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Changes in greenhouse gas emissions from agriculture in selected European Union countries

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Abstract. The aim of the research was to identify changes in greenhouse gas emissions from EU countries in the years 2008-2022. The research used available Eurostat data from 24 EU countries. Descriptive statistics, the Ward method and shift share analysis were used. The survey shows that in 2021 the agricultural sector was responsible for 15.3% of total greenhouse emissions in EU. Most carbon emissions from farming come from methane (54%), followed by nitrous oxide (28%) and carbon dioxide (18%). The research shows that the largest increases in carbon pollution, creating a carbon footprint in the exploring period, were recorded in Bulgaria, Estonia, Romania, Latvia and Hungary. A different situation occurred in Croatia and Germany, where carbon dioxide and methane emissions from cultivation were reduced. The research confirms that the dynamics of changes in greenhouse gas emissions depend on the intensity of agribusiness. Moreover, the structure of greenhouse emissions varies regionally. Therefore, the European Union's policy on reducing the carbon footprint should consider regional conditions.

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1. INTRODUCTION

The world population is expected to increase to 10 billion by 2060 (United Nations, 2015). The growth of the global population generates an increasing demand for food (Jägermeyr, 2020), which poses a serious challenge for governments (O'neill et al., 2018). At the same time, thanks to significant improvements in productivity, global agricultural production is increasing, cutting food shortages (Alston & Pardey, 2014). Increased productivity and modernization of agronomy contribute to the growth of profitability of the agricultural sector, but at the same time increase the demand for energy, water consumption and greenhouse gas emissions (Yu et al., 2022). The main greenhouse gases emitted by tillage include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Their excessive emission contributes to the greenhouse effect, i.e., an increase in the average global temperature of the planet, disturbing the balance in the environment. Given the growing global population and the increasing demand for food, with current eating styles and preferences, greenhouse emissions from food construction, transportation and storage processes could increase several-fold in the future (Poore & Nemecek, 2018; Żarczuk & Klepacki, 2021).

Carbon footprint is used to measure carbon emissions. This term is now quite common and has become a global concept (Wiedmann & Minx, 2008). It defines all amounts of GHG for which a given person or organisation is responsible (Carbon trust, 2008).

The growing interest in carbon foot printing is primarily due to the need to monitor carbon pollution to combat climate change and global warming. Agriculture is responsible for about 12% of global greenhouse gas emissions, estimated at 7.1 gigatonnes of CO_2 equivalent per year, mainly through methane (54%), nitrous oxide (28%) and carbon dioxide (18%). This sector of the economy is an outstanding contributor to climate change and at the same time is very affected by its consequences (Rosa & Gabrielli, 2023). Extreme weather effects in the form of droughts, floods, heat waves, fires and changes in rainfall, in combination with other ecosystem threats such as soil degradation that affect agricultural activities and crop yields worldwide. It is increasingly being pointed out that agronomics and global food security are directly threatened by climate change (Ceglarek et al., 2023). As climate change becomes increasingly serious, controlling greenhouse gas has become an overarching issue facing all countries (Becerril Torres et al., 2025; Miao et al., 2023; Mishchuk et al., 2023).

CO_2 emissions in husbandry are generated by the combustion of fuels such as diesel or petrol, the generation of heat from the combustion of fuel oil and gas, and the use of electricity. CH_4 emissions occur during enteric fermentation in ruminants and during the storage of manure or slurry. On the other hand, remarkable amounts of N_2O are emitted because of the use of natural and mineral fertilisers on agricultural land (Vergé, et al., 2007; Bieńkowski, et al., 2015). Understanding the sources and scale of greenhouse emissions is crucial to develop strategies to mitigate their impact on climate change.

The European Climate Law sets out the EU's commitment to a climate-neutral economy by 2050, with an intermediate target of reducing greenhouse gas emissions by at least 55% by 2030. Carbon emissions from agriculture are covered by the EU's Effort Sharing Regulation (ESR) (Rozporządzenie, 2018), which sets annual targets for each Member State for the period 2021-2030. Emissions from transport, buildings and waste are also covered by national ESR targets, which aim is to knock off total GHG from sectors not covered by the Emissions Trading System (ETS).

The aim of the study was to identify changes in greenhouse gas from agriculture in EU countries in the years 2008-2022. Three research hypotheses were formulated in the study:

H1. In countries with more forest cover, agriculture generates a lower carbon footprint.

H2. The dynamics of changes in greenhouse emissions from agriculture are regionally diversified.

H3. The structure of carbon dioxide and methane emissions is shaped by the intensity and type of agricultural production.

2. LITERATURE REVIEW

The concept of carbon foot printing first appeared in the literature in 2000, and five years later British Petroleum (BP) began a campaign to promote the general concept. In 2005, during the debate on monitoring and controlling greenhouse gas emissions defined the details of the carbon emission concept (Frączek & Śleszyński, 2016).

The issue of carbon pollution refers to greenhouse gases that should be included in its assessment. The most universal definition is the one that considers carbon footprint as the impact of an entity on the climate, based on data considering all significant sources of emission, absorption and storage of GHG during production and consumption with specific restrictions (Peters, 2010). Therefore, carbon footprint is a measure of the total amount of emissions of such gases, which are directly and indirectly caused by human activity or are accumulated during the subsequent stages of the product's life (Wiedmann & Minx, 2007). According to Gao et al., carbon footprint is defined as "a measurement of the total greenhouse gas emissions caused directly or indirectly by a person, organisation or even a product, expressed as carbon dioxide equivalent (CO_{2e})" (Gao, et al., 2014). Carbon dioxide equivalent is calculated as the product of the mass of a given gas by the appropriate global warming potential over a certain time horizon, usually 100 years. The global warming potential is a dimensionless unit and expresses the impact of a given gas on global warming in comparison to CO_2, which has a GWP of 1(Solomon et al., 2007). This leads to increased governmental efforts across different states to promote eco-efficient technologies and tools to support agriculture, particularly through agri-environmental subsidies and changes in taxation (Gesevičienė et al., 2025; Samusevych et al., 2024).

Many authors compare the term carbon emission with ecological footprint, but these concepts are not the same. The ecological pollution is a measure of the regenerative capacity of the environment (expressed in the relevant manufacturing area), while most definitions of carbon footprint focus on the physical amount of carbon dioxide (or equivalent gases) produced because of specific activities. From these definitions it follows that these are different issues, but these concepts retain a common part due to the measurement of the impact of human making or consumption activities on the environment. Carbon footprint measures the level of consumption of natural resources and waste generated by human activity. It is a key indicator of humanity's impact on ecosystems and the biosphere. Reducing the carbon footprint is one of humanity's challenges in the fight against the deterioration of the quality of life through the destruction of ecosystems and climate change. Unfortunately, the safe limits of the use of natural resources have already been exceeded, and decisive action is needed to stop this trend.

Due to concerns about climate change, research on the carbon footprint of agriculture is widely reported in the literature. Clune et al. (2017) summarised the results of 369 articles on the carbon footprint of fresh food products in five categories: fruits, vegetables, staple foods (cereals, legumes, nuts, seeds, rice), dairy products, and meat. The meta-analysis showed that fruits and vegetables have the smallest carbon footprint per 1 kg of product, while ruminant meat has a carbon footprint more than 100 times larger. Zhang et al. (2017) determined the carbon footprint of the main crops in China, which include grain maize, wheat, and rice. Polish research on the carbon footprint includes the cultivation of, among others, winter rapeseed (Bieńkowski, et al., 2017), grain maize (Holka & Bieńkowski, 2020), winter wheat (Holka, 2016), and winter triticale (Bieńkowski & Holka, 2019). Although, there are large differences in the results obtained for the same plant in different studies, depending on the methodology adopted, the study area, and the quality and representativeness of the data used for calculations. For example, in the meta-analysis by Clune et al. (2017) showed that the carbon footprint of cereal cultivation determined in different publications ranged from 0.11 to 1.38 kg CO_2 eq. kg–1.

