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Simulation of soil organic carbon in long-term experiments in Poland using the DNDC model

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Abstract

In this paper, simulations with a Denitrification – Decomposition (DNDC) model were used to evaluate the impact of different management options on carbon (C) sequestration and emission of greenhouse gases: methane (CH_4) and nitrous oxide (N_2O). Two cropping systems were analyzed. The first included potato, winter wheat, spring barley and forage maize (P-W-B-M). The second included potato, winter wheat, spring barley with clover and grass mixture (P-W-B-C). In both cropping systems, different farmyard manure (FYM) rates were applied. The application of additional nitrogen (N) using FYM increased the C sequestration, as well as N_2O emissions and had a little effect on CH_4 uptake. An estimate into the average annual increases in N_2O emissions, which were converted into carbon dioxide (CO_2) equivalent emissions with 100-year global warming potential (GWP) multipliers, were offset by 56-144% of the C sequestration, depending on the management option. After 16 years of the experiment, the accumulation of C and N per hectare increased in the soil organic matter (SOM) pool. In P-W-B-M rotation, with manure applied at 325 kg N ha^{-1}, the accumulation of C increased to 5,760 and N 585 kg ha^{-1}, respectively. In P-W-B-C rotation, where a higher rate of manure was applied, the increase of C was at 10,796 and N 740 kg ha^{-1}. The highest influence in the rise of C and N accumulation was in humates. The high value of C sequestration in soil outweighs the emissions of N_2O. In P-W-B-M rotations, the rate of applied FYM switched its average annual net GWP balance from net losses to a net sink. In P-W-B-C rotations, the applied FYM increased the annual rate of GHG emissions by 3%. The average annual N_2O emissions increased by 44% under P-W-B-C rotation and by 142% under P-W-B-M rotations. Increases in the soil organic carbon (SOC) were by 234% and 408%, respectively, for P-W-B-C and P-W-B-M rotations. Our study showed that usage of FYM should be managed correctly, because applications at high rates have a negative impact on environment.

Key words: Soil carbon sequestration, DNDC model, nitrous oxide, greenhouse gas emission, farmyard manure.

Introduction

Agriculture practices contribute to greenhouse gas (GHG) emissions and also to carbon dioxide (CO_2) absorption and soil sequestration of carbon into a solid organic form. Land management can strongly influence soil carbon stock; therefore, careful management must be used to sequestered soil carbon [1]. Carbon sequestration is a process through agricultural practices in removing CO_2 from the atmosphere into a form that does not affect the atmospheric chemistry [12]. Through the process of photosynthesis, CO_2 is absorbed by plants and converted into their tissue. Upon their death, plant tissues decompose, primarily by soil microorganisms, and the carbon in the plant material is released back into the atmosphere as CO_2. However, some of the carbon (C) in the plant material forms soil organic matter (SOM). Soil organic carbon (SOC) is essential for maintaining the fertility of the soil, water retention and plant production. The amount of SOC stored in the soil is defined by a balance between the primary productivity of the vegetation and connected with litter inputs and decomposition of SOM [8]. This causes that changes in the organic carbon level are slower. SOC decreases with agriculture activities, e.g. tillage, fertilization and manure application. Economic analysis suggests that C sequestration is among the most beneficial and cost effective options available for reducing greenhouse gas emissions [7]. However, through changing agricultural practices there is a potential for restoring organic carbon levels as well as a reduction of nitrous oxide (N_2O) emissions. Roberson and Vitousek [21] reported that since the late 1950s global synthetic N fertilizer consumption has increased from 10 to 100 Tg nitrogen (N) in 2008. This is mainly due to the fact that N is generally the most limiting nutrient in intensive crop production systems [21]. Globally, agricultural N_2O emissions have increased by nearly 17% from 1990 to 2005, and they account for about 60% of global anthropogenic N_2O emissions [10]. Several field and laboratory experiments have established a positive relation between N_2O flux and SOC [14]. Bowman [2] and Vinther [26] stated that soils with higher SOC have higher N_2O fluxes. An increase of the soil N_2O emission is mainly due to an increase of the soil total N and activity of microorganisms [14]. N applied to soil is not always used efficiently. The majority of the N fertilizer is lost from agricultural fields. According to Tilman *et al.* [25], only 30-50% of N fertilizer is taken up by crops. Similar results were obtained by Janzen *et al.* [11]. The surplus of N is sensitive to the emission of N_2O [19]. However, improving the efficiency of N usage might reduce N_2O emissions. Reducing the N application should be the main target of arable crop production, together with storing carbon in soil. Therefore, it is necessary to aim for a higher nutrition efficiency which could be achieved by applying fertilizer during periods of greatest crop demand and by distributing more precisely into the soil (i.e. near the plant roots). Roberts [20] maintains that the basis of good N fertilizer management in cropland agriculture is using the right N source, at a correct rate, at the right time, and with the accurate placement. Accurate estimates of annual N_2O emissions and SOC are necessary in order to compare the impact of management strategies and describe management practices that will lower GHG emissions.

