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The Effects of Greenhouse Gas Emissions on Cereal Production in the European Union

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Abstract: Considering food security and climate change mitigation as the main sustainability challenges for agriculture, the main goal is to achieve agricultural production at an acceptable level of greenhouse gas (GHG) emissions. In this paper, the effects of GHGs are described. Panel data models are built to assess the impact of greenhouse gases on harvested production of cereals in EU countries. The study is focused on the climate change cause by GHG emissions that have a direct impact on agriculture in what concerns cereal production. Therefore, the impact of GHGs on cereal production in the European Union, except Malta, in the period 2000–2016 was assessed. Moreover, the effects of GHGs on agricultural irrigated land in Denmark and Hungary, two EU countries with the large agricultural surface, were computed. The results indicated a positive impact of GHGs from agriculture and fertilizer consumption in the previous year on cereal production in the EU. Moreover, only in Hungary did the increase in GHG emissions determined a slow increase in the volume of agricultural irrigated lands in the period of 2000–2016.

Keywords: greenhouse gas emissions; agricultural production; cereals; agricultural irrigated land; climate change

1. Introduction

Human activity, including agriculture, contributes to the creation of greenhouse gases (GHG) that have been growing fast since the start of the industrial age [1]. The major challenges for agriculture in developing countries are represented by food security and climate change mitigation [2]. Since 1970, the global agricultural production has increased, on average, by more than two2 times with a contribution of almost a quarter of the total GHG burden in 2010. Food production has to grow to satisfy our growing demands, but climate change should be addressed and GHG emissions have to decrease. Bennetzen et al. [3] showed that except for the energy use in farming, the GHG emissions from all sources grew less than agricultural production. The authors stated there is decoupling between GHG emissions and agricultural production in recent decades.

By measuring GHG emissions from the production of various food commodities, researchers, farmers, and policymakers can better manage these emissions and identify suitable mitigation strategies to ensure higher food security and sustainable development [4,5].

At the world level, agriculture is the main source of climate change, contributing around 14% of anthropogenic greenhouse gas (GHG) emissions, and another 17% through land use change. Most of the next increases in agricultural emissions will be, most probably, registered in low- to middle-income countries [6].

The latest data from the European Union indicate a slow increase in GHG as of 2017, this growth by 0.6% in 2017 as compared to 2016 being mostly attributed to the transportation sector. Chances to achieve the 2020 targets are getting smaller with every new day, thus, constant efforts should be made to achieve the newer targets established for 2030 already. In this context, the EU countries should deliver measures and policies to meet the Paris agreement commitments and the new targets for 2030. Changes in the EU climate legislation were made in 2018 stipulating a decrease in GHG by minimum 40% until 2030 as compared to the 1990 level. In case of full implementation of the EU policies, the emissions are expected to decrease by 45% until 2030, which would be a better performance than that established by the Paris Agreement [7]. There is still a significant decoupling between emissions and economic growth, even if the CO_2 per unit of GDP decreased as compared to 1990. The emission of GHG from agriculture, transportation and international aviation has grown in the last five years. The efforts made in the direction to low carbon transition were supported by the integration of climate issues into the EU budget. Climate aspects required 20% of this budget in 2017. For the next budget, this share will be increased to 25% in order to achieve the climate objectives for the period of 2021–2027 [7].

Industrialized countries made efforts to reduce their actual levels of GHG emissions, while developing countries are still struggling to find an alternative to low-carbon development pathways. One of these alternatives is climate-smart agriculture (CSA) that transforms agricultural systems to achieve three goals: increased food security, climate change adaptation, and mitigation. In developing countries, mitigation is a co-benefit, the main propriety being food security and adaptation [8,9]. CSA is complementary with sustainable intensification (SI) that focuses on the growing agricultural productivity using actual agricultural land when environmental impact is reduced. Increased resource use efficiency contributes to SI like CSA through productivity growth and lowers GHG emissions per unit of output [8]. CSA and SI both focus on the potential trade-offs between agricultural production and environmental integrity. The trade-off's potential helps in achieving a more productive and sustainable agricultural sector [10–13].

Agriculture releases to the air significant quantities of carbon dioxide, methane, and nitrous oxide [14]. The major challenge of GHG is the climate change that consists in extreme phenomena like storms, cyclones or very high temperatures. These climate conditions have a direct impact on production.

Agriculture land occupies around 40–50% of the land surface generating almost 12% of the total GHG emissions at the world level [10]. Greenhouse gas emissions are influenced by land utilisation, especially by the types of crops. The emission might vary with a crop type. In general, long-run effects of land use are smaller than short-term ones. Land use effects on the emission of CO_2 are dominated by tillage. In case of N_2O, the highest emissions are usually caused by fertilized grasslands [12]. The ploughing-in of residues can generate CO_2 and N_2O emissions. Industrialization cannot be directly responsible for changes in the concentration of water vapour, the main cause of these changes being attributed to climate warming [13].

There are just few studies dealing with assessment of impacts of GHG emissions from agriculture and their impacts [3,12–14]. These studies do not provide assessment of GHG emissions on cereal production or irrigated land. The main input of this study is assessment of GHG emissions impact on cereal production by taking into account mineral consumption. Therefore, our study attempts to assess the impact of GHG emissions from agriculture on the cereal production in the states of the European Union, excluding Malta, which does not produce cereals as such. On the other hand, during drought periods GHG emissions cause the necessity for extra irrigation. Therefore, the effects from GHG emissions might also be assessed taking the share of agricultural irrigated lands into account. In this paper, we will evaluate the relation between irrigated surfaces and GHG emissions from agriculture for Denmark and Hungary, the countries with large irrigated areas in EU agriculture. After a short review of literature regarding the necessity to reduce GHG emissions due to their negative consequences, the paper presents the assessment of the GHG emissions' impact on cereals' production and irrigated lands in EU countries. The last part of this paper draws some final conclusions.

2. The Greenhouse Gas Emissions from Agriculture and the Necessity to Mitigate Them

2.1. The Impact of GHG Emissions on Agriculture

The greenhouse gas (GHG) emission has significant effects on the environment:

- Temperature increases determine increases in the water levels through dilatation and melting of the glaciers which could bring the disappearance of some territories (the Maldives islands and coral islands are the most vulnerable ones in this regard) [14];
- Climate conditions are becoming more extreme with the fluctuations in the directions of storms and droughts;
- Significant changes in climate might lead to the sinking of low-altitude coastal areas, now exploitable in agriculture, because of the rise in sea level;
- Human health can be affected by climate transformations too: the waves of extreme heat cause deaths, encourage bacteria and mould, increase the quantity of insects (mosquitoes) and the infections (malaria and yellow fever in particular) [15].

Among the extreme meteorological events we should pay special attention to cyclones. These extreme climatic phenomena are usually named hurricanes when they are produced in the Atlantic Ocean, or typhoons when they are formed in the Pacific Ocean. They are also called tropical cyclones when they take place in the Indian Ocean [14]. For example, Irma was the most intense cyclone in the history with its 50 days of meteorological registrations by the satellite. It was also the strongest hurricane ever in the Atlantic Ocean. The previous record was registered by the super-typhoon Haiyan that affected the Philippines archipelago back in 2013 [4].

Glaciers in Switzerland melt at a high speed, losing almost one cubic kilometre of ice in the last year which means 900 billion litres of water. Zwally et al. [15] showed that glaciers melt intensified in the last 10 years and this tendency will continue even if the global warming will stop. Each year, the glaciers lose between 0.5–1 m from their bulk which is by 2–3 times more than the average loss in the previous century [15].

The currents' change might also have disastrous effects. The actual climatic zones might migrate towards the Poles which would provoke the movement of temperate climate with 200–300 km for each additional degree Celsius. The consequences for the ecosystem can be critical because the move of these favourable areas might turn out to be too fast and the natural regeneration might not take place as such [11].

In Northern Europe, abundant rains could be favourable for the agriculture on the one hand, however, the floods might be dangerous. In the south, the waves of heat are more frequent and threat the sources of drinking water. In Siberia, the thaw of permafrost moves the areas of vegetation 150–500 km closer to the North Pole [15]. In the Middle East, very strong droughts increase the areas under the desert, which leads to decrease in the sources of water, thus, agriculture is affected [11]. In South America, tropical cyclones, storms and floods are becoming more and more frequent.

2.2. GHG Mitigation Policies in Agriculture

According to experts, human activity is responsible for intensification of the Earth warming processes. Brunetière et al. [16] pointed out that the greenhouse gas emissions into the atmosphere in France are caused by transport (26% of them), industry (22%), animal husbandry (19%) and agriculture (19%). At the world level, the carbon dioxide (CO_2) from human activity comes from the following domains: 43% from agriculture, 24% from transportation, 19% from industries and 14% from the cities. The methane gas comes from animal husbandry (30%), rice plantation (22%), exploitation of oils deposits (17%), fires (11%) and waste decomposition (11%) [16]. There are no natural halocarbons in the atmosphere. Human activity is always responsible for their existence and, consequently, for the Earth's warming.

