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Carbon Footprint of Crop Production in Ukraine

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ABSTRACT

The carbon footprint of crop production on the lands of agricultural enterprises in Ukraine under crops of wheat, maize, sunflower seeds, rapeseed, soy beans, sugar beets, potatoes and vegetables were determined using the UN IPCC methodology. An increase in the carbon footprint of crop production in Ukraine during 1990–2021 was revealed, which is associated with a high level of nitrogen input from mineral fertilizers to the soil and mineralization of humus. In Ukraine, during 1990–2021, a high level of humus mineralization was observed on the agricultural lands under crops of wheat, maize, sunflower seed, rapeseed, soy bean, sugar beet, potatoes, and vegetables – 8–1998 kg/ha/year with emitted into the air from 0.2 to 63.0 Tg of CO_2/year. The average CO_2 emissions from agricultural land per 1 Mg of main production of studied crops of Ukraine during 1990–2021 were 46–1109 kg and N_2O emissions were 33–452 kg CO_2-eq., respectively. Among the studied crops, the highest emissions of CO_2 per unit of production due to the mineralization of humus are for the cultivation of sunflower seeds – 1109 kg/Mg/year, maize – 868 and rapeseed – 531 kg/Mg/year, and the lowest emissions for the cultivation of vegetables – 46 kg/Mg/year (2021). The highest N_2O emissions from agricultural land per unit of production for the cultivation of rapeseed – 452 kg CO_2-eq./Mg/year, sunflower seeds – 368 and soy beans – 300 kg CO_2-eq./Mg/year, and the lowest emissions for the cultivation of vegetables and sugar beet – 33 kg CO_2-eq./Mg/year (2021). According to the prognosis, this tendency will lead not only to an increase in GHG emissions, but also to soil depletion and a decrease in the country's food security. By 2035, the average level of humus mineralization will be about 2200 kg/ha/year ($R^2 = 0.725$), CO_2 emissions per unit of the main production of crops will be about 800 kg of CO_2 per 1 Mg of production per year ($R^2 = 0.657$) and emissions of N_2O from agricultural land per 1 Mg of main production of crops will be about 200 kg CO_2-eq./year ($R^2 = 0.0591$).

Keywords: agrocenoses, greenhouse gases, mineralization, biogenic released and emissions of CO_2, carbon balance, fertilizers, agricultural crops.

INTRODUCTION

The fight against global warming depends mainly on the implementation of the measures to reduce the carbon footprint, which is understood as the sum of all greenhouse gas (GHG) emissions – CO_2, N_2O, NO_x, CH_4 etc., during the use of natural resources, production and waste disposal. The carbon footprint (CF) is considered a generally accepted indicator of the intensity of GHG emissions from different types of economic activity. Due to its important role in raising the awareness of global warming, scientists and policymakers also use it as a management tool to assess environmental pollution (Balogh, 2019; Cammarata et al., 2023).

CF is an official environmental concept recognized by international organizations. At the international level, strategic directions in the context of GHG reduction are defined by the following documents: United Nations Environment Programme (UNEP); OECD green growth strategy, convention on long-range transboundary air pollution of the UNECE; United Nations Framework Convention on Climate Change (UNFCCC), including the Paris Agreement and the Kyoto Protocol.

Given the climate change problem and the demands put forward by the EU in the area of gradual decarbonization of production, it is necessary to implement the solutions to reduce the GHG emissions in agricultural practices (Holka et al., 2020). The food safety principles and requirements set by the EU are becoming the standard for all food products available on the EU market, and this should be taken into account by agri-food exporting countries such as Ukraine. The European market shows increasing differentiation of agri-food products in terms of sustainability and ecology, in particular carbon footprint indicators. Innovative focus on carbon-neutral agriculture, in addition to the development of national GHG emission accounting capacity, monitoring strategies, economic instruments, development of relevant standards and certification schemes (Popova et al., 2022). Sometimes imported products have a lower CF of production than in the importing country, depending on the local production system (Theurl et al., 2014).

The carbon footprint accounts for more than 50% of the total ecological footprint in the world (Mate et al., 2019). Agriculture accounts for 12% of the global annual GHG emissions (7.1 Gt CO_2-eq.) – CH_4 (54%), N_2O (28%) and CO_2 (18%), so mitigating climate change by reducing GHG emissions from agriculture is important (Rosa et al., 2023). This can be achieved by carefully assessing the CF of agricultural production, which is also one of the most important indicators for evaluating the efficiency and sustainability of agricultural systems (Avasthe et al., 2023; Al-Mansour et al., 2017).

Assessment of CF in crop production may include food and feed crop growing processes, analysis of input raw materials and output. CF assessment can provide insight into the contribution of crop production to climate change and help identify the opportunities for reducing GHG emissions and areas for optimizing production technologies (Cheng et al., 2015; Hillier et al., 2009; Li et al., 2023; Manoj et al., 2022; Wróbel-Jędrzejewska et al., 2024). In crop production, organic carbon stocks are the amount of carbon stored in various reservoirs: soil organic matter (humus), above- and below-ground plant biomass, as well as dead organic matter. By definition, an increase in carbon stocks is a biogenic released of CO_2 into the humus, and a decrease in carbon stocks is a biogenic emission of CO_2 into the atmosphere. The change in carbon stocks in a biogenic carbon reservoir corresponds to the sum of the emissions and released of CO_2. (Butrym, 2018; Mathew et al., 2020).

The N_2O and CH_4 emissions from crop production occur naturally from agricultural lands as a result of the microbiological processes of denitrification and methanogenesis. Traditional rice cultivation in flooded fields produces large amounts of CH_4. This is especially true for Asian countries, where over the past 50 years there has been an increase in rice cultivation area by 22% and a decrease in the area of other grain crops with a lower CF (Diksha et al., 2018).

Intensification of agricultural production results in additional GHG emissions and affects the ecological indicators of agricultural ecosystems. When maximizing crop yields, CF management should take into account the ecological factors of land use. Structure, moisture, temperature and porosity are the main soil properties directly related to GHG emissions. These properties and GHG emissions are affected by land use changes, soil types and agricultural practices (Ozlu et al., 2022).

Currently, there are seven key agricultural tactics that are effective in increasing grain production while reducing carbon emissions: the use of diversified farming systems compared to monoculture systems; decrease in the level of use of nitrogenous mineral fertilizers; intensification of crop rotation with reduction of summer steam; increase of carbon absorption by the soil and transformation of carbon from atmospheric CO_2 into plant biomass; the use of reduced tillage in combination with the preservation of crop residues; integration of the main methods of growing agricultural crops; and inclusion of N_2-fixing legumes in crop rotations, which will reduce the use of mineral fertilizers (Liu et al., 2016). In particular, excessive use of nitrogenous mineral fertilizers in crop production leads to an increase in the volume of N_2O emissions in the overall CF (Kumar et al., 2021). It was also found that corn not only has a higher grain yield, but also has a lower carbon footprint compared to wheat (Hou et al., 2021). Integration of sustainable practices, such as frequent tillage and sowing of legumes, changes the accumulated energy and GHG emissions from corn production by 37% and 42%, consistently (Gustavo et al., 2013). Vegetable intercropping systems reduce GHG emissions by 31% compared to monoculture (Pereira et al., 2022). The main factors of carbon management are application of nitrogen fertilizers (8–49%), straw burning (0–70%), energy consumption of machinery (6–40%), energy consumption of irrigation (0–44%) and CH_4 emissions from rice fields (15–73%). The main factors of carbon sequestration are the return of straw crop to the soil (41–90%), application of chemical nitrogen fertilizers (10–59%) and no-till cropping system (0–10%) (Zhang et al., 2017). Improved mechanization of irrigation and soil cultivation under wheat and corn crops helps reduce GHG emissions (Huo et al., 2024). It was found that when using reduced tillage, cover crops and green waste compost (resource-saving crop rotation), the average annual soil carbon sequestration and the impact on climate change were 0.91 t/ha and 434 kg CO_2-eq./ha, respectively, compared to a conventional crop rotation (-0.24 t/ha and 3867 kg CO_2-eq./ha, respectively) (Guidoboni et al., 2023). Owing to a combination of agricultural practices (fertilization based on soil analysis, reduction in the frequency of summer fallow, and rotation of cereals with grain legumes), wheat absorbs more CO_2 from the atmosphere – 0.027–0.377 kg CO_2-eq./kg grain – than is emitted during its production (Gan et al., 2014).

In the global effort to combat climate change, sustainable agriculture and soil conservation services are increasingly being implemented through "carbon farming" – a carbon management system that helps accumulate and store GHG in the Earth's systems (Singh et al., 2024). Agriculture faces serious challenges, as it is both dependent on and contributing to climate change (Rajput et al., 2021). Plants remove CO_2 from the atmosphere through photosynthesis. Since crop production relies on this process, a combination of technologies to reduce emissions and improve soil health by sequestering carbon in the soil will allow the sector to minimize emissions while maintaining high productivity (Northrup et al., 2021). The current global focus on reducing GHG emissions has increased the attention to the potential for mitigating emissions through climate-smart agricultural practices – regenerative, digital and controlled farming systems (Kazimierczuk et al., 2023).

In the process of assessing the carbon footprint to optimize agricultural management, some authors propose to additionally analyze other pollutants, water and energy footprints. The creation of a carbon accounting model in accordance with local realities will provide scientific support for the development of low-carbon agriculture (Miao et al., 2023). Other authors propose that agriculture should abandon the generally accepted assessment of CO_2-equivalent emissions, which does not reflect the historical or expected contribution of various GHGs to global climate change. For example, CO_2 is a stock gases, and CH_4 is a flow gases. Unlike a stock gases, flow gases are short-lived and are removed from the atmosphere much faster. Flow gases do not accumulate in the atmosphere, so their heating is shorter than that of stock gases (Lynch et al., 2022).

It is also necessary to separate conventional and urban agriculture (UA), which differ significantly in the level of GHG emissions. The carbon footprint of the food products from UA is 6 times greater than that of conventional agriculture (Hawes et al., 2023).