The most reliable source of information about GHG emissions from different management practices are long-term experiments [16]. However, time and cost are limiting factors. Simulation models provide an alternative method of assessment for agricultural practices with low time requirements and cost [16].

The aim of our study was to estimate changes in SOC and net GHG fluxes from arable soil in Poland, under different cropping systems by using the Denitrification – Decomposition (DNDC) model.

Materials and Methods

Data source: The data used in the calculation of different management scenarios for two crop rotations, originated from a field experiment conducted between 1991 to 2007 at the Grabow Experimental Station (51°21' N, 21°40' E and 167 m.a.s.l.) of the Institute of Soil Science and Plant Cultivation - State Research Institute, Pulawy (IUNG-PIB). The soil is classified as sandy loam, with a pH of 6.8 for the first cropping system and 5.7 for the second. Soil bulk density was 1.4 g cm^{-3}, clay fraction 0.09% and initial value of SOC 0.01 kg C kg^{-1}. The long-term average precipitation for the Grabow area is 614 mm. All these parameters were used as input data for the DNDC. In this study, the first cropping system included the following crops: potato, winter wheat, spring barley and forage maize (called P-W-B-M). The second one included potato, winter wheat, spring barley with clover and grass mixture (P-W-B-C). Two treatments were simulated for P-W-B-M rotation. Treatment A0 was conducted with fertilizer N and A1 with fertilizer N, with manure applied on potato at a rate of N 325 kg ha^{-1} every four years. In the P-W-B-C crop rotation, two treatments, B1 and B2, were simulated. Both of them received the same rates of N fertilizers, which varied according to the crop. However, the rates of applied manure were different. In B1, manure was applied before barley and in B2 before barley and potato. Table 1 presents the amounts of applied fertilizer and manure in A0, A1, B1 and B2 rotations. In our study, we used ammonium nitrate fertilizer.

The crops in both crop rotations also received P and K fertilizers. The amount of applied fertilizers was equal in both treatments in each crop rotation (Table 2). On both fields, a four year cropping sequence was duplicated in four cycles. All crops were grown using recommended agronomic practices in terms of seeding date and depth, plant density, pest control and fertilizer application. In both management scenarios, we calculated the mean annual net SOC, mean annual net N_2O emissions and CH_4 uptake by soil over a 16-year simulation. Net N_2O, CH_4 and CO_2 fluxes were expressed in kg of carbon dioxide equivalents (kg CO_2 eq. ha^{-1}) using the assumed global warming potential (GWP) concept, with a 100-year time horizon (298 for N_2O and 23 CH_4, and 1 for CO_2) [10]. Changes in CO_2 eq. emissions resulting from alternative management were compared to the change in net carbon sequestration resulting from this management. Additionally, after 16 years of experiments, the accumulation of C and N in soil was calculated.

Table 1. The amount of N fertilizer and FYM applied under A0, A1, B1 and B2 crop rotations.

Crop rotation A0	Fertilizer N application rate (kg ha^{-1} y^{-1})	Manure N (kg N ha^{-1} yr^{-1})	Crop rotation A1	Fertilizer N application rate (kg ha^{-1} y^{-1})	Manure application (kg N ha^{-1} yr^{-1})
P-W-B-M	90-120-80-135	0	P-W-B-M	90-120-80-135	325-0-0-0
P-W-B-M	90-80-80-135	0	P-W-B-M	90-80-80-135	325-0-0-0
P-W-B-M	90-80-80-135	0	P-W-B-M	90-80-80-135	325-0-0-0
P-W-B-M	90-80-80-150	0	P-W-B-M	90-80-80-150	325-0-0-0
Crop rotation B1	Fertilizer N application rate (kg ha^{-1} y^{-1})	Manure N (kg N ha^{-1} yr^{-1})	Crop rotation B2	Fertilizer N application rate (kg ha^{-1} y^{-1})	Manure application (kg N ha^{-1} yr^{-1})
P-W-B-C	90-240-90-360	79-0-103-0	P-W-B-C	90-240-90-360	436-0-123-0
P-W-B-C	90-80-60-135	0-0-70-0	P-W-B-C	90-80-60-135	325-0-103-0
P-W-B-C	90-160-80-360	0-0-80-0	P-W-B-C	90-160-80-360	325-0-99-0
P-W-B-C	90-80-80-150	0-0-113-0	P-W-B-C	90-80-80-150	325-0-212-0

P potato; W winter wheat; B spring barley; M forage maize; C grass mixture.