The GHG emissions' variation, especially those of CO_2, is tracked down by an international network collecting atmospheric samples. Today this method of data collection is additionally strengthened by the air collection techniques practiced over the continents. As humans are responsible for GHG emissions' excess, it is our duty to reduce the level of these emissions as soon as possible. In this regard, the experts propose, inter alia, the following measures:

- The production of energy coming from fossil fuel combustion should be limited using instead the renewable energy like solar, wind, biomass, tide, nuclear etc. [15];
- The reduction of GHG emissions from the main producing sectors: industry, agriculture, energy sector, construction etc. [16];
- Protection of natural carbon sinks (the ecosystems that might absorb CO_2 from the atmosphere, like oceans and forests) and intensification of the creation of complex carbon sinks [14].

However, these proposed measures are not enough. Some countries have already reacted to the negative consequences from the excess in GHG emissions, France being among them. Since 1990, the GHG emissions in this country decreased by 22% in industry, by 10% in agriculture, by 9% in the energy sector and by 8% in the sector of waste treatment [16].

Various international meetings have been taking place proposing policies to reduce GHG emissions. The most famous of them took place in June 1992, at Rio de Janeiro. The main objective of this conference was to ensure the level of gases that does not affect the climate. The Kyoto Protocol as of 1997 forced 38 industrialized countries to reduce their GHG emissions by 5% until 2012 as compared to the level in 1990. The Protocol constrained the US, the European Union and Japan to reduce the level of GHG emissions by 7%, 8% and, respectively, by 6%, even though later the US refused and asked for simple rules [1]. The conference held in Hague in 2000 proposed the application of this US offer which led, together with several other issues, to the suspension of talks as such without any compromise being achieved

The 2015 Paris Agreement of the United Nations Framework Convention on Climate Change established that GHG emissions from agriculture should be reduced as to respond to climate change and also that they have to decrease by 2 °C by 2100 [17].

Relatively recently, in June 2017, almost 300 delegates from the IMO Member States, intergovernmental organizations and NGOs participated in the first meeting of a working group concerned with the reduction of GHG emissions from ships.

2.3. Major Challenges of GHG Mitigation in Agriculture

Agricultural production brings off-farm emissions because of the accompanying manufacturing and transportation of herbicides, fertilizers, and pesticides. Almost 1.6 bln ha of land are used these days for crop production. In developing countries, around 1 bln ha are used for crop production. At the world level, almost 25% of the CO_2, 50% of the CH_4 and 70% of the N_2O from agriculture are produced by cultivated lands [18]. The GHG emissions together with ozone-depleting chlorofluorocarbons generate almost 96% of increase in radiative forcing since 1750.

Lands for agriculture that should meet the global food demand come from grasslands, forests, and other natural habitats [19]. Agriculture plays an important role in the global fluxes of carbon dioxide, methane, and nitrous oxide [20,21]. Carbon dioxide is mainly released from soil organic matter, burning of plant litter and microbial decay [22]. Methane appears when organic materials decompose due to lack of oxygen, mainly from fermentative digestion by stored manures, ruminant livestock, and rice grown in floods [23]. Nitrous oxide comes from the microbial transformation of nitrogen in manures and soils [24]. Agricultural GHG emissions are heterogeneous and complex, but they could be decreased [25]. Many mitigation opportunities stem from the currently available technologies. Burney et al. [26] considered that investment in agriculture is a good strategy to mitigate GHG emissions.

Table 1 presents the most frequent mitigation practices for GHG emissions.

Table 1. Measures aimed at reducing the GHG emissions from agricultural ecosystems.

Measures	Examples	CO_2	N_2O	CH_4	Observations
organic soil management [27–30]	Avoiding the drainage of wetlands	Reduced emissions	Uncertain effect	Increased emissions	Arable farmed organic soils could be large emitters of CO_2 and N_2O
Bioenergy [31–33]	Residues, energy crops, liquid, solid, biogas	Reduced emissions	Uncertain effect		Energy created by converting biomass from agriculture and by converting biogas from landfills and dairy cattle industry provides additional carbon-neutral energy sources
Degraded lands' restoration [34]	Nutrient and organic amendments, erosion control	Reduced emissions	Uncertain effect		A sustainable landscape management approach could indicate land degradation neutrality in order to improve the land resources' condition
Biosolid/manure management [35,36]	Anaerobic digestion		Uncertain effect	Reduced emissions	Manure management means optimizing the rate, period, and technique of manure application to crops
	More efficient use as a nutrient source	Reduced emissions	Reduced emissions		
	Improved storage and handling		Uncertain effect	Reduced emissions	
Livestock management [36,37]	Dietary additives and specific agents			Reduced emissions	Feasibility of this mitigation practice depends on cost-effectiveness, while the mitigation potential should be expressed per unit of product in order to evaluate the possible negative effects on animal production
	Improved feeding practices			Reduced emissions	
	Longer-term management and structural modifications and animal breeding			Reduced emissions	
Cropland management [36–38]	Residue/tillage management	Reduced emissions	Uncertain effects		Mitigation practices in cropland management might include: better agronomic practices, residue/tillage management, nutrient management, agroforestry, water management, rice management, land use change
	Agronomy	Reduced emissions	Uncertain effect		
	Nutrient management	Reduced emissions	Reduced emissions		
	Water management	Uncertain effect	Reduced emissions		
	Rice management		Uncertain effect	Reduced emissions	
	Agroforestry	Reduced emissions	Uncertain effect		
	Set-aside, land-use change	Reduced emissions	Reduced emissions	Reduced emissions	
Management of grazing lands/pasture improvement [39,40]	Grazing intensity	Uncertain effect	Uncertain effect		Grazing lands might be minor sinks of soil organic of CH_4 and N_2O, but strong sinks of soil organic carbon; grazing practices that decrease forage maturity will reduce neutral detergent fibre concentration, contributing to the reduction in CH_4 level
	Nutrient management	Reduced emissions	Uncertain effect		
	Growth in productivity	Uncertain effect	Uncertain effect		
	Fire management	Reduced emissions	Uncertain effect		
	Species introduction	Reduced emissions	Uncertain effect		

Source: Own compilation from the sources mentioned in the first column of this table.

Searchinger et al. [41] built a worldwide agricultural model to compute the GHG emissions from land-use change. Their results indicated that corn-based ethanol almost doubled the greenhouse emissions in the last 30 years and contributed to the increase in greenhouse gas emissions. Biofuels from switchgrass in the U.S. corn lands grew the GHG emissions by 50%. The utilization of good cropland to expand production of biofuels might intensify the global warming in a similar way like the conversion of grasslands and forests [41].

Various practices from agriculture (spraying, fertilizing, sowing, harvesting, soil tillage, transportation) require the use of tractors and, consequently, massive consumption of diesel fuel. For Turkey, Beran et al. [42] showed that agricultural diesel consumption produces up to 6606.7 thousand tonnes of CO_2. Therefore, the CO_2 emissions might be decreased by using more energy efficient tractors and also by means of applying innovative technologies and practices so that to improve the agricultural energy budget at the same time.

3. The Impact of Greenhouse Gas Emissions on Cereal Production and Agricultural Irrigated Lands in the European Union

3.1. Data and Methods

Given the fact that the main effect of greenhouse gases is related to climate change, our empirical study will assess the impact of greenhouse gas emissions on agriculture in terms of cereal production and use of agricultural irrigated lands in the European Union. The data availability preconditioned us to consider only two countries when studying the impact of greenhouse gas emissions on irrigated lands.

There are other factors that affect cereal production, actually. CO_2 is generated along with the utilization of fertilizer and the production of fertilizer. The use of fertilizer increases the cereal production, but after a period of fertilizer consumption. However, the fact that fertilizer is used gives us important information about the fact that the previous and the actual production is not large enough and more fertilizer is needed.

Our empirical analysis will be focused on newer directions of research in the related field:

- The evaluation of the effect from greenhouse gas emissions from agriculture and fertilizer consumption on the production of cereals in the states of the European Union (except Malta which does not have cereal production as such);
- The evaluation of the effect of greenhouse gas emissions from agriculture on the agricultural irrigated lands (% of the total agricultural lands) in Denmark and Hungary, the countries with large agricultural surfaces, as compared to the rest of the European Union.

Greenhouse gas emissions expressed in thousand tonnes include: CO_2, CH_4 in CO_2 equivalent, N_2O in CO_2 equivalent, PFC in CO_2 equivalent, HFC in CO_2 equivalent, SF_6 in CO_2 equivalent and NF_3 in CO_2 equivalent. The GHG emission indicator is measured only for agriculture. The sources of CO_2 in agriculture are: fossil fuels, land use changes and oil organic matter of the croplands. CO_2 emissions are predetermined in the first place by the use of agriculture machines and by production of fertilizers.

Fertilizers' consumption expressed in kilograms per hectare of arable land indicates the quantity of plant nutrients utilized per unit of arable land. Fertilizer products include potash, nitrogenous and phosphate fertilizers.

Harvested production here refers only to cereals, including seeds.

Agricultural irrigated land includes the agricultural areas purposely provided with water. The lands irrigated by means of controlled flooding are included into this category.

The data on greenhouse gas emissions and harvest production are obtained from the Eurostat database. The data on agricultural irrigated lands in Denmark and Hungary and fertilizer consumption in the EU countries are obtained from the World Bank database. All the data covers the period of 2000–2016, more details are presented in Appendix A where the set of data for all the EU countries is presented. The data we need has been available since 2002 for fertilizers' consumption and since 2000 only for the rest of the variables. Therefore, suitable techniques that could be applied on small sets of data were employed: panel data models and Bayesian models. In Table 2 we summarize the variables and the corresponding models.

Table 2. Variables and the corresponding models.

