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Emissions from Managed Agricultural Soils in Context of Consumption of Inorganic Nitrogen Fertilisers in Selected EU Countries

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Abstract: In addition to industry, transport, and waste management, the agricultural sector is also a major emitter of CO_2 emissions. This article focuses on CO_2 equivalent emissions from soil in the context of mineral nitrogen fertiliser management. The methodology itself consists of several successive phases, the first of which is to determine basic statistical characteristics for all EU countries, primarily in terms of mineral nitrogen fertiliser consumption, but also in terms of the area of crops grown. EU countries with similar cropping patterns were selected for comparison so that the results could be compared. The results show that there are quite significant differences in CO_2 equivalent emissions between countries under similar conditions. At the same time, the values of the marginal increment of CO_2 emissions as a function of mineral nitrogen fertiliser consumption were calculated. On the basis of the results of the selected countries, an upper limit in terms of CO_2 emissions per hectare of arable land was also determined, and recommendations were made from a national perspective. The emissions themselves can be seen as a negative production externality that is not accounted for in the market mechanism and can thus also distort the price of agricultural production. The methodology used in this paper can be used to set an upper limit on CO_2 emissions from soil due to the use of mineral nitrogen fertilisers and can then be used as an indicator for regulating and defining future agricultural policy instruments within the EU, where the objective is to reduce the level of CO_2 emissions.

Keywords: mineral fertilisers; CO_2 emissions; organic fertilisers; arable land; European Union

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1. Introduction

Global warming is currently a highly debated topic due to the possible consequences. For example, the EPA (Environmental Protection Agency) tracks the global warming potential over a 100-year time period [1]. There are a number of different gases that contribute to global warming. Agricultural activities are responsible for two-thirds of anthropogenic nitrogen monoxide (N_2O) emissions worldwide [2]. The main factors that affect the level of N_2O emissions from agricultural land can be considered in the following main categories: environmental and land management factors. The emission estimates themselves are based on simulation models, which have both weaknesses and strengths [3]. Most emissions from synthetic nitrogen fertilisers occur after they are applied to the soil and enter the atmosphere as nitrogen monoxide (N_2O), a persistent greenhouse gas with 265 times more global warming potential than carbon dioxide (CO_2). Less discussed, however, is the fact that nearly 40% of the greenhouse gas emissions of synthetic nitrogen fertilisers are generated during production and transport, mostly in the form of CO_2 caused by the burning of fossil fuels during production. According to the Food and Agriculture Organisation (FAO), the global consumption of synthetic nitrogen fertilisers will increase by more than 50% by 2050 [4]. According to an FAO study (2019), the global demand for nitrogen fertilisers (expressed in thousands of tonnes of nitrogen) totalled

105,893 thousand tonnes, and in 2022, the FAO study estimates nitrogen consumption at the level of 111,591 thousand tons—a global increase in demand for nitrogen of 5.4% over four years. The demand for nitrogen fertiliser in Europe as a whole in 2022 is estimated at 17,552 thousand tonnes of nitrogen, which is 15.7% of the total world consumption [5]. As already mentioned, the production, transport and use of mineral fertilisers contribute directly and indirectly to greenhouse gas emissions, in particular CO_2 and N_2O. Fertilisers also increase agricultural productivity and stimulate CO_2 uptake by crops. They increase yield and reduce the need to cultivate new land, thus avoiding greenhouse gas emissions from the land use change [6]. The production of ammonia (NH_3), and thus the production of synthetic nitrogen fertilisers, was an important invention of the 20th century and has enabled a significant increase in food production [7,8]. A nitrogen fertiliser can be applied in the form of mineral nitrogen, namely in the forms of ammonium, nitrate and amide, or combinations thereof. The ammonia is a key intermediate in the production of all nitrogen fertilisers. Urea is the main nitrogen fertiliser; it has a high nitrogen content and is relatively easy and cheap to transport. The production of urea requires the supply of CO_2, which is a by-product of ammonia production [9]. While it is desirable to use the inorganic nitrogen for farmland, we do not need or want additional nitrogen in our atmosphere or watercourses. This means that a balance must be struck between the positive benefits of nitrogen fertilization and the negative consequences of the release of nitrogen fertilisers into the environment [7,8]. However, the irrational use of nitrogen in agricultural production systems can menace crop yields and cause environmental and soil damage [10]. The emission of ammonia from fertilised soils to the atmosphere and the subsequent deposition on the land surface has adverse effects on the biogeochemical nitrogen cycle. Emission factors for regions and crops for ammonia application are not well developed, which may affect the estimation of global NH_3 emissions from soils. Regionally, Southeast Asia had the highest contribution to total soil emissions (19%), whereas Europe had the lowest (6%) [11]. The official EMEP (European Monitoring and Evaluation Programme) study reported that the average ammonia emissions per kg of nitrogen applied to arable land (evaporative loss in % of nitrogen) were 11.5% for urea and 6% for ammonium nitrate. The lowest losses by volatilization were reported by EMEP for calcium ammonium nitrate (CAN) and other ammonium nitrate based fertilisers, with only a 0.6% loss by volatilization [12].

Cultivated plants are fundamentally dependent on inorganic nitrogen fertilisers, mainly in the form of NO_3^- and NH_4^+ [13]. In soil, nitrogen undergoes a transformation depending on the chemical composition of the applied nitrogen. While nitrate (NO_3^-) is taken up directly by plants, transformation losses of nitrogen can occur when ammonium (NH_4^+) and urea (NH_2CONH_2) are converted to nitrate, as ammonium and urea must be converted first. Denitrification occurs when soil micro-organisms lack oxygen—this may be due to waterlogging and soil compaction. In this process, soil bacteria convert nitrate and nitrite into nitrous oxide gas, nitric oxide, and nitrogen. These gases are released into the air [14]. The effect of various environmental factors on the N_2O emission flux after fertiliser application was also investigated. The results provide recommendations for monitoring and controlling the carbon to nitrogen ratio in the case of the organic fertiliser application [15]. In the case of the mineral form of nitrogen fertiliser application, emissions may vary strongly in seasonal dynamics, which could be partly related to weather effects [16].

An efficient ratio between basal and broadcast nitrogen application is the most important factor in nitrogen fertilizer management and, in combination with PGRs (plant growth regulators), can be a sustainable strategy for improving crop yield and reducing input costs, while also reducing environmental risks [17,18]. Releasing urea mixtures or standard urea with appropriate levels of nitrogen is a practice that can lead to economic and environmental benefits and thus mitigate environmental impacts [19]. Another way to reduce the impact of agricultural emissions on total greenhouse gases is to change the way fertilisers are applied. Based on the study, suitable agronomic practices may include variable rate nitrogen fertiliser spreading technology. This practice led to a reduction in the average fertiliser rate of 10 kg/ha, which in turn reduced CO_2 emissions by 47 kg/ha [20].

For example, in Brazil, urea is the most-used nitrogen fertiliser for agricultural production and pasture. According to research, a change to non-urea fertilisers or the use of inhibitors could reduce N_2O emissions by up to 23% [21]. Similarly, in Canada, for example, the use of nitrogen fertilisers is a significant source of N_2O emissions. In this case, the authors point to differences in emissions between years of the experiment, with the highest emissions occurring in the first year after application. However, they also point out the influence of weather, especially rainfall activity, and also the time of fertiliser application [22]. Current research is looking at, for example, nitrogen fertilisers with increased efficiency, where the aim is to synchronize nitrogen supply according to crop needs to increase crop production and profitability, while minimizing environmental impacts. However, the results so far do not show a significant difference from, for example, conventional urea [23]. An option for reducing emissions in the case of orchard fruit production is the use of BCRF (bag-controlled release fertiliser). The results show that BCRF reduced the amount of nitrogen fertiliser applied by 65–82% compared to conventional fertiliser application methods, but at the same time there was no reduction in yield. Such a significant reduction indicates a very high application potential [24]. Another possible and very simple tool for reducing emissions from agriculture is the cultivation of suitable crop varieties. In the case of the rice experiment, the Indica variety tended to have higher methane emissions than the Japonica variety. The results showed that methane emissions were significantly dependent on the type of nitrogen fertiliser and rice variety [25]. Currently, another promising option for reducing emissions is the application of nitrogen fertilisers with enhanced efficiency (including nitrification inhibitors) and slow-release fertilisers, which can lead to stable or slightly higher crop yields. However, an appropriate combination of optimal nitrogen fertilization and irrigation management is necessary, especially in dry areas [26,27]. Excessive amounts of ammonia (NH_3) released from nitrogen fertilisers in global agricultural areas play an important role in atmospheric aerosol production, resulting in reduced visibility and regional haze. However, large uncertainties exist in estimates of NH_3 emissions from global and regional agricultural areas using different data and methods. The annual increase in NH_3 emissions shows large spatial variations over the global land surface. South Asia, including China and India, has accounted for more than 50% of total global NH_3 emissions since the 1980s, followed by North America and Europe. Rice cultivation has been the largest contributor to total global NH_3 emissions since the 1990s, followed by maize and wheat. Moreover, the results show that empirical methods that do not account for environmental factors (constant emission factor in IPCC Tier 1—Intergovernmental Panel on Climate Change) could underestimate NH_3 emissions in the context of climate change [28]. This is why many EU member states are limiting the risk of ammonia emissions to air and nitrogen leaching groundwater through their internal legislative procedures. One example is Germany, which as of 1 February 2020 allows the use of urea only with an inhibitor as part of its national legislation. An expected impact of this legislation may be a potential increase in the already widely used calcium ammonium nitrate (CAN) [29]. The Czech Republic has joined a number of other countries where urea fertilisation without a urease inhibitor or without the immediate incorporation into the soil is banned from 1 July 2022. The application of a urease inhibitor allows for long-term planning, independent of weather patterns, and allows for the better flexibility of industrial nitrogen fertilization [30].

The present paper was preceded by studies on nitrogen use with respect to its impact on crop production in the European Union using Eurostat and FAO national data. At the same time, these studies produced the EuropeAGriDBv1.0 database of 2021, which allows for the construction of scenarios for the future [31–33]. The above shows a focus on the effect of the magnitude of nitrogen fertiliser inputs on the volume of crop production in terms of the value of nitrogen produced.

The degree of intensification of agricultural production shows significant differences between countries. The excessive use of nitrogen fertilisers leads to dramatic environmental problems or, conversely, very low nitrogen use can lead to the depletion of soil nitrogen reserves [34–37].

