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ESTIMATION OF NITROUS OXIDE EMISSIONS FROM AGRICULTURAL SOILS IN VOIVODESHIPS IN POLAND

Key words: nitrous oxide emission, GHG, cropping systems, DNDC model, IPCC

ABSTRACT. The purpose of this study was to estimate nitrogen oxide emissions from soils used for agricultural purposes by voivodships. Compared N_2O emissions were estimated according to the recommended IPCC (tier 1) method with simulated emissions using the DNDC (tier 3) model. Analyses were done for crop rotation (winter rape, winter wheat, winter wheat, winter triticale) in four cropping systems. Moreover, simulated N_2O emissions from winter rape and winter triticale cultivation showed lower emissions and constituted 14-75% and 13-76% of IPCC estimated emissions, respectively. The use of the model also enabled the determination of factors, which have an impact on nitrous oxide emissions and define its regional differentiation. The analysis showed that with increasing initial soil organic content, emissions of N_2O rise and decrease with increasing precipitation or carbon sequestration. Considering the requirements for reduction GHG emissions, improving the methodology used in estimating nitrous oxide emissions is of significant practical value.

INTRODUCTION

Efforts to achieve stable levels of greenhouse gases that cause global warming, as well as the increasing and more noticeable climate change, determine new goals and directions for measures that need to be taken. Regulation (EU) 2018/842 of the European Parliament and of The Council "on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending the Regulation (EU)" No525/2013 (Effort Sharing Regulation) sets individual greenhouse gas (GHG) emission reduction goals for each Member State [Official Journal of the European Union, L 156/26]. The regulation applies to sectors of the economy not participating in the emissions trading scheme (non-ETS), such as the agriculture sector. According to these guidelines, Poland should take efforts to reduce greenhouse gas emissions by at least 7% in comparison with 2005 levels.

Countries which are signatories to the United Nations Framework Convention on Climate Change are obliged to monitor and carry out GHG inventory. The methodology for estimating GHG emissions was developed by the Intergovernmental Panel on Climate

Change following the methods described in the Guidelines for National Greenhouse Gas Inventories [IPCC 2006]. Calculations of emissions can be made at different levels of accuracy (Tier 1, 2 and 3). The most commonly used model is Tier 1. However, the IPCC promotes the use of Tier 3 – more detailed methods. In Poland, the institution responsible for reporting GHG emissions is the National Centre for Emissions Management (KOBiZE).

Nitrous oxide is one of the greenhouse gases emitted from agriculture. Due to the fact that it has high potential to create the greenhouse effect and has a long life-cycle in the atmosphere, nitrous oxide constitutes a serious pollutant. According to KOBiZE, N_2O emissions (excluding the LULUCF category i.e. emissions or removals of greenhouse gases from land use, land use change and forestry) in 2018 amounted to 74.18 kt, which is an equivalent of about 22.11 million tonnes of CO_2. Agriculture is the main source of N_2O emissions: the share of total emissions from agriculture is 79.6%, of which 69.5% comes from agricultural soils, 10% from livestock manure management and 0.1% from burning crop residues [KOBiZE 2020].

As mentioned above, the main anthropogenic source of N_2O emissions is agricultural soils. Emission levels are determined by complex interactions between soil properties (soil structure, temperature and humidity, soil aeration, pH and availability of organic carbon) and factors related to farm management (crop species, cultivation practices, type and application technique of nitrogen fertilisation) as well as weather conditions. Moreover, higher emissions of nitrous oxide are also generated by ploughing manure and nitrogen-rich crop residues [Jarosz, Faber 2017].

The purpose of the study was to estimate the amount of nitrous oxide emissions from agricultural soil use in voivodships and specify the contribution of various aspects of regional differentiation of emissions.

MATERIAL AND METHODS

The assessment of N_2O emissions by voivodships was carried out using two methods: the IPCC (Tier 1) method and the DNDC (Denitrification – Decomposition; Tier 3) model calibrated to Polish conditions [http://www.dndc.sr.unh.edu]. The DNDC model has commonly been used to analyse the changes and balance of coal and nitrogen in the European Union [Leip et al. 2007, 2008] and Poland [Faber, Jarosz 2018a, 2018b]. Simulations were done for the whole are of Poland divided into 136 squares of 50x50 km, for a 20-year period.