Countries	Dependent Variable	Explanatory Variables	Models
EU countries, except Malta	Cereal production	GHG emissions from agriculture Fertilizers' consumption	Panel data models
Denmark	Agricultural irrigated lands	GHG emissions from agriculture	Bayesian model
Hungary	Agricultural irrigated lands	GHG emissions from agriculture	Bayesian model

Source: Authors' construction.

The volume of agricultural irrigated lands had a significant tendency to increase in the period of 2000–2012 in Denmark, but in 2013 it abruptly decreased. In Hungary, this parameter was demonstrating fluctuations that can be explained by varying temperatures during summers. In the EU-28, due to different environmental policies, the greenhouse gas emissions from agriculture alone decreased by almost 6%. However, these GHG emissions still remain a challenge, particularly for agriculture.

Since the data are organized by countries and for a specific time period, we have used panel data regression models to estimate the impact of greenhouse gas emissions on cereal production. This method was also previously used in several similar environmental sociological studies [42,43]. A fixed-effect model controls for any unobserved, time-constant characteristics between the countries, as well as the events that occurred in each year effecting the countries at the same time. Therefore, the models indirectly control for any variables linked to GHG emissions from cereal production that are not observed within the model. The panel data model is presented below:

$$y_{it} = c + b \cdot x_{1it} + d \cdot x_{2it} + a_i + \varepsilon_{it} \tag{1}$$

where:

y_{it}—dependent variable in country i and year t;
x_{1it}, x_{2it}—explanatory variables in country i and year t;
a_i—individual effects;
ε_{it}—the error;
c—constant value;
b, d—parameters.

In our particular case, we get the following models estimated in Stata 15 (StataCorp LLC, Texas, USA):

Model 1:

$$\begin{aligned} cereals\_production_{it} \\ &= c_1 + b_1 \cdot GHG\_emisssions\_agriculture_{it} + d_1 \cdot fertilizer\_consumption_{it} \\ &+ a_{1i} + \varepsilon_{it} \end{aligned}$$

Then we conduct individual time series analysis for Denmark and Hungary to assess the impact of GHG emissions on irrigated lands. Due to the small time series (2000–2016), Bayesian linear models will be built using Gibbs sampling method of estimation in R.

Model 2:

$$irrigated\_land_t = \alpha + \beta \cdot GHG\_emissions\_agriculture_t + \varepsilon_t$$

Model 2 is necessary in this analysis because irrigated land is also influenced by GHG emissions. Global warming, due to GHG emissions, also contributes to the expansion of irrigated lands.

Bayesian linear models and panel data models have the main advantage of solving the issue of small sets of data. However, Bayesian models have also limits due to the method of estimation (Gibbs sampling). This method might marginalize out the closed form of parameters. Moreover, the samples are not independent as it is the case of rejection sampling. Gibbs sampling may fail if there is no path between islands of high-probability states and when all the states have positive probability and one island with high probability states. In this case, we considered a normal conjugate prior distribution for the model and an inverse-gamma distribution for error variance:

$$\left(\sigma^2\right) \rightarrow i.i.d.N\left(0, \sigma^2\right)$$

$$\sigma^2 \rightarrow InvGamma(1, 1)$$

3.2. Results

Panel data models are built to assess the impact of greenhouse gas emissions on harvested production of cereals in all of the EU countries, except Malta. The panel data for each variable were stationary at 5% level of significance according to Levin–Lin–Chu and Fisher-type test (Appendix B). Some random-effects models and a fixed-effects model were estimated to explain the production of cereals based on the quantity of greenhouse gas emissions from agriculture.

We checked the correlation between GHG emissions from agriculture and mineral fertilizer consumption and there is no significant contemporaneous correlation between these variables (according to a cross-sectional time series FGLS regression, the coefficient of fertilizers' consumption is 4.23 (p-value = 0.6320)) which means that it is possible to consider the two variables as explanatory ones in the same model (see Table 3).

Table 3. Random-effects GLS regression model explaining the cereal production based on greenhouse gas emissions from agriculture (2000–2016).

Variable	Coefficient	Standard Error	Z	p-value
Greenhouse gas emissions from agriculture	0.680	0.047	13.310	0.000
Fertilizer consumption	−3.410	1.230	−2.770	0.006
Constant	835.396	1312.081	0.640	0.524

Source: Own calculations.

A total of 87.63% of the variation in production can be explained by the differences between the countries in terms of greenhouse gas emission quantities. According to Table 3, greenhouse gas emissions from agriculture had a positive and significant impact on cereal production in the European Union. As expected, the increase in cereal production is explained by the higher level of greenhouse gas emissions from agriculture which might be due to extensive cultivation of cereals, but also due to more mineral fertilizers that were previously used, thus producing more GHG emissions. Fertilizers' consumption in the same period had a negative impact on cereal production, because fertilizer needs time to action. Indeed, the model suggests that the lands with low cereal production needed more fertilizers' consumption. In this context, a generalized estimating equation (GEE) population averaged model with autoregression of order one is considered to measure the positive impact of fertilizers' consumption (see Table 4).

Table 4. GEE population averaged model explaining cereal production in the EU countries (2000–2016).

Variable	Coefficient	Standard Error	Z	*p*-value
GHG emissions from agriculture	0.455	0.045	10.030	0.000
Fertilizers' consumption	8.534	1.876	4.550	0.000
Constant	−766.771	393.563	−1.950	0.051

Source: Own calculations of the authors.

As expected, after considering an autoregressive structure of order one in the population averaged model, we detected a strong positive impact of fertilizers' consumption on cereal production and lower impact of GHG emissions from agriculture on it. This econometric technique made a necessary separation between current GHG emission level and the current consumption of fertilizers that will later generate GHG emissions.

Knowing that there are significant differences between the countries in the panel set, a better methodological solution is to employ a cross-sectional time series FGLS regression under the hypothesis of heteroskedastic panels and no autocorrelation (see Table 5).

Table 5. Cross-sectional time series FGLS regression model explaining cereal production based on greenhouse gas emissions from agriculture and fertilizers' consumption (2000–2016).

Variable	Coefficient	Standard Error	Z	P > |z|
Greenhouse gas emissions from agriculture	0.707	0.008	84.550	0.000
Fertilizers' consumption	−7.922	2.3020	−3.440	0.001
Constant	−613.044	33.508	−18.300	0.000

Source: Own calculations.

According to Table 5, the greenhouse gas emissions from agriculture had a more significant positive impact on the cereal production in the European Union. This result reflects the positive effect of greenhouse gas emissions on agricultural production due to higher temperature ensured by these GHG emissions. As expected, fertilizers' consumption had no immediate impact on cereal production growth. Low production level, in turn, stimulated the use of more fertilizer.

We also built a dynamic panel data model with Arellano–Bover–Blundell–Bond estimation (see Table 6) to explain cereal production, considering the production in the previous year and fertilizers' consumption in the previous year.

Table 6. Dynamic panel data model (Arellano–Bover–Blundell–Bond estimation) to explain cereal production.

Variable	Coefficient	Standard Error	Z	P > |z|
Cereal production in the previous year	0.189	0.043	4.370	0.000
Greenhouse gas emissions from agriculture	0.703	0.039	17.780	0.000
Fertilizers' consumption in the previous year	7.168	3.030	2.360	0.018
Constant	−1045.466	635.019	−1.650	0.100

Source: Own calculations.

According to the dynamic panel data model in Table 6, cereal production in the previous year, GHG emissions and fertilizers' consumption in the previous year had, on average, a positive impact on cereal production. The strongest influence belongs to fertilizers' consumption. An increase in the fertilizers; consumption in the previous year by 1000 tonnes determines, on average, an increase in the actual cereal production by 189 tonnes. If fertilizers' consumption in the previous year grew, on average, by 1000 tonnes, the cereal production increased by 7168 tonnes. Actually, the increase in cereal production due to fertilizers' consumption in the previous year is by around 10 times more than the increase due to GHG emissions in agriculture. According to dynamic panel data model, an increase in the annual GHG emissions from agriculture by 1000 tonnes determines, on average, an increase in the actual cereal production by 703 tonnes in the period 2000–2016.

Denmark and Hungary have quite large agriculture surfaces. Now we will check whether greenhouse emissions have affected the agricultural irrigated land (as % of the total agricultural lands) in Denmark and Hungary as both these countries use irrigation quite extensively. Due to relatively small dataset (time series from 2000–2016), some Bayesian linear regression models will be constructed for each country.

According to Table 7, when the quantity of greenhouse gases from agriculture in Denmark increased by one thousand tonnes, the share of irrigated lands in total agricultural areas decreased, on average, by almost 0.33 percentage points.

Table 7. Bayesian model explaining the impact of greenhouse emissions in agriculture on agricultural irrigated lands in Denmark (2000–2016).

Variable	Mean	Standard Deviation
Constant	44.364400	9.657605
Greenhouse gas emissions from agriculture	−0.003250	0.000904
Variance	1.710600	0.788105

Source: Own calculations.

According to Table 8, if the quantity of greenhouse gas emissions from Hungarian agriculture increased by one thousand tonnes, the share of irrigated lands in total agricultural areas increased, on average, by almost 0.04 percentage points. This confirms the fact that mitigation of GHG emissions from agriculture should be top priority for less irrigated areas.

Table 8. Bayesian model explaining the impact of greenhouse gas emissions from agriculture on irrigated lands in Hungary (2000–2016).