In this case, our paper differs from previous studies in that we assess the effect of mineral nitrogen fertiliser use in relation to CO_2 emissions from arable land in selected EU countries. Another distinctive feature, and the main contribution of this paper, is the determination of the maximum possible CO_2 emission limits per ha of arable land for selected EU countries based on the analyses performed. From the above emission limits, the maximum possible mineral nitrogen fertiliser use per ha of arable land (in terms of net nitrogen) was then calculated. This methodology should lead to a better balance between countries in terms of CO_2 emissions from mineral nitrogen fertilisers per ha of arable land. For this reason, the following research questions were set:

RQ1: Has the consumption of mineral nitrogen fertiliser increased by more than 20% over the period 2010–2019 for any of the assessed countries?
RQ2: In the assessment period of 2010–2019, were there any EU countries that consumed more than 1.5 tonnes of mineral nitrogen fertiliser per 1 tonne of organic fertiliser (measured in terms of net nitrogen)?
RQ3: Are there countries where an increase in mineral nitrogen fertiliser consumption (in net nutrient terms) of 1 kg will lead to an increase in CO_2 emissions of more than 7.5 kg?

The main objective of this scientific paper is to demonstrate differences between emissions from managed agricultural soils in the context of the consumption of inorganic nitrogen fertilisers for a homogeneous sample of selected EU member states. The comparability of the created homogeneous sample will be conditioned by similar cropping patterns on arable land within each EU country. The scientific contribution provides a new methodological perspective on the possibility of comparing soil emissions from the use of artificial nitrogen fertilisers in selected EU member states with a comparable cropping structure on arable land.

2. Materials and Methods

In order to achieve this objective, the data used are first described, including a detailed specification, and then the individual methodological steps for calculating the sub-indicators necessary for evaluating the research questions are described.

The underlying data for this scientific paper are obtained from the publicly available Eurostat database and consist of the following three basic files: 1. gross nutrient balance [online data code: AEI_PR_GNB], 2. greenhouse gas emissions by source sector [online data code: ENV_AIR_GGE__custom_2987611, air pollutants and greenhouse gases: managed agricultural soils, CO_2, N_2O in CO_2 equivalent, CH_4 in CO_2 equivalent, HFC in CO_2 equivalent, PFC in CO_2 equivalent, SF6 in CO_2 equivalent, NF_3 in CO_2 equivalent], 3. utilised agricultural area by categories [online data code: TAG00025].

> *Notice/Eurostat definition: The Utilised agricultural area (abbreviated as UAA) describes the area used for farming. It includes the following land categories: (a) arable land; (b) permanent grassland; (c) permanent crops; (d) other agricultural land, such as kitchen gardens (even if they only represent small areas of the total UAA). The term does not include unused agricultural land, woodland, and land occupied by buildings, farmyards, tracks, ponds, etc. This indicator uses the concept of "main area" that means the area of the land parcel. In the case of annual crops, the main area corresponds to the sown area; in the case of permanent crops, to the total planted area; in the case of successive crops, to the main crop that occupied the parcel during that year; and in the case of simultaneous crops, to the corresponding area of the different crops.*

The three basic files from the Eurostat public database mentioned above are analysed in turn in the sub-stages of the research and the results of the analyses are subsequently presented in Section 3 the section "Results and Discussion".

FIRST STAGE—analysis of the total nitrogen fertiliser consumption (tonnes of nutrient) and determination of the relationship between mineral fertiliser consumption, manure consumption, and the consumption of other organic fertilisers (plant compost, digestate, fugate, and other crop residues). In the first stage, the data from gross nutrient balance file 1

(AEI_PR_GNB) will be used, the basic characteristics of the data from file 1 are as follows: time frequency FREQ: annual (A)—time 2010–2019, nutrient NUTRIENT: nitrogen (N), agricultural indicator INDIC_AG: total consumption of fertilisers (except manure, tonnes of nutrient) [I_FRT], consumption of mineral fertilisers (tonnes of nutrient) [I_FRT_MIN], consumption of organic fertilisers (except manure) (tonnes of nutrient), [I_FRT_ORG], and manure input (tonnes of nutrient) [I_MNR]. The selected baseline data are then applied to the following EU countries:

Belgium [BE], Bulgaria [BG], Czechia [CZ], Denmark [DK], Germany (until 1990 former territory of the FRG) [DE], Estonia [EE], Ireland [IE], Greece [EL], Spain [ES], France [FR], Croatia [HR], Italy [IT], Cyprus [CY], Latvia [LV], Lithuania [LT], Luxembourg [LU], Hungary [HU], Malta [MT], Netherlands [NL], Austria [AT], Poland [PL], Portugal [PT], Romania [RO], Slovenia [SI], Slovakia [SK], Finland [FI], Sweden [SE], Norway [NO], Switzerland [CH], United Kingdom [UK].

The "Visegrad group" of the four countries (V4) Czech Republic, Poland, Hungary, and the Slovak Republic will be selected as the basic group to be analysed. The results of the V4 countries will be compared with the Romania-Bulgaria and Germany-France pairs. Changes in the consumption of mineral nitrogen fertilisers and manure (tonnes of nutrient) in the time period 2010–2019 will be determined, the base index (2019/2010) will be used to assess the changes. The calculation is based on the following formula:

$$Base\ index = \frac{Yt}{Y0} \quad (1)$$

where:

Yt is the consumption of mineral nitrogen fertilisers of the i-th country in tonnes of net nutrients in 2019;

*Y*0 is the consumption of mineral nitrogen fertilisers of the i-th country in tonnes of net nutrients in 2010.

Furthermore, the calculation of the consumption of mineral nitrogen fertilisers per kg of manure and other organic matter will be made (*CMF_MOF ratio*). The calculation is based on the following formula:

$$CMF_MOF\ ratio = Xi/Yi \quad (2)$$

where:

Xi is the annual consumption of mineral nitrogen fertilisers of the i-th country in tonnes of net nutrients

Yi is the annual consumption of manure and other organic matter of the i-th country in tonnes of net nutrients

The CMF_MOF ratio will be calculated for the two groups of countries. The first analysed group will include the Czech Republic, Poland, Hungary, the Slovak Republic, Romania, and Bulgaria. The second group will include the following countries: the Netherlands, Austria, Italy, Portugal, and Spain. The results of Germany and France will serve as a benchmark for both groups. The results of each country will be compared with the V4 average and the EU average.

SECOND STAGE—data processing and comparison between EU countries—CO_2 emissions of individual EU countries—national statistics related to the application of industrial nitrogen fertilisers.

Nitrogen consumption—EUROSTAT (consumption of inorganic fertilisers—AEI_FM_USEFERT, nitrogen), soil emissions—greenhouse gases CO_2 equivalent managed agricultural soils—ENV_AIR_GGE), for all EU countries.

THIRD STAGE—baseline set in terms of production characteristics—the cropland structure will be determined (calculated) for all countries. Arable land (ARA; %) of basic crop commodities: crop structure: wheat and spelt (C1100), rye and winter cereal mixtures

(C1200), barley (C1300), oats and spelt cereal mixtures (C1400), grain maize and corn-cob-mix (C1500), triticale (C1600), potatoes (R1000), sugar beet (R2000), rape and turnip rape seeds (I1110), sunflower (I1120), and green maize (G3000).

A vertical analysis is used to determine the structure of the cropped area, where the aim is to determine the share of each selected crop in the arable land.

FOURTH STAGE—selection of countries from the core set suitable for benchmarking. The fourth stage results in a shortlist of countries with a similar structure of arable land for the cultivated crops. The V4 countries (Czech Republic, Hungary, Poland, and Slovakia) and Romania, Bulgaria, Germany, and France are selected for a more detailed analysis. The results of the vertical analysis will show which countries have a very similar cropping pattern on arable land for each crop.

FIFTH STAGE—calculation of CO_2 emissions in kg per hectare of arable land for selected EU countries in 2020 (CO_2_HA_2020) and calculation of the five-year average of this indicator for the years 2016–2020 for each country assessed (CO_2_HA_5Y_AVERAGE). Subsequently, an overall average indicator for the whole group of assessed countries will be calculated (CO_2_MAX). Basic Excel tools will be used to calculate these baseline values.

The value of the group indicator CO_2_MAX will be considered as the upper non-transgressible limit of CO_2 emissions per hectare of arable land for all assessed countries (MAX_LIMIT).

SIXTH STAGE— calculation of the correlation analysis for the sample set. Independent variable: mineral nitrogen fertiliser consumption (kg/ha arable land); dependent variable: CO_2 emissions (kg/ha arable land). Correlation analysis will be performed using STATISTICA software, version 14.05. A linear function (Y = ax + b) will be chosen. The linear relationship is not entirely ideal in terms of the complexity of the whole issue of CO_2 emissions, but at the same time it has a major advantage—it is relatively easy to interpret the results obtained.

SEVENTH STAGE— The value of the variable MAX_LIMIT (CO_2_MAX) will be fitted into the theoretical equations of linear dependencies for each of the countries under study and the maximum theoretical allowable consumption of nitrogen mineral fertilisers in kg of net nutrients per ha of arable land for each of the countries evaluated (TEOR) will be calculated. The maximum theoretical consumption of nitrogen fertiliser (TEOR) will be compared with the average real consumption for each country for the years 2016–2020 (AVG). The absolute difference between real and theoretical mineral nitrogen fertiliser rates per hectare of arable land DIFER = TEOR-AVG will be calculated and the relative relationship between the values REL = TEOR/AVG will be calculated. These results then show the facts, presented towards the end of the results section of this paper, about the reduction or possible increase in the use of mineral nitrogen fertiliser in each country.

3. Results and Discussion

This section is divided into three parts. In the first part, there is a discussion of the development of the consumption of all nitrogen fertilisers (mineral, manure, and other organic fertilisers); in selected EU countries, descriptive statistics are used, and the ratio between the consumption of mineral nitrogen fertilisers and the consumption of organic fertilisers (CMF_MOF) is calculated. In the second part, there is a discussion on the evolution of CO_2 production per hectare of arable land, and descriptive statistics are also used. In the third part, a correlation analysis is performed between the values of all nitrogen fertiliser consumed and CO_2 production, and differences between groups of countries are discussed.

3.1. Development of Nitrogen Fertiliser Consumption in Selected EU Countries for the Period 2010–2019

In the first stage of the research, a basic analysis of selected EU countries is carried out on the volume and structure of use of all types of nitrogen fertilisers, i.e., mineral fertilisers, manure, and other organic fertilisers (compost, digestate, and other crop residues).

The group of V4 countries (Visegrad Group)—the Czech Republic (or Czechia), Poland, Hungary, and the Slovak Republic (or Slovakia)—was selected as the basic group to be analysed. The results of the V4 countries are compared with the Romania-Bulgaria and Germany-France pairs. The basic structure of consumption of all types of nitrogen fertilisers in 2019 for the above-mentioned countries is shown in Figure 1.