Changes in agricultural management practices in agricultural land ecosystems are increasingly being assessed for their potential impact on climate change, by quantifying the carbon footprint of crops from planting to harvest (Zhang et al., 2021). Studies have shown that the main contributors to GHG emissions include agricultural machinery use (Mantoam et al., 2020), plant food and pesticide application, and territory use change (Torres et al., 2015). However, studies of greenhouse gas emissions from agricultural crops have mainly focused on nitrogen fertiliser care (Huang et al., 2021; Li et al., 2018).

One of the ways to reduce CO_2 emissions into the atmosphere is through soil carbon sequestration. This involves adopting land administration practices that increase the amount of carbon dioxide (CO_2) in the soil, stored as organic matter. Such activities are considered best practices for handling greenhouse gas emissions. For example, a good solution is to cover crops, i.e. sowing crops in crop rotation solely to improve soil structure and nutrients. Most arable soils are poor in organic matter, so increasing their content has a positive effect on the fertility of agricultural state. Research shows that sequestering carbon in agricultural soils can eliminate some carbon emissions and even make the carbon footprint negative (Xue et al., 2014; Ray et al., 2020).

A major difficulty in estimating the carbon footprint of selected crops at the national level is the lack of access to detailed statistics. The CSO studies present average yields of selected plants. Nevertheless, there is a lack of information on the technology of growing individual plants, especially the amount of organic and mineral fertilisers used.

The largest contribution to greenhouse gas emissions from agricultural crops is made by nitrous oxide emissions from soil (52%), the use of mineral fertilisers (24%), and the use of fuels during the use of agricultural machinery (19%). Other sources, such as CO_2 emissions from soils resulting from the use of urea and lime fertilisers, and emissions related to the production of plant protection products and seeds, together account for about 5%. Due to the structure of greenhouse gas emissions, the greatest potential for reducing the carbon footprint of crops is associated with rational nitrogen fertilisation (GUS, 2017).

Cutting the carbon footprint of crops is possible using technological and biological progress and can be achieved by decreasing emissions or increasing yields. Forests play a key role in mitigating the effects of climate change, as they absorb carbon dioxide from the atmosphere and store it in biomass and soil. Estimates show that between 2001 and 2019, forests around the world absorbed twice as much carbon dioxide as they emitted (7.6 billion metric tons of CO_2 per year). Forests therefore have a key capacity to remove greenhouse gases (GHG) from the atmosphere and help avoid the effects of the climate crisis. According to the Intergovernmental Panel on Climate Change (IPCC), the agriculture, forestry and other land use (AFOLU) sector can provide up to 30% of the greenhouse gas emission reductions needed to limit global warming by 2°C, at a relatively low cost (Żyłowski, 2022).

The production, transportation, and storage of products throughout the food supply chain generate varying amounts of greenhouse gases (Filho, 2022). In total, 23–42% is generated by the food system, of which 18% is generated by the supply chain and 6% by food transportation (Poore & Nemecek, 2018; World in Data, 2019). Large amounts of greenhouse gases are also produced by livestock farming, manure treatment, and agricultural machinery (Jaiswal & Agrawal, 2019; Greblikaite et al., 2025).

3. METHODOLOGY

The survey of the carbon footprint from agriculture was carried out for 24 selected countries in relation to the level of development of this phenomenon in the European Union. The choice of countries was dictated by the availability of data. The research included 24 EU member states, Malta, Cyprus and Luxembourg were omitted due to the lack of data.

Eurostat data were used in the study. They describe the size of the carbon footprint in individual countries (r = 1, ..., 24) and its structural division (i = 1, ..., 3; crops and livestock, forestry, fisheries). The time scope of the research covered the years 2008 and 2022.

Descriptive statistics and Ward's method were used to group the research objects, which is one of the most common techniques of agglomerative cluster analysis. Its goal is to minimize the increase in the sum of squared within-cluster deviations with each subsequent group merger (Ward, 1963). Unlike other hierarchical methods, the merger criterion in Ward's method is based directly on the analysis of variance, which favours the formation of relatively homogeneous and compact clusters (Everitt et al., 2011). The procedure begins by treating each object as a separate cluster and then iteratively merging the two groups whose merger results in the smallest increase in total within-cluster variance, most often using the squared Euclidean distance (Hair et al., 2019). In research on differences in countries' carbon footprint emissions, this method is particularly useful because it allows for the identification of structural similarities across countries while maintaining high internal consistency of clusters and the interpretability of results (Kaufman & Rousseeuw, 2005).

In turn, the classical shift share analysis (SSA) was used in the data examining, which is often used to study changes in economic and social phenomena. Shift share look over allowed for the decomposition of the changes into regional and global effects, as well as the identification of the so-called allocation effect leading to the classification of the countries studied due to the occurring combinations of local specialisation and competitiveness benefits (Sobczak, 2013). For the first time, the assumptions of shift share investigation were first described by Creamer in 1943. Then, this method was popularised by Dunn in his 1960 work entitled "A statistics and research technique for regional analysis" (Edgar & Dunn, 1960). In its assumption, this method is used to describe regional and structural changes in the studied phenomenon, which allows for the detection of changes in the competitive position of the studied region against the background of the reference unit, otherwise referred to as the reference unit. In the early 1980s, this method was often used by many economists in the marketing field, as well as in research on urban development. In 1980, Stevens and Moore, emphasising the simplicity of the method, stated that it is a useful tool in identifying changes in the studied phenomenon (Benjamin, et al., 1980). The objective of shift-share analysis is to compare the sectoral distributions of the studied variable between two geographical areas (usually a region versus the nation as a whole) to answer three questions (Murray, 2010):

i) Does the regional economic structure yield more growth than the national one?

ii) Is the regional sectoral growth higher on average than the national one?

iii) From the results to i) and ii), which one from the structure or the sectoral efficiency contributes more to the observed differential in aggregate variable growth between the region and the nation? (Artige & van Neuss, 2014).

The use of shift share evaluation allows for parameterization of changes in the studied phenomenon in three dimensions:

- calculation of the potential of individual countries against the background of the entire European Union.
- determination of the structure of the carbon footprint in individual countries,
- parameterization of the competitiveness of countries due to the carbon footprint.

Shift share analysis is usually used in the description of regional and industrial, economic growth and in the study of regional or industrial structural and competitive effects, considering changes over time (Stevens & Moore, 1980). It is often used in regional and political economics, marketing, geography and urban studies (Szymańska et al., 2023; Montania et al., 2023; Trubnik & Mazurenko, 2020; Toh et al., 2004; Toh et al., 2003).

In the classical construction of shifts shares analysis, the formation of the quantified TX variable is studied in the form of a complex absolute gain or rate of change (Trzpiot, 2013; Suchecki, 2010). The application of SSA analysis in the development of specific socio-economic areas, the inclusion of the distribution of the change of the variable into three components, which are used in the first equation (Dunn, 1960; Perloff, et al. 1960):

$$tx_{ri} = tx_{..} + \sum_i w_{r.(i)}(tx_{.i} - tx_{..}) + \sum_i w_{r.(i)}(tx_{ri} - tx_{.i}) \quad (1)$$

where:

$m = tx_{..} = \frac{\sum_{r=1}^{R}\sum_{i=1}^{S}(x_{ri}^{*}-x_{ri})}{\sum_{r=1}^{R}\sum_{i=1}^{S}x_{ri}}$ – national (global) regional growth factor;

$e_i = tx_{.i} - tx_{..} = \frac{\sum_{r=1}^{R}(x_{ri}^{*}-x_{ri})}{\sum_{r=1}^{R}x_{ri}} - \frac{\sum_{r=1}^{R}\sum_{i=1}^{S}(x_{ri}^{*}-x_{ri})}{\sum_{r=1}^{R}\sum_{i=1}^{S}x_{ri}}$ – sectoral (structural) factor of regional growth;

$u_{ri} = tx_{ri} - tx_{.i} = \frac{x_{ri}^{*}-x_{ri}}{x_{ri}} - \frac{\sum_{r=1}^{R}(x_{ri}^{*}-x_{ri})}{\sum_{r=1}^{R}x_{ri}}$ – local (geographic, competitive, differentiating) growth factor in the i-th sector of the r-th region;

$w_{r.(i)} = \frac{x_{ri}}{x_{r.}}$ - regional weights;

x_{ri} – value of the analyzed variable in the r-th region in the i-th group of the cross-sectional division in the initial period;

x_{ri}^{*} - value of the analyzed variable in the r-th region in the i-th group of the cross-sectional division in the final period.