The input data for the DNDC model are daily meteorological data (minimum and maximum temperature and precipitation), parameters characterizing the physical and chemical properties of soils (colloidal clay content, bulk density, pH and carbon content) and data characterizing the farming technique (crop rotation, dates, types and depths of cultivation practices, application rates and dates of mineral and natural fertilizer application as well as quantity of crop residues left in the field) [Li 2007]. Daily meteorological data were collected from the databases of the European Commission's Joint Research Centre. The soil characteristics needed for the model were provided from the IUNG-PIB databases. Simulations were done for crop rotation: winter rape – winter wheat – winter wheat – winter triticale in four cropping systems:

1. Full tillage (ploughing) harvesting all crop residues.
2. Tillage ploughing all crop residues.
3. Reduced tillage (without ploughing) leaving all crop residues at the field.
4. No-tillage (direct seeding) leaving all crop residues at the field.

The N_2O emissions estimated, based on IPCC methodology, were compared with emissions simulated using the DNDC model. Moreover, the use of the DNDC model to simulate nitrous oxide emissions allowed for conducting analysis and indicating which factors impacted its quantity. Correlations were determined using multiple linear regression with a stepwise selection of variables. The study only presents the results for those variables which had a statistically significant impact on simulated N_2O values.

Simulated regional differentiation of nitrous oxide emissions depending on the initial soil carbon content and carbon sequestration, as the main modifying variables, was characterized by the results of cluster analysis (k-Ward method) using the statistical package Statgraphics Centurion ver. 16.1.11.

RESULTS

Conducted simulations of nitrous oxide emissions showed certain variability both in the tested cultivations and the cropping systems.

In winter wheat cultivated using full tillage harvesting all crop residues, N_2O emissions estimated using the IPCC method ranged from 2.79 to 3.17 kg N_2O/ha/year (Table 1, System 1). Ploughing all crop residues (System 2) increased nitrous oxide emissions. The reason for this was the input of additional nitrogen in crop residues. Reduced tillage leaving all crop residues in the field (Table 1, System 3) generated N_2O emissions at a similar level as in system 2. The estimated emissions in the no-tillage system leaving all crop residues in the field (Table 1, System 4) showed a slight decrease. A similar trend was observed in nitrous oxide emissions simulated using the DNDC model. However, regardless of the cropping system, simulated N_2O emissions were lower than those estimated by IPCC. The ratio of the simulated DNDC to estimated IPCC strongly varied – it ranged between 9-46%.

Concerning the cultivation of winter rape, the lowest estimated N_2O emissions according to the IPCC method were observed in the full tillage harvesting all crop residues (Table 2, System 1). The other rape cropping systems had similar nitrous oxide emissions and values ranging from 3.65-3.72 kg N_2O/ha/year. The N_2O emissions generated by full tillage harvesting all crop residues simulated using the DNDC model varied between 0.49-2.10 kg N_2O/ha/year and were several times lower than those estimated in IPCC. A small reduction in emissions can be achieved by changing the cropping system, with the use of reduced or no-tillage leaving all crop residues in the field (Table 2, System 3 and 4). Also, in this case, the emissions simulated were smaller than those estimated using the IPCC method, and their share was 18-72% in the reduced system and 16-58% in the no-tillage system, respectively (Table 2).

Also, in triticale cultivation, the lowest estimated emissions were found in full tillage harvesting all crop residues (Table 3, System 1). In other triticale cultivation systems,

Table 1. Nitrous oxide emissions estimated using the IPCC and DNDC methods for winter wheat cultivation