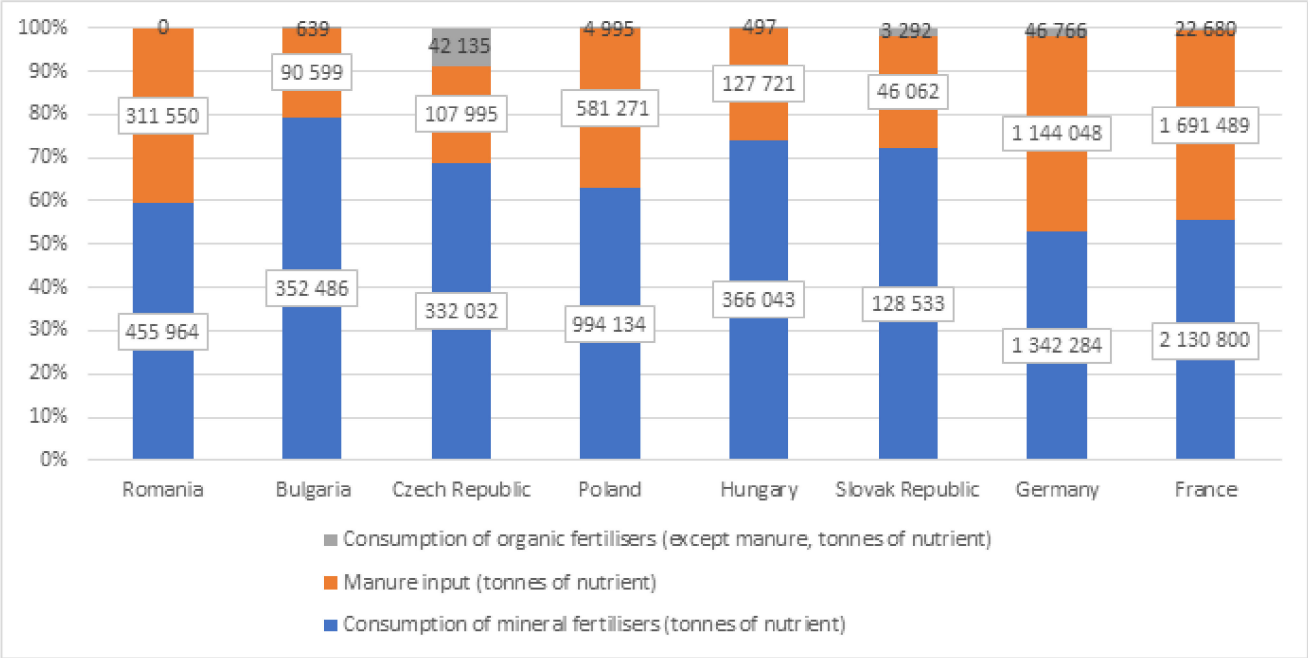


Figure 1. Total consumption of nitrogen fertilisers (2019, tonnes). Source: own calculation based on Eurostat.

As can be seen from Figure 1, there are two subgroups (pairs) among the V4 countries. For the first subgroup of countries Slovakia-Hungary, the share of nitrogenous mineral fertilisers in the total consumption of all nitrogen fertilisers ranges from 72.3% to 74.1%, i.e., the representation is above 70% of the total consumption of nitrogen fertilisers. For the second pair of countries Poland-Czechia, the share of mineral fertilisers in the total consumption of all nitrogen fertilisers is at a lower level, it is a share ranging from 62.9% to 68.9% of the total consumption of all types of fertilisers (inorganic and organic). Furthermore, Figure 1 shows that the Germany-France pair has a much lower share of artificial (mineral) nitrogen fertilisers in the total consumption of all nitrogen fertilisers, compared to the V4 group as a whole. In Germany in 2019, the share of artificial nitrogen fertilisers was only 53.1% of the total organic and inorganic fertiliser consumption. For France, the share of mineral fertilisers was also lower, reaching 55.4% in 2019. The structure of nitrogen fertiliser consumption for the other country pair Romania-Bulgaria is quite different. While in Romania in 2019 the share of consumed artificial nitrogen fertilisers was only 59.4% of all N-fertiliser consumption, Bulgaria represented the opposite extreme in 2019, with almost 80% (namely 79.4%) of all nitrogen-fertilisers consumed in the form of artificial nitrogen fertilisers. Looking at the results of Figure 1 from a different perspective, it can be noted that in 2019 France had the largest share of manure (in terms of nitrogen value) of the total nitrogen-fertiliser consumed. The share of manure in France was 44.0%, followed by Germany with 45.2% of manure consumption as a nitrogen-fertiliser. Romania had the highest share of 40.6%, followed by Poland (36.8%), Slovakia (25.9%), Hungary (25.8%), and the Czech Republic (22.4%). Bulgaria had the lowest share of manure consumption of all countries assessed (20.4%).

The shares of other organic fertilisers (excluding manure) in the total consumption of all nitrogen fertilisers (converted to nitrogen value) are low for all assessed countries in

2019: below 2% of the total consumption structure, except for in the Czech Republic, where a value of 8.74% is reported. Another exception is Romania, where zero consumption of other organic fertilisers (compost, digestate, etc.) is reported. The shares of organic fertilisers of selected countries in 2019 (below 2% of the total nitrogen fertiliser structure) were as follows (listed in descending order): Germany 1.85%, Slovakia 1.85%, France 0.59%, Poland 0.32%, Bulgaria 0.14%, and Hungary 0.10%.

Another angle through which to analyse the consumption of nitrogen fertilisers is the trend in the development of the nitrogen fertiliser sub-items over time. The results of the analysis for selected EU countries are presented in Table 1.

Table 1. Changes in mineral nitrogen fertiliser and manure consumption (2019/2010, tonnes of nutrient, base index). Source: own calculation based on Eurostat.

	Mineral Fertilisers (Tonnes of Nutrient)		Base Index	Manure (Tonnes of Nutrient)		Base Index
	2010	2019	2019/2010	2010	2019	2019/2010
Romania	305,757	455,964	1.49	361,122	311,550	0.86
Bulgaria	199,083	352,486	1.77	96,779	90,599	0.94
Czech Republic	270,256	332,032	1.23	108,635	107,995	0.99
Poland	1,027,430	994,134	0.97	559,549	581,271	1.04
Hungary	281,428	366,043	1.30	121,259	127,721	1.05
Slovakia	106,513	128,533	1.21	60,399	46,062	0.76
Germany	1,569,045	1,342,284	0.86	1,245,772	1,144,048	0.92
France	2,080,333	2,130,800	1.02	1,789,725	1,691,489	0.95

Table 1 shows that France, as the largest consumer of mineral nitrogen fertilisers in the EU (consumption of 2.13 million tonnes of mineral nitrogen fertilisers in 2019), has seen almost no increase in the consumption of artificial nitrogen fertilisers since 2010 (base index value of 1.02). Germany, on the other hand, has seen a significant decrease in its consumption of artificial nitrogen fertilisers from 1.57 million tonnes in 2010 to 1.34 million tonnes in 2019 (base index 0.86). Poland also showed a decrease in mineral fertiliser consumption, with 1.03 million tonnes of synthetic N-fertiliser consumed in 2010 and 0.99 million tonnes of mineral N-fertiliser consumed in 2019 (base index 0.97). For all V4 countries except for Poland, there was an increase in the consumption of nitrogen-fertilisers over the period 2010–2019. The base indices for these countries (Czech Republic, Hungary, and Slovakia) range from 1.21 to 1.30. The Eastern European countries Romania (base index 1.49) and Bulgaria (base index 1.77) show the highest dynamics in mineral fertiliser consumption between 2010–2019.

Table 1 also shows that the consumption of manure as a nitrogen fertiliser has been declining in almost all of the countries studied over the period of 2010–2019. The largest decreases in manure consumption were recorded for Slovakia (base index 0.76) and Romania (base index 0.86). In contrast, the consumption of manure as a nitrogen fertiliser increased in two of the countries surveyed over the 2010–2019 period. These are Poland (base index 1.04) and Hungary (base index 1.05).

From these results, it is also possible to answer RQ1 defined in the introduction section. Within the countries evaluated, it is clear that there was an increase in the consumption of mineral nitrogen fertilisers of more than 20% over the period under consideration in Slovakia, the Czech Republic, Hungary, Romania, and Bulgaria. Thus, almost all V4 countries are involved. It is also interesting to observe the decline in the use of manure as a fertiliser. A possible explanation may be the decrease in livestock production (especially in Slovakia and Romania). Poor nitrogen management is a serious problem globally, as farmers typically overuse chemical fertilisers to increase yields and consequently their income. The over-supply of chemical fertilisers, especially nitrogen-based fertilisers, has brought about serious environmental problems, including the deterioration of water quality, impacts of global warming, soil acidification, and eutrophication of water [38]. The increasing use

of nitrogen fertilisers is also a concern in India, where fertiliser consumption may double by 2050 [39].

The authors of the paper believe that an important methodological indicator that can be used to analyse the differences between the countries evaluated very well is a relative indicator: consumption of mineral fertilisers per 1 kg of manure and other organic fertilisers (CMF_MOF). The calculated values of this indicator are captured in Figure 2.