Transforming equation (1) into the form:

$$tx_{ri} - tx_{..} = \sum_i w_{r.(i)}(tx_{.i} - tx_{..}) + \sum_i w_{r.(i)}(tx_{ri} - tx_{.i}) \quad (2)$$

the pure regional growth (txri – t..) was obtained, defined as the difference between the regional and national growth rates.

The relation described by equation (2) is called structural-geographic equality, in which the geographical differentiation of the excess of the average regional growth rate over the national growth rate is decomposed into two effects:

- structural: $s_r = \sum_i w_{r.(i)}(tx_{.i} - tx_{..})$ - which is equal to the weighted average of the deviations of the average growth rates in the sectors and the national growth rate and indicates that the regions are differentiated by deviations in distribution;
- geographic: $g_r = \sum_i w_{r.(i)}(tx_{ri} - tx_{.i})$ - defined as the weighted average of the regional variations assigning cross-sectional quality criterion categories to the corresponding regions.

4. EMPIRICAL RESULTS AND DISCUSSION

4.1. Carbon footprint in agriculture in EU countries

Agriculture is one of the major source of greenhouse gas (GHG) emissions and has a great potential to mitigate climate change. In 2021, the agronomy sector was responsible for 15.3% of total GHG emissions in EU. The contribution of food systems to the carbon footprint was even higher at 42%. Land use change generated 31% of emissions, food processing, transport, retail generated 20%, and food waste disposal 7% of GHGs (Rosa & Gabrielli, 2023). According to FAO (2013), GHG emissions from this culture, forestry and fisheries have doubled over the past half-century and could increase by another 30% by 2050. A global solution is thus needed to stabilise GHG concentrations in the atmosphere. According to Rokicki et al. (2020), greenhouse gas emissions from agriculture decreased slightly across the EU between 2004 and 2017.

However, these changes were mixed. Generally, greenhouse gas emissions from agriculture increased in developing countries, while remaining at a similar level in developed countries.

In the generation of a carbon footprint in husbandry, a significant factor is the structure of spatial development, which reflects the reproductive potential of natural resources. In the case of horticulture, it should be assumed that the more forested areas there are in a country, the smaller the carbon footprint will be. Forests in the European Union cover an area of 159 million ha, which is 43.5% of the EU area. There are outstanding differences between individual EU countries, for example: forests cover just over 10% of the area of Malta and almost 70% of Finland (European Parliament, 2017). For that reason, the considerations took into account the afforestation index, i.e. the ratio of the area of forested land to the area of agricultural territory (forest/ agricultural area (sq. km)). This index was used to find the answer to the question to what extent a larger share of forests affects the size of the carbon footprint, i.e. greenhouse gas emissions. In the period from 2008 to 2022, the average level of this index increased slightly in the investigated EU countries. However, in terms of diversity measured by the coefficient of variation, no changes were noted (Table 1).

Table 1

Basic descriptive statistics the indicator of countries forestation to agricultural land area in 2008 and 2022

Years	mean	min	max	st.dev
indic_2008	2,541	0,188	12,581	3,163
indic_2022	2,837	0,317	16,238	4,142

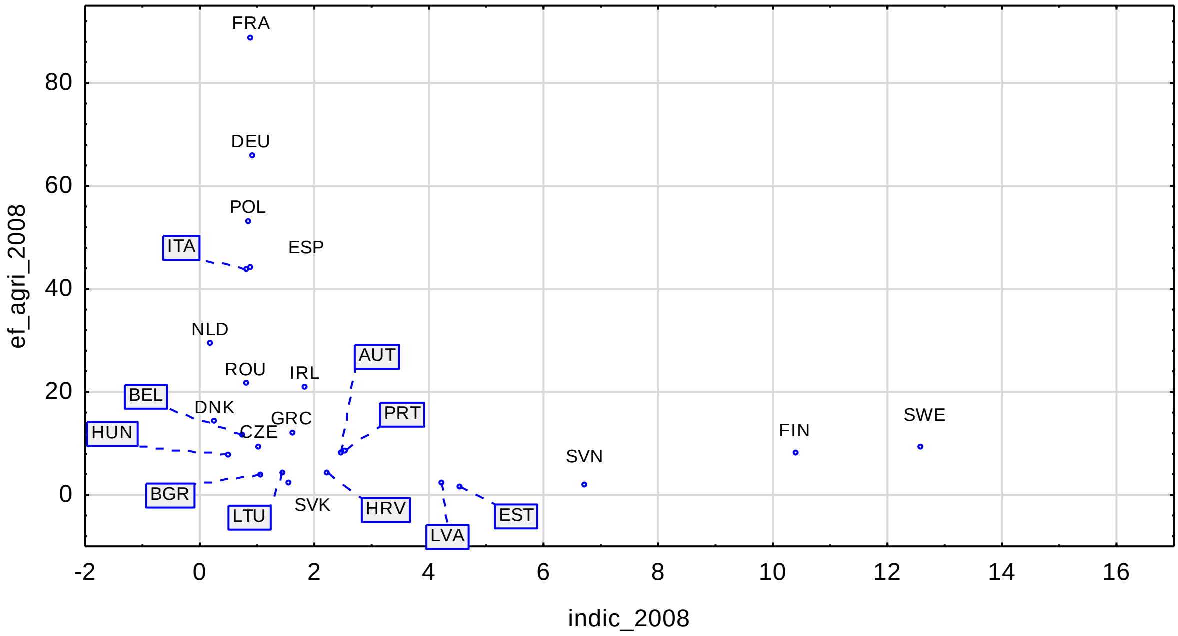
Source: own elaboration.

When examining the distribution of the carbon footprint and the afforestation rate, notable differences were observed between the inspected EU countries. The highest afforestation rate is observed in Finland and Sweden. In these countries, the ratio of forested areas to agricultural land is the highest. By contrast, countries such as Spain, Poland, Germany and France are characterised by a lower afforestation rate and at the same time a high level of carbon footprint. The first hypothesis (H1) was therefore positively verified. The presented results are consequently consistent with those presented in the literature Balsalobre-Lorente et al., (2022) (Fig. 1).

As a result of the application of the Ward clustering method, dendrograms were obtained, which illustrate the hierarchical structure of the set of objects due to decreasing similarity between them. First, the results of grouping countries according to the total greenhouse gas emissions (CO_2, N_2O in CO_2 equivalent, CH_4 in CO_2 equivalent) of agriculture were presented on the Figure 1.

The hierarchical structures created indicate the greatest distance between countries from group I and countries from group III. Within each of the groups, the looked over countries are similar to each other. The search for similarities between countries in the area of carbon footprint research using the Ward method showed that the created clusters differ in the amount of greenhouse gas emissions. The diversity of countries belonging to different clusters results from the different nature and intensity of tillage. In 2008, Ward's method of grouping countries by agricultural carbon footprint primarily reflected differences in the scale and intensity of agricultural production. This group includes countries with diverse agricultural models, but most often with relatively high livestock production intensity (especially in Western European countries such as the Netherlands, Denmark, and Ireland) or with a significant share of agriculture in the economic structure (e.g., Romania, Bulgaria). The emission profile in this group was likely determined by the high share of methane (CH_4) from enteric fermentation and nitrous oxide (N_2O) from agricultural soils. Group II (Estonia, Latvia, Slovenia, Finland, and Sweden) includes countries with smaller-scale agricultural production, lower population density, and more extensive farming practices. In the case of Nordic countries such as Finland and Sweden, a high share of forests in land use also plays a significant role, reducing the relative pressure on the agricultural sector. Group III (Germany, France, Spain, Italy, Poland) comprises the largest agricultural economies in the EU – including France, Germany, and Poland – characterized by large-scale production, significant agricultural land, and high livestock populations, which translates into high absolute emissions.