Variable	Mean	Standard Deviation
Constant	−0.486444	3.114722
Greenhouse gas emissions from agriculture	0.000391	0.000507
Variance	0.286080	0.131798

Source: Own calculations.

The obtained results can be explained by the economic development of the countries that has helped them reduce the costs of irrigation and achieve higher rates of production at the same time. There are few methods for reducing costs of irrigation. For example, if drip systems are used, these systems reduce the water utilization up to 20% compared to sprinkler system. Actually, drip system provides a steadier water flow which goes directly into the soil. The use of landscaping strategies and the proper plants, correct irrigation scheduling and control, overhead systems for large areas, oversight and proper maintenance are usual practices for reducing costs of irrigation. In Denmark, further efforts should be made to reduce GHG emissions from agriculture: better management of manure to reduce nitrous oxide, extension of rotational grazing, energy conservation, etc.

4. Discussion

GHG emissions have been increasing during the whole last century because of fossil fuel burning and associated human activities [44]. Agriculture remains a major global source of GHG emissions. The growing world population puts pressure on agricultural production that aims to guarantee food security under GHG emissions' minimizing.

Our results are in line with the conclusions of Bennetzen et al. [3] who showed the decoupling between agricultural production and GHG emissions in the last decades. Several previous studies also showed that many techniques were applied to mitigate the GHG emissions from agriculture [27,45–47].

The positive effects of GHG emissions from agriculture on cereal production are revealed in this study. This might be explained by the increase in temperature which is favourable for cereal vegetation in some regions of Europe [25].

The obtained results are in line with [48] indicating that increase in GHG emissions have positive impact on crop yields in Northern and Eastern Europe. A study [48] also revealed a negative impact of increase in GHG emissions and climate change on crop yields just in the Mediterranean region. The impact of climate change on crop yields in other regions of EU was neutral [48]. The important limitation of current study is that EU regions were not singled out in the course of analysis. The impact of GHG emissions on cereal production needs to be addressed separately for North and Eastern Europe as well as for the Mediterranean Region, etc. Comparisons between these European regions will be made in order to assess the degree of achieving sustainable development which allows us to make recommendations for reducing the development gaps between regions. This issue will be analysed in a future research where the impact of GHG emissions on cereal production will be analysed in the context of achieving the objective of sustainable development.

Our results are in line with Venkat [49], Williams [50], Galnaitytė et al. [51] and Reif [52], all explaining that organic farming practices produce more greenhouse gas emissions as compared to conventional farming because of lower yields and extra reliance on machinery. We also obtained the result of higher cereal production under higher GHG emissions, which might be also explained by organic farming practices. Moreover, our econometric approach suggests higher impact of fertilizers' consumption on cereal production as compared to GHG emissions. This result is in line with Ladha et al. who proved the efficiency of fertilizers in cereal production [53]. However, the effects of fertilizers' consumption are not immediate, a lag of one year being necessary in this case to stimulate cereal production. The results of dynamic panel data model suggest that the increase in fertilizers' consumption in the previous year with one unit generates an increase in cereal production by 10 times more than GHG emissions growth. The suitable fertilizer contributes to biomass production growth that restores and maintains soil organic carbon levels. An efficient strategy to manage GHG emissions is necessary in order to apply ecologically intensive management practices for crops. Snyder et al. suggested that this type of strategy ensures nutrient use efficiency maintaining cereal production growth [54,55]. On the other hand, high-yielding crops might mitigate GHG emissions due to extra storage of carbon in the soil. The results for both countries that we have chosen to analyse separately indicate that when greenhouse gas emissions increased, the share of irrigated areas in Denmark decreased, while in Hungary we observe an increase in the share of irrigated lands. This might be explained by the fact that Denmark, as a developed country, unlike Hungary, made more investments in agriculture as to reduce the quantity of irrigations. Water retention in the soil could be enhanced using farming methods like conservation tillage, residue management, bunds, field levelling. Moreover, Denmark has implemented various technologies that decrease the nitrogen losses without affecting the crops.

Moreover, Denmark is the single country from the Baltic region that registered net export for agricultural products. This country has a significant percentage of arable lands and a moderate climate which is favourable for agriculture production. Also, high productivity of Danish agriculture can be explained by well-developed infrastructure and the use of most advanced technologies in this field.

At the same time, these results might be cautiously retained since the decreased share of irrigated areas might be also explained by the environmental legislation that requires more parks and forests instead of farmers' lands.

5. Conclusions

The increase of GHG emissions into the atmosphere has already led to global warming and accompanying climate change. Food production imposes high costs on the environment because of large GHG emissions from plants, soil, and livestock.

In this paper, we assess the impact of GHG emissions on cereal production in the EU countries, except Malta, and on agricultural irrigated lands in Denmark and Hungary, the EU countries with large agricultural areas. GHG emissions might affect cereal production and the volume of water needed for agricultural irrigation systems. Therefore, we employed the selected econometric techniques to evaluate the impact of GHG emissions on cereal production in the period of 2000–2016.

The main results show that the increase in GHG emissions from agriculture had a positive impact on cereal production in the EU. This means that the increase in GHG emissions brought the cereal production growth. This result suggests that efforts were made for a sustainable agriculture that produces more cereals in the conditions of ascending GHG. However, the impact of GHG emissions on cereal production needs to be addressed separately for Northern and Eastern Europe as well as for the Mediterranean region, etc. This could become one of the directions for future research in the same direction. The increased GHG emissions induced higher temperatures in Hungary and, consequently, more irrigated lands as compared to Denmark where control over GHG emissions is higher and a part of agricultural lands have been recently transformed into parks and forests.

Our study is limited by the fact that GHG emissions were not measured for the entirety of agriculture, but only for the lands covered by cereals, while GHG emissions arrive in the atmosphere from different various agricultural sources at the same time which is difficult to measure. However, most of the agricultural lands in Europe are designated to cereals. The relationship between GHG emissions and agricultural irrigated lands is checked for two countries only due to the lack of long data series for other EU countries. In a future study, we may consider the effects of GHG emissions on other indicators (productions of other plants, for example vegetables and some fruits). Moreover, it is useful to compare the impact of GHG emissions on the production of cereals, fruits and vegetables and to propose some measures to have an optimal effect of GHG emissions on each type of agricultural culture.

GHG emissions and utilization of global lands might develop in different directions depending on the trends in energy systems' and agriculture development [51]. An efficient use of land is required as to preserve energy and ensure a maximum production without negatively affect the environment. Sustainable Development Goals focus on poverty reduction and on promotion of a sustainable economic growth path by protecting the planet from degradation [52–56]. While these goals build on earlier commitments, their incorporation indicates the interest of countries worldwide to cooperate more on sustainable development issues. While some improvements have been already observed in what concerns fighting against global poverty, the environmental goals were not achieved as such and the reduction of GHG emissions should be an important objective for future debates on sustainable agriculture development.

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Appendix A

Table A1. Data for calculations.

Country	Country Index	Year	Cereal Production in Million Tones	GHG from Agriculture in Tones of CO_2 Equivalent	Total GHG in Tones of CO_2 Equivalent	Fertilizers Consumption in Kilograms Per Hectare of Arable Land
Belgium	1	2000	2512.9	11,350.62	147,323.6	
Bulgaria	2	2000	5242.5	4987.47	49,756.29	
Czech Republic	3	2000	6454.2	8975.75	139,419.5	
Denmark	4	2000	9412.7	11,227.9	74,119.51	
Germany	5	2000	45,271.2	67,562.78	1,004,997	
Estonia	6	2000	696.1	1078.02	13,916.58	
Ireland	7	2000	2173.9	20,295.16	75,014.25	
Greece	8	2000	4233.75	9124.74	124,216.5	