Table 2. The amount of P_2O_5 and K_2O applied under A0, A1, B1 and B2 crop rotations.

Crop rotation A0, A1	P_2O_5 (kg ha^{-1} y^{-1})	K_2O (kg ha^{-1} y^{-1})
P-W-B-M	54-54-54-54	160-100-85-120
Crop rotation B1, B2		
P-W-B-C	54-54-54-54	160-100-85-115

P potato; W winter wheat; B spring barley; M forage maize; C grass mixture.

DNDC Model: In this study, the Denitrification - Decomposition (DNDC) model (version 9.2; http://www.dndc.sr.unhu.edu) was used to estimate changes of SOC. The DNDC consists of six sub-models for simulating the soil climate, plant growth, decomposition, nitrification, denitrification and fermentation. To simulate SOC changes in agricultural land, DNDC requires a number of input parameters including daily meteorological data (air temperature and precipitation), soil properties (bulk density and initial SOC context), and management practices (crop rotation, fertilization and manure application). DNDC has been tested against numerous field data sets of long-term change SOC and N_2O emissions at a regional and national scale [5, 17, 18, 23, 24]. In our study, the DNDC calibration was done only for the yield, as the SOC data were not available. Crop yields were measured during a field trial and used to calibrate the DNDC model simulations. During the calibration process, all the parameters related to physiological and phenology parameters were modified.

Statistical analyses: The evaluation of the model was done by the calculation of the root mean square error (RMSE) and relative root square error (rRMSE). The data was analysed by using the Statgraphics Centurion and Microsoft Office Excel 2010 software. All data were checked for normal distribution. One-way ANOVA and difference test (Tukey HSD) were used to check difference between the data.

Results and Discussion

Model validation: A 16-year simulation was carried out using the DNDC model for two crop rotations with two treatments of fertilizer at a controlled rate:

one with N fertilizer applied annually, and the second with the same amount of N fertilizer applied annually plus manure applied once during crop rotation. The simulations match the field fertilizing practices. The output is presented as an average over all the period. Table 3 presents a comparison between measured and simulated yields. There were no significant differences between the yields of potato, spring barley and maize under A0 and A1 cropping systems. However, the grain yields of winter wheat were statistically different. The difference in yields under B1 and B2 crop rotations was not statistically significant. The model results are presented as the root mean squared error (RMSE) and the relative root mean squared error (rRMSE). Under A0 crop rotation, the RMSE was recorded at 12.4 dt dm ha^{-1}, and rRMSE 20%, while under A1, the values were 8.6 dt dm ha^{-1} and 13.8%, respectively. The values of coefficients under B1 were for RMSE 12.1 dt dm ha^{-1} and for rRMSE 19.4%, respectively. Under B2 crop rotation the coefficients were slightly higher for the RMSE at 16.6 dt dm ha^{-1} and rRMSE 24.3%, respectively. A rRMSE between 10 and 20% means that the model was calibrated correctly. The values of rRMSE in A0, A1, and B1 were lower than 20%, but in the case of B2, the value was slightly higher. The relation between the measured and modelled yields of A0 and A1 crop rotations is presented in Fig.1a-b. In both crop rotations, the coefficients of variation were very high.

The correct calibration of the model permitted for the creation of a simulation for over 16 years. The results are presented as an average. Table 4 shows the model predictions of emissions change of N_2O, CH_4 and CO_2 in both cropping system. The average N_2O emission under A0 crop rotation was 0.78 kg ha^{-1}, whereas under A1, it was significantly higher ($P \leq 0.000$; $\alpha = 0.05$) 1.89 kg ha^{-1}. The difference between average N_2O emissions between B1 and B2 rotation was 3.6 kg ha^{-1}. However, the difference was not statistically significant. The mean annual emission rates from arable soil in Europe are generally below N 3 kg ha^{-1} [14], but higher rates than 10 kg ha^{-1} are exceptions [6]. Data from our study fell within these ranges. The application of manure directly added organic matter into the SOC pool and increased the N_2O emission rate through elevating nitrate and soluble concentrations in soils [13]. Skiba and Smith [22] assumed that applying higher amounts of N improves the conditions for denitrification. A two-fold increase of N_2O fluxes was recorded after an application of manure in the cultivation of barley in Bavaria [14]. Grant *et al.* [9] reported that increasing N-fertilizer application rates by 50% increased average emissions from 22 to 47% across Canada. With an increase of soil moisture, N_2O emissions are increasing. However, a reduction by 50% of the N-fertilizer rate causes a decrease in emissions from 5 to 27% [9]. In China, an increase in the fertilizer application rate from 90 to 270 kg N ha^{-1} y^{-1} for winter wheat-maize rotation increased the emission rate from 0.7 to 1.8 kg N ha^{-1} yr^{1} [15].