(a)



(b)

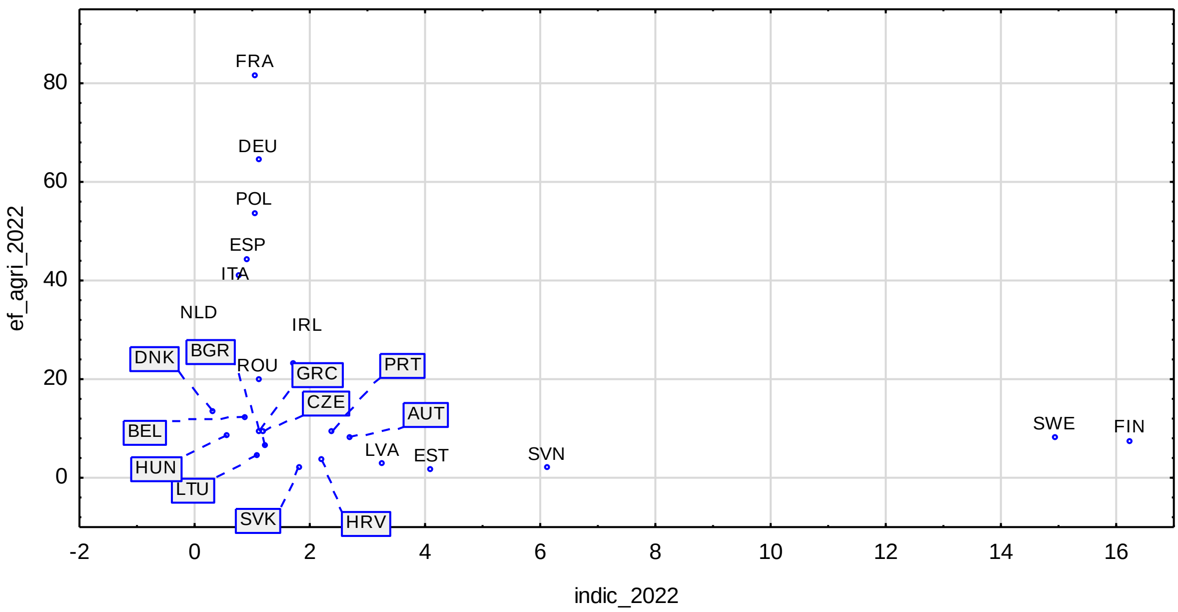


Figure 1. Carbon footprint and indicator of countries forestation to agricultural land area in 2008 (a) and 2022 (b)

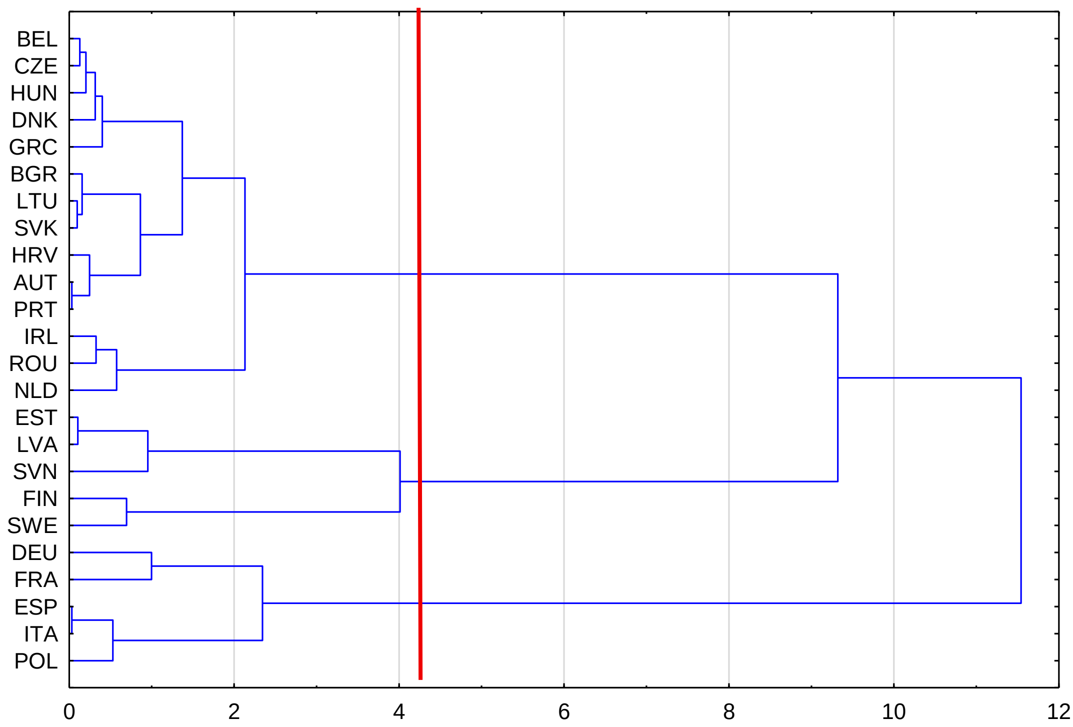
Source: own elaboration.

Note: Where the country codes used by Eurostat and national statistical institutes have been used: AUT-Austria, BEL-Belgium, BGR-Bulgaria, CZE-Czechia, DNK-Denmark, DEU-Germany, EST-Estonia, IRL-Ireland, GRC-Greece, ESP-Spain, FRA-France, HRV-Croatia, ITA-Italy, LVA-Latvia, LTU-Lithuania, HUN-Hungary, NLD-Netherlands, POL-Poland, PRT-Portugal, ROU-Romania, SVN-Slovenia, SVK-Slovakia, FIN-Finland, SWE-Sweden.

In 2022, Group I expanded significantly compared to 2008, encompassing, in addition to the previous countries, Estonia, Latvia, and Slovenia. This means that, in terms of their carbon footprint from agriculture, these countries have become similar to those with moderate or medium-high agricultural production intensity. This group includes countries with diverse agrarian structures, but they share a common feature: the significant role of livestock production and methane (CH_4) and nitrous oxide (N_2O) emissions. In countries such as the Netherlands, Denmark, and Ireland, intensive cattle and pig farming dominates, generating high emissions per unit of area. In Central and Eastern European countries, such as Romania, Hungary, and Bulgaria, emissions from agricultural soils and modernization processes taking place in the sector since 2008 are significant. The inclusion of the Baltic countries in this group may indicate an increase in production intensity, a change in crop structure, or convergence in emissions levels relative to the core group. Thus, in 2022, Group I represents a broad cluster of countries with a moderate but structurally similar agricultural emissions profile, positioned between the clearly low-emission Group II (the Nordic countries) and Group III, which includes the largest EU agricultural economies (including France and Germany), characterized by the highest absolute emissions.

Due to different conditions in the distinguished groups of countries, the strategies for reducing greenhouse gas emissions must be differentiated. The solutions applied should not limit cultivation and the competitiveness of farms.