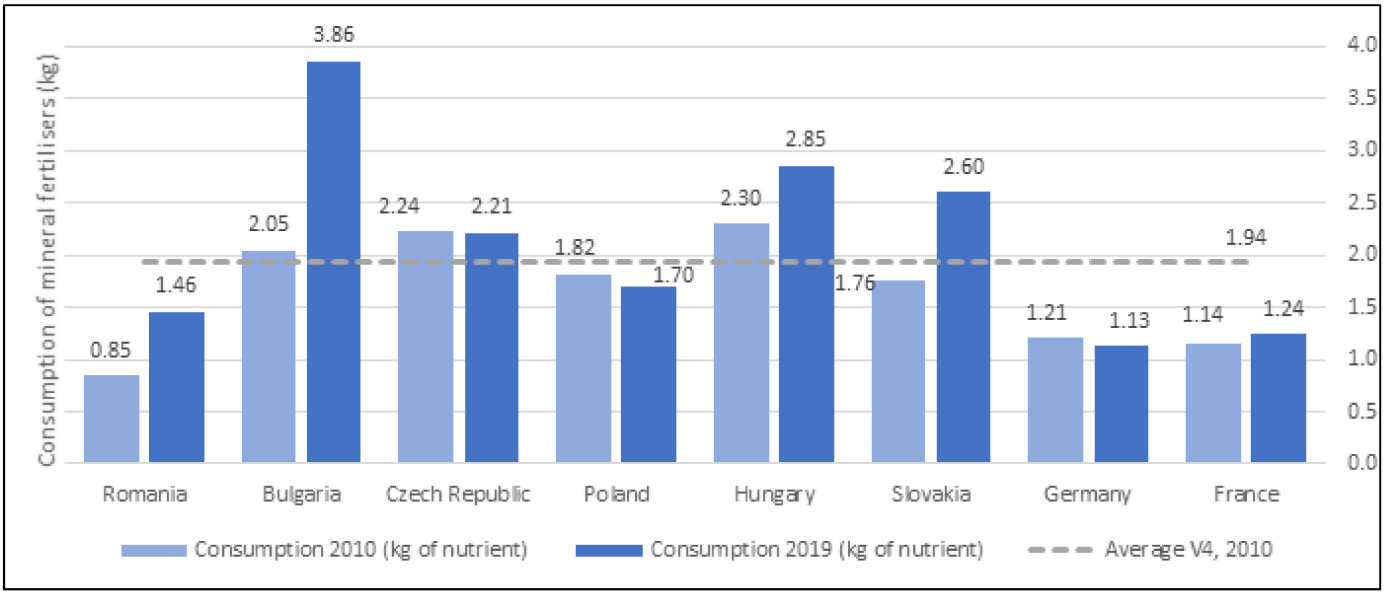


Figure 2. Consumption of mineral fertilisers per 1 kg of manure and other organic fertilisers. Source: own calculation based on Eurostat.

As Figure 2 shows, the average consumption of mineral fertilisers per 1 kg of manure and other organic fertilisers in the V4 countries in 2010 was 1.94. This was therefore almost double the volume of mineral fertiliser applied compared to the application of any form of organic matter (converted to the nitrogen value). In 2019, the ratio (coefficient) increased even more, the average of the V4 countries reached a value of 2.34, the number of artificial fertilisers in relation to the application of a unit of organic fertiliser changed significantly to the detriment of organic matter (manure and other organic fertilisers, i.e., plant composts, digestate, fugate, etc.). The most dramatic increase in the ratio of the two components was reported for Hungary and Slovakia. In Hungary, 2.30 times more artificial fertilisers were used in 2010 than organic fertilisers and in 2019 almost three times more nitrogen artificial fertilisers were used compared to any form of organic fertilisers, including manure (a factor of 2.85). In Slovakia, 1.76 times more artificial fertilisers were used in 2010 than organic fertilisers, and in 2019 almost two and a half times more artificial nitrogen fertilisers were used compared to any form of organic fertilisers, including manure (coefficient 2.60). In the time interval under review, Slovakia showed higher growth dynamics for the above-mentioned CMF_MOF indicator (ratio of applied nitrogen fertilisers). The Czech Republic, on the other hand, showed a decrease in the ratio of nitrogen fertilisers applied in the period of 2010–2019, in favour of organic matter. One factor that could have an impact on this indicator is the significant investment support for the construction of biogas plants, along with the subsidy of the purchase price of energy from this renewable energy source. The increase in the biogas plant capacity is linked to an increase in the production of organic fertiliser in the form of fugate and digestate. Like the Czech Republic, Poland also showed a decrease in the nitrogen fertiliser ratio between 2010 and 2019, in favour of organic fertiliser—the coefficient decreased from a higher value of 1.82x (predominance of artificial fertilisers) to 1.70 (lower value of the predominance of artificial nitrogen fertilisers, measured in nitrogen content). Romania-Bulgaria and Germany-France were chosen as

benchmarks to assess the situation in the V4 countries. While the Western European countries Germany-France show a time series dominance of artificial nitrogen fertilisers over organic nitrogen fertilisers at 1.21 and 1.14 in 2010 and at 1.13 and 1.24 in 2019, the representative of the group of Eastern European countries, Bulgaria, shows a value of 2.05 in 2010, with a dramatic increase to a value of 3.86 in 2019. Thus, Bulgaria saw the most significant changes, with the predominance of artificial nitrogen fertilisers almost four times higher than nitrogen fertilisers in the form of manure and other organic matter.

From the above results, it is possible to answer RQ2. In terms of the combination of mineral and organic nitrogen fertilisers, it is possible to see significant differences between countries. It is possible to see a slight similarity, especially in the south-western countries where organic nitrogen fertilisers predominate (mainly the Netherlands, Italy, Portugal, and Spain, but also Austria, Germany, and France). A significantly higher share of mineral fertilisers is then evident, especially in the central-eastern EU countries, where 1.46–3.86 kg of mineral nitrogen per 1 kg of organic nitrogen is used (all V4 countries including Bulgaria and Romania). This may also be of interest in terms of nitrogen fertiliser imports in future years when food security will require food production to be maintained at a similar level to the present.

Nitrogen fertiliser consumption in Europe is not expected to change dramatically over the next 10 years. However, the range of fertilisers is changing due to the need to optimise nitrogen fertilisation [40]. However, in some countries, there is evidence of lower efficiency in the relationship between fertiliser production and consumption, with farms consuming too much fertiliser to produce the same output as other more efficient farms [41].

As shown in Figure 3, the EU-wide average of the CMF_MOF indicator showed a value of 1.04 in 2010 (the value for all EU countries). This is therefore on average an almost balanced 1:1 ratio between the application of artificial and organic fertilisers (measured in nitrogen content). Within the selected western EU countries (the Netherlands, Austria, Italy, Portugal, Spain, Germany, and France), the ratio of mineral to organic nitrogen fertiliser was 0.79:1 in 2010 and almost unchanged in 2019 (0.78:1). The Germany-France-Spain trio of countries is different from the Netherlands-Austria-Italy-Portugal quadruple. The first mentioned trio of states is close to the European average (the CMF_MOF indicator is around 1) (Figure 3). In contrast, the second four countries show values ranging from 0.48 (the Netherlands) to 0.62 (Portugal). It can be noted that the Netherlands has the lowest consumption of artificial mineral nitrogen fertiliser per unit of organic fertiliser (measured in nitrogen content). This is a country with a high volume of livestock production per unit of land.

Synthesising the results from Figures 2 and 3, it can be seen that there are abysmal differences in the CMF_MOF indicator between the V4 countries and between selected groups of Western European countries. These differences should be taken into account in the formulation of strategies for reducing the emission load arising from both the production of nitrogen fertilisers and their transport and application. The specificities of the groups of countries analysed should be respected in these measures.

This is confirmed, for example, by a study [42] where EU policy on sustainable agricultural development limits the use of chemical fertilisers, in order to protect the environment, promote biodiversity, and ensure food safety. This policy is welcome, but it must be adapted to the actual average consumption and also take into account the different needs of countries in terms of productivity, farmers' incomes, and, last but not least, profit levels.

3.2. Evolution of CO_2 Emissions per ha of Arable Land for Selected EU Countries for the Period 2010–2020

Another area of comparison in this article is the calculation of CO_2 emissions per hectare of arable land for selected groups of countries. The V4 countries, the pair of Eastern European countries (Romania-Bulgaria), and the pair of Western European countries (Germany-France) are considered. The results are presented in Figure 4.

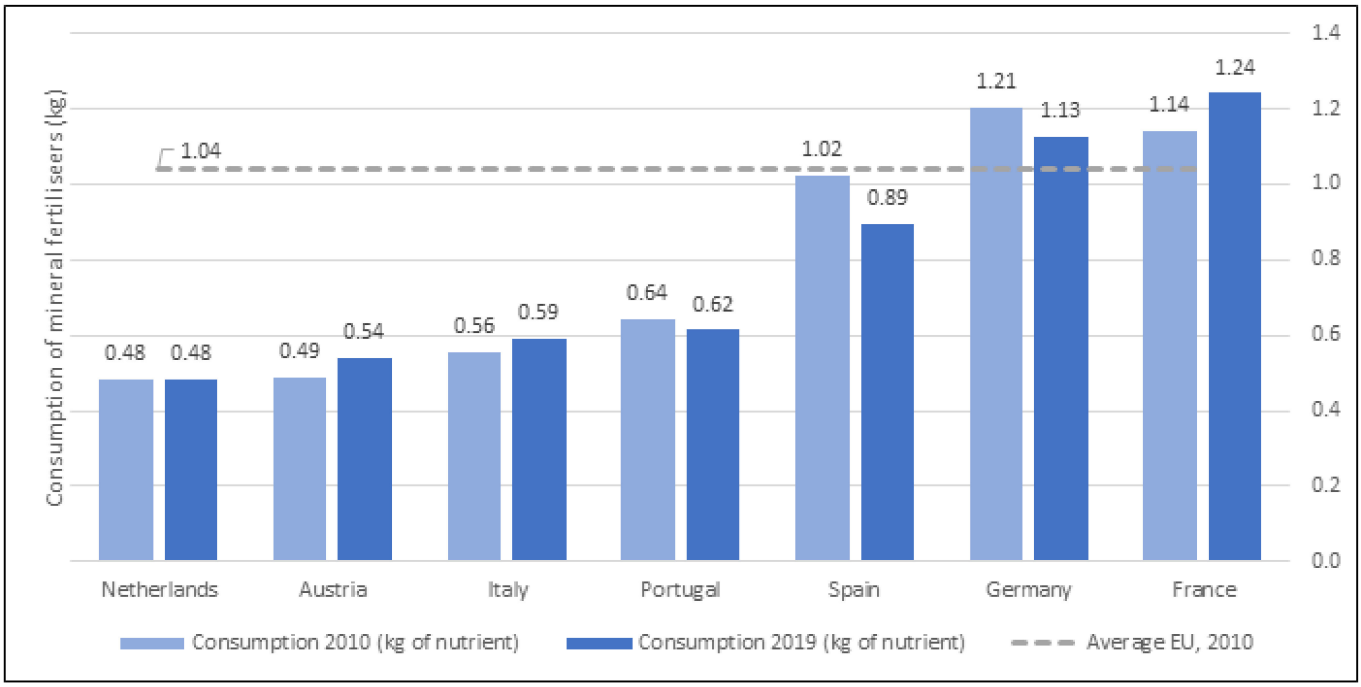


Figure 3. Consumption of mineral fertilisers per 1 kg of manure and other organic fertilisers. Source: own calculation based on Eurostat.