The carbon footprint of crop production consists of three components: 1 – production of agricultural inputs such as chemical fertilizers, pesticides, etc.; 2 – production of grain in the fields; 3 – carbon sequestration/emissions by the soil as a result of grain production. Carbon emission factors include direct emission factors of CO_2, CH_4 and N_2O and indirect emission factors of N_2O from ammonia (NH_4) volatilization and nitrate leaching (Dan et al., 2016).

With government support and incentives for the development and implementation of zero-GHG emission technologies, agriculture can transform from a significant source of emissions into a carbon sink. The objective of this work was to assess the current state and dynamics of biogenic CO_2 and N_2O emissions from soil during the growing season of the main agricultural crops in Ukraine.

MATERIALS AND METHODS

The carbon footprint of crop production on the lands of agricultural enterprises in Ukraine under crops of wheat, maize, sunflower seeds, rapeseed, soy beans, sugar beets, potatoes and vegetables was determined.

The volumes of changes in carbon stocks in the soil reservoir subjected to anthropogenic impact are calculated based on the determination of the dynamics of the content of soil nitrogen. The calculation is based on an assessment of the balance between the volumes of N removal from the soil with crop yields as well as its entry into plants and soil. The result is transferred to C through the ratio coefficient between the content of N and C in humus [IPCC, 2006; Butrym, 2018].

The values obtained for nitrogen credit and debit are converted into carbon volumes, modified Equation 1 (MEPR, 2023):

$$\overline{C_r} = \left(\sum N_{D_i} + \sum N_j\right) \times k_{C:N_s} - \sum \mathrm{C} \tag{1}$$

where: C_r – the average annual carbon balance of soil humus, Gg/ha; r – the index of the territory for which the estimation is performed; N_{Di} – the total amount of nitrogen released into the humus as a result of humification of dead organic matter (above- and below-ground) under crops grown for 2 years prior to the inventory, Gg/ha; i – the type of crop; N_j – the total amount of nitrogen released into the humus as a result of humification of organic fertilizers introduced into soil in the inventory year, Gg/ha; j – the index of the type of organic fertilizer (manure bedding, liquid manure, poultry manure); $k_{C:Ns}$ – carbon to nitrogen content ratio (C:N) in humic substances of ploughed layer; s – the index of the soil type for which estimations were performed; C – the total amount of carbon released/emission into/from managed soil, Gg/year (MEPR, 2023).

The average annual carbon balance value for a country is calculated as the sum of the balance values for individual areas of territories with a certain soil type (Cr) on agricultural land.

The amount of nitrogen generated as a result of humification of the dead below- and aboveground organic matter (N_{Di}) of agricultural crop biomass is estimated by multiplying the amount of biomass returned into soil after harvesting by the value of nitrogen content in it (taking into account direct emissions of nitrogen), and by humification factors, using Equation 2 (MEPR, 2023):

$$N_{D_i} = \sum Rs_i\,[(B \times \eta - N_{CR}) \times k] + \\ + \sum Rt_i\,[(B \times \eta - N_{CR}) \times k] \tag{2}$$

where: B – the amount of above-ground (Rs_i) and below-ground (Rt_i) crop residues, Gg/ha (MEPR, 2023); η – nitrogen content is above-ground (Rs_i) and below-ground (Rt_i) crop residues, relative units (MEPR, 2023); k – the factor of humification of above-ground (Rs_i) and below-ground (Rt_i) crop residues, relative units (MEPR, 2023); N_{CR} – the amount of nitrogen that is released annually as direct emissions from above-ground (Rs_i) i and below-ground (Rt_i) crop residues, Gg/ha; i – the crop index.

The amount of nitrogen appeared as a result of humification of organic fertilizers (Nj) is calculated by multiplying the values for the amount of their application (by type) by the value of nitrogen content in them (excluding direct and indirect emissions of nitrogen), using Equation 3 (MEPR, 2023):

$$N_j = N_j^{`} \times k_r \tag{3}$$

where: N_j' – the amount of nitrogen introduced into the soil with organic fertilizers (this factor accounts for nitrogen loss through leaching processes – the IPCC default value of 30% was used), Gg N; k_r – manure humification factor, % (MEPR, 2023).

The total amount of carbon released/emission into/from managed soil (C) were calculated using Equation 4 (Butrym, 2018):

$$\mathrm{C} = N_{balance} \times k_{mnr} \times k_{C:N_s} \tag{4}$$

where: $N_{balance}$ – the nitrogen balance of crops; k_{mnr} – the factor to consider the links among the processes of nitrogen consumption by crops and humus mineralization, p.p. (MEPR, 2023); $k_{C:Ns}$ – carbon to nitrogen content ratio (C:N) in humic substances of ploughed layer (MEPR, 2023).

The total nitrogen balance ($N_{balance}$) in crop production was calculated as the difference between the sum of input nitrogen flows in crop production and the sum of the output flows of nitrogen with crop production according to Equation 5 (OECD, 2013; UN, 2014]:

$$N_{balance} = \sum N_{inputs} - \sum N_{outputs} \tag{5}$$

where: N_{inputs} – input nitrogen flows in crop production (mineral and organic fertilizers, seeds and planting materials, biological fixation of nitrogen, atmospheric deposition and crop residues), Gg N; $N_{outputs}$ – output flows of nitrogen with crop production (food crops and crop residues), Gg N.

The factor to consider the links between the processes of plant consumption of nitrogen and the processes of humus mineralization of (k_{mnr}) in Equation 4 is calculated by taking into account the correction factors for the soil particle size distribution and the type of agricultural plants based on the equation 6 (MEPR, 2023):

$$k_{mnr} = k_i \times k_s. \quad (6)$$

where: k_i – mineralization factors to account for the effect of the type of crop cultivated (MEPR, 2023); k_s – factors to account the soil particle size distribution (MEPR, 2023).

Conversion of CO_2–C to CO_2 released/emission into/from managed soil were calculated using Equation 7 (IPCC, 2006):

$$CO_2 = C \times \frac{44}{12} \quad (7)$$

where: C – carbon released/emission into/from managed soil, Gg CO_2/year; 44/12 – stoichiometric ratio between the carbon content in CO_2–C and CO_2.

Annual direct N_2O emissions produced from managed soils were calculated using Equation 8 (IPCC, 2006):

$$N_2O_{Direct} = N_2O - N_{N_{inputs}} \times \frac{44}{28} \quad (8)$$

where: N_2O_{Direct} – annual direct N_2O emissions produced from managed soils, kg N_2O/year; $N_2O–N_{Ninputs.}$ – annual direct N_2O–N emissions from N inputs to managed soils, kg N_2O–N/ year; 44/28 – stoichiometric ratio between the nitrogen content in N_2O–N and N_2O.

Annual direct N_2O–N emissions from N inputs to managed soils ($N_2O_i–N_{Ninputs.}$) were calculated using Equation 9 (IPCC, 2006):

$$N_2O - N_{N_{inputs}} = [(F_{SN} + F_{ON} + F_{CR}) \times EF_1] \quad (9)$$

where: F_{SN} – annual amount of synthetic fertilizer N applied to soils, kg N/year; F_{ON} – annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N/year; F_{CR} – annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils, kg N/year; EF_1 – emission factor for N_2O emissions from N inputs, kg N_2O–N/kg N input (IPCC, 2006, MEPR, 2023).

Annual amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils were calculated using Equation 10 (IPCC, 2006):

$$N_2O_{(ATD)} = \begin{bmatrix} (F_{SN} \times Frac_{GASF}) + \\ + \left((F_{ON} + F_{PRP,CPP}) \times Frac_{GASM}\right) \end{bmatrix} \times EF_4 \times \frac{44}{28} \quad (10)$$

where: $N_2O_{(ATD)}$ – annual amount of N_2O produced from atmospheric deposition of N volatilized from managed soils, kg N_2O/year; F_{SN} – annual amount of synthetic fertilizer N applied to soils, kg N/year; $Frac_{GASF}$ – fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x, kg N volatilized/kg N input (IPCC, 2006; MEPR, 2023); F_{ON} – annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N/year; $F_{PRP,CPP}$ – annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg/year; $Frac_{GASM}$ – fraction of applied organic N fertilizer materials (FON) and of urine and dung N deposited by grazing animals (FPRP) that volatilizes as NH_3 and NO_x, kg N volatilized/kg of N applied or deposited (IPCC, 2006; MEPR, 2023); EF_4 – emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, kg N_2O–N/kg NH_3–N+NO_x–N volatilized (IPCC, 2006; MEPR, 2023); 44/28 – stoichiometric ratio between the nitrogen content in N_2O–N and N_2O.

The N_2O emissions from leaching and runoff in the regions where leaching and runoff occurs were calculated using Equation 11 (IPCC, 2006):

$$N_2O_{(L)} = (F_{SN} + F_{ON} + F_{CR}) \times \\ \times Frac_{LEACH-(H)} \times EF_5 \times \frac{44}{28}, \quad (11)$$

where: $N_2O_{(L)}$ – annual amount of N_2O produced from leaching and runoff of N additions to managed soils in the regions where leaching/runoff occurs, kg N_2O/year; F_{SN} – annual amount of synthetic fertilizer N applied to soils in the regions where leaching/runoff occurs, kg N/year; F_{ON} – annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils in regions where leaching/runoff occurs, kg N/year; F_{CR} – amount of N in crop residues (above- and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually in the regions where leaching/runoff occurs, kg N/year; $Frac_{LEACH-(H)}$ – fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N/kg of N additions (IPCC, 2006; MEPR, 2023); EF_5 – emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N/kg N leached and runoff (IPCC, 2006; MEPR, 2023); 44/28 – stoichiometric ratio between the nitrogen content in N_2O–N and N_2O.