(a)



(b)

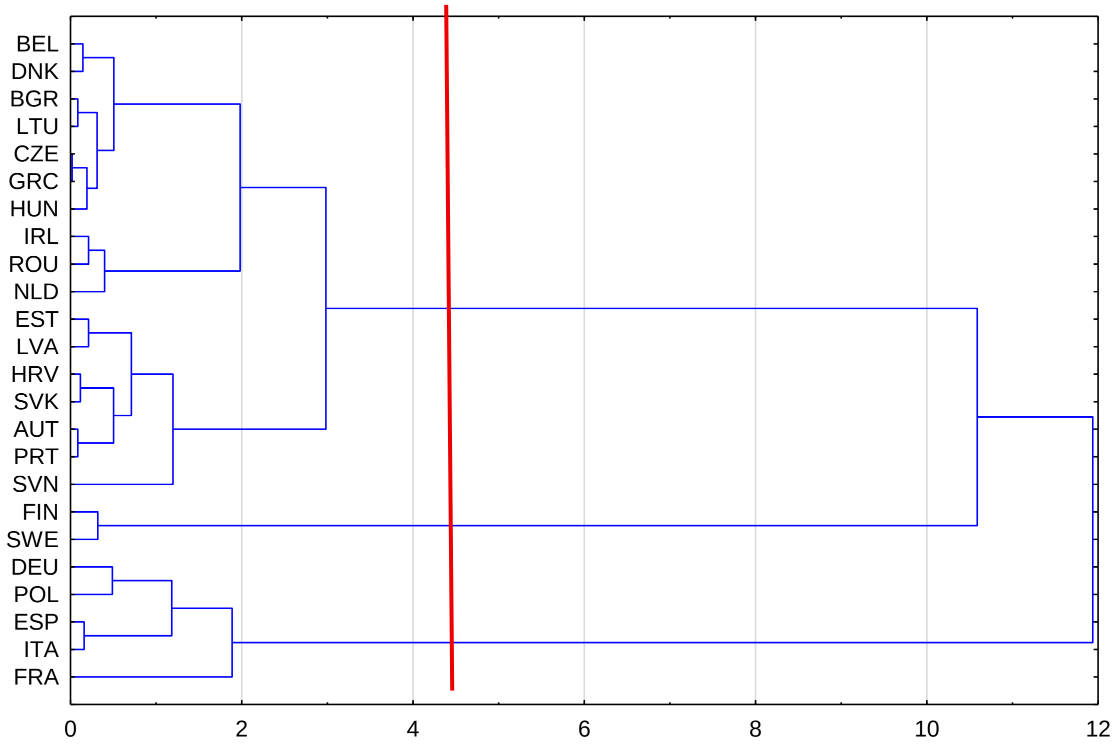


Figure 2. Dendrograms obtained using Ward's method 2008 (a) and 2022 (b)

Source: own elaboration.

Note: Where the country codes used by Eurostat and national statistical institutes have been used: AUT-Austria, BEL-Belgium, BGR-Bulgaria, CZE-Czechia, DNK-Denmark, DEU-Germany, EST-Estonia, IRL-Ireland, GRC-Greece, ESP-Spain, FRA-France, HRV-Croatia, ITA-Italy, LVA-Latvia, LTU-Lithuania, HUN-Hungary, NLD-Netherlands, POL-Poland, PRT-Portugal, ROU-Romania, SVN-Slovenia, SVK-Slovakia, FIN-Finland, SWE-Sweden.

The presented changes are confirmed by the data in Table 2. They show that between 2008 and 2022, there was a general increase in the mean values and standard deviation in groups I and II. In group III, the average carbon footprint remained similar. However, the indicator's standard deviation decreased, indicating slightly greater data consistency in this group in 2022.

Table 2

Basic descriptive statistics the indicator of countries forestation to agricultural land area in 2008 and 2022

Years	parameter	Group I	Group II	Group III
2008	mean	0,862	7,930	1,663
	st. dev.	0,036	3,639	1,535
2022	mean	0,973	9,629	1,647
	st. dev.	0,117	5,977	1,378

Source: own elaboration.

4.2. Analysis of changes in the carbon footprint from agriculture in 2008-2022

The structural effect plays an important role in shaping the carbon footprint of agriculture in European Union countries, because changes in the production structure – such as the relationship between crop and animal production, the concentration of animal breeding, the intensity of fertilization or the structure of energy consumption – directly determine the level of greenhouse gas emissions. To identify changes, the rate of growth or decline of the carbon footprint of agriculture in individual countries in the years 2008–2022 was compared with the average growth of the carbon footprint for all the countries studied, which is 3.4%. Based on the comparisons made, countries with a higher level of changes in the phenomenon than its average pace in the EU were distinguished. This group included countries such as: Austria, Belgium, Bulgaria, the Czech Republic, Estonia, Spain, Lithuania, Ireland, Latvia, Germany, Poland, Portugal, Slovakia and Hungary. A slower pace of change than the EU average was recorded in Croatia, Denmark, the Netherlands, Finland, France, Greece, the Netherlands, Romania, Slovenia, Sweden and Italy (Fig. 3).

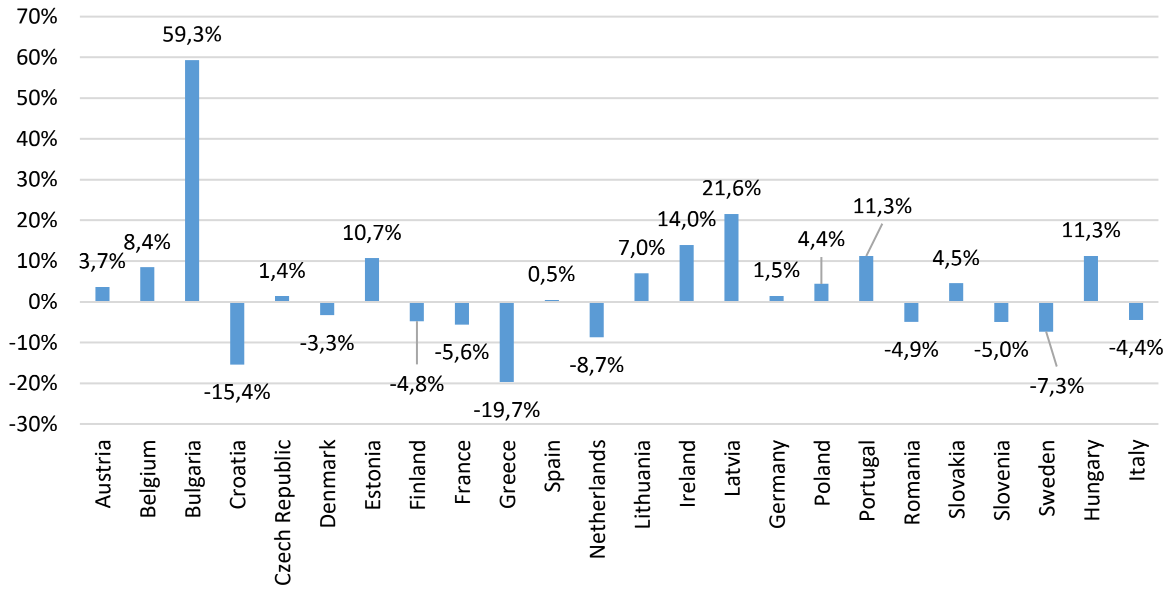


Figure 3. Changes in the size of the agricultural carbon footprint in 2008–2022

Source: own elaboration.

The largest increase in the carbon footprint of agronomy occurred in Bulgaria by 59.3% and Latvia by 21.6%. These changes were mainly due to the increase in the use of mineral composts in crop production. The use of nitrogen fertilisers in Bulgaria in 2008 amounted to about 173 thousand tons, while in 2022 it was 350 thousand tons. In the same period, the use of phosphate manures increased from 13 thousand tons in 2008 to 32 thousand tons in 2022. In turn, the largest decrease in the size of the carbon footprint from husbandry, at the level of -19.74%, was recorded in Greece, followed by Croatia (-15.38%).

According to Peng et al. (2024), transformations in the structure of energy consumption and organizational changes in the sector had a significant, albeit varied, impact on the dynamics of GHG emissions. Analyses of changes in greenhouse gas emissions in EU countries also show that in some countries, emission reductions resulted not only from improved technological efficiency but also from structural changes, such as reduced animal populations or modified cropping patterns (Witkowska-Dąbrowska, 2018). Studies for Central European countries also confirm that structural factors – including the added value of agriculture, agricultural area, and the level of production inputs – significantly influence CO_2 emissions in the agricultural sector (Supron, 2024). Consequently, the structural effect should be considered one of the key determinants of changes in the carbon footprint of agriculture in the EU, with its significance varying according to the specificity of each country's agricultural production structure and the degree of its modernization.