Voivodships	Tillage systems [kg N_2O/ha/year]*											
	1.			2.			3.			4.		
	IPCC	DNDC	DNDC/ IPCC [%]	IPCC	DNDC	DNDC/ IPCC [%]	IPCC	DNDC	DNDC/ IPCC [%]	IPCC	DNDC	DNDC/ IPCC [%]
Dolnośląskie	2.88	0.55	19	3.46	0.89	26	3.49	0.92	27	3.29	0.75	23
Kujawsko-Pomorskie	3.03	0.94	31	3.61	1.44	39	3.60	1.69	46	3.59	1.05	29
Lubelskie	2.87	0.34	12	3.35	0.56	16	3.42	0.50	15	3.30	0.52	15
Lubuskie	3.17	0.84	26	3.69	1.41	37	3.69	1.14	30	3.61	0.60	17
Łódzkie	2.91	0.34	12	3.40	0.61	18	3.44	0.55	16	3.28	0.51	16
Małopolskie	2.95	0.38	13	3.42	0.68	20	3.53	0.59	17	3.36	0.57	18
Mazowieckie	2.80	0.32	11	3.32	0.48	15	3.36	0.46	14	3.23	0.51	16
Opolskie	2.79	0.67	23	3.26	1.16	34	3.31	0.82	23	3.19	0.60	18
Podkarpackie	2.90	0.48	16	3.41	0.93	28	3.49	0.65	19	3.30	0.64	19
Podlaskie	2.82	0.30	11	3.35	0.43	13	3.36	0.44	13	3.21	0.45	14
Pomorskie	2.92	0.32	11	3.46	0.53	15	3.57	0.51	14	3.27	0.46	14
Śląskie	2.84	0.25	9	3.37	0.50	15	3.47	0.44	13	3.31	0.47	14
Świętokrzyskie	3.06	0.46	15	3.53	0.78	22	3.59	0.63	18	3.34	0.53	16
Warmińsko-Mazurskie	2.85	0.38	13	3.34	0.55	17	3.45	0.54	16	3.26	0.53	16
Wielkopolskie	2.92	0.38	13	3.45	0.70	20	3.47	0.56	16	3.29	0.46	14
Zachodniopomorskie	2.88	0.39	14	3.42	0.67	20	3.52	0.65	19	3.27	0.48	14
Poland	2.91	0.46	16	3.43	0.77	22	3.49	0.69	20	3.32	0.57	17

* system 1-4:
1. Full tillage harvesting all crop residues
2. Tillage ploughing all crop residues
3. Reduced tillage leaving all crop residues in the field
4. No-tillage leaving all crop residues in the field
Source: own study

Table 2. Nitrous oxide emissions estimated using IPCC and DNDC methods for winter rape cultivation

Voivodships	Tillage systems [kg N_2O/ha/year]*											
	1.			2.			3.			4.		
	IPCC	DNDC	DNDC/ IPCC [%]	IPCC	DNDC	DNDC/ IPCC [%]	IPCC	DNDC	DNDC/ IPCC [%]	IPCC	DNDC	DNDC/ IPCC [%]
Dolnośląskie	3.66	1.07	29	3.68	1.43	39	3.68	1.36	37	3.68	1.13	31
Kujawsko-Pomorskie	3.82	2.10	58	3.82	2.57	64	3.82	2.57	67	3.82	2.21	58
Lubelskie	3.64	0.66	18	3.66	0.79	21	3.66	0.75	20	3.66	0.62	17
Lubuskie	3.66	2.06	56	3.66	2.73	75	3.66	2.61	72	3.65	1.79	49
Łódzkie	3.65	0.75	20	3.65	1.10	30	3.65	1.09	30	3.65	0.99	27
Małopolskie	3.65	0.80	22	3.70	1.14	31	3.70	1.06	29	3.68	0.89	24
Mazowieckie	3.65	0.53	14	3.69	0.80	22	3.69	0.78	22	3.67	0.67	18
Opolskie	3.65	0.78	21	3.71	0.99	27	3.72	0.97	26	3.68	0.92	25
Podkarpackie	3.65	0.75	21	3.69	0.95	26	3.69	0.92	25	3.68	0.83	23
Podlaskie	3.62	0.49	14	3.65	0.73	20	3.65	0.71	19	3.66	0.65	18
Pomorskie	3.65	0.55	15	3.70	0.71	19	3.70	0.70	19	3.69	0.62	17
Śląskie	3.64	0.59	16	3.67	0.90	25	3.67	0.92	25	3.66	0.77	21
Świętokrzyskie	3.65	1.15	32	3.68	1.42	39	3.68	1.30	35	3.68	0.92	25
Warmińsko-Mazurskie	3.65	0.55	15	3.70	0.69	19	3.69	0.68	18	3.69	0.60	16
Wielkopolskie	3.65	1.15	32	3.70	1.55	43	3.70	1.50	41	3.69	1.33	37
Zachodniopomorskie	3.64	0.79	21	3.68	0.87	23	3.68	0.85	23	3.68	0.74	20
Poland	3.66	0.92	25	3.69	1.21	33	3.69	1.17	32	3.68	0.98	27

* system 1-4: see Table 1
Source: own study

Table 3. Nitrous oxide emissions estimated using IPCC and DNDC methods for winter triticale cultivation