The carbon footprint in terms of main products of crop (CF_y) was evaluated using Equation 12, 13, proposed by Cheng et. al., 2017, in the following form:

$$CF_y = \frac{CO_2}{Y} \times 1000 \quad (12)$$

where: CF_y – the carbon footprint (CF_y) per season of crop cultivation, kg CO_2-eq./Mg of the grain produced/year; CO_2 – CO_2 emissions produced from managed soils per season of crop cultivation, Mg CO_2/year; Y – denotes grain yield of a given crop, Mg/year.

$$CF_y = \frac{N_2O_{Direct} + N_2O_{(ATD)} + N_2O_{(L)}}{Y} \times 1000 \quad (13)$$

where: N_2O_{Direct} – annual direct N_2O emissions produced from managed soils, Gg CO_2-eq./year; $N_2O_{(ATD)}$ – annual amount of N_2O produced from atmospheric deposition of N volatilized from managed soils, Mg CO_2-eq./year; $N_2O_{(L)}$ – annual amount of N_2O produced from leaching and runoff of N additions to managed soils in the regions where leaching/runoff occurs, Mg CO_2-eq./year.

The initial data for the calculations were taken from the electronic resource of the State Statistics Service of Ukraine (http://www.ukrstat.gov.ua). Calculations, construction of cartograms and forecasting were carried out in the MS Excel 2021.

RESULTS AND DISCUSSION

Currently, most of the land in Ukraine is used for growing agricultural crops – up to 100 Tg of grain are produced annually, while livestock is not sufficiently developed and, in general, the total number of farm animals has been decreasing over the past 30 years. These factors change the balance between the removal of organic matter and its return to the soil.

Ukraine is an agrarian country – currently in the structure of the land fund of Ukraine the share of agricultural land is 68.5%, of which arable land predominates – 79.3% (Fig. 1). In the process of crop production, the source of organic matter in the soil is organic fertilizers and crop residues. The carbon balance in the soil is directly affected by the level of use of organic and mineral

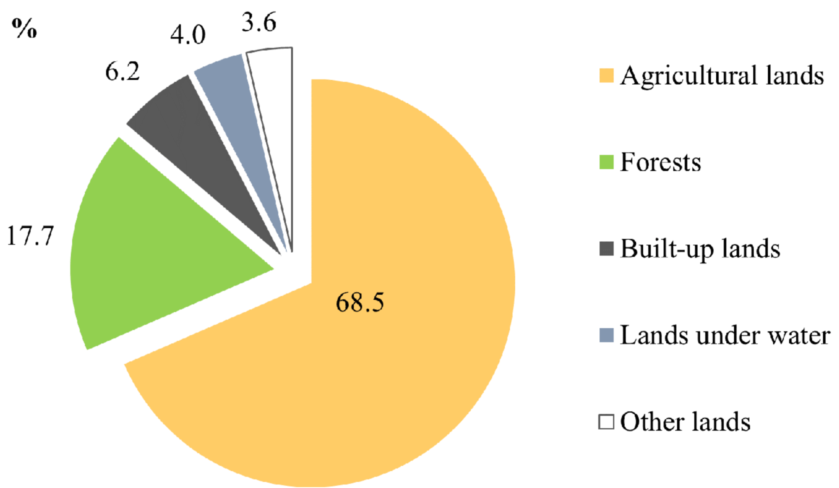

Figure 1. The structure of the land fund (2020), % (data of the State Statistics Service of Ukraine, 2021)

fertilizers in agriculture. There is a tendency to increase the amount of mineral fertilizers and decrease organic fertilizers during 1990–2021. The input of organic fertilizers to the total sown area in 1990 were 14.4 Mg/ha, in 2021 – only 0.46 Mg/ha (Fig. 2). Nitrogen input from mineral fertilizers to the total sown area during 1990–2021 amounted to 13.6–120.3 kg N/ha/year (Fig. 3). If in 1990 the most organic fertilizers input to potatoes – 62.8 Mg/ha/year, sugar beet – 35.7, vegetables – 20.1, maize – 12.5 and wheat – 9.6 Mg/ha/year, then in 2021 less than 1 Mg/ha/year were input to most of the studied crops (Table 1). During 1990–2021, the most nitrogen input from mineral fertilizers in

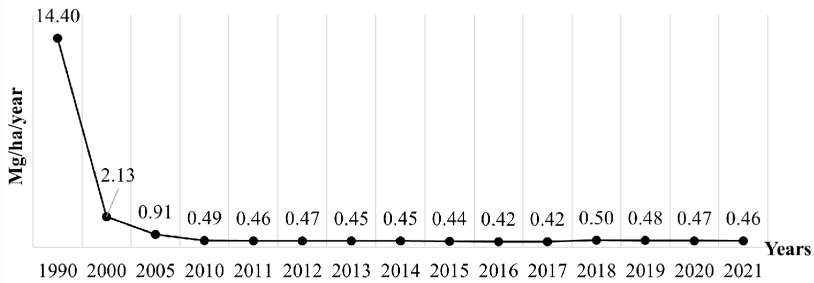

Figure 2. Input of organic fertilizers to the total sown area of agricultural crops (1990–2021) (data of the State Statistics Service of Ukraine, 1990–2021)

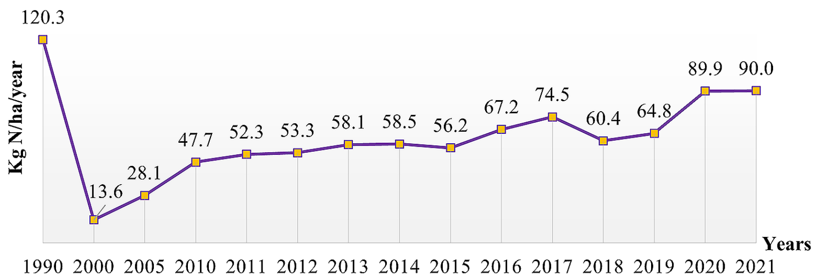

Figure 3. Nitrogen input from mineral fertilizers to the total sown area of agricultural crops (1990–2021) (data of the State Statistics Service of Ukraine, 1990–2021)

Table 1. Input of organic fertilizers to the sown area of agricultural crops (1990–2021), Mg/ha/year (data of the State Statistics Service of Ukraine, 1990–2021)

Years	Cultures							
	Wheat	Maize	Sunflower seeds	Rapeseed	Soya beans	Sugar beet	Potatoes	Vegetables
1990	9.60	12.50	2.90	–	3.80	35.70	62.80	20.10
2000	1.40	0.90	0.20	–	0.60	13.60	40.10	2.90
2005	0.70	0.70	0.10	–	0.20	8.30	17.10	1.30
2010	0.42	0.73	0.17	0.13	0.12	3.85	4.91	1.05
2011	0.39	0.63	0.18	0.28	0.20	3.15	4.07	0.57
2012	0.46	0.59	0.17	0.33	0.17	3.46	3.30	0.51
2013	0.40	0.66	0.24	0.22	0.20	3.57	2.42	0.33
2014	0.39	0.67	0.19	0.25	0.31	3.64	2.56	0.54
2015	0.34	0.73	0.21	0.33	0.30	4.50	2.47	0.39
2016	0.32	0.69	0.23	0.45	0.23	3.36	1.68	0.64
2017	0.27	0.71	0.22	0.49	0.20	3.68	1.42	0.42
2018	0.32	0.77	0.33	0.42	0.30	4.60	1.63	0.55
2019	0.36	0.74	0.39	0.32	0.27	3.35	0.44	1.18
2020	0.33	0.69	0.37	0.30	0.35	3.44	0.64	0.71
2021	0.29	0.72	0.38	0.42	0.33	3.07	0.69	0.99

the last 2 years (more than 100 kg N/ha/year) under the crops of most of the studied crops – sugar beet, vegetables, potatoes, rapeseed, wheat and maize (Table 2).

By the administrative regions of Ukraine in 2021, the most organic fertilizers input to the sown area in Ivano-Frankivsk – 3.7 Mg/ha, Kyiv – 1.3, Donetsk – 1.3 and Volyn regions – 1.2 Mg/ha, and in the rest of the region – less than 1 Mg/ha (Fig. 4). Nitrogen input from mineral fertilizers reached more than 100 kg N/ha/year in the 9th regions of Ukraine, the most in the Volyn region – 166 kg N/ha/year. The least is in Luhansk (69 kg N/ha/year), Kirovohrad, Odesa and Chernihiv regions (72

Table 2. Nitrogen input from mineral fertilizers to the sown area of the agricultural crops (1990–2021), kg N/ha/year (data of the State Statistics Service of Ukraine, 1990–2021)

Years	Agricultural crops							
	Wheat	Maize	Sunflower seeds	Rapeseed	Soya beans	Sugar beet	Potatoes	Vegetables
1990	112.0	177.4	62.0	–	66.9	211.6	84.3	79.1
2000	18.0	9.8	1.6	–	6.7	33.9	23.6	11.1
2005	31.6	45.0	9.0	–	13.3	86.8	67.1	43.4
2010	55.1	67.1	17.3	67.7	25.1	130.3	79.4	65.6
2011	60.3	67.4	20.9	84.0	24.1	129.7	82.3	67.0
2012	65.2	68.9	22.6	93.7	24.0	137.4	73.0	79.1
2013	64.6	81.7	25.6	89.5	25.8	131.6	86.9	72.2
2014	70.1	81.4	26.5	92.3	27.5	122.9	95.7	79.6
2015	66.1	81.7	27.0	97.1	26.5	131.4	87.0	96.6
2016	85.0	94.4	35.8	117.2	31.4	132.3	102.7	109.2
2017	94.1	98.5	41.1	119.2	34.5	154.6	123.6	123.3
2018	79.1	81.9	28.0	98.9	19.9	111.0	82.5	84.6
2019	84.0	81.7	32.6	100.7	19.4	97.9	82.3	96.3
2020	110.5	108.1	55.0	134.5	37.4	157.5	140.4	124.4
2021	109.0	111.0	55.1	131.8	36.4	152.2	133.3	134.5