Most Member States' forecasts predict a continuation of current trends if current actions are maintained. However, some countries may experience changes. This is the case, for example, in Greece and Romania. It is estimated that the carbon footprint in these countries will start to increase if further actions to minimise greenhouse gas emissions are not implemented. The implementation of additional actions is expected to have a particularly strong impact on reducing greenhouse gas emissions from horticulture in Austria, Croatia, Denmark, Finland, Germany, Spain and Sweden. In these countries, the reduction in the carbon footprint could even exceed 10% by 2030 compared to forecasts based solely on existing actions. In the searched group, nine EU Member States (France, Italy, Lithuania, the Netherlands, Poland, Portugal, Belgium, the Czech Republic and Slovakia) have not reported any additional actions for the coming years to cut back greenhouse gas emissions (European Environment Agency, 2023).

4.3. Analysis of the impact of the regional effect on the carbon footprint of agriculture in selected EU countries

Empirical studies also confirm heterogeneity in emissions changes across Member States. Such variation may be related to specific agricultural practices, food production structures, nitrogen fertilizer use, and animal husbandry intensity—the main determinants of CH_4 and N_2O emissions (Mielcarek-Bocheńska & Rzeźnik, 2021). There were significant differences in the size of the carbon footprint in the key sectors of the economy in the years 2008-2022 (Fig. 4). The greatest changes were recorded in forestry. In the period under review, the size of the carbon footprint generated by forestry increased on average by 9%. On this basis, it can be concluded that the ecological safety of European forestry is seriously threatened, because excessive logging contributes to the decline of tree stands and in the era of climate change, the ability of trees to mitigate the negative effects of climate warming, including by storing CO_2, is very important. There is therefore an urgent need for joint management of forest resources to limit the increase in the carbon footprint. Common reference points should be established within the EU policy. In general, EU countries should strive to tighten regulations on logging and encourage new plantings.

The smallest changes in the carbon footprint were recorded for agricultural land, where the increase in greenhouse gas emissions in carbon equivalent was only 1.1%. Yet, it should be noted that agricultural territory is not homogeneous in terms of cropping structure and production intensity. This may indicate that individual countries have different environmental protection policies.

Land use optimization is an integral part of the process of resolving area use conflicts (Dembińska, 2010). Particular attention should be paid to the rational spatial distribution of land for construction and agriculture in order to balance the use of land resources. Moreover, as noted by Tang et al. (2021), when the expansion of cropland encroaches on areas used for non-agricultural activities, e.g. forests, grasslands, wetlands, which reduces carbon storage, which affects climate change (Fig. 4).

The majority of greenhouse gas emissions from agronomics come from methane, accounting for 54%, followed by nitrous oxide (28%) and carbon dioxide (18%). Both methane and nitrous oxide are potent greenhouse gases with a global warming potential that is 28 and 265 times greater than carbon dioxide over a 100-year time scale, respectively (IPCC, 2022).

Carbon dioxide (CO_2) is the most important greenhouse gas in the Earth's atmosphere. It is produced when carbon and its compounds are burned in oxygen. It is also released by animals and plants during respiration. Carbon dioxide emissions come from increased decomposition of plant matter in the soil and conversion of land to agricultural use. These can be brought down by introducing additional crops outside the main growing season, known as cover crops. Another good solution in this regard is to use farming methods that cause less soil disturbance, such as grazing.

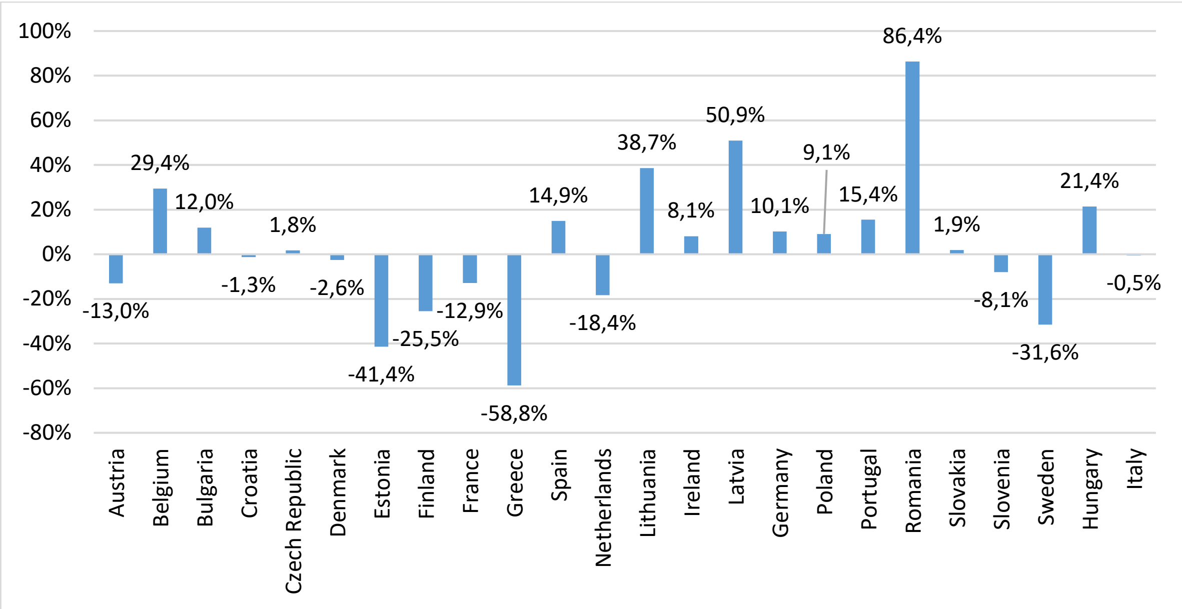


Figure 4. Regional effect in emission of CO_2 for selected EU countries in 2008–2022

Source: own elaboration.

Carbon dioxide is also emitted by agricultural machinery moving across farm fields during ploughing, planting, applying pesticides and fertilisers, and harvesting. The more times machinery moves across a farm field, the greater the carbon dioxide emissions. Another source of carbon dioxide is the transportation of crops and food products through supply chains from farmlands to consumers (Sierra Club, 2023).

In the years 2008-2022, the largest changes in CO_2 emissions compared to the average level for all European Union countries were recorded in Romania (+86.4%) and Latvia (+50.9%) (Fig. 5). The increases in CO_2 emissions could be caused, among others, by the increase in the consumption of energy carriers in cultivation. However, eleven countries (Austria, Croatia, Denmark, Estonia, Finland, France, Greece, the Netherlands, Slovenia, Sweden, Italy) lessened CO_2 emissions in the years 2008-2022. The largest CO_2 cutdown was recorded in Greece (-58.8%) and Estonia (-41.1%). In general, CO2 emissions can be decreased by using more efficient irrigation systems, limiting the use of mineral composts, and introducing organic farming (Ślad węglowy, 2024). Changing the cultivation technique to strip cultivation, abandoning ploughing and intensive soil loosening, as well as reducing fuel consumption for agricultural purposes, and thus decreasing the use of agricultural machinery, can also help reduce emissions. Implementing so-called carbon sequestration techniques, i.e. catch crops, crop rotations and agroforestry, is also very important in this respect. Such activities contribute to the storage of carbon dioxide in the soil (Czasek, 2023).

One of the most important greenhouse gases is methane. In agriculture, it is mainly emitted from the digestive tracts of ruminant animals (cattle, sheep, goats, buffalo) in a process called enteric fermentation (Sierra Club, 2023). In this way, the amount of methane emitted depends on the number of animals, the digestive system and the type and mass of the food being fed (Gibbs, et al., 2002). The most methane is produced by ruminants (nolt, sheep, goats), which have multi-chambered stomachs. An important source of methane in agronomy is also animal excrements, which decompose in anaerobic conditions. The amount of methane produced depends on the mass of excrements and the technology of their management (storage method). From the point A technology that is unfavourable from the point of view of methane emissions is the storage of excrements in liquid form. When storing solid excrements, air penetration limits the occurrence of anaerobic conditions. Direct removal and spreading of excrements on the field (with only short-term storage or without storage) is, due to environmental pollution with methane, the relatively most favourable solution. Methane is also produced during the combustion of crop residues, but in many EU countries this is not a remarkable source (Zaliwski, 2007).

Among the EU countries, the largest increase in methane emissions in the years 2008-2022 occurred in Bulgaria (+45.9%), Hungary (+22.6%) and Estonia (+22.9%) (Fig. 5).