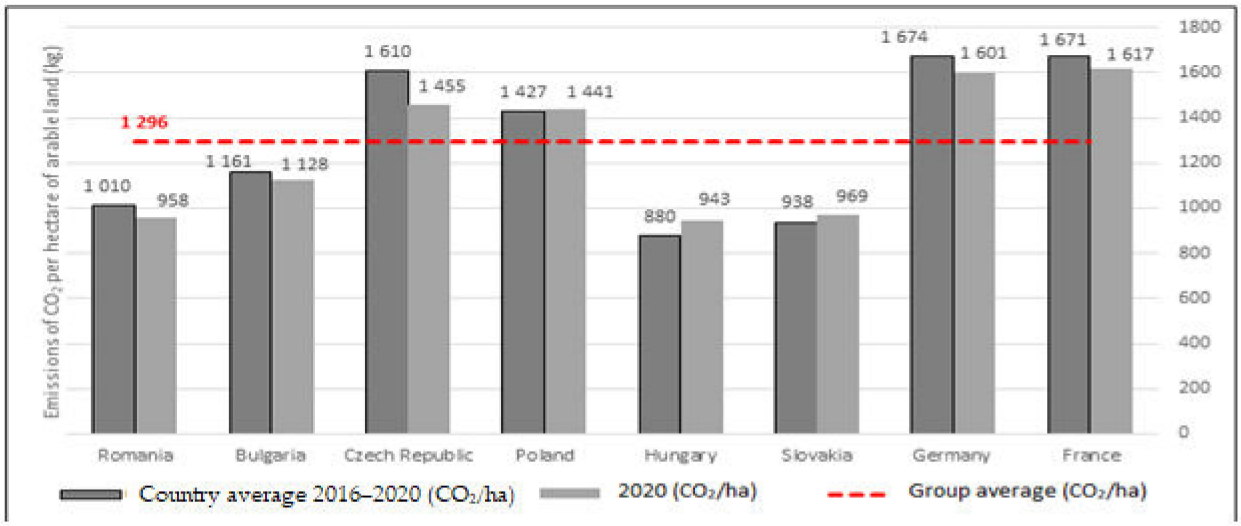


Figure 4. Emissions of CO_2 per hectare of arable land (kg). Source: own calculation based on Eurostat.

As shown in Figure 4, almost all of the countries analysed saw a decrease in the value of CO_2 emissions per hectare of arable land in 2020 when compared to their five-year average (2016–2020). This is a very positive trend. For Romania, the decrease was from 1100 tonnes of CO_2 to 958 tonnes of CO_2, i.e., a 5.2% decrease. For Bulgaria, CO_2 emissions in 2020 fell to 1128 tonnes of CO_2 compared to the five-year average of 1161 tonnes of CO_2 (a decrease of 2.8%). For the Czech Republic, CO_2 emissions in 2020 fell to 1455 tonnes of CO_2 compared to the five-year average of 1610 tonnes of CO_2 per hectare of arable land (a decrease of 9.6%). For Germany, CO_2 emissions fell to 1601 tonnes of CO_2 per hectare of arable land, while the five-year average was higher, at 1674 tonnes of CO_2 (down 4.4%). France also showed a decrease in emissions, with emissions of 1617 tonnes of CO_2 per hectare of arable land in 2020, but the five-year average was 1671 tonnes of CO_2 (a decrease of 3.2%). However, three countries in the V4 group (Poland, Hungary, and

Slovakia) showed either an unchanged CO_2 production (Poland) or an increase in the value of CO_2 emissions per hectare of arable land. For Hungary, emissions in 2020 increased to 943 tonnes of CO_2/ha, while the five-year average was 880 tonnes of CO_2 (an increase of 7.1%). For Slovakia, emissions in 2020 increased to 959 tonnes of CO_2, while the five-year average was 938 tonnes (an increase of 3.3%).

In general, other studies also point to the need to reduce nitrogen emissions in agricultural production [43]. Another option is to focus on more efficient nitrogen use, as most applied nitrogen fertilisers are fast acting, which also causes high emissions [44].

Furthermore, it should be noted that, not only the trend of CO_2 production per hectare of arable land over the period of 2016–2020 is an important indicator, but also the magnitude of CO_2 production per hectare of arable land. The authors of the article are aware that comparing countries on the basis of CO_2 production per 1 ha of arable land may be confronted with a view that prefers to calculate CO_2 emissions per tonne of crop production (taking into account intensive or extensive farming methods). The authors of the paper believe that CO_2 production per area can better indicate the location of the producer.

As shown in the values presented in Figure 4, in 2020, France and Germany were the largest producers of emissions per hectare of arable land. France and Germany reached values of 1617 and 1601 tonnes of CO_2 emissions per hectare of arable land, respectively. The average for both countries was 1609 tonnes of CO_2. The two V4 countries (Hungary and Slovakia) only reached 58–60% lower CO_2 emission levels in 2020, compared to the German-French average. The other two V4 countries (Poland and the Czech Republic) showed a higher CO_2 emission value in relation to the Germany-France countries. The Czech Republic produced emissions of 1455 tonnes of CO_2/ha of arable land in 2020, which was 90.4% of the level of the Germany-France countries. Poland emitted 1441 tonnes of CO_2/ha of arable land in 2020, which was 89.6% of the emission level of the Germany-France countries.

The high CO_2/ha emissions are also highlighted by a study [45] which examined emissions from maize cultivation. Important results include the differences in soil emissions during the growing season and in the post-harvest period. The influence of atmospheric temperature and humidity is also pointed out, with the highest soil emissions at a higher humidity when anaerobic conditions are established in the soil [46]. Another factor influencing emissions is the salt content of the soil. Globally, about 831 million hectares of agricultural land are affected by salt. Salinity and sodicity adversely affect soil microbial diversity and enzymatic activities, and thus carbon and nitrogen dynamics and greenhouse gas (GHG) emissions from soils [47].

Subsequently, the authors of the paper present for discussion a methodological tool in which, for selected EU countries with similar cropping patterns on arable land, an upper limit of CO_2 emissions could be established to serve as an indicator for regulation and for the establishment of future policy instruments to reduce CO_2 emissions from arable land from all types of nitrogen fertilisers. For the purposes of this article, a CO_2 emission cap of 1296 tonnes of CO_2 per hectare of arable land has been set. This standard (CO_2_MAX) was derived from the five-year average of CO_2 emissions of selected countries (V4 countries, Romania-Bulgaria, and Germany-France).

3.3. CO_2 Emissions Per Hectare of Arable Land as a Function of Nitrogen Fertiliser Consumption, Correlation Analysis

Another area addressed in this paper is the calculation of the strength of the relationship between the value of nitrogen fertiliser consumption per hectare of arable land (kg/1 ha) and the value of emissions from this hectare (tonnes CO_2/ha). The countries considered are the V4, Eastern European (Romania-Bulgaria) pairs and the Western European (Germany-France) pairs. The results of the correlation analysis are presented in Table 2 and Figure 5; more detailed results, including graphical representation, are presented in Figures A1–A8.

Table 2. Results of correlation analysis (2009–2020). Source: own calculation based on Eurostat.

Countries	Equation	Coefficient of Determination
Romania	Y = 9.8832x + 524.32	0.7675
Bulgaria	Y = 7.6408x + 366.01	0.9244
Czech Republic	Y = 7.2314x + 536.75	0.9067
Poland	Y = 7.0717x + 710.69	0.7365
Hungary	Y = 6.9027x + 199.51	0.9761
Slovakia	Y = 6.2882x + 351.98	0.4996
Germany	Y = 4.2692x + 1119.7	0.6885
France	Y =8.6646x + 656.85	0.7099

Note: Y = emissions of CO_2 from hectare of agriculture land, x = consumption of nitrogen fertilizer in Kg/hectare.

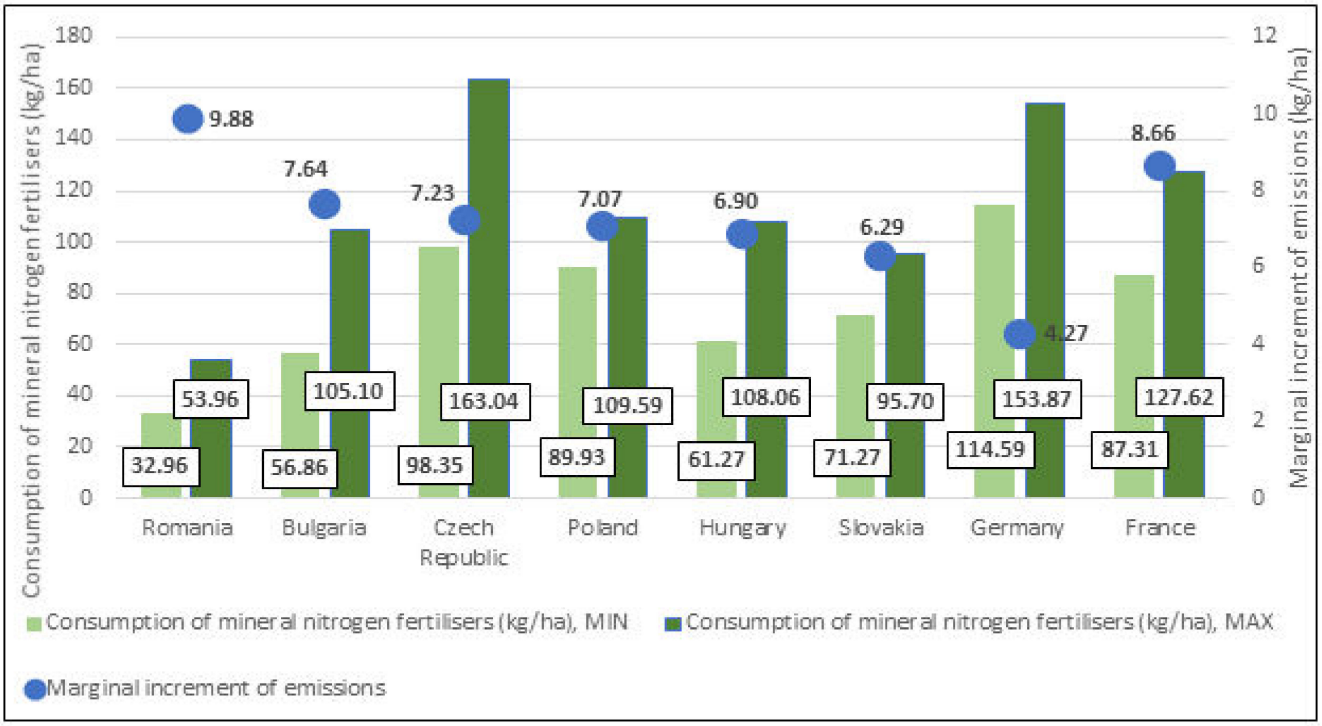


Figure 5. Consumption of mineral nitrogen fertilisers in kg per hectare of arable land (in nitrogen value). Source: own calculation based on Eurostat.