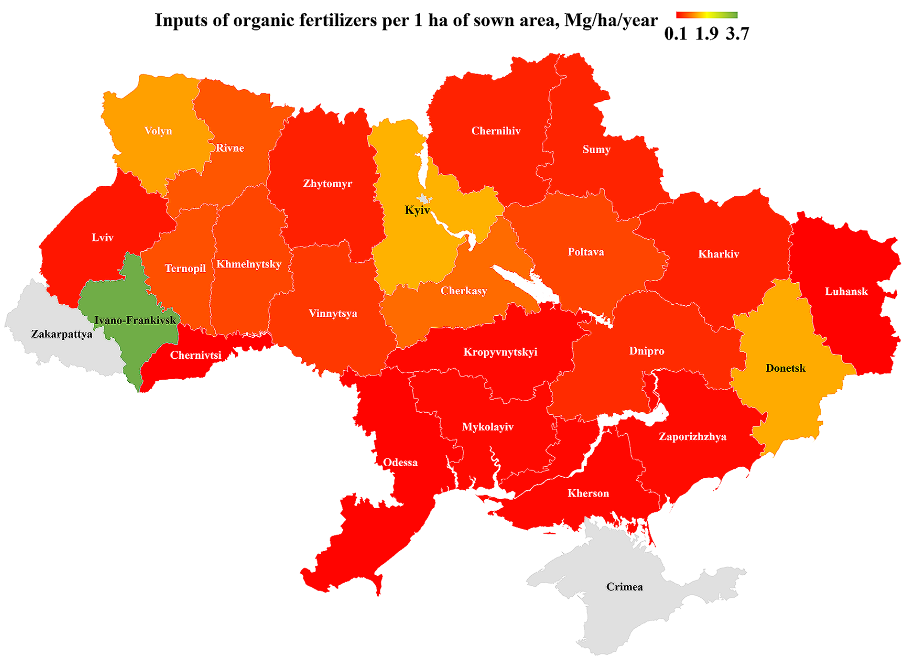

Figure 4. Organic fertilizers inputs to the sown area by administrative regions (2021) (data of the State Statistics Service of Ukraine, 2021)

kg N/ha/year) (Fig. 5). Currently, the main component of organic fertilizers input to the soil in Ukraine is manure (dropping) of livestock, which accounts for 88% (Fig. 6). In 1990, 182.8 Tg/year of organic fertilizers (manure, litter, sludge, sapropel, peat, etc.) were input to the soil in Ukraine, which amounted to 84% from excreted manure of livestock, but by 2021 it had decreased to 8.4 Tg/year and 24%, respectively (Fig. 7).

Figure 8 shows the level of usage of manure from excreted of livestock as organic fertilizer by administrative regions of Ukraine in 2021. The most prevalent use of manure as an organic fertilizer occurs in Ivano-Frankivsk – 76%, Donetsk – 49% and Rivne regions – 36%. The least quantities of manure are used in Lviv – 7% and Chernivtsi regions – 3%, whereas the Zakarpattia region does not use organic fertilizers at all.

Separately, it is necessary to note the regions of Ukraine with the highest of manure use as organic fertilizer – Ivano-Frankivsk (76%) and Donetsk (49%) regions, where, when recalculated for the sowing area, provide for the application of only 3.7 and 1.3 Mg/ha/year, respectively. Consequently, in some regions of Ukraine, there is actually a deficit of manure for crop production needs, which is associated with the low number of livestock. Another source of organic matter in the soil is crop residues (roots, stubble, straw and leaves) that remain in the field after harvesting the main products of crop (grain and fruits). In Ukraine, part of the by-products of crops (straw

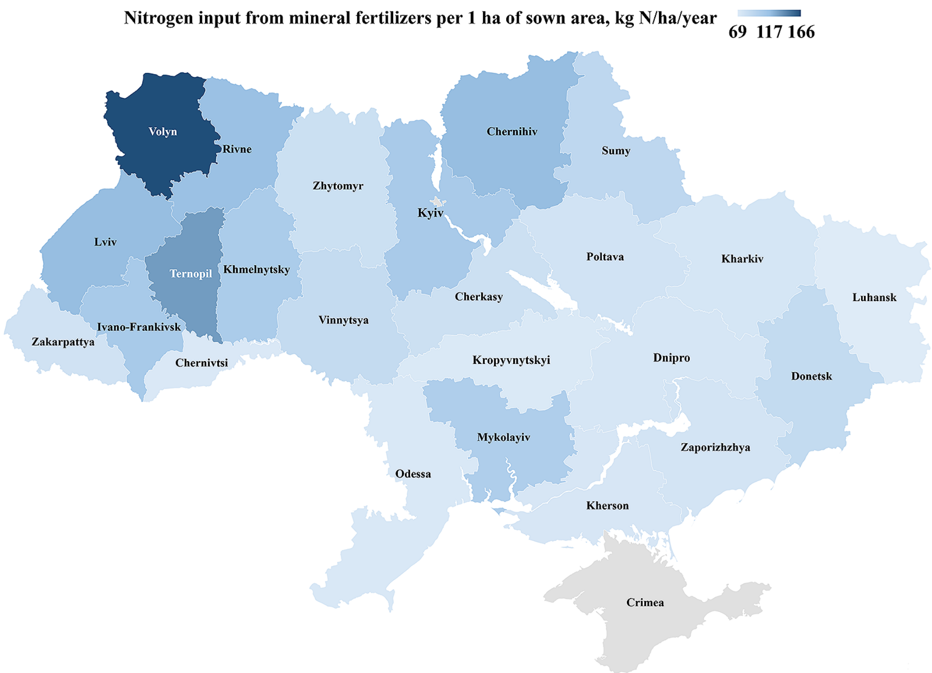

Figure 5. Nitrogen input from mineral fertilizers to the sown area by administrative regions (2021) (data of the State Statistics Service of Ukraine, 2021)

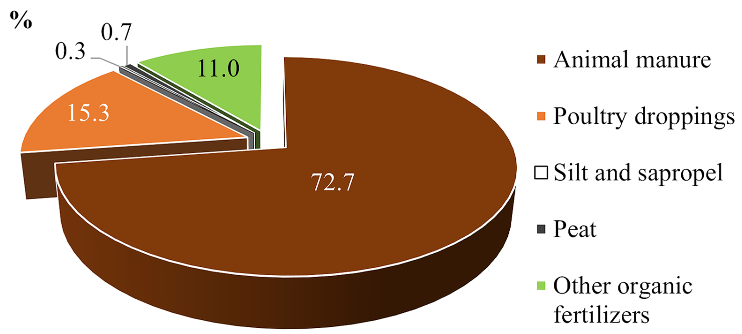

Figure 6. Share of organic fertilizers based on manure (poultry droppings) (2021) (data of the State Statistics Service of Ukraine, 2021)

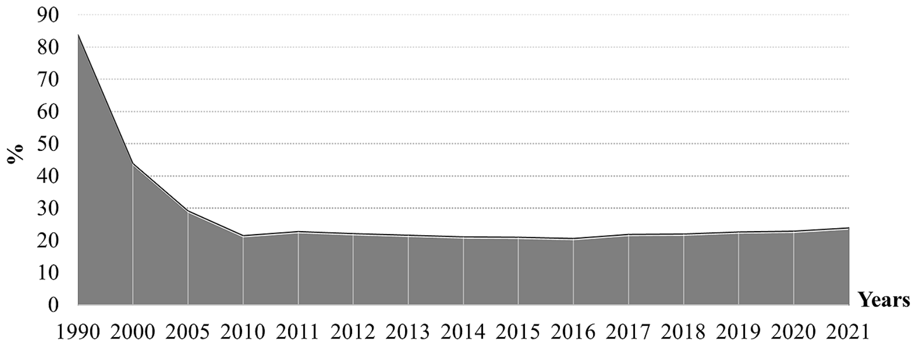

Figure 7. Use of manure as organic fertilizer from excreted manure of livestock (1990–2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 1990–2021)

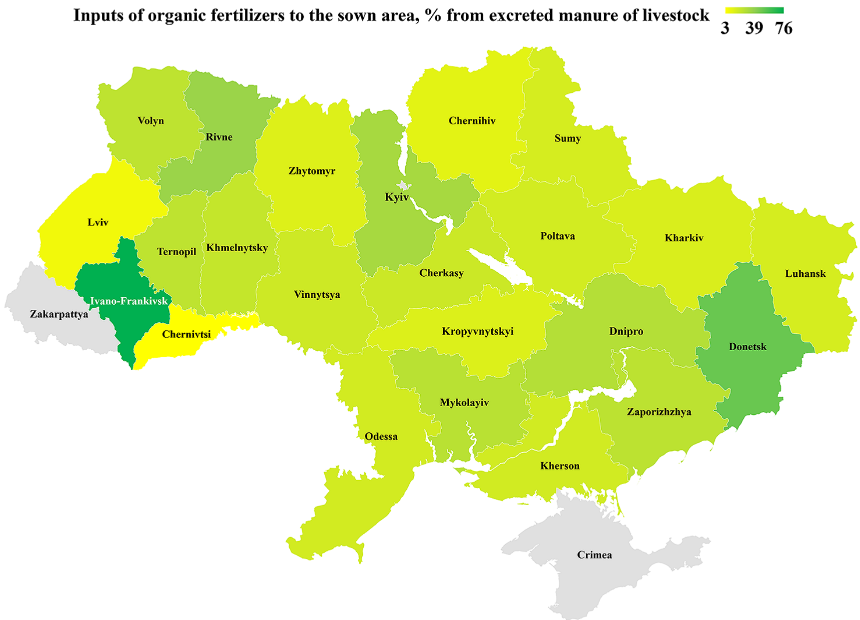

Figure 8. Use of manure as organic fertilizer from excreted manure of livestock by administrative regions (2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 2021)

and leaves) is used for bedding and feeding livestock. The return of organic matter to the soil from crop residues was calculated (Fig. 9).

During 1990–2021, 3.43–9.59 Mg/ha of crop residue biomass is annually returned to the soil, which is 30–59% of the total crop biomass. However, grain and fruits of crops have a higher nutrient content compared to crop residues, which must be taken into account when planning crop rotations. At the same time, monoculture crop rotations are quite common in the world and Ukraine for growing maize and sunflower, which has negative consequences for the soil with long-term use [Pinchuk et al., 2021].