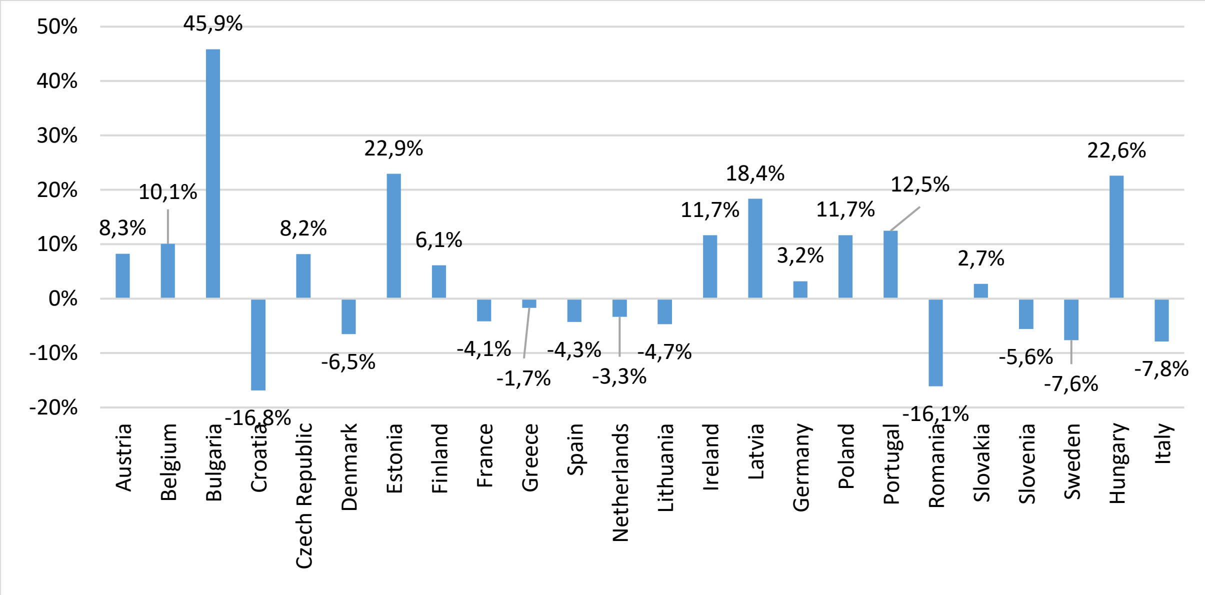


Figure 5. Regional effect in emission of CH_4 in CO_2 equivalent for selected EU countries in 2008–2022

Source: own elaboration.

In eleven countries (Croatia, Denmark, France, Greece, Spain, the Netherlands, Lithuania, Romania, Slovenia, Sweden, Italy) a cut in methane emissions from agriculture was recorded in the analysed period. The average rebate in methane emissions was 7%, while the average increases amounted to 14%.

Nitrous oxide (N_2O) is also a greenhouse gas. Its significant source in agriculture is the use of mineral fertilizers, animal manure, the cultivation of nitrogen-fixing plants and the use of mineral and organic soils leading to intensive mineralization of organic matter. Nitrous oxide can be emitted directly from soil, livestock installations and pastures, but also indirectly as a result of nitrogen transport from soil to surface waters through leaching and surface runoff and from agricultural systems to soil through the transport and deposition of ammonia and nitrogen oxides NO_x (Zaliwski, 2007).

Nitrous oxide is produced primarily in the microbiological processes of nitrification and denitrification of nitrogen, which occurs in the soil, but also outside it in water bodies and in animal excrements before their use as natural fertiliser. Nitrification is the process of oxidising ammonia NH_4 to NO_3 and occurs only in the presence of oxygen, but continuously (Faber, 2001). It is carried out by autotrophic soil bacteria. This process is beneficial from the point of view of soil fertility, because as a result, nitrogen compounds that are not assimilable for plants are transformed into easily accessible ones. A different process is denitrification, which depletes the soil of assimilable nitrogen.

In terms of nitrous oxide emissions in the EU, Bulgaria is the dominant country, followed by Estonia, Latvia and Lithuania (Fig. 6). In these countries, the increase in nitrogen oxide emissions was notably higher than the average level for the countries examined. In turn, the Czech Republic, Greece and Germany minimised N_2O emissions as part of the regional effect, negative values were recorded for these countries.

This indicates a decrease in the size of the carbon footprint generated, caused by the restrictions introduced as a result of regional policies.