Table A1. *Cont.*

Country	Country Index	Year	Cereal Production in Million Tones	GHG from Agriculture in Tones of CO_2 Equivalent	Total GHG in Tones of CO_2 Equivalent	Fertilizers Consumption in Kilograms Per Hectare of Arable Land
Spain	9	2000	24,566.9	39,998.8	348,018.2	
France	10	2000	65,698.4	83,696.04	528,762.3	
Croatia	11	2000	2311.9	2887.95	17,750.01	
Italy	12	2000	20,622.2	34,914.39	536,621.4	
Cyprus	13	2000	48	632.31	8251.89	
Latvia	14	2000	923.6	2081.38	3641.24	
Lithuania	15	2000	2657.7	4156.97	9779.82	
Luxembourg	16	2000	152.8	695.38	8914.96	
Hungary	17	2000	10,036.4	6100.63	72,693.58	
Netherlands	18	2000	1818.8	21,243.78	225,422.9	
Austria	19	2000	4490.2	7506.43	64,306.92	
Poland	20	2000	22,340.6	31,005.77	359,134.4	
Portugal	21	2000	1623.46	7343.64	77,204.08	
Romania	22	2000	10,477.51	18,456.03	117,344.8	
Slovenia	23	2000	493.8	1873.69	12,976.94	
Slovakia	24	2000	2201.3	3378.74	40,144.17	
Finland	25	2000	4089.3	6466.33	48,188.59	
Sweden	26	2000	5670.3	7804.74	30,775.23	
United Kingdom	27	2000	23,985	49,551.63	710,020.2	
Belgium	1	2001	2358.5	11,132.17	145,635	
Bulgaria	2	2001	6055.8	4786.46	55,807.35	
Czech Republic	3	2001	7337.6	9082.41	138,744.5	
Denmark	4	2001	9423.1	11,224.88	76,481.69	
Germany	5	2001	49,709.3	67,125.01	1,019,402	
Estonia	6	2001	558.4	1090.55	16,204.51	
Ireland	7	2001	2165.1	19,996.11	77,843.59	
Greece	8	2001	4236.78	9109.03	124,785.4	
Spain	9	2001	18,055.4	39,306.84	344,860.3	
France	10	2001	60,246	83,127.12	518,344.5	
Croatia	11	2001	2829	3015.1	18,484.98	
Italy	12	2001	19,933.2	34,366.38	536,627	
Cyprus	13	2001	127.4	690.97	8146.61	
Latvia	14	2001	928	2201.84	3535.03	
Lithuania	15	2001	2345.3	4054.6	12,433.75	
Luxembourg	16	2001	144.3	681.24	9389.21	
Hungary	17	2001	15,046.9	6283.97	73,202.92	
Netherlands	18	2001	1862.6	20,762.88	225,785	
Austria	19	2001	4833.8	7448.97	65,428.22	
Poland	20	2001	26,960.3	30,614.99	367,460.5	
Portugal	21	2001	1307.16	7113.47	73,303.89	
Romania	22	2001	18,870.93	18,580.83	123,581.6	
Slovenia	23	2001	495.97	1851.17	12,660.12	
Slovakia	24	2001	3212	3398.24	43,410.81	
Finland	25	2001	3661	6511.77	51,845.23	
Sweden	26	2001	5390.7	7260.3	25,963.33	
United Kingdom	27	2001	18,959.4	46,979.11	712,637.6	
Belgium	1	2002	2639.3	10,999.97	143,580	327.8918
Bulgaria	2	2002	6754	4931.69	51,524.56	113.7684
Czech Republic	3	2002	6770.8	8855.49	135,603.1	81.67916
Denmark	4	2002	8803.7	11,302.85	77,219.48	97.55844
Germany	5	2002	43,391.3	65,025.57	1,032,688	220.074
Estonia	6	2002	524.7	1029.38	15,148.9	44.01402
Ireland	7	2002	1963.6	19,660.94	76,168.23	597.0178
Greece	8	2002	4249.66	9132.75	124,485	156.3769
Spain	9	2002	21,682.7	38,860.27	362,965.4	164.4518
France	10	2002	69,660.9	81,849.54	504,843.6	211.2838

Table A1. *Cont.*

Country	Country Index	Year	Cereal Production in Million Tones	GHG from Agriculture in Tones of CO_2 Equivalent	Total GHG in Tones of CO_2 Equivalent	Fertilizers Consumption in Kilograms Per Hectare of Arable Land
Croatia	11	2002	3080.2	2926.78	19,283.78	256.9883
Italy	12	2002	21,256.1	33,729.47	531,928.8	171.1219
Cyprus	13	2002	141.8	717.35	8350.11	159.65
Latvia	14	2002	1028.5	2183.59	4998.72	50.59507
Lithuania	15	2002	2539.1	4226.85	13,578.96	110.155
Luxembourg	16	2002	168.8	667.34	10,166.68	581.1452
Hungary	17	2002	11,705.7	6317.11	72,059.87	94.87625
Netherlands	18	2002	1823.9	19,576.38	223,663.6	428.8231
Austria	19	2002	4757.3	7336.49	71,950.76	234.0238
Poland	20	2002	26,877.3	29,929.56	347,981.8	116.1952
Portugal	21	2002	1508.44	7007.25	77,973.94	191.054
Romania	22	2002	14,356.5	18,892.92	125,370.6	34.78274
Slovenia	23	2002	610.73	1911.72	12,529.35	83.10638
Slovakia	24	2002	3193.6	3417.03	40,830.68	403.4762
Finland	25	2002	3939.4	6615.73	53,737.97	136.1426
Sweden	26	2002	5461.9	7393.26	29,274.46	99.88793
United Kingdom	27	2002	22,965.4	46,717.91	691,496.2	309.0218
Belgium	1	2003	2613.6	10,626.75	143,905.3	313.8371
Bulgaria	2	2003	3814.1	4827.31	55,298.22	147.3274
Czech Republic	3	2003	5762.4	8388.58	140,425	91.57431
Denmark	4	2003	9050.9	11,046.16	81,829.39	136.4003
Germany	5	2003	39,426	64,080.43	1,027,593	219.6981
Estonia	6	2003	505.7	1081.34	16,691.48	71.64954
Ireland	7	2003	2146.9	19,843.15	76,389.18	533.7733
Greece	8	2003	4290.68	9099.06	128,493.2	162.0903
Spain	9	2003	21,170.2	40,519.29	371,292.8	175.271
France	10	2003	54,982	79,336.78	505,548.6	223.3639
Croatia	11	2003	2013.84	2849.91	21,337.54	292.8021
Italy	12	2003	17,864.1	33,640.31	554,343	177.7025
Cyprus	13	2003	164.69	703.55	8740.66	158.2321
Latvia	14	2003	932.4	2234.8	5669.04	49.49425
Lithuania	15	2003	2631.8	4339.91	13,864.82	147.3843
Luxembourg	16	2003	164.1	633.59	10,646.59	267.4677
Hungary	17	2003	8769.6	6143.84	72,646.19	95.49706
Netherlands	18	2003	1917.1	19,175.87	224,073.2	438.2914
Austria	19	2003	4263.8	7188.72	87,005.24	297.1385
Poland	20	2003	23,390.8	29,364.19	358,489.6	128.8711
Portugal	21	2003	1194.71	6552.93	83,602.27	174.404
Romania	22	2003	12,964.4	19,451.89	130,665.2	38.63282
Slovenia	23	2003	398.75	1815.94	12,476.73	78.94834
Slovakia	24	2003	2490.3	3273.44	41,514.29	400.289
Finland	25	2003	3782.8	6476.98	60,660.28	118.386
Sweden	26	2003	5352.1	7399.75	32,698.22	98.23706
United Kingdom	27	2003	21,644.8	46,909.71	698,586.2	314.1898
Belgium	1	2004	2951	10,534.33	145,477.1	339.856
Bulgaria	2	2004	7462.8	5277.21	53,706.39	80.8518
Czech Republic	3	2004	8783.8	8583.03	140,765.8	87.00808
Denmark	4	2004	8963.2	10,983.24	75,393.19	144.7845
Germany	5	2004	51,097	64,012.91	1,007,915	215.1258
Estonia	6	2004	607.8	1121.78	16,853.04	84.30965
Ireland	7	2004	2501	19,572.03	73,921.37	466.4315
Greece	8	2004	4540.02	9139.04	129,205.1	176.4176
Spain	9	2004	24,848.6	39,629.37	387,324.6	165.4026
France	10	2004	70,496.6	79,460.75	503,629.5	212.108
Croatia	11	2004	3067.48	3054.24	21,319.49	312.5844
Italy	12	2004	23,294.2	33,376.68	552,996.7	181.4181
Cyprus	13	2004	111.41	681.98	8971.67	131.4071
Latvia	14	2004	1059.5	2168.01	7072.58	64.12884
Lithuania	15	2004	2859.4	4387.73	14,879.37	173.7602