The increase in the amount of crop residues during 1990–2021 is explained by the relative increase in the sown area of crops that have a lot of green biomasses plowed into the soil – maize, sunflower, soy beans and vegetables and by the increase in the yield of certain crops (Table 3).

Among the regions of Ukraine in 2021, the highest rate of return of organic matter to the soil from crop residues was found in Cherkasy – 13.5 Mg/ha, Sumy – 13.3 and Chernihiv Region – 13.2 Mg/ha (Fig. 10).

During 2000–2021, more nutrients were output from agricultural lands for growing the studied crops than were input. The imbalance of organic matter circulation in Ukraine leads to the mineralization of soil humus. Over the past 20 years, a high level of humus mineralization has been observed on agricultural lands in Ukraine,

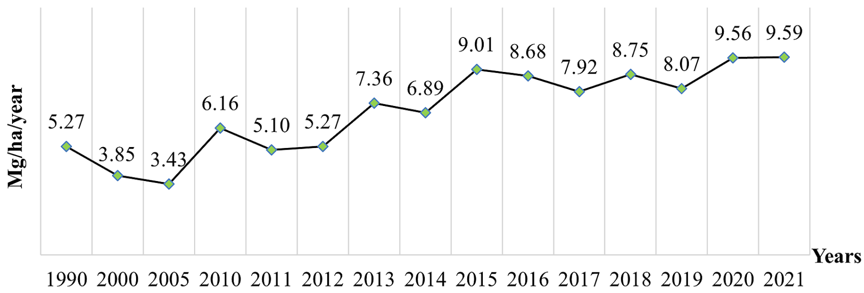

Figure 9. Crop residues inputs to the total sown area (1990–2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 1990–2021)

Table 3. Crop residues with studied crops inputs to the sown area (1990–2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 1990–2021)

Years	Crop residues, Mg/ha/year							
	Wheat	Maize	Sunflower seeds	Rapeseed	Soya beans	Sugar beet	Potatoes	Vegetables
1990	5.11	10.99	6.47	2.55	3.72	2.50	3.38	3.22
2000	3.07	7.69	5.08	1.49	3.53	1.45	3.13	1.76
2005	0.93	12.39	5.49	0.56	1.84	2.08	4.63	3.70
2010	5.60	11.28	5.99	4.75	2.36	2.16	4.21	4.35
2011	4.52	7.69	5.44	3.39	2.82	1.64	3.02	3.23
2012	4.45	7.27	5.41	4.12	3.56	2.78	2.69	3.91
2013	4.77	13.30	7.09	2.25	4.82	6.35	6.65	5.76
2014	4.08	13.05	6.86	2.01	4.02	4.58	6.98	5.30
2015	4.39	21.80	8.89	4.84	3.71	3.47	7.60	4.56
2016	4.86	19.53	6.86	6.57	5.51	4.23	8.63	5.56
2017	5.59	14.59	7.43	2.97	5.88	2.58	7.06	6.20
2018	5.14	17.10	8.95	1.48	6.54	4.06	7.75	6.23
2019	4.98	13.80	8.59	2.24	7.33	5.45	6.97	6.83
2020	5.07	17.90	8.71	3.27	8.57	5.05	6.11	6.47
2021	5.16	17.79	8.91	4.42	7.56	3.60	4.54	7.22

i.e. the processes of biogenic CO_2 emission prevail over the processes of biogenic CO_2 released into the soil as a result of humification (Table 4). Currently, such a negative tendency is observed in all regions of Ukraine (Table 5).

On average, the level of humus mineralization in Ukraine during 1990–2021 ranged from 136 to 1998 kg/ha/year (Fig. 11).

Ukraine is famous for its fertile lands, but intensive anthropogenic load on the soil over decades can lead to depletion and reduction of soil fertility. On the basis of the calculated level of humus mineralization on the lands of agricultural enterprises of Ukraine during 1990–2021, a forecast was made until 2035 (Fig. 12).

If the detected negative tendency does not change (Fig. 11), then by 2035 the average level of humus mineralization will be about 2200 kg/ha/year ($R^2 = 0.725$).

Among the regions of Ukraine in 2021, the highest level of humus mineralization was found in Zhytomyr – 3072 kg/ha/year, Chernihiv – 3027 kg/ha/year and Ivano-Frankivsk regions – 2851 kg/ha/year. The lowest level in Luhansk – 774 kg/ha/year, Kharkiv – 1015 and Mykolaiv regions – 1049 kg/ha/year (Fig. 13).

As a result of the shown level of humus mineralization during 1990–2021, from 0.2 to 63.0 Tg CO_2/year is annually emitted into the air (Fig. 14). On the basis of the calculated level of gross CO_2 emissions as a result of humus mineralization on the agricultural lands of Ukraine during 1990–2021, a forecast was made until 2035 (Fig. 15).

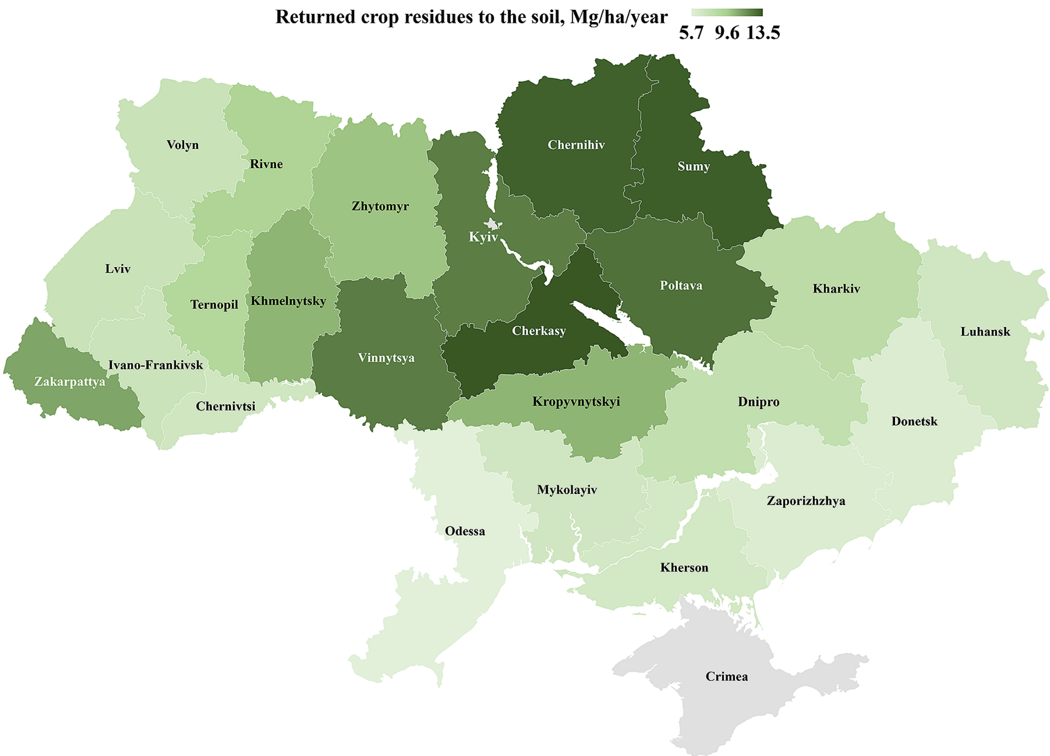

Figure 10. Crop residues inputs to the total sown area by administrative regions (2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 2019; 2021)

Table 4. Carbon biogenic released and emissions as a result of humification and mineralization in the soil (1990–2021) (the indices were calculated by the data of the State Statistics Service of Ukraine, 1990–2021)

Years	Carbon biogenic released		Carbon biogenic emissions		Carbon balance	
	Gg/year	kg/ha	Gg/year	kg/ha	Gg/year	kg/ha
1990	0.80	63.0	881.0	69.3	-80.7	-6.4
2000	0.23	24.9	3143.0	337.9	-2911.0	-312.9
2005	0.20	18.9	5386.7	519.3	-5190.3	-500.4
2010	0.42	32.6	5400.6	418.2	-4979.5	-385.6
2011	0.38	27.0	11.09	779.1	-10.70	-752.1
2012	0.41	28.8	8.44	593.8	-8.03	-565.0
2013	0.61	39.1	12.33	794.9	-11.72	-755.7
2014	0.56	36.7	12.24	804.6	-11.68	-767.9
2015	0.74	47.7	9.85	635.2	-9.11	-587.4
2016	0.67	43.9	12.68	826.3	-12.00	-782.4
2017	0.64	39.7	10.73	662.9	-10.09	-623.2
2018	0.71	43.0	16.57	1002.1	-15.86	-959.1
2019	0.66	39.3	17.17	1016.5	-16.51	-977.2
2020	0.81	47.2	9.79	572.2	-8.98	-525.0
2021	0.83	46.7	16.90	953.0	-16.07	-906.3

According to the prognosis, CO_2 emissions from agricultural land due to humus mineralization will amount to about 70 Tg/year by 2035 ($R^2 = 0.7903$). CO_2 emissions as a result of humus mineralization on the agricultural lands by administrative regions of Ukraine is shown in Fig. 16. The highest total CO_2 emissions due to humus mineralization on agricultural lands were found

Table 5. Carbon biogenic released and emissions as a result of humification and mineralization in the soil by administrative regions (2021) (the indices were calculated by the data of the State Statistics Service of Ukraine, 2019; 2021)