Voivodships	Tillage systems [kg N_2O/ha/year]*											
	1.			2.			3.			4.		
	IPCC	DNDC	DNDC/ IPCC [%]	IPCC	DNDC	DNDC/ IPCC [%]	IPCC	DNDC	DNDC/ IPCC [%]	IPCC	DNDC	DNDC/ IPCC [%]
Dolnośląskie	2.92	1.02	35	3.51	2.07	59	3.50	1.80	53	3.50	1.50	44
Kujawsko-Pomorskie	2.71	0.52	20	3.32	0.56	17	3.38	0.56	17	3.32	0.55	17
Lubelskie	2.77	0.46	16	3.46	0.98	28	3.49	0.98	27	3.41	0.96	27
Lubuskie	2.79	1.87	63	3.40	2.68	75	3.40	2.70	76	3.37	1.55	45
Łódzkie	2.85	0.57	21	3.49	1.13	32	3.45	1.09	32	3.45	0.98	28
Małopolskie	2.92	0.44	15	3.60	0.94	26	3.65	0.95	26	3.52	0.95	27
Mazowieckie	2.82	0.44	16	3.48	0.83	23	3.53	0.82	23	3.44	0.77	21
Opolskie	2.81	0.58	21	3.47	0.87	25	3.47	0.95	27	3.46	0.82	24
Podkarpackie	2.88	0.43	15	3.60	0.86	25	3.63	0.99	28	3.49	0.98	28
Podlaskie	2.73	0.40	13	3.45	0.69	21	3.46	0.69	20	3.39	0.68	20
Pomorskie	2.89	0.50	18	3.57	0.88	25	3.61	0.88	25	3.49	0.88	25
Śląskie	2.74	0.47	17	3.41	1.05	30	3.47	1.06	30	3.42	1.02	29
Świętokrzyskie	2.94	0.63	22	3.66	1.16	32	3.71	1.17	32	3.57	1.15	32
Warmińsko-Mazurskie	2.80	0.39	14	3.50	0.86	24	3.55	0.86	23	3.46	0.82	23
Wielkopolskie	2.79	1.17	43	3.40	1.93	56	3.40	1.97	59	3.40	1.50	44
Zachodniopomorskie	2.96	0.49	16	3.55	0.86	25	3.61	0.94	26	3.51	0.81	23
Poland	2.83	0.65	23	3.49	1.15	33	3.52	1.15	33	3.45	1.00	29

* system 1-4: see Table 1
Source: own study

the N_2O emissions estimated using the IPCC method were at similar levels. A wider variability of nitrous oxide emissions was obtained using the DNDC model (Table 3). The smallest simulated emissions were observed in full tillage harvesting all crop residues, while ploughing crop residues caused an increase in N_2O emissions (Table 3, System 2). A reduced or no-tillage system, leaving crop residues in the field, resulted in a decrease in nitrous oxide emissions (Table 3, System 3 and 4). For winter triticale, N_2O emissions simulated using the DNDC model were lower in comparison to those estimated in the IPCC method. These emissions constituted 13-76% of those calculated using the IPCC method.

Concluding, the methodology itself for estimating GHG emissions (also nitrous oxide) is of key importance considering the need for limiting GHG emissions and related requirements. The research undertaken by Jan Peter Lesschen and others [2011] at a European level has also confirmed that N_2O emissions in a large area of Poland are lower than those estimated using the IPCC method.

By using the DNDC model, it was possible to determine which variables had an impact on simulated N_2O emissions. The analysis showed that emissions were mainly affected by soil carbon content and precipitation (Table 4).

Table 4. The relationship between nitrous oxide emissions (E_{N2O}) [kg N/ha], soil organic carbon content (SOC) [t C/ha] and total annual precipitation (P_{ann}) [mm]

Tillage system*	Regression	R^2 [%]
1.	E_{N2O} = 0.019 SOC – 0.001 P_{ann}	91.8
2.	E_{N2O} = 0.022 SOC – 0.001 P_{ann}	91.4
3.	E_{N2O} = 0.016 SOC – 0.001 P_{ann}	93.4
4.	E_{N2O} = 0.017 SOC – 0.001 P_{ann}	91.6

* system 1-4: see Table 1
Source: own study

In all cropping systems, it was observed that with increasing initial soil organic content, nitrogen oxide emissions also rose and decreased as precipitation levels grew. The implementation of carbon sequestration as an additional independent variable changed the correlation (Table 5). Emissions of N_2O increased with initial organic content and decreased with higher carbon sequestration.