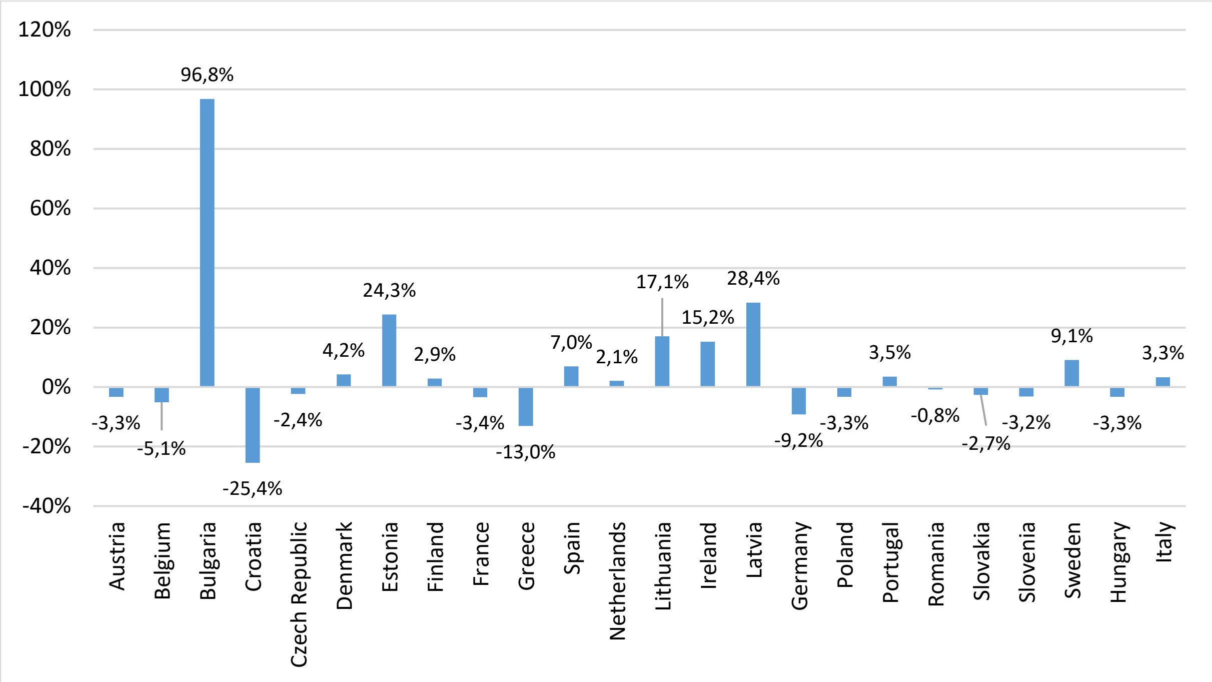


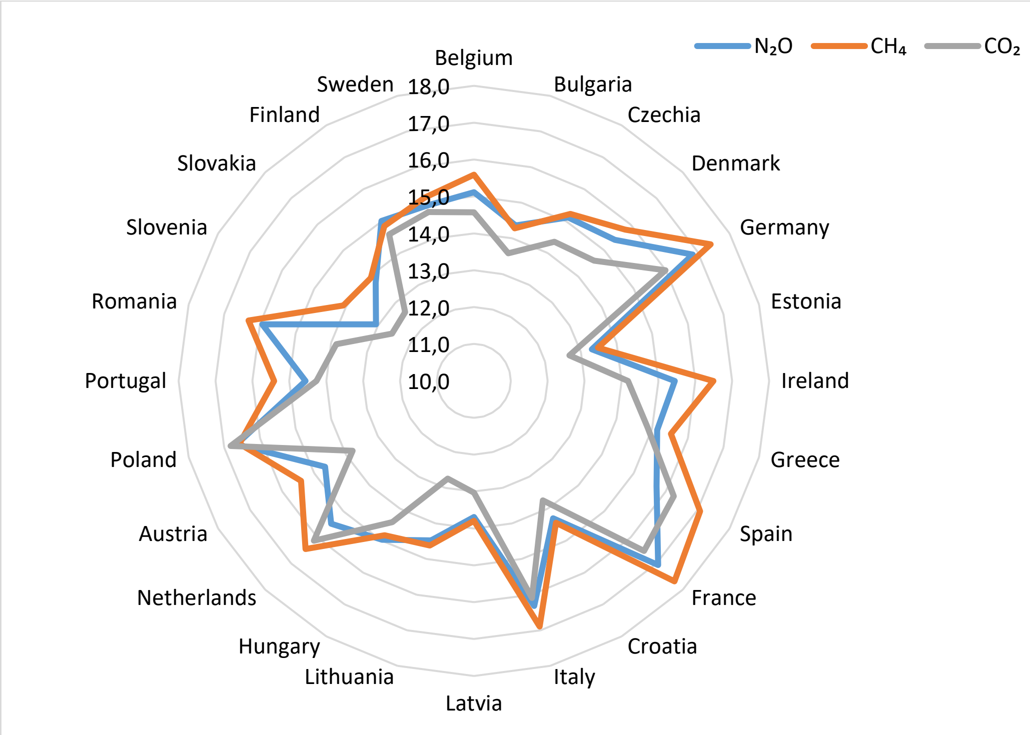
Figure 6. Regional effect in emission of N_2O in CO_2 equivalent for selected countries UE in 2008–2022

Source: own elaboration.

The survey performed confirms that the dynamics of changes in greenhouse gas emissions are regionally diversified. Thus, the second hypothesis (H2) was positively verified.

Studies show that agriculture emits the most methane and nitrous oxide into the atmosphere. However, it produces the least carbon dioxide, which results from its absorption by plants. Among EU countries, the most greenhouse gases are produced in farms in France, Germany and Italy (Fig. 7). These three countries emit the most methane, of which France emits about 45%. A similar situation occurs in the scope of other greenhouse gases. This is related to the intensity of agricultural construction and the share of animal production in these countries. In Estonia, Slovakia and Lithuania, the small area and low intensity of manufacture limit the generation of the carbon footprint. This situation continued both in 2008 and 2022.

a)



b)

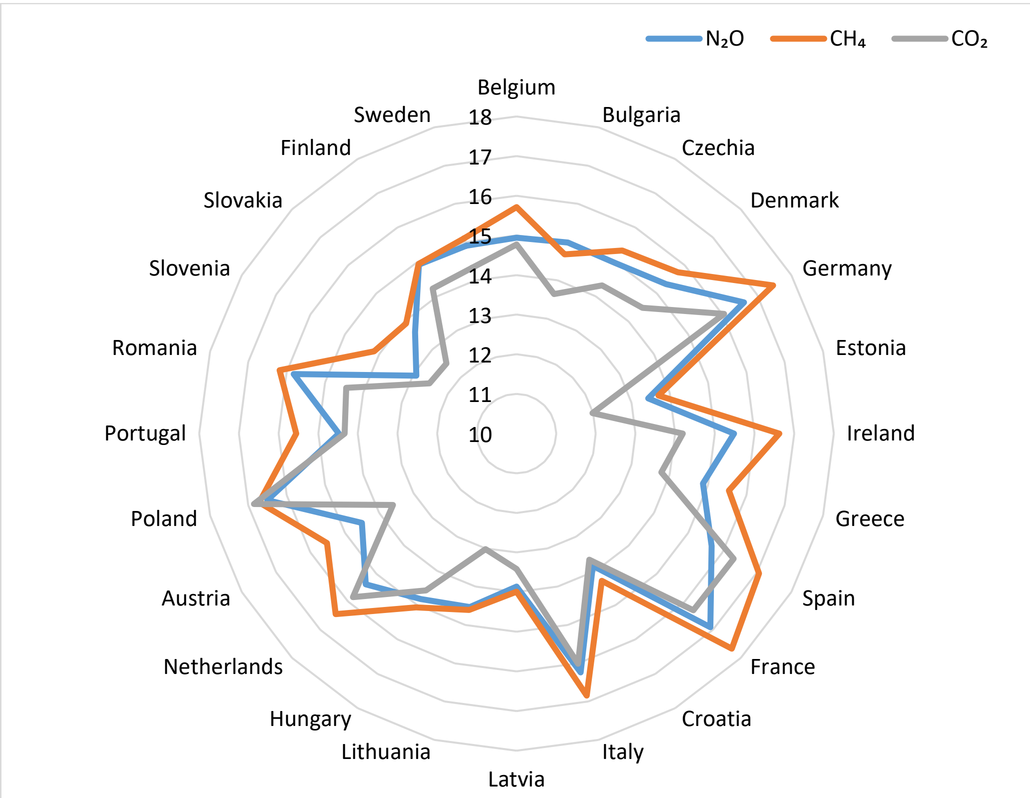


Figure 7. Carbon dioxide, nitrogen and methane emissions in 2008 and 2022

Source: own elaboration.

On the other hand, the Scandinavian countries are considered to be the most ecological: Finland and Sweden occupy intermediate places in the ranking of EU countries in terms of greenhouse gas emissions. Therefore, it should be assumed that the intensity and structure of agricultural production, which meanwhile depends on natural conditions, play a significant role in the generation of the carbon footprint. The third hypothesis (H3) was as a consequence verified positively.

5. CONCLUSION

Agriculture is a major source of greenhouse gas (GHG) emissions and has an important potential to mitigate climate change. In 2021, the EU agronomy sector was responsible for 15.3% of total global greenhouse gas emissions from husbandry. The majority of GHG emissions in the form of methane come from cattle and pig farming. Nitrous oxide also accounts for a large share, from mineral fertilisation and animal manure management. Carbon dioxide is emitted from the combustion of fuels used in agricultural machinery and transport. Carbon footprint study allows for the identification of areas where innovations or changes in agricultural practices can be introduced to reduce GHG emissions.

In the spatial development process, the basic element of sustainable development is the rational shaping of the structure of the use of natural resources. The insufficient level of implementation of sustainable soil and water administration practices in tillage contributes to the increase in greenhouse gas emissions. At the same time, the increase in the share of forest areas that absorb CO_2 has a particularly beneficial effect on the decrease in the size of the carbon footprint. The introduction of mid-field afforestation, especially in areas of marginal importance for agricultural production, remarkably increasing the capacity of the agricultural environment to absorb CO_2, can also strongly strengthen actions compensating for emissions from agriculture.

For the selection of countries in the European Union, the applied shift share analysis allowed them to stand out from the rest in terms of greenhouse gas emissions. The largest increases in emissions of individual gases included in the carbon footprint were recorded in Bulgaria, Estonia, Latvia, Romania and Hungary. A different situation occurred in Croatia and Germany, where carbon emissions from agriculture were limited. Differences in greenhouse emissions in the selected countries result from different directions of development and specialisation in animal and plant production.

The pursuit of low-emission agriculture will depend on the effectiveness of GHG emission decrease measures in animal and plant production. Due to methane emissions during enteric fermentation in animals, one of the possibilities for reducing it is to lower the number of cattle and pigs. In turn, the popularisation of sustainable agriculture principles in plant production can reverse the unfavourable trend of CO_2 emissions from arable soils and trigger sequestration processes. They consist in adopting land management practices that increase the amount of carbon dioxide (CO_2) in the soil, stored as organic matter. Such actions are considered the best practices for handling greenhouse gas emissions.

The scope of the research carried out limits access to detailed data in individual countries. Another significant limitation is the estimated calculation of the carbon footprint. In further research, it is advisable to consider in more detail the factors that determine the level of greenhouse gas emissions in agriculture and link them to the size of the carbon footprint. An important source of knowledge would also be the use of the shifting share method analysis covering other continents.

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