Administrative regions of Ukraine	Carbon biogenic released		Carbon biogenic emissions		Carbon balance	
	Gg/year	kg/ha	Gg/year	kg/ha	Gg/year	kg/ha
Vinnyts'ka	61.9	55.4	1498.4	1341.2	-1436.5	-1285.8
Volyns'ka	8.5	31.7	198.2	734.2	-189.6	-702.5
Dnipropetrovs'ka	45.2	38.4	837.2	711.0	-792.0	-672.6
Donets'ka	17.5	27.8	366.0	580.0	-348.5	-552.2
Zhytomyrs'ka	29.9	43.2	1016.6	1469.7	-986.7	-1426.5
Zakarpats'ka	1.8	52.5	29.2	861.6	-27.4	-809.1
Zaporiz'ka	25.4	24.8	689.8	674.5	-664.4	-649.6
Ivano-Frankivs'ka	7.7	45.8	228.3	1364.0	-220.7	-1318.2
Kyyivs'ka	48.8	57.5	867.4	1021.4	-818.6	-963.9
Kirovohrads'ka	58.0	53.4	1101.4	1014.1	-1043.4	-960.7
Luhans'ka	19.5	30.4	264.3	411.7	-244.8	-381.3
L'vivs'ka	13.3	36.8	385.7	1066.6	-372.4	-1029.8
Mykolayivs'ka	26.9	31.2	480.9	557.9	-454.0	-526.7
Odes'ka	28.6	28.1	729.9	715.2	-701.3	-687.1
Poltavs'ka	82.8	68.6	1131.1	937.3	-1048.3	-868.7
Rivnens'ka	11.8	39.2	362.1	1200.3	-350.3	-1161.1
Sums'ka	66.3	71.1	817.1	876.2	-750.8	-805.1
Ternopil's'ka	26.9	49.5	610.5	1126.3	-583.6	-1076.8
Kharkivs'ka	48.8	39.9	643.7	525.9	-594.9	-486.1
Khersons'ka	23.5	30.7	651.2	852.2	-627.7	-821.5
Khmel'nyts'ka	43.5	50.4	1138.9	1319.3	-1095.4	-1268.9
Cherkas'ka	70.4	82.5	1264.2	1481.1	-1193.8	-1398.7
Chernivets'ka	3.1	34.9	105.1	1171.6	-102.0	-1136.7
Chernihivs'ka	57.7	56.4	1482.7	1448.4	-1424.9	-1391.9

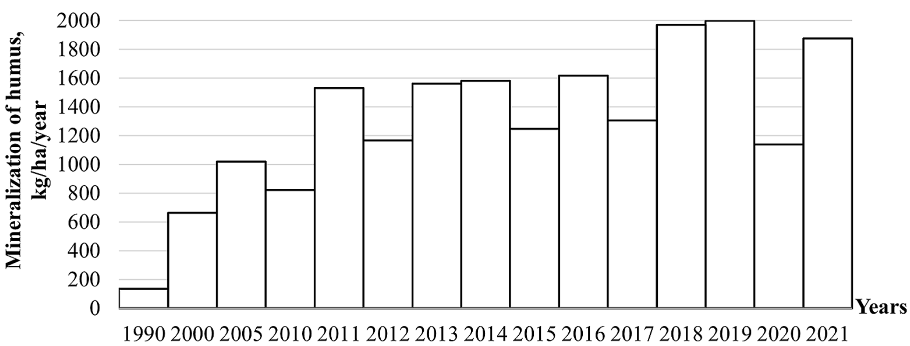

Figure 11. Mineralization of humus on the agricultural lands (1990–2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 1990–2021)

in Vinnytsia – 5.49 Tg/year, Chernihiv – 5.44 and Cherkasy regions – 4.64 Tg/year. The lowest CO_2 emissions in Zakarpattia – 0.11 Tg/year, Chernivtsi – 0.39 Tg/year and Volyn regions – 0.73 Tg/year. The CO_2 emissions due to humus mineralization per unit of main production of crop during 1990–2021 were determined (Fig. 17). It was established that during 1990–2021 for the production of 1 Mg of the main production of crops up to 746 kg of CO_2/year is emitted from the soil. If the detected negative tendency does not change, then by 2035 CO_2 emissions per unit

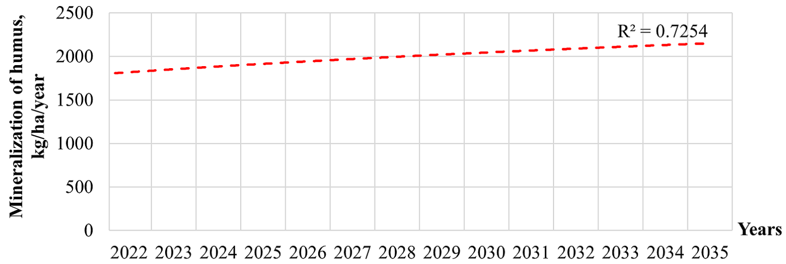

Figure 12. Forecast of the level mineralization of humus on the agricultural lands (2022–2035)

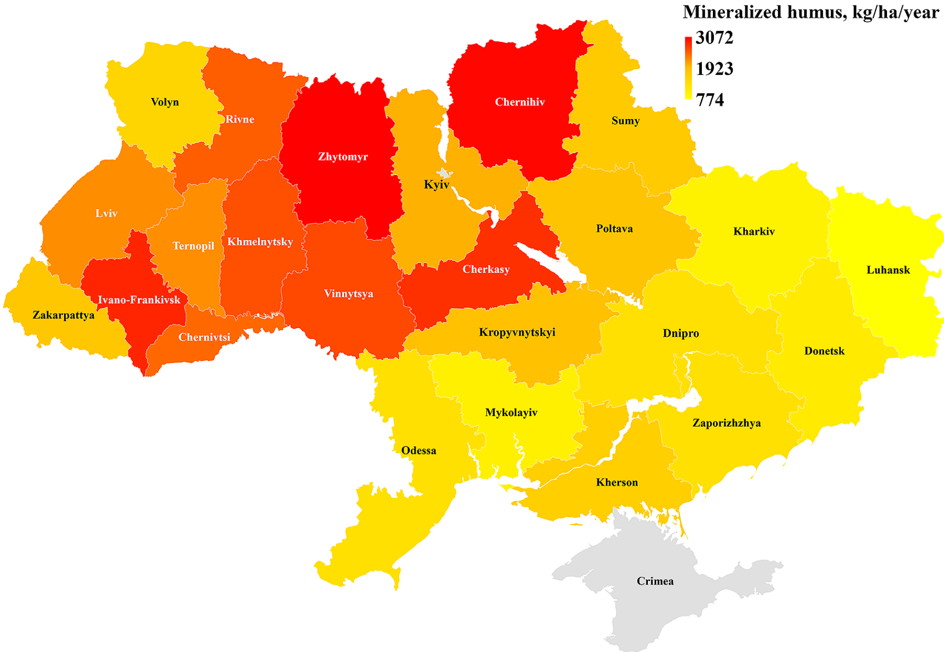

Figure 13. Mineralization of humus on the agricultural lands by administrative regions (2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 2019; 2021)

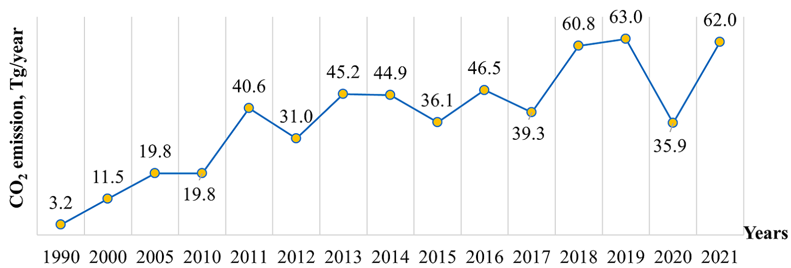

Figure 14. Gross emissions of CO_2 due to humus mineralization on the agricultural lands (1990–2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 1990–2021)

of the main production of crops will increase by 8% and will be about 800 kg of CO_2 per 1 Mg of production per year ($R^2 = 0.657$) (Fig. 18).

Among the regions of Ukraine in 2021, the highest level of CO_2 emissions due to the mineralization of humus per unit of the main production of crops recorded in Zhytomyr – 928 kg of CO_2/Mg of production/year, Chernivtsi – 918 and Ivano-Frankivsk regions – 878 kg of CO_2/Mg of production/year. The lowest CO_2 emissions were found in Volynsk – 459 kg of CO_2/Mg of production/year, Kharkiv – 466 and Lviv regions – 529 kg of CO_2/Mg of production/year (Fig. 19). Among the studied crops, the highest

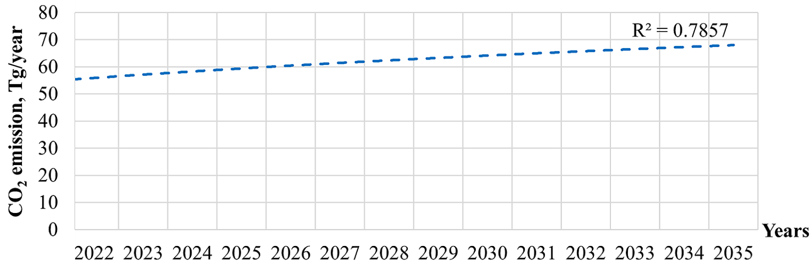

Figure 15. Forecast of the gross CO_2 emissions due to humus mineralization on the agricultural lands (2022–2035)