As Table 2 shows, for almost all of the countries analysed, the value of the coefficient of determination is between 0.69 and 0.98, which corresponds to a high level of quality of the regression linear model. The only exception is Slovakia, where the coefficient of determination is 0.4996.

The marginal increment of CO_2 emissions (a) is expressed by the slope of the linear function of the form Y = ax + b. As can be seen from Table 2, the highest values of the marginal increment of emissions were reported for Romania (a = 9.8832) and France (a = 8.6646). The marginal increment of CO_2 emissions of the Visegrad Group (V4) is quite balanced across the whole assessed group, ranging from 6.2882 (Slovakia) to 7.2314 (the Czech Republic). Hungary (6.9027) and Poland (7.0717) are in the middle of the V4 countries' interval. Based on the results of the correlation analysis, it is possible to answer RQ3. The linear relationship is not entirely ideal given the complexity of the whole issue of CO_2 emissions, but at the same time it has a major advantage—it is relatively easy to interpret the results obtained. From the results, it can be seen that, for Romania and Bulgaria, as well as France, there is a situation where every additional 1 kg of mineral fertiliser results in an increase of CO_2 emissions of more than 7.5 kg. In this case, it would also be interesting to see which fertilisers are used and in which quantities in each country.

The results also show the different values of the parameter "b" in the equation from country to country. This also implies that the nitrogen stock in the soil differs from country to country. The excessive use of nitrogen fertilisers leads to dramatic environmental problems or, conversely, very low nitrogen use can lead to the depletion of soil nitrogen stocks [34–37].

Figure 5 compares the values of the marginal increment of CO_2 emissions (a) depending on the consumption of mineral nitrogen fertilisers with the five-year average consumption of these mineral fertilisers (in kg/hectare, in nitrogen value) in the analysed countries. The consumption of fertilisers in the last year analysed, i.e., 2020, is also shown.

As shown in Figure 5, between 2009 and 2020, different countries showed different ranges of intervals between the minimum and maximum mineral fertiliser consumption. The largest differences between MIN and MAX values are shown by Romania (1.637 times greater maximum than minimum) and Bulgaria (1.85 times greater maximum fertiliser consumption than minimum. In parallel, Romania shows the highest value of the marginal increment of CO_2 emissions as a function of mineral nitrogen fertiliser consumption (a = 9.8832). For the V4 group of countries, the multiplication of MAX/MIN values by fertiliser consumption is as follows: the Czech Republic 1.65×, Poland 1.22×, Hungary 1.76×, and Slovakia 1.34×. For the next pair of countries evaluated, the MAX/MIN multiples of mineral nitrogen consumption are as follows: Germany 1.34× and France 1.46×. Thus, the above values confirm the reality that the dynamics of mineral nitrogen consumption between 2009 and 2020 were highest for the Eastern European pair Romania-Bulgaria and lowest for the Western European pair Germany-France. The Visegrad group countries are between the above-mentioned country pairs in terms of the dynamics of mineral nitrogen fertiliser consumption.

Soil is one of the main biological sources of nitrous oxide (N_2O) and the processes of nitrification and denitrification are the main factors in the production of N_2O in soils. Nitrogen from mineral and organic fertilisers applied to fields is readily involved in the biogeochemical cycling of soil nitrogen and contributes to N_2O emissions in the atmosphere [48]. However, agriculture contributes relatively little to the total CO_2 equivalent emissions [49].

One of the methodological approaches in future regulatory policies for CO_2 emissions from the mineral nitrogen fertiliser application may be a theoretical approach in which the maximum possible limit of emissions produced from one hectare of arable land is determined on the basis of the average CO_2 emissions, regardless of the amount of crop production from this hectare of arable land. In this research study, the MAX_LIMIT of 1296 tonnes of CO_2 emissions per hectare of arable land was chosen by the authors of the paper. This MAX_LIMIT was derived from the five-year averages of the emissions of the V4 countries and the country pairs Romania-Bulgaria and Germany France. A more detailed analysis is presented in Figure 4. Subsequently, this MAX_LIMIT was back-fitted into the equations that were derived using the correlation analysis method (Table 2). The results of the theoretical calculations are shown in Table 3.

Table 3. Calculation of the maximum theoretical mineral nitrogen fertiliser consumption (in kg/ha of arable land in nitrogen value). Source: own calculation based on Eurostat.

	Average (2016–2020) (kg/ha)	Theoretical Value (kg/ha)	Difference (kg/ha)	Teor/Avg
Romania	48.43	78.08	+29.65	161.2%
Bulgaria	102.14	121.71	+19.57	119.2%
Czechia	142.24	104.99	−37.25	73.8%
Poland	98.71	82.77	−15.94	83.8%
Hungary	98.77	158.85	+60.08	160.8%
Slovakia	94.16	150.13	+55.97	159.4%
Germany	129.23	41.30	−87.93	32.0%
France	118.34	73.77	−44.57	62.3%

As can be seen from Table 3 above and from the TEOR/AVG indicator, the potential for an increase in the consumption of nitrogen fertilisers per 1 ha of arable land at the MAX_LIMIT setting of 1296 tonnes of CO_2 emissions/ha exists in the country of Romania (the potential for fertiliser consumption can be increased to 161.2% of the current kilogram consumption) and in the countries of Hungary and Slovakia (the potential for fertiliser consumption can also be increased to approximately 160% of the current consumption of mineral nitrogen fertilisers).

In contrast, two V4 countries should, according to theoretical calculations, reduce their consumption of mineral nitrogen fertilisers to 74–84% of the current fertiliser consumption. The biggest impacts of setting the MAX_LIMIT for CO_2 would be on the mineral N fertiliser consumption in France (63% of current consumption) and Germany (32.0% of current consumption). Reducing nitrogen emissions from soils in future years will be a necessity, or else nitrogen fertilisers may need to be modified to be slower and more effective [43,44].

4. Conclusions

The results show that, between 2010 and 2019, the consumption of mineral nitrogen fertilisers increased in all countries surveyed except for Germany and Poland, where it decreased. The consumption of these fertilisers was almost at the same level in the case of France. For the other countries, an increase of more than 20% in the consumption of nitrogen fertilisers was recorded, which also answers the first research question.

The second research question identified five countries that consume more than 1.5 tonnes of mineral nitrogen fertiliser per 1 tonne of organic fertiliser, namely all V4 countries and Bulgaria. Only Germany reduced this ratio by 6.6% in the period under review. In the case of France and Romania, there were increases, but the ratio remains below 1.5.

As regards the third research question, it can be answered on the basis of the results of the correlation analysis. A linear relationship is not ideal, given the complexity of the whole issue of CO_2 emissions, but it has a major advantage—it is relatively easy to interpret the results obtained. These show that, for Romania and Bulgaria and also France, there is a situation where every additional 1 kg of mineral fertiliser resulted in an increase in CO_2 emissions of more than 7.5 kg. In this case, it would also be interesting to see which fertilisers are used and in which quantities in each country.

The authors of the paper recommend that the methodology for calculating the carbon footprint of mineral nitrogen fertilisers be divided into four stages in future research: production, transport, application, and soil uptake. Within the first stage (production of mineral nitrogen fertilisers), it is recommended to use scientific methods to make objective calculations of the carbon footprint in the production of so-called grey ammonia (from gas or coal, from fossil fuels), blue ammonia (from gas or coal with simultaneous CO_2 capture), and green ammonia (produced from renewable energy sources)—it is recommended to confront the results of scientific calculations with the declared values of the carbon footprint from commercial producers for partial types of fertilisers. While in the first step of the carbon footprint calculation (in production) relatively standardised results of carbon footprint values can be assumed, due to the unification of industrial production, a higher variability of calculated carbon footprint values can be assumed when calculating the carbon footprint from transport, from the application of mineral fertilisers, and from their absorption by the soil. The variability in carbon footprint calculations may be due to differences between the quality of soil profiles and their absorption characteristics, the intensity of the applied doses, the type of mineral fertiliser applied, the climatic conditions at the time of application and immediately after application, agronomic timing and the specific agronomic practices chosen.

The methodology presented by the authors in this paper can be used for the purpose of designing instruments within the Common Agricultural Policy, not only at the international level (comparison of carbon footprints from mineral nitrogen fertilisers between countries and their subsequent regulation), but also at the local level (comparison of carbon footprints from mineral nitrogen fertilisers between farms). According to the authors of the article,

the reduction of carbon footprints between farms should be linked to positive incentives for farms, i.e., the provision of operating subsidies, which partly cover the increased costs of farms associated with measures suitable for reducing carbon footprints from mineral nitrogen fertilisers.

In view of high emissions and global warming, this is a very important issue, also with regard to the farmers themselves who farm land that should serve as a factor of production for future generations. In this context, CO_2 emissions themselves are generally seen as a non-productive function of land (or as a negative production externality), which is not expressed in economic terms, and which may be the subject of further research.

Author Contributions: H.Ř.: conceptualization, methodology, formal analysis; J.S.: conceptualization, data curation, writing—review and editing; J.M.: translation, visualization, control of results, conclusion. All authors have read and agreed to the published version of the manuscript.

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Appendix A

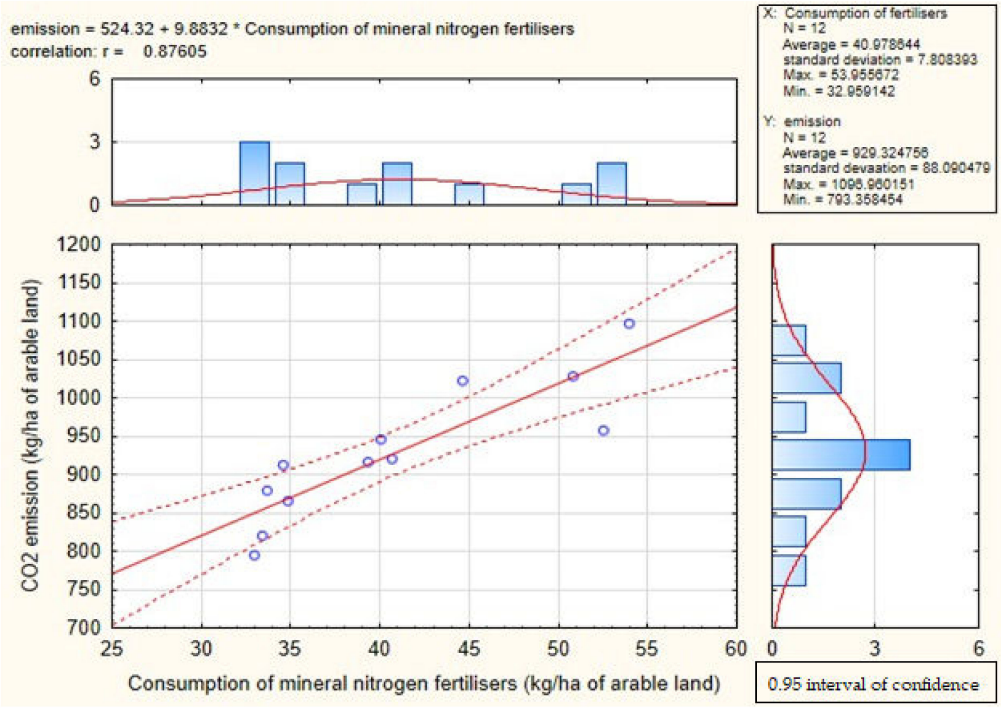


Figure A1. Results of correlations analysis: Romania. Source: own calculation based on Eurostat. Note: purple dot: observation, red solid line: linear function, red dashed lines: 95% interval of confidence.