Table A1. *Cont.*

Country	Country Index	Year	Cereal Production in Million Tones	GHG from Agriculture in Tones of CO_2 Equivalent	Total GHG in Tones of CO_2 Equivalent	Fertilizers Consumption in Kilograms Per Hectare of Arable Land
Luxembourg	16	2004	179	647.2	12,035.66	333.6129
Hungary	17	2004	16,779.3	6409.91	72,519.4	98.5211
Netherlands	18	2004	1923.3	19,019.46	224,972.6	357.3135
Austria	19	2004	5315.3	7170.01	82,409.48	131.3427
Poland	20	2004	29,635.1	29,354.21	352,015.8	129.1356
Portugal	21	2004	1378.83	6663.75	77,024.28	215.9395
Romania	22	2004	24,403.01	20,302.75	130,171.2	42.62524
Slovenia	23	2004	583.17	1753.99	12,681.63	83.66691
Slovakia	24	2004	3793.2	3036.22	42,473.47	358.6989
Finland	25	2004	3618.7	6434.47	55,410.34	132.7455
Sweden	26	2004	5507.8	7091.16	32,788.17	97.85392
United Kingdom	27	2004	22,074.5	46,894.88	694,623	287.3346
Belgium	1	2005	2817.5	10,312.48	141,556.3	329.1435
Bulgaria	2	2005	5839.1	4963.06	54,429.75	74.23196
Czech Republic	3	2005	7659.85	8257.49	138,395.1	89.555
Denmark	4	2005	9283.1	10,787.98	70,876.07	137.1171
Germany	5	2005	45,980.2	63,446.45	979,873.1	208.7571
Estonia	6	2005	759.7	1129.09	16,465.84	60.95134
Ireland	7	2005	1939.9	19,248.76	75,184.82	458.0372
Greece	8	2005	4416.61	8936.41	132,888.9	143.0409
Spain	9	2005	14,325	37,359.67	400,812	142.1395
France	10	2005	64,080.1	78,601.81	504,018.1	192.4626
Croatia	11	2005	3038.84	3029.67	21,504.31	294.5086
Italy	12	2005	21,505.1	32,711.68	551,063.7	171.7531
Cyprus	13	2005	70.19	624.16	9127.27	108.9756
Latvia	14	2005	1314.3	2245.76	7818.58	68.04029
Lithuania	15	2005	2811.1	4420.46	16,739.58	97.56412
Luxembourg	16	2005	160.6	635.84	12,325.27	313.15
Hungary	17	2005	16,212.5	6071.82	69,916.72	85.19887
Netherlands	18	2005	1857.3	18,822.76	220,081.6	337.8065
Austria	19	2005	4898.3	7103.85	81,908.82	135.7159
Poland	20	2005	26,927.8	29,511.99	353,281.6	161.9389
Portugal	21	2005	802.54	6613	87,654.33	202.7615
Romania	22	2005	19,345.46	20,505.81	126,331.7	51.35136
Slovenia	23	2005	576.29	1774.29	13,007.21	80.50395
Slovakia	24	2005	3585.3	3021.66	45,790.67	329.5511
Finland	25	2005	4058.3	6457.3	42,425.22	134.2173
Sweden	26	2005	5050.6	7096.57	32,095.52	87.76872
United Kingdom	27	2005	21,024.9	46,084.36	686,115.4	272.8225
Belgium	1	2006	2741.8	10,097.34	138,976.7	316.4525
Bulgaria	2	2006	5531.8	4845.77	54,212.51	73.93997
Czech Republic	3	2006	6386.1	8111.66	142,242.6	94.27358
Denmark	4	2006	8632.3	10,525.38	79,011.52	138.5812
Germany	5	2006	43,474.8	62,559.62	986,776	194.419
Estonia	6	2006	619	1123.75	15,895.8	75.65373
Ireland	7	2006	2083.07	18,932.99	75,386.18	431.8768
Greece	8	2006	3811.31	8839.92	128,908	124.6293
Spain	9	2006	19,091.8	36,669.01	387,950.2	142.3295
France	10	2006	61,707.9	78,626.58	489,253.1	190.3826
Croatia	11	2006	3034.64	2976.48	22,009.37	380.7877
Italy	12	2006	20,206.6	32,336.12	540,314.7	177.0316
Cyprus	13	2006	66.83	647.41	9391.46	109.0261
Latvia	14	2006	1158.7	2253.68	7199.35	62.6556
Lithuania	15	2006	1857.8	4396.09	17,967.8	102.1679
Luxembourg	16	2006	161.5	627.26	12,244.2	293.6333
Hungary	17	2006	14,467.4	6055.67	71,022.17	99.19513
Netherlands	18	2006	1749.9	18,806.84	215,118.6	353.1464
Austria	19	2006	4460	7077.16	84,416.76	130.6992
Poland	20	2006	21,775.9	30,221.1	373,160.7	159.3386

Table A1. *Cont.*

Country	Country Index	Year	Cereal Production in Million Tones	GHG from Agriculture in Tones of CO_2 Equivalent	Total GHG in Tones of CO_2 Equivalent	Fertilizers Consumption in Kilograms Per Hectare of Arable Land
Portugal	21	2006	1200.18	6551.88	73,155.79	137.0609
Romania	22	2006	15,759.32	20,522.75	127,335.6	40.59559
Slovenia	23	2006	493.56	1768.61	13,240.94	91.78157
Slovakia	24	2006	2928.8	2951.14	42,934.74	322.0056
Finland	25	2006	3790	6414.82	47,266.57	134.4955
Sweden	26	2006	4128.4	7252.1	27,477.61	86.29002
United Kingdom	27	2006	20,805.4	45,637.32	680,174.3	254.1844
Belgium	1	2007	2786.8	10,277.61	135,555	355.1847
Bulgaria	2	2007	3201.9	4701.61	59,387.79	102.0094
Czech Republic	3	2007	7152.9	8265.07	145,923	100.1696
Denmark	4	2007	8220.2	10,750.22	71,688.29	142.412
Germany	5	2007	40,632.1	61,972.9	960,477.9	221.8718
Estonia	6	2007	879.1	1179.45	19,198.73	75.87185
Ireland	7	2007	1997.04	18,629.4	73,345.53	427.5217
Greece	8	2007	3974.37	8971.78	133,216.3	96.90339
Spain	9	2007	24,543.7	37,842.12	401,775.3	157.7222
France	10	2007	59,469.9	79,534.12	480,286.4	209.3382
Croatia	11	2007	2534.23	2920.35	24,049.87	410.0634
Italy	12	2007	20,303.7	32,979.21	555,783.1	190.23
Cyprus	13	2007	63.53	643.89	9797.57	109.8361
Latvia	14	2007	1535.2	2347.46	8250.38	67.72475
Lithuania	15	2007	3017	4488.55	18,462.24	90.06537
Luxembourg	16	2007	148.4	641.42	11,751.41	276.4098
Hungary	17	2007	9652.9	6051.96	68,833.14	110.4094
Netherlands	18	2007	1622.6	18,556.54	214,239.8	302.1391
Austria	19	2007	4757.9	7118.3	81,349.05	110.2667
Poland	20	2007	27,142.8	30,854.09	379,013.5	181.1723
Portugal	21	2007	1066.84	6681.1	66,999.73	199.9086
Romania	22	2007	7814.83	20,613.75	132,581.1	44.63585
Slovenia	23	2007	531.89	1823.95	13,016.35	89.95062
Slovakia	24	2007	2793.2	3014.18	41,409.46	324.5257
Finland	25	2007	4137.3	6390.74	53,337.44	123.5029
Sweden	26	2007	5066.8	6869.15	23,524.66	89.33031
United Kingdom	27	2007	19,045	44,934.51	667,957.7	253.2457
Belgium	1	2008	3307.2	10,129.36	135,870.5	242.891
Bulgaria	2	2008	7015.6	4952.1	56,882.38	111.2429
Czech Republic	3	2008	8369.5	8382.73	138,224.6	87.26412
Denmark	4	2008	9073.5	10,693.69	63,232.79	147.6761
Germany	5	2008	50,104.9	64,327.79	955,916.3	159.5827
Estonia	6	2008	863.8	1236.16	17,235.75	100.363
Ireland	7	2008	2461.29	18,464.63	71,557.34	378.109
Greece	8	2008	5058.75	8715.16	128,418.6	119.0477
Spain	9	2008	24,179.7	34,787.88	369,970	106.5446
France	10	2008	70,246	79,988.68	473,840.5	152.4465
Croatia	11	2008	3725.5	2909.42	22,543.17	495.2283
Italy	12	2008	21,847.93	31,991.35	523,176.8	143.4763
Cyprus	13	2008	6.34	616.78	9931.03	112.0146
Latvia	14	2008	1689.4	2325.77	7378.31	66.94701
Lithuania	15	2008	3421.9	4340.16	17,378.31	86.68117
Luxembourg	16	2008	189.7	655.35	11,621.2	250.5161
Hungary	17	2008	16,840.6	6073.5	65,424.06	96.70076
Netherlands	18	2008	2062.6	18,619.91	213,569.5	267.7086
Austria	19	2008	5747.8	7225.72	82,401.8	110.0453
Poland	20	2008	27,664.3	30,928.18	372,487	157.7182
Portugal	21	2008	1313.19	6630.12	62,875.41	155.4888
Romania	22	2008	16,826.44	20,261.46	127,631.7	45.63525
Slovenia	23	2008	579.64	1739.62	14,554.47	75.08394
Slovakia	24	2008	4137	2904.63	43,233.55	279.843
Finland	25	2008	4229.1	6469.37	46,385	130.5808
Sweden	26	2008	5201.2	6968.36	21,437.18	99.01141
United Kingdom	27	2008	24,282	44,024.15	647,517.9	213.9883