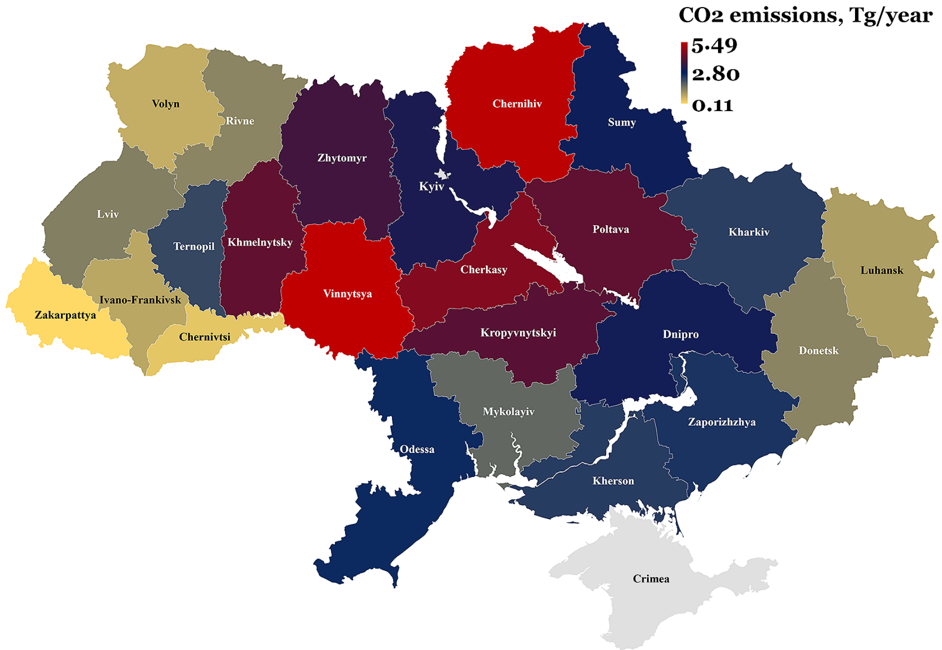

Figure 16. Gross CO_2 emissions due to humus mineralization on the agricultural lands by administrative regions (2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 2019; 2021)

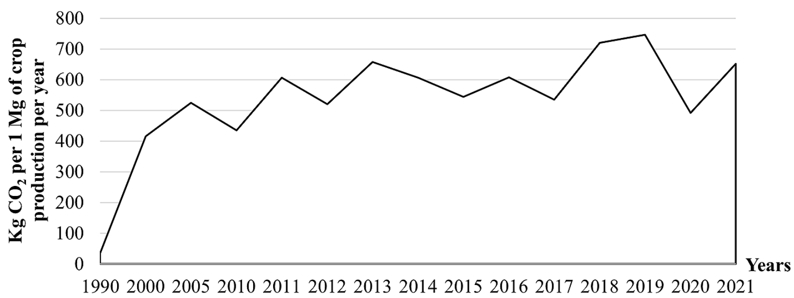

Figure 17. Gross CO_2 emissions due to humus mineralization per unit of the main production of crops on the agricultural lands (1990–2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 1990–2021)

emissions of CO_2 per unit of production due to the mineralization of humus are for the cultivation of sunflower seeds – 1109 kg/Mg/year, maize – 868 and rapeseed – 531 kg/Mg/year, and the lowest emissions for the cultivation of vegetables – 46 kg/Mg/year (Fig. 20). The emissions of N_2O from agricultural land per 1 Mg of main production of crop during 1990–2021 were determined, which amount to 155–376 kg CO_2-eq. (Fig. 21).

If the detected tendency does not change, then by 2035 the average level of emissions of N_2O from agricultural land per 1 Mg of main

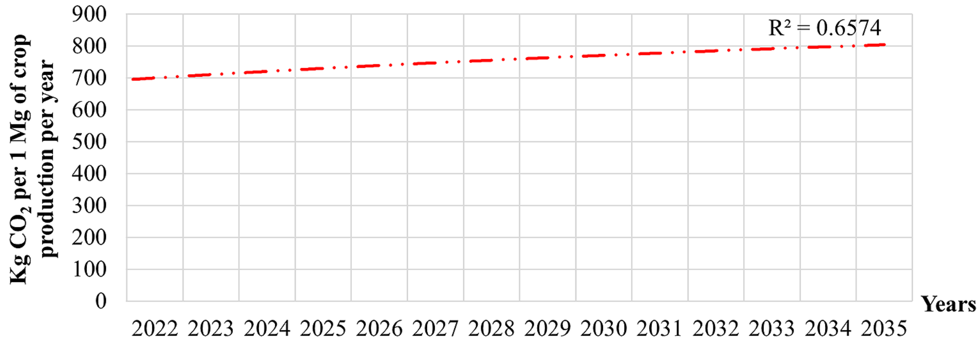

Figure 18. Forecast of the gross CO_2 emissions due to humus mineralization per unit of the main production of crops on the agricultural lands (2022–2035)

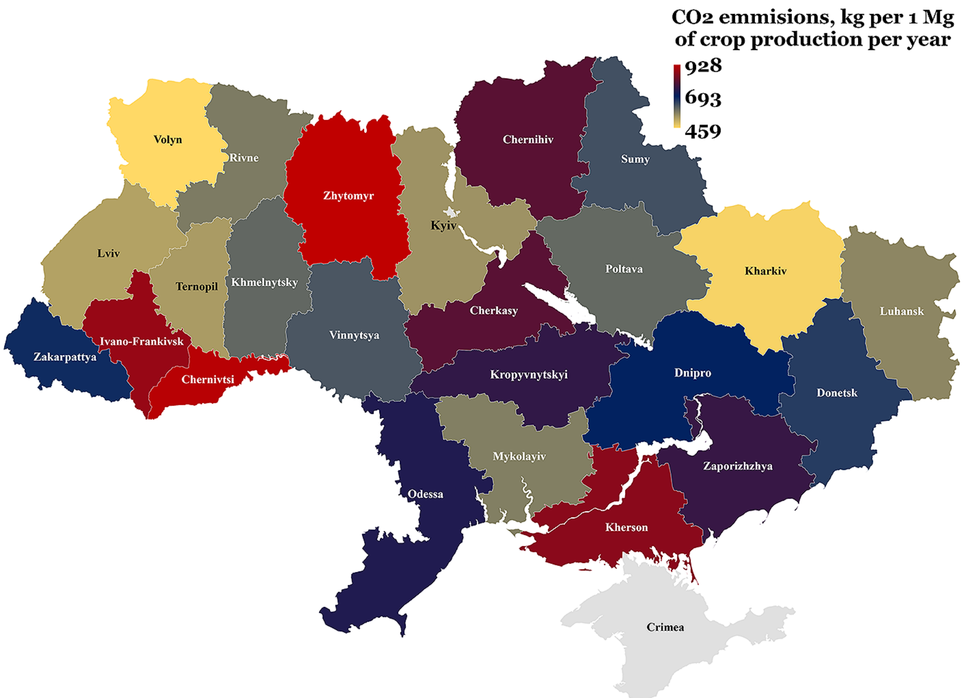

Figure 19. Gross CO_2 emissions due to humus mineralization per unit of the main production of crops on the agricultural lands by administrative regions (2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 2019; 2021)

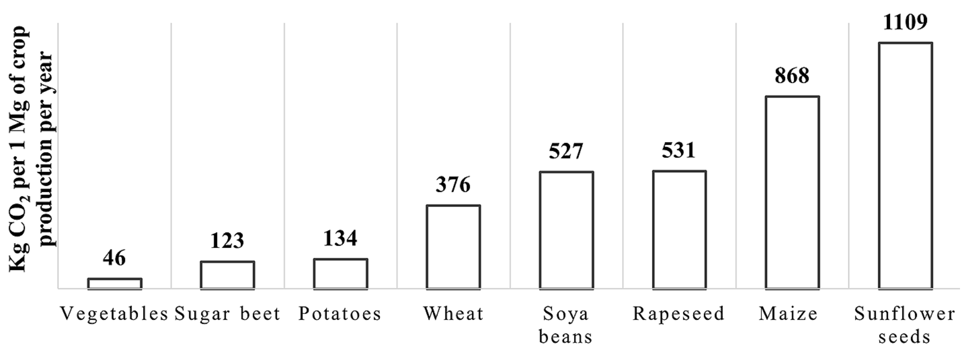

Figure 20. CO_2 emissions due to humus mineralization per unit of the main production of various crops on the agricultural lands (2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 2019; 2021)

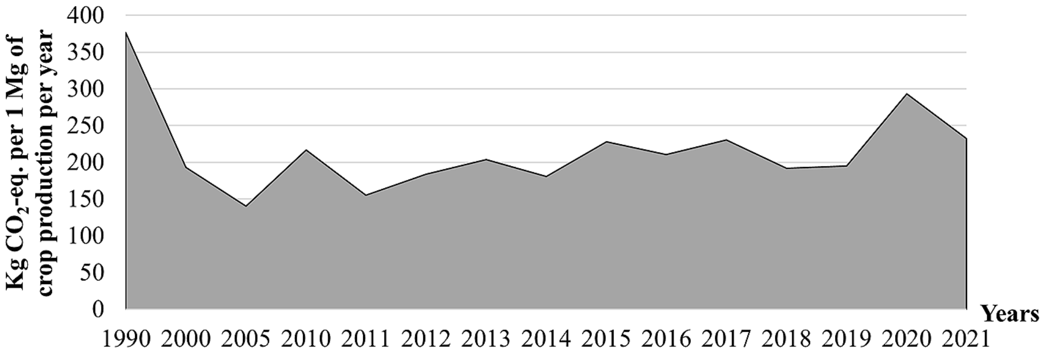

Figure 21. Gross N_2O emissions from agricultural lands per unit of the main production of crops (1990–2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 1990–2021)

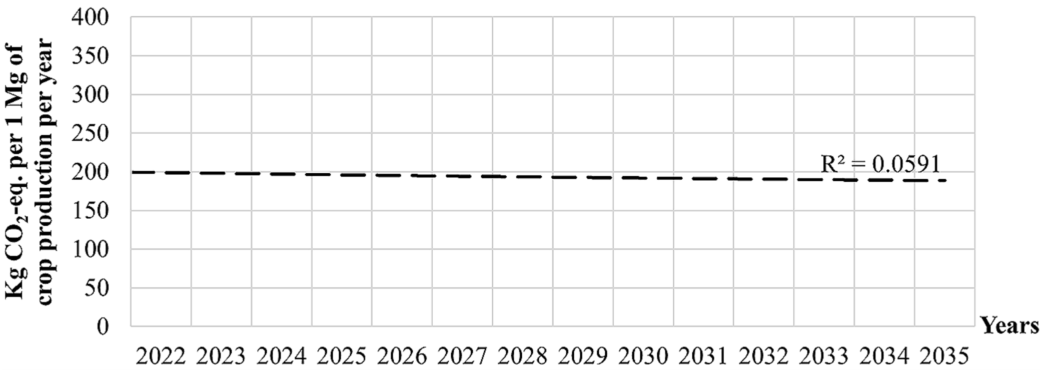

Figure 22. Forecast of the gross N_2O emissions from agricultural lands per unit of the main production of crops (2022–2035)