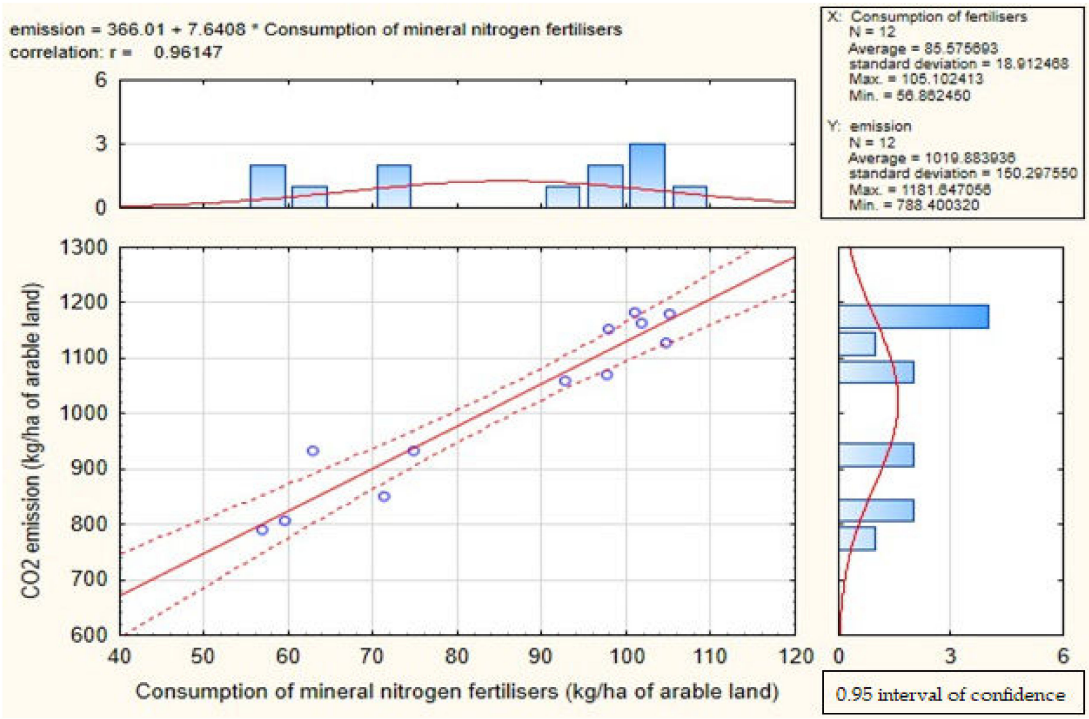


Figure A2. Results of correlations analysis: Bulgaria. Source: own calculation based on Eurostat. Note: purple dot: observation, red solid line: linear function, red dashed lines: 95% interval of confidence.

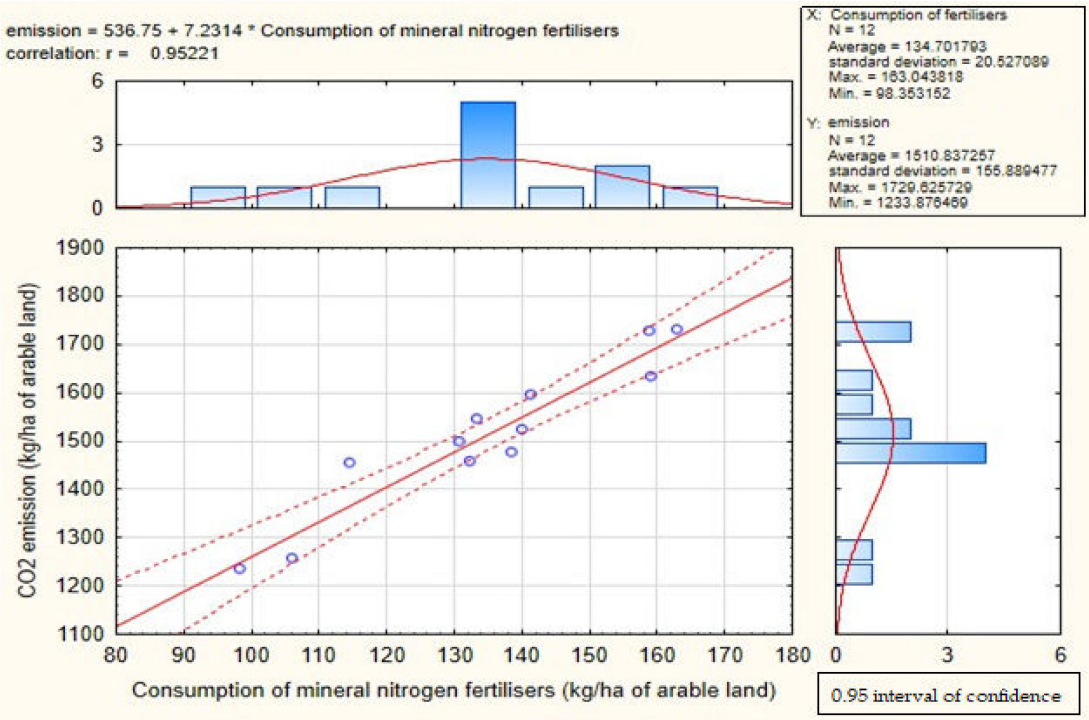


Figure A3. Results of correlations analysis: Czechia. Source: own calculation based on Eurostat. Note: purple dot: observation, red solid line: linear function, red dashed lines: 95% interval of confidence.

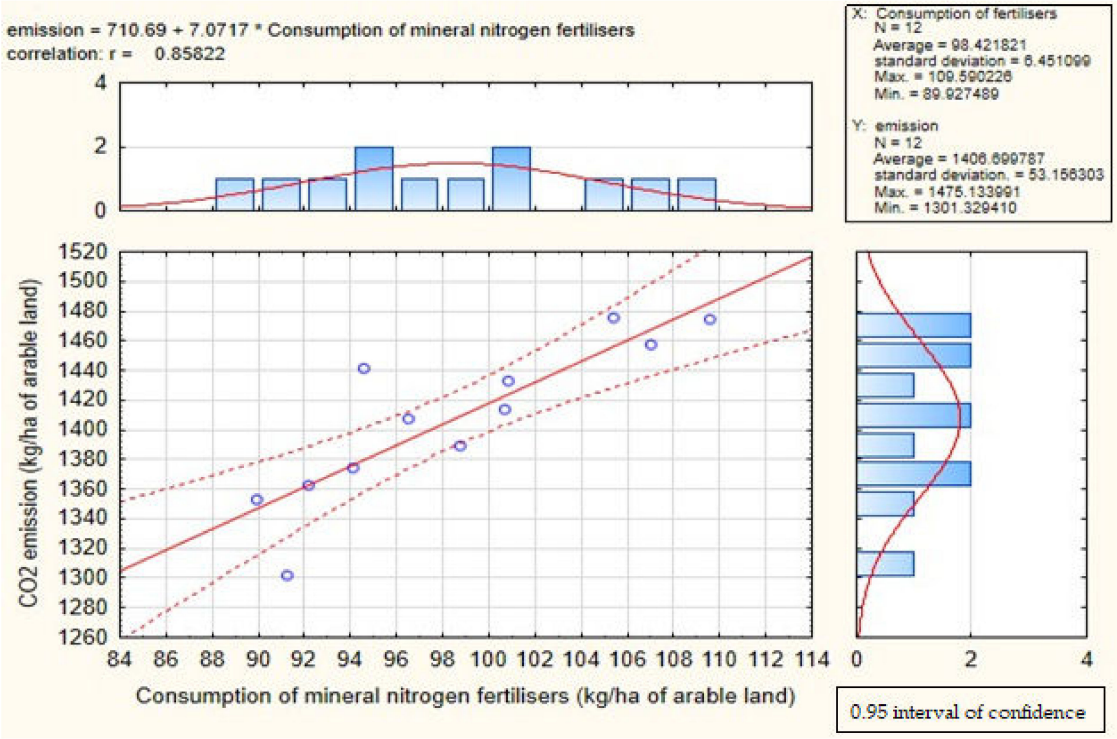


Figure A4. Results of correlations analysis: Poland. Source: own calculation based on Eurostat. Note: purple dot: observation, red solid line: linear function, red dashed lines: 95% interval of confidence.