Table A1. *Cont.*

Country	Country Index	Year	Cereal Production in Million Tones	GHG from Agriculture in Tones of CO_2 Equivalent	Total GHG in Tones of CO_2 Equivalent	Fertilizers Consumption in Kilograms Per Hectare of Arable Land
Belgium	1	2009	3324.3	10,288.06	122,880.3	300
Bulgaria	2	2009	6427.2	4772.11	48,621.55	104.6004
Czech Republic	3	2009	7832	7929.92	128,903.6	88.51698
Denmark	4	2009	10,116.8	10,406.89	64,572.13	102.9181
Germany	5	2009	49,748.2	63,664.35	888,919.9	181.4144
Estonia	6	2009	873.1	1173.28	13,902.32	69.41314
Ireland	7	2009	2063.03	18,278.6	65,347.07	477.3737
Greece	8	2009	5269.54	8497.16	121,095.6	63.09619
Spain	9	2009	17,827.3	35,403.55	332,777.4	96.92694
France	10	2009	69,999.9	79,150.97	458,784.6	120.5634
Croatia	11	2009	3441.8	2796.26	20,563.14	164.6793
Italy	12	2009	17,562.91	31,330.52	469,849.8	120.1116
Cyprus	13	2009	56.82	611.74	9694.45	181.4499
Latvia	14	2009	1663.1	2353.79	10,738.45	64.88356
Lithuania	15	2009	3806.6	4381.11	12,502.46	44.25573
Luxembourg	16	2009	188.6	658.86	11,105.47	244.5847
Hungary	17	2009	13,590.4	5722.63	60,802.64	77.48222
Netherlands	18	2009	2088.8	18,474.1	208,220.4	238.1711
Austria	19	2009	5144.2	7244.78	75,853	83.40627
Poland	20	2009	29,826.6	30,232.31	356,617.3	147.265
Portugal	21	2009	1119.83	6541.58	59,852.01	118.5657
Romania	22	2009	14,872.95	19,605.96	108,192	48.49323
Slovenia	23	2009	532.84	1753.24	12,701.26	78.3097
Slovakia	24	2009	3330	2798.28	38,824.93	233.8345
Finland	25	2009	4260.9	6487.93	29,373.94	107.9839
Sweden	26	2009	5250.2	6715.78	15,180.76	63.91205
United Kingdom	27	2009	21,618	43,830.67	590,443.1	239.8744
Belgium	1	2010	3105.2	10,235.8	130,524.1	344.1247
Bulgaria	2	2010	7136.41	5245.13	50,693.57	97.05336
Czech Republic	3	2010	6877.62	7761.98	131,425.8	95.84579
Denmark	4	2010	8747.7	10,326.04	61,863.82	113.7121
Germany	5	2010	44,069.94	62,853.35	925,381.6	211.5968
Estonia	6	2010	678	1192.37	19,219.06	68.38915
Ireland	7	2010	2040.32	18,349.23	65,861.86	462.4411
Greece	8	2010	4592.12	8815.94	114,983.9	122.4959
Spain	9	2010	19,869.15	34,712.01	318,328	130.6753
France	10	2010	65,505.66	77,780.83	472,139.2	150.538
Croatia	11	2010	3007.18	2717.5	20,065.22	297.3098
Italy	12	2010	20,960.33	30,526.61	473,438.3	122.746
Cyprus	13	2010	65.73	637.48	9408.37	202.7724
Latvia	14	2010	1435.5	2376	14,221.31	77.64791
Lithuania	15	2010	2796.7	4329.22	10,881.33	103.5348
Luxembourg	16	2010	166.19	668.17	11,997.12	258.1921
Hungary	17	2010	12,262	5642.44	60,853.54	84.33424
Netherlands	18	2010	1887	18,495.31	220,056.8	293.3258
Austria	19	2010	4817.87	7094.42	79,171.92	108.4873
Poland	20	2010	27,228.1	29,717.72	376,248.8	180.4783
Portugal	21	2010	1020.52	6472.12	58,381.3	148.9574
Romania	22	2010	16,712.88	17,505.79	102,402.8	52.54625
Slovenia	23	2010	568.83	1720.16	12,803.12	85.06394
Slovakia	24	2010	2571.24	2813.38	40,547.07	266.5692
Finland	25	2010	2989.3	6576.22	48,287.81	124.0797
Sweden	26	2010	4286.8	6799.98	16,513.4	81.73032
United Kingdom	27	2010	20,946	44,114.86	606,250.8	250.7538
Belgium	1	2011	2944.2	10,140.34	120,117.1	338.1818
Bulgaria	2	2011	7520.4	4897.07	60,030.54	133.0825
Czech Republic	3	2011	8284.81	7904.13	128,528.6	100.5765
Denmark	4	2011	8793.5	10,328.39	55,056.89	112.8487
Germany	5	2011	41,960.4	64,537.51	906,630.1	191.487

Table A1. *Cont.*

Country	Country Index	Year	Cereal Production in Million Tones	GHG from Agriculture in Tones of CO_2 Equivalent	Total GHG in Tones of CO_2 Equivalent	Fertilizers Consumption in Kilograms Per Hectare of Arable Land
Estonia	6	2011	771.2	1218.35	19,104.08	71.51802
Ireland	7	2011	2509.42	17,748.11	61,715.79	430.4802
Greece	8	2011	4785.69	8574.71	111,918.6	159.7077
Spain	9	2011	22,094.52	34,236.16	320,069.2	122.6165
France	10	2011	63,825.48	77,362.01	448,477.2	141.2993
Croatia	11	2011	2827.5	2785.56	20,677.9	311.0115
Italy	12	2011	17,923.47	30,861.56	465,141.3	134.3225
Cyprus	13	2011	70.2	619.21	9106.4	151.2024
Latvia	14	2011	1412	2395.87	13,214.96	83.2323
Lithuania	15	2011	3225.9	4345.41	11,116.61	77.6328
Luxembourg	16	2011	149.59	662	11,767.56	270.6053
Hungary	17	2011	13,678.21	5881.38	59,700.1	93.28828
Netherlands	18	2011	1685	18,173.86	206,237.6	246.8111
Austria	19	2011	5704.27	7146.13	76,509.92	103.3892
Poland	20	2011	26,767.4	30,088.15	368,514.2	169.7423
Portugal	21	2011	1158.46	6436.58	57,097.91	132.5053
Romania	22	2011	20,842.16	17,774.04	108,187.6	54.13496
Slovenia	23	2011	607.96	1696.47	12,959.41	95.93732
Slovakia	24	2011	3714.1	2806.24	39,046.5	256.5066
Finland	25	2011	3667.8	6410.69	38,898.46	80.23195
Sweden	26	2011	4646.4	7171.39	19,459.69	85.08148
United Kingdom	27	2011	21,485	44,013.6	557,965.8	238.7001
Belgium	1	2012	3011.5	9911.06	117,176.6	348.6924
Bulgaria	2	2012	6988	5017.11	54,872.99	95.86976
Czech Republic	3	2012	6595.49	7895.79	125,008.7	127.6652
Denmark	4	2012	9460.4	10,274.3	52,410.93	107.1133
Germany	5	2012	45,441	64,076.53	912,374.2	198.9216
Estonia	6	2012	991.2	1307.4	18,034.42	81.0701
Ireland	7	2012	2125.18	18,094.93	62,699.1	469.7325
Greece	8	2012	4282.21	8446.56	108,648.5	109.4488
Spain	9	2012	17,543.12	33,113.7	317,673.5	122.5808
France	10	2012	68,457.75	77,059.12	438,671.9	160.7863
Croatia	11	2012	2686.55	2704.64	19,144.4	191.3879
Italy	12	2012	18,958.76	31,455.39	451,413.9	122.5063
Cyprus	13	2012	90.75	593.81	8605.24	196.5268
Latvia	14	2012	2124.5	2506.49	11,971.32	91.56537
Lithuania	15	2012	4656.6	4379.52	12,010.84	107.056
Luxembourg	16	2012	153.43	642.5	11,389.24	258.5198
Hungary	17	2012	10,372.74	5945.19	55,277.76	99.61542
Netherlands	18	2012	1826	17,970.34	201,475.1	289.8121
Austria	19	2012	4875.88	7077.38	74,404.87	125.452
Poland	20	2012	28,543.8	29,956.2	361,368.6	177.8856
Portugal	21	2012	1178.9	6481.31	57,667.59	150.8605
Romania	22	2012	12,824.14	17,623.42	106,481.1	49.78086
Slovenia	23	2012	576.41	1679.31	12,517.31	106.9195
Slovakia	24	2012	3035.81	2890.52	35,629.74	250.3811
Finland	25	2012	3658.7	6373.21	30,057.66	80.28189
Sweden	26	2012	5070.6	6679.75	10,350.98	75.96158
United Kingdom	27	2012	19,515	43,534.5	575,575.3	235.029
Belgium	1	2013	3155.9	9904.48	117,438.4	340.31
Bulgaria	2	2013	9153.93	5497.68	48,946.29	109.1383
Czech Republic	3	2013	7512.61	8128.87	121,829.6	161.483
Denmark	4	2013	9050.7	10,277.98	55,618.9	116.6228
Germany	5	2013	47,793.2	65,242.18	930,850.9	203.4706
Estonia	6	2013	975.5	1303.52	20,368.99	82.3558
Ireland	7	2013	2400.6	18,923.95	62,263.3	472.9048
Greece	8	2013	4620.24	8380.53	100,571.8	117.2323
Spain	9	2013	25,373.44	33,373.32	286,432.1	143.5965
France	10	2013	67,323.34	75,832.11	436,461.4	169.4174