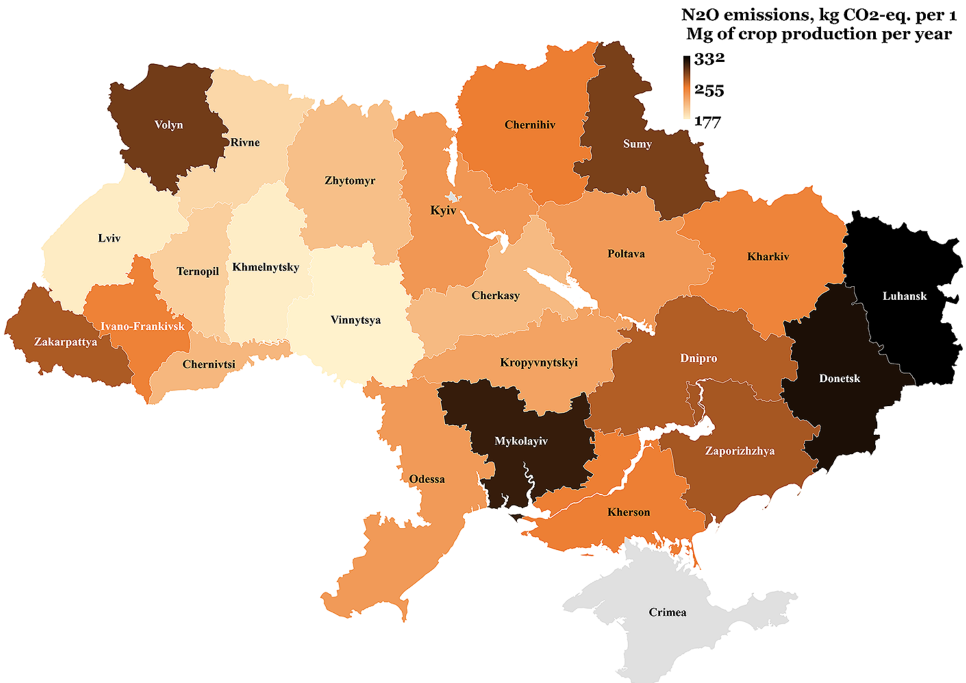

Figure 23. Gross N_2O emissions from agricultural lands per unit of the main production of crops by administrative regions (2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 2019; 2021)

production of crops will be about 200 kg CO_2-eq./year (R^2 = 0.0591) (Fig. 22).

Among the regions of Ukraine in 2021, the highest level of N_2O emissions from agricultural land per unit of crop products were recorded in Luhansk – 332 kg CO_2-eq./Mg of product/year, Donetsk – 323 and Mykolaiv regions – 315 kg CO_2-eq./Mg of product/year. The lowest N_2O emissions were found in Vinnytsia – 177 kg CO_2-eq./Mg of product/year, Khmelnytskyi – 180 and Lviv regions – 181 kg CO_2-eq./Mg of product/year (Fig. 23).

Among the studied crops, the highest N_2O emissions from agricultural land per unit of production were found for the cultivation of rapeseed – 452 kg CO_2-eq./Mg/year, sunflower seeds – 368 and soy beans – 300 kg CO_2-eq./Mg/year, and the lowest emissions were obtained for the cultivation of vegetables and sugar beet – 33 kg CO_2-eq./Mg/year (Fig. 24).

Ukraine, which is the third world exporter of grain in the world, exports more than half of all grown products (Fig. 25).

Organic substances are permanently lost in the grain that is exported without the possibility of returning it to the soil. Currently, this tendency is observed in all regions of Ukraine, which is one of the reasons for the decrease in the humus level in the soil (Pinchuk et al., 2023).

The territory of Ukraine is divided into five nature-agricultural zones: Forest, Forest-Steppe, Steppe, Arid Steppe and Dry Steppe and two mountain regions (Carpathian Mountain Region and Crimean Mountain Region), 19 provinces and 33 districts with different ecological and economic characteristics, including soil and climatic factors (Martyn et al., 2018). The structure of crop production in Ukraine is primarily formed in accordance with local natural and climatic conditions (zoning) and the conjuncture of the domestic and foreign markets. The increase in the carbon footprint of crop production in Ukraine during 1990–2021 is mainly due to the use of intensive crop cultivation technologies, which provide a high level of mineral fertilizer input to the soil, low use of organic fertilizers and siderates, and monoculture cultivation. This applies to the cultivation practices of all studied crops. This practice is aimed at obtaining the highest possible crop yield per unit of sown area, but according to the forecast, it will lead not only to an increase in GHG emissions, but also to soil depletion and a

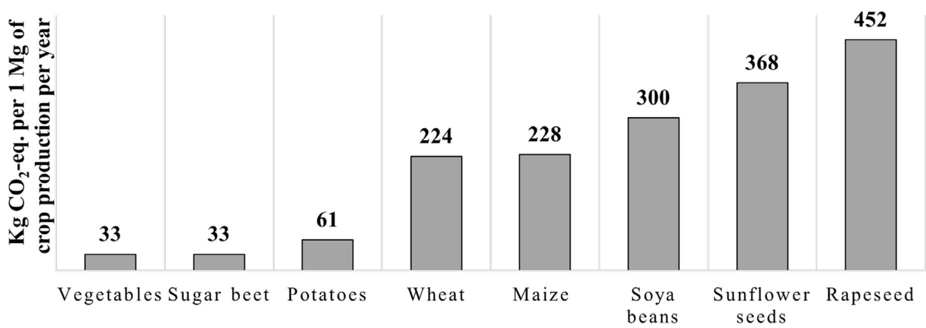

Figure 24. The N_2O emissions from agricultural lands per unit of the main production of various crops (2021) (the index is calculated by the data of the State Statistics Service of Ukraine, 2019; 2021)

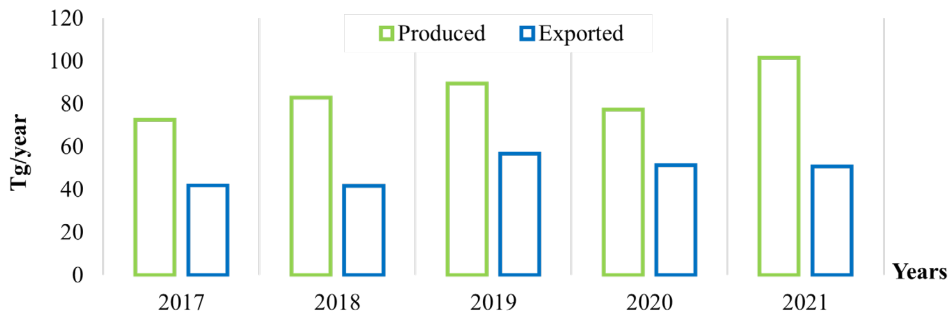

Figure 25. Production and export of grain and oilseeds (2017–2021) (data of the State Statistics Service of Ukraine, 2017–2021)

decrease in the country's food security. To minimize the carbon footprint of crop production, Ukraine needs to implement low-carbon crop cultivation technologies in accordance with the EU requirements. Global climate change affects the crop production in Ukraine at the local level as a result of the recorded increase in average annual temperature and decrease in soil moisture. In particular, using the example of the Odessa region, there is a change in the list of zoned crop varieties due to their insufficient drought resistance. In Ukraine, "Programs for the Development and Support of the Crop Production Sector" are developed at the regional level every five years. Climate change also affects soil erosion and desertification, changes in flora, fauna and soil microbiome, a reduction in the duration of optimal weather conditions during the crop growing season, etc., which indirectly affects the GHG emissions from the soil. At the moment, it is difficult to predict how the carbon footprint of crop production in Ukraine will change as a result of climate change, due to the complexity and duration of the process and the necessary multi-vector research. This work used only three criteria by which GHG emissions were assessed using the UN IPCC methodology – humus mineralization, the use of fertilizers and green manure in crop production. If only abiotic factors that affect the intensity of biological processes in the soil are taken into account – an increase in temperature, a decrease in humidity and the amount of organic matter in the soil – under otherwise identical conditions, then GHG emissions should decrease in the long term.

CONCLUSIONS

The main source of the CO_2 emissions from the soil in crop production in Ukraine is the negative balance of soil organic matter due to the low level of use of organic fertilizers.

In Ukraine, since 2000, there has been a negative tendency both in terms of the level of use of organic fertilizers in crop production and the presence of a manure deficit in certain regions, which is one of the reasons for the decrease in the level of humus in the soil and the pollution of the environmental by by-products of livestock.

In Ukraine, during 1990–2021, a high level of humus mineralization was observed on the agricultural lands under crops of wheat, maize, sunflower seed, rapeseed, soy bean, sugar beet, potatoes, and vegetables – 8–1998 kg/ha/year with emitted into the air from 0.2 to 63.0 Tg of CO_2/year.

The average CO_2 emissions from agricultural land per 1 Mg of main production of studied crops of Ukraine during 1990–2021 were 46–1109 kg. Among the studied crops, the highest emissions of CO_2 per unit of production due to the mineralization of humus were for the cultivation of sunflower seeds – 1109 kg/Mg/year, maize – 868 and rapeseed – 531 kg/Mg/year (2021).

The main source of N_2O emissions from the soil is the input of a high amount of nitrogenous mineral fertilizers – 13.6–120.3 kg N/ha/year (1990–2021). The average N_2O emissions from agricultural land per 1 Mg of main product of studied crops of Ukraine during 1990–2021 were 33–452 kg CO_2-eq. Among the studied crops, the highest N_2O emissions from agricultural land per unit of production resulted from the cultivation of rapeseed – 452 kg CO_2-eq./Mg/year, sunflower seeds – 368 and soy beans – 300 kg CO_2-eq./Mg/year (2021).

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