Table 5. The relationship between nitrous oxide emissions (E_{N2O}) [kg N/ha], soil organic carbon content (SOC) [t C/ha] and carbon sequestration (C_{seq}) [t C/ha/year]

Tillage system*	Regression	R^2 [%]
1.	E_{N2O} = 0.009 SOC – 1.624 C_{seq}	89.3
2.	E_{N2O}= 0.029 SOC – 2.543 C_{seq}	92.3
3.	E_{N2O} = 0.019 SOC – 1.399 C_{seq}	93.7
4.	E_{N2O} = 0.019 SOC – 0.293 C_{seq}	92.3

* system 1-4: see Table 1
Source: own study

The cluster analysis for voivodships was conducted based on the main variables modifying N_2O emissions (Table 5). This analysis allowed to distinguish homogeneous nitrous oxide emissions in three groups of voivodship (Figure 1).

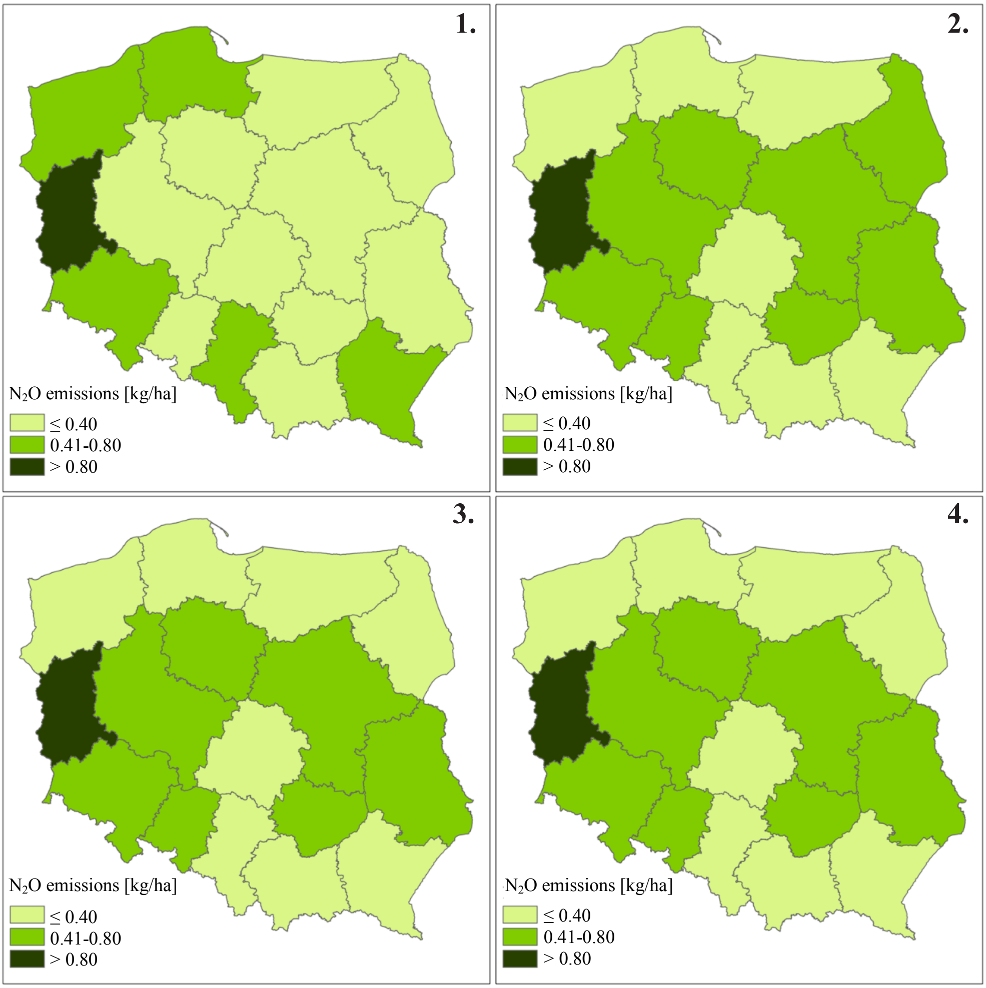

Figure 1. Voivodship groups diversified in terms of N_2O emissions depending on soil organic carbon content and carbon sequestration

Source: own study

Groups of variables under analysis are presented in Table 6. The results show that N_2O emissions were strongly affected by high soil initial carbon content (SOC) and low carbon sequestration (Cseq) values. In the tillage system harvesting straw, the highest emissions were found in cluster 3 (the Lubuskie Voivodship) characterized by the highest content of organic carbon in soil, hence the lowest value of carbon sequestration. Whereas increased carbon sequestration and lower values of carbon content in different cultivation systems resulted in lower N_2O emissions.