Table A1. *Cont.*

Country	Country Index	Year	Cereal Production in Million Tones	GHG from Agriculture in Tones of CO_2 Equivalent	Total GHG in Tones of CO_2 Equivalent	Fertilizers Consumption in Kilograms Per Hectare of Arable Land
Croatia	11	2013	3187.88	2536.99	17,400.73	160.8101
Italy	12	2013	18,212.33	30,252.61	406,621.6	129.3035
Cyprus	13	2013	51.92	550.18	7876.57	183.8706
Latvia	14	2013	1948.7	2570.33	12,342.1	100.6565
Lithuania	15	2013	4474.8	4357.33	11,443.61	109.6359
Luxembourg	16	2013	173.3	658.25	10,677.71	247.5901
Hungary	17	2013	13,609.91	6340.13	53,526.08	113.5586
Netherlands	18	2013	1823	18,447.22	202,059.4	231.1277
Austria	19	2013	4590.15	7059.12	75,636.8	135.6105
Poland	20	2013	28,455.1	30,497.88	355,081.6	179.3273
Portugal	21	2013	1363.56	6468.34	56,260.18	168.4289
Romania	22	2013	20,897.08	18,193.88	97,156.71	56.23496
Slovenia	23	2013	457.34	1662.5	12,631.87	109.3302
Slovakia	24	2013	3411.96	2970.82	34,814.36	254.1252
Finland	25	2013	4062.8	6483.94	36,859.69	80.85607
Sweden	26	2013	4992.6	6900.33	10,829.38	84.30115
United Kingdom	27	2013	20,022	43,798.3	558,701.5	246.5924
Belgium	1	2014	3172.99	10,107.03	112,149	322.481
Bulgaria	2	2014	9530.42	5084.9	50,369.88	108.8032
Czech Republic	3	2014	8779.3	8280.62	118,037.5	162.6573
Denmark	4	2014	9764.4	10,399.55	50,523.64	120.5029
Germany	5	2014	52,048.2	66,590.89	889,384.9	217.659
Estonia	6	2014	1221.6	1341.93	19,326.18	85.34098
Ireland	7	2014	2597.81	18,882.49	62,398.47	499.294
Greece	8	2014	4297.44	8294.91	98,909.79	123.0625
Spain	9	2014	20,564.24	34,899.25	284,839.5	151.3561
France	10	2014	72,714.92	78,860.91	413,626.7	168.4267
Croatia	11	2014	2994.8	2427.05	16,457.73	192.077
Italy	12	2014	19,412.82	29,757.88	388,986.8	126.5641
Cyprus	13	2014	7.36	537.75	8250.3	158.2065
Latvia	14	2014	2227.2	2663.32	15,533.33	101.1241
Lithuania	15	2014	5123.2	4529.73	12,537.14	111.7522
Luxembourg	16	2014	168.56	666.53	10,299.72	240.7603
Hungary	17	2014	16,613.38	6493.9	52,518.22	112.7082
Netherlands	18	2014	1767	18,616.7	194,047.7	247.8533
Austria	19	2014	5710.27	7183.51	71,495.84	144.5557
Poland	20	2014	31,945.43	30,472.43	350,800.6	164.0007
Portugal	21	2014	1334.49	6566.04	54,497.6	179.8445
Romania	22	2014	22,070.74	18,190.23	97,155.02	51.51959
Slovenia	23	2014	649.06	1707.55	10,903.26	116.4788
Slovakia	24	2014	4708.34	3047.13	34,556.04	263.0787
Finland	25	2014	4127.8	6510.8	30,735.96	85.88443
Sweden	26	2014	5782.5	6975.81	8659.96	92.65934
United Kingdom	27	2014	24,525	44,698.03	515,491.6	243.3625
Belgium	1	2015	3282.54	10,002.78	115,537.4	323.8505
Bulgaria	2	2015	8728.97	5937.8	54,608.01	112.0156
Czech Republic	3	2015	8183.51	8482.99	120,486.1	192.0822
Denmark	4	2015	10,024.4	10,298.62	52,071.86	132.374
Germany	5	2015	48,917.7	66,955.17	887,351.7	202.2227
Estonia	6	2015	1535.3	1337.62	15,681.26	116.1867
Ireland	7	2015	2633.55	19,227.11	64,191.82	1273.853
Greece	8	2015	3437.14	8309.97	92,574.66	118.2727
Spain	9	2015	20,140.95	35,978.59	296,889.7	151.5015
France	10	2015	72,633.16	78,372.94	421,318.8	170.401
Croatia	11	2015	2796.8	2555.32	18,510.43	181.7
Italy	12	2015	16,118.99	29,953.42	396,806.1	134.127
Cyprus	13	2015	88.13	559.3	8262.48	156.6778
Latvia	14	2015	3021.5	2739.64	12,679.81	104.7593
Lithuania	15	2015	6066.71	4600.3	13,391.18	122.5821

Table A1. *Cont.*

Country	Country Index	Year	Cereal Production in Million Tones	GHG from Agriculture in Tones of CO_2 Equivalent	Total GHG in Tones of CO_2 Equivalent	Fertilizers Consumption in Kilograms Per Hectare of Arable Land
Luxembourg	16	2015	176.52	680.83	9863.99	242.6752
Hungary	17	2015	14,145.17	6676.35	54,579.64	120.2579
Netherlands	18	2015	1706.47	19,210.26	201,749.5	269.1291
Austria	19	2015	4843.8	7167.99	74,027.14	144.7092
Poland	20	2015	28,002.7	29,649.89	356,997.9	174.0975
Portugal	21	2015	1241.32	6623.53	60,275.48	173.3919
Romania	22	2015	19,286.24	18,613.03	98,168.54	60.68603
Slovenia	23	2015	624.05	1743.51	11,202.48	112.9911
Slovakia	24	2015	3805.71	3014.46	34,840.7	267.9463
Finland	25	2015	3682.8	6480.97	29,516.44	82.87651
Sweden	26	2015	6168.8	6894.67	3177.33	96.5354
United Kingdom	27	2015	24,735	44,615.35	496,123.1	248.378
Belgium	1	2016	2333.53	10,029.5	2300.4	327.8918
Bulgaria	2	2016	8938.66	5999.2	8956.2	113.7684
Czech Republic	3	2016	8596.41	8503.5	8694.3	81.67916
Denmark	4	2016	9130.2	10,199.7	9033.7	97.55844
Germany	5	2016	45,401	64,200	42,300	220.074
Estonia	6	2016	934.1	1378.62	946.3	44.01402
Ireland	7	2016	2310.94	19,108.11	2258.9	597.0178
Greece	8	2016	3473.83	8322	3479.6	156.3769
Spain	9	2016	24,227.2	33,298.6	23,996	164.4518
France	10	2016	54,209.47	75,004	53,668.3	211.2838
Croatia	11	2016	3457.6	2587	3469.1	256.9883
Italy	12	2016	18,218.72	27,883	17,889	171.1219
Cyprus	13	2016	27.89	569	27.89	159.65
Latvia	14	2016	2703.2	2767	2758.4	50.59507
Lithuania	15	2016	5069.66	4505	5112.9	110.155
Luxembourg	16	2016	139.26	672	137.8	581.1452
Hungary	17	2016	16,726.07	6636	16,884	94.87625
Netherlands	18	2016	1369.69	19,023	1302.7	428.8231
Austria	19	2016	5691.32	7189	5684.7	234.0238
Poland	20	2016	29,849.22	29,833.5	30,003	116.1952
Portugal	21	2016	1149.65	6633.9	1167.2	191.054
Romania	22	2016	19,928.26	18,657.9	20,003	34.78274
Slovenia	23	2016	643.88	1779.4	645.7	83.10638
Slovakia	24	2016	4745.52	3000.96	4883.1	403.4762
Finland	25	2016	3520.4	6480.97	3528.1	136.1426
Sweden	26	2016	5458.3	6778.1	5332.8	99.88793
United Kingdom	27	2016	21,965	44,045.35	19,726	309.0218

Table A2. Irrigated land in Denmark and Hungary (percent of total agricultural land).

Irrigated Land in Denmark, %	Irrigated land in Hungary, %
7.623318	2.48
7.654784	2.5
7.580888	2.540494
7.709751	2.04502
9.678611	1.280914
9.667897	1.341367
9.538115	2.081798
9.52024	1.382383
9.643128	1.846101
12.14775	0.840352
11.384	1.894323
10.7783	2.337954
9.275585	2.224719
8.9364	1.857838
8.9936	1.9
9.0364	2.1

Appendix B

```
Levin-Lin-Chu unit-root test for ghg_agriculture
------------------------------------------------
Ho: Panels contain unit roots                Number of panels  =     27
Ha: Panels are stationary                    Number of periods =     16

AR parameter: Common                         Asymptotics: N/T -> 0
Panel means:  Included
Time trend:   Not included

ADF regressions: 1 lag
LR variance:     Bartlett kernel, 8.00 lags average (chosen by LLC)
------------------------------------------------------------------------------
                    Statistic      p-value
------------------------------------------------------------------------------
 Unadjusted t        -7.8176
 Adjusted t*         -2.9653        0.0015
------------------------------------------------------------------------------

. xtunitroot llc production

Levin-Lin-Chu unit-root test for production
-------------------------------------------
Ho: Panels contain unit roots                Number of panels  =     27
Ha: Panels are stationary                    Number of periods =     17

AR parameter: Common                         Asymptotics: N/T -> 0
Panel means:  Included
Time trend:   Not included

ADF regressions: 1 lag
LR variance:     Bartlett kernel, 8.00 lags average (chosen by LLC)
------------------------------------------------------------------------------
                    Statistic      p-value
------------------------------------------------------------------------------
 Unadjusted t       -11.2096
 Adjusted t*         -4.2483        0.0000
------------------------------------------------------------------------------

Fisher-type unit-root test for ghg_total
Based on augmented Dickey-Fuller tests
----------------------------------------
Ho: All panels contain unit roots            Number of panels       =     26
Ha: At least one panel is stationary         Avg. number of periods =  16.62

AR parameter: Panel-specific                 Asymptotics: T -> Infinity
Panel means:  Included
Time trend:   Not included
Drift term:   Not included                   ADF regressions: 0 lags
------------------------------------------------------------------------------
                                  Statistic      p-value
------------------------------------------------------------------------------
 Inverse chi-squared(52)   P       453.8905       0.0000
 Inverse normal            Z       -17.7589       0.0000
 Inverse logit t(134)      L*      -24.5511       0.0000
 Modified inv. chi-squared Pm       39.4086       0.0000
------------------------------------------------------------------------------
 P statistic requires number of panels to be finite.
 Other statistics are suitable for finite or infinite number of panels.
```

Figure A1. Panel unit root tests.

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