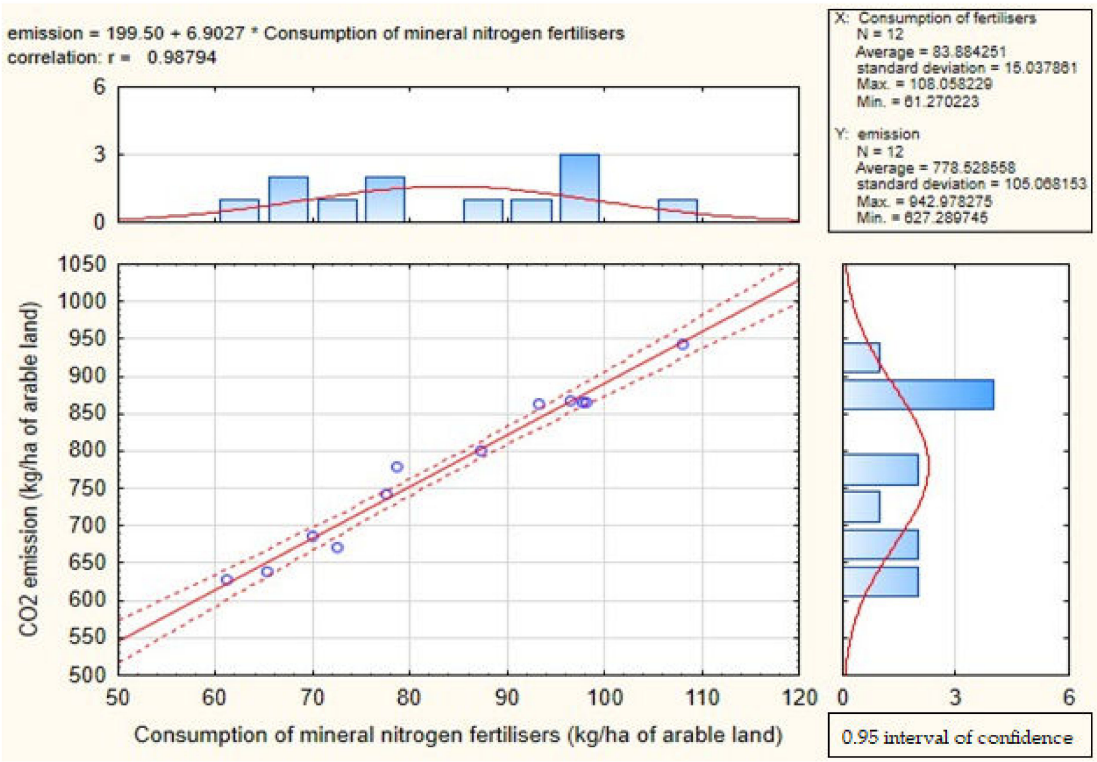


Figure A5. Results of correlations analysis: Hungary. Source: own calculation based on Eurostat. Note: purple dot: observation, red solid line: linear function, red dashed lines: 95% interval of confidence.

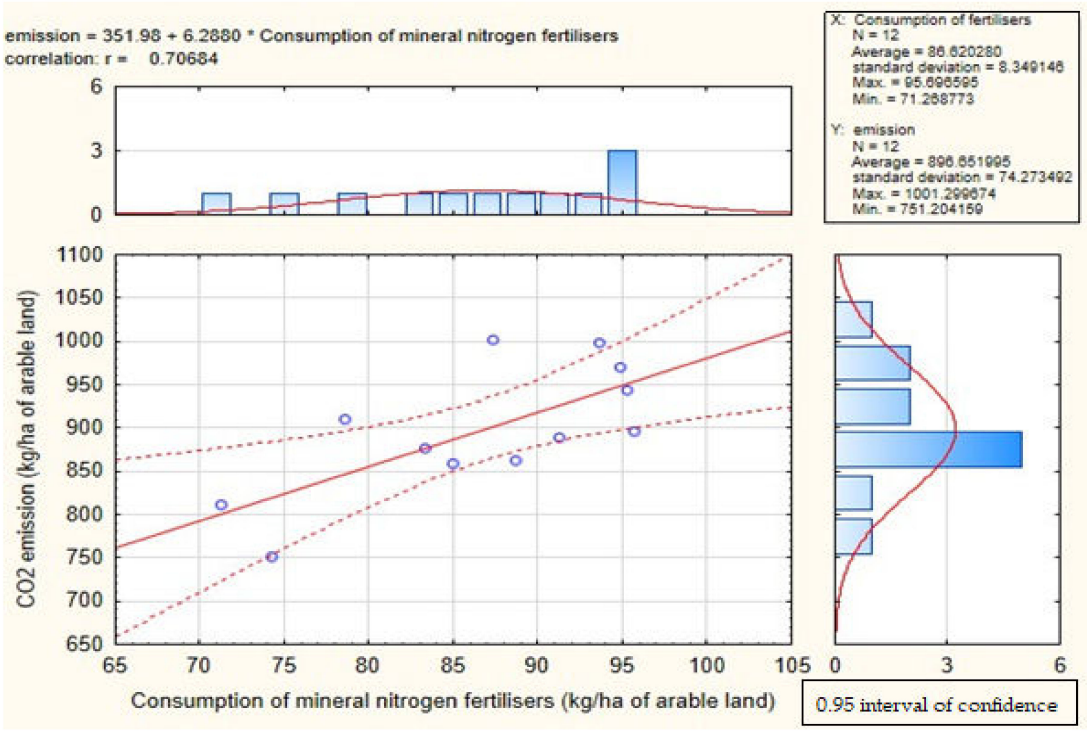


Figure A6. Results of correlations analysis: Slovakia. Source: own calculation based on Eurostat. Note: purple dot: observation, red solid line: linear function, red dashed lines: 95% interval of confidence.

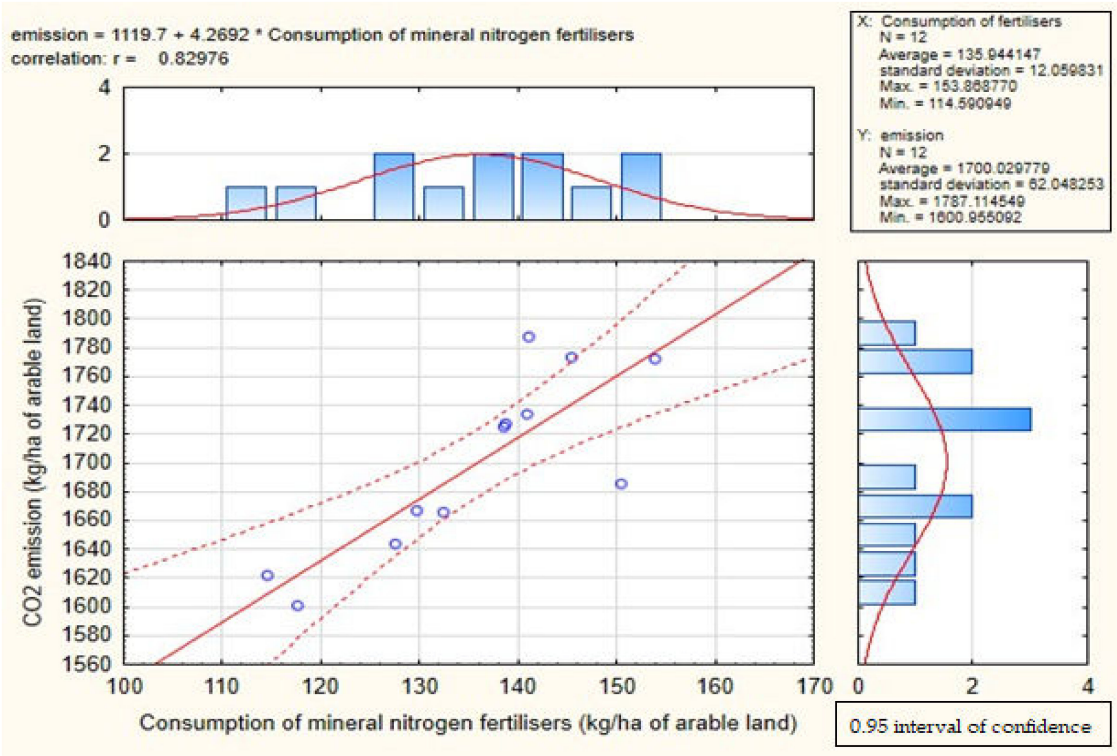


Figure A7. Results of correlations analysis: Germany. Source: own calculation based on Eurostat. Note: purple dot: observation, red solid line: linear function, red dashed lines: 95% interval of confidence.

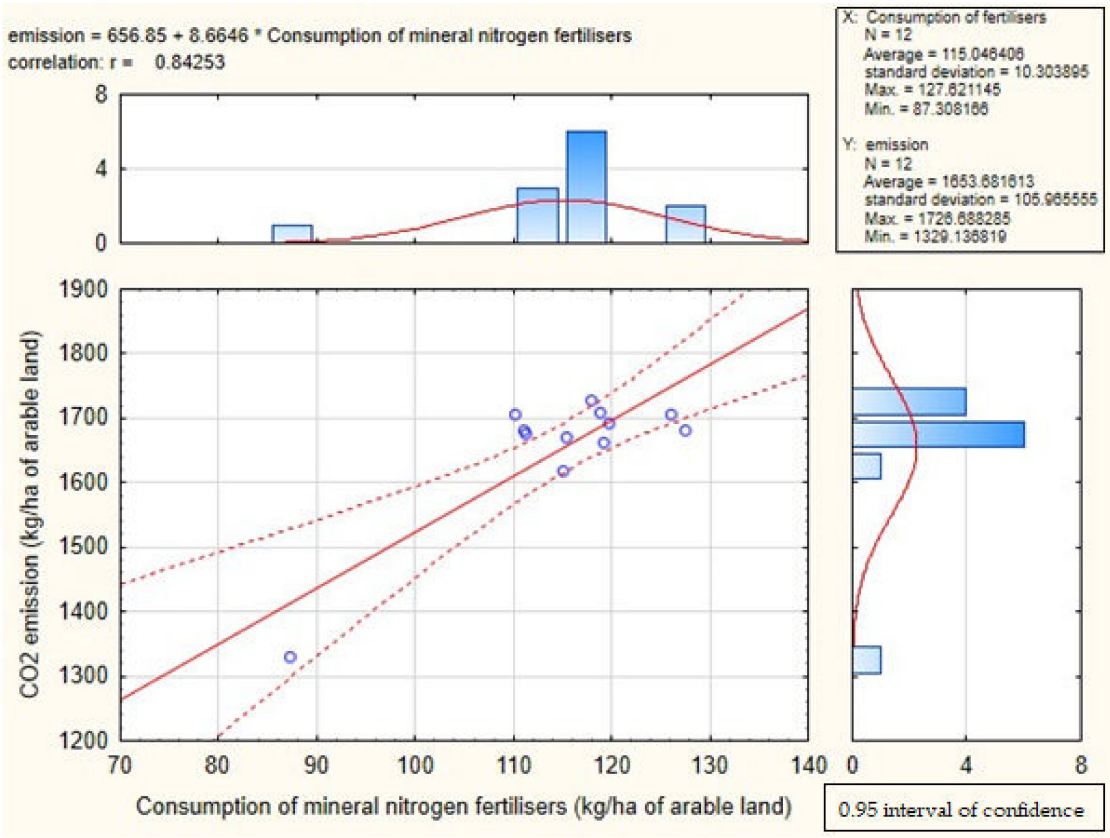


Figure A8. Results of correlations analysis: France. Source: own calculation based on Eurostat. Note: purple dot: observation, red solid line: linear function, red dashed lines: 95% interval of confidence.

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