Table 6. Differentiation of variables (Cseq, SOC) in separate voivodship groups

Cluster	Tillage systems*											
	1.			2.			3.			4.		
	N_2O	C_{seq}	SOC	N_2O	C_{seq}	SOC	N_2O	C_{seq}	SOC	N_2O	C_{seq}	SOC
1	0.46	0.00	66.8	0.47	0.46	55.4	0.46	0.46	56.3	0.87	2.19	75.5
2	0.37	0.08	54.0	1.42	0.46	80.0	1.12	0.46	80.0	0.40	2.35	53.3
3	1.26	-0.07	80.0	0.40	0.49	61.6	0.37	0.50	60.0	0.36	2.62	62.8

* system 1-4: see Table 1
Source: own study

The analysis showed that, in all crops, despite the estimation methodology applied, the highest nitrous oxide emissions were observed in full tillage ploughing all crop residues and reduced tillage leaving all crop residues in the field. However, studies conducted by Antoni Faber and Zuzanna Jarosz [2018b] showed that ploughing or leaving harvest residues in these cropping systems also improves carbon sequestration, and those high values balance or exceed N_2O emissions, consequently leading to a reduction in total GHG emissions.

According to the latest IPCC guidelines [IPCC 2019] and the newest Global Warming Potential GWPs presented in the 5th IPCC Climate Change Assessment Report [IPCC 2013], it can be supposed that new standards in estimating GHG emissions will apply soon and will be recommended for use by IPCC [2019]. These guidelines provide a framework for new, detailed analyses of greenhouse gas emissions, such as the net worth emissions of nitrous oxide, and will be further investigated.

CONCLUSIONS

Nowadays, there is strong pressure and a growing need to limit GHG emissions, and improving estimation methodologies (including those for nitrous oxide) has an important practical aspect. The basic method of estimating N_2O emissions, recommended by the IPCC, refers to a standard indicator which determines that nitrous oxide emissions constitute 1% of applied nitrogen. The conducted analysis showed that the use of more accurate methods, i.e. so-called models to simulate emissions allows to take many factors (soil type, cropping method, fertiliser type and application, etc.) affecting the volume of emissions into account and consider the interactions between those factors. Furthermore, the application of the model determines which factors have a significant statistical impact on simulated emissions. The cluster analysis enabled the separation of homogeneous groups of voivodships depending on the initial soil organic carbon content and carbon sequestration. Increased sequestration and lower initial carbon values significantly reduced nitrous oxide emissions in all cultivation systems.

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SZACOWANIE EMISJI PODTLENKU AZOTU Z GLEB ROLNYCH W POLSCE W PRZEKROJU WOJEWÓDZTW

Słowa kluczowe: emisja podtlenku azotu, GHG, systemy uprawy, model DNDC, IPCC

ABSTRAKT

Celem badań było oszacowanie wielkości emisji podtlenku azotu z rolniczego użytkowania gleb w przekroju województw. Porównano wielkości emisji N_2O oszacowane według zalecanej metodyki IPCC (tier 1) z emisjami symulowanymi, z wykorzystaniem modelu DNDC (tier 3). Symulacje były przeprowadzone dla zmianowania upraw (rzepak ozimy, pszenica ozima, pszenica ozima, pszenżyto ozime) w czterech systemach uprawy. Model DNDC wykazał, że emisje podtlenku azotu z uprawy pszenicy ozimej stanowiły 9-46% emisji szacowanych metodą IPCC. Również symulowane emisje N_2O z uprawy rzepaku ozimego i pszenżyta były zdecydowanie niższe i mieściły się w przedziale odpowiednio: 14-75% oraz 13-76% emisji szacowanych według IPCC. Zastosowanie modelu pozwoliło także na określenie, które czynniki wpływają na wielkość emisji podtlenku azotu i decydują o jej regionalnym zróżnicowaniu. Przeprowadzona analiza wykazała, że emisje N_2O zwiększają się wraz ze wzrostem początkowej zawartości materii organicznej, zmniejszają się zaś ze wzrostem opadów lub sekwestracji węgla. Dlatego, uwzględniając wymagania w zakresie ograniczania emisji gazów cieplarnianych, doskonalenie metodyki szacowania emisji podtlenku azotu ma istotne znaczenie utylitarne.

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