xi^* + \varepsilon_s \left(\sum_{i=1}^{m} R_i^x d_i^{x+*} + \sum_{r=1}^{s} R_r^g d_r^{g*} + \sum_{f=1}^{h} R_f^b d_f^{b*}\right)\right]$$

The degree of $IUIM_{z\to \mathrm{t-1\&t}}^R$ (Inter-temporal Unified Index from the z-th period to the t 1 & t-th periods) of the k-th DMU in the z-th period is obtained by the following model:

$$Max\ \xi + \varepsilon_s \left[\sum_{i=1}^{m} R_i^x d_i^{x+} + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b\right]$$

$$s.t. \sum_{j\varepsilon J_{\mathrm{t-1\&t}}} x_{ij\mathrm{t-1\&t}}\ \lambda_{j\mathrm{t-1\&t}} - d_i^{x+} = x_{ikz}\ ;\ \forall\ k\varepsilon J_z\ ;\ i = 1, \dots, m$$

$$\sum_{j\varepsilon J_{\mathrm{t-1\&t}}} g_{rj\mathrm{t-1\&t}}\ \lambda_{j\mathrm{t-1\&t}} - d_r^g\ -\ \xi\ g_{rkz} = g_{rkz};\ \forall\ k\varepsilon J_z\ ;\ r = 1, \dots, s$$

$$\sum_{j\varepsilon J_{t-1\&t}} b_{fj\mathrm{t-1\&t}}\ \lambda_{j\mathrm{t-1\&t}} + d_f^b\ +\ \xi\ b_{fkz} = b_{fkz};\ \forall\ k\varepsilon J_z\ ;\ f = 1, \dots, h$$

$$\lambda_{j\mathrm{t-1\&t}} \geq 0;\ j = 1, \dots, n \text{ and specific } t;\ \xi \text{ Unrestricted}; d_i^{x+} \geq 0; i = 1, \dots, m$$

$$d_r^g \geq 0; r = 1, \dots, s;\ d_f^b \geq 0;\ f = 1, \dots, h$$

Therefore, the degree of $IUIM^R_{z\to\mathrm{t-1\&t}}$ with respect to the k-th DMUs can be measured by:

$$IUIM^R_{z\to\mathrm{t-1\&t}} = 1 - \left[\ \xi^* + \varepsilon_s \left(\sum_{i=1}^{m} R_i^x d_i^{x+*} + \sum_{r=1}^{s} R_r^g d_r^{g*} + \sum_{f=1}^{h} R_f^b d_f^{b*} \right)\right]$$

The degree of $IUIM^R_{t\to z}$ (Inter-temporal Unified Index from the t-th period to the z-th period) of the k-th DMU in the t-th period is determined by the following model:

$$Max\ \xi + \varepsilon_s \left[\sum_{i=1}^{m} R_i^x d_i^{x+} + \sum_{r=1}^{s} R_r^g d_r^g + \sum_{f=1}^{h} R_f^b d_f^b \right]$$

$$s.t. \sum_{j\varepsilon J_z} x_{ijz}\ \lambda_{jz} + d_i^{x+} = x_{ikt}\ ;\ \forall\ k\varepsilon J_t\ ;\ i = 1, \dots, m$$

$$\sum_{j\varepsilon J_z} g_{rjz}\ \lambda_{jz} - d_r^g\ -\ \xi\ g_{rkt} = g_{rkt};\ \forall\ k\varepsilon J_t\ ;\ r = 1, \dots, s$$

$$\sum_{j\varepsilon J_z} b_{fjz}\ \lambda_{jz} + d_f^b\ +\ \xi\ b_{fkt} = b_{fkt};\ \forall\ k\varepsilon J_t\ ;\ f = 1, \dots, h$$

$$\lambda_{jz} \geq 0;\ j = 1, \dots, n; \text{specific } t;\ \xi \text{ Unrestricted}; d_i^{x+} \geq 0; i = 1, \dots, m$$

$$d_r^g \geq 0; r = 1, \dots, s;\ d_f^b \geq 0;\ f = 1, \dots, h$$

Therefore, the degree of $IUIM^R_{t\to z}$ with respect to the k-th DMU is measured by:

$$IUIM^R_{t\to z} = 1 - \left[\ \xi^* + \varepsilon_s \left(\sum_{i=1}^{m} R_i^x d_i^{x+*} + \sum_{r=1}^{s} R_r^g d_r^{g*} + \sum_{f=1}^{h} R_f^b d_f^{b*} \right)\right]$$

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