Under A0 crop rotation, methane uptake was 0.63 kg C ha^{-1} y^{-1}. Treatment with manure increased the methane uptake to 0.80 kg C ha^{-1} y^{-1}. The increase was statistically significant ($P \leq 0.000$; $\alpha = 0.05$). A higher input of N under B2 rotation raised the methane uptake compared to B1. The increase of emission by 20% was statistically significant.

The average accumulation of SOC (kg C ha^{-1} y^{-1}) varied between crop rotation and the amount of kg organic N applied. The average highest rate of accumulation was under B2 693 kg C ha^{-1} y^{-1} and increased by 449 kg C ha^{-1} y^{-1} compared to the B1 cropping system. However, the difference was not statically significant ($P \leq 0.644$; $\alpha = 0.05$). The increase of SOC under A1 crop rotation was 359 kg C ha^{-1} y^{-1}, compared to the A0 cropping system. The difference between the annual accumulations of SOC was high, but not statistically significant ($P \leq 0.648$; $\alpha = 0.05$). The positive effect of

Table 4. Estimated (means and standard deviation) annual N_2O, CH_4 emissions and C–sequestration for different cropping systems.

Cropping system	A0*	A1*	B1*	B2*
N_2O flux (kg N $ha^{-1}y^{-1}$)	0.78±0.53a	1.89±0.94b	8.16±10.84a	11.76±13.60a
CH_4 flux (kg C ha^{-1} y^{-1})	-0.63±0.05a	-0.80±0.08b	-0.64±0.05a	-0.78±0.08b
SOC (kg C ha^{-1} y^{-1})	88±593a	447±3029a	190±315a	639±3702a

* Values with different letter in a same row indicate significant differences between the cropping systems at p<0.05 (Tukey HSD, test).

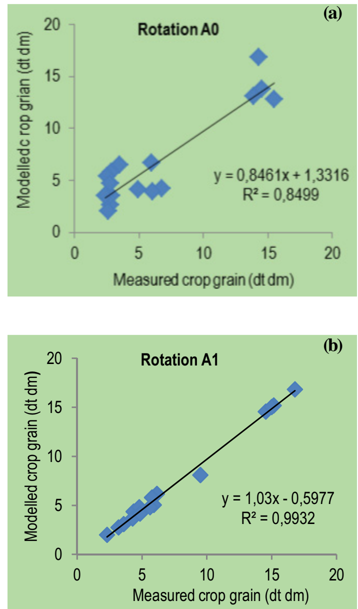

Figure 1. Correlation between the model simulated and field measured yields for A0 (a) and A1 (b) crop rotations.

Table 3. Measured (means and standard deviation) and modelled yields under different treatment for both crop rotations.

Yields (dt dm[a] ha^{-1})	A0*		A1*		B1*		B2*	
	measured	modelled	measured	modelled	measured	modelled	measured	modelled
Potato	27.4±3.3bc	21.8±6.1c	24.3±3.8abc	27.9±3.7bc	25.8±4.8ab	31.5±9.0abc	26.6±7.8abc	31.5±9.0abc
Winter wheat	24.5±5.8c	13.1±2.3a	29.2±10.2c	23.5±5.6abc	25.11±6.8ab	18.7±2.5ab	22.0±4.2ab	25.2±7.2abc
Spring barley	14.9±5.2ab	12.7±5.4a	16.1±4.8ab	14.0±1.8a	16.3±4.9a	15.4±3.6a	14.3±4.3a	15.4±3.3ab
Forage maize	65.0±8.4d	67.0±3.0d	70.8±4.5d	69.1±2.5d	-	-	-	-
Grass mixture	-	-	-	-	43.9±26.6bc	52.84±12c	38.3±23.6cd	47.2±3.2d
RMSE (dt ha^{-1})	-	12.4	-	8.6	-	12.1	-	16.6
RRMSE (%)	-	20.0	-	13.8	-	19.4	-	24.3

* Values with different letter in a same crop indicate significant differences between the crops at p<0.05 (Tukey HSD, test).

a higher rate of the applied manure increased the rate of SOC, but the negative effect increased the N_2O fluxes.

The DNDC simulations generate C sequestration in the litter, humates and humus. After 16 years of simulations, SOM under A0 crop rotation was increased by 1,443 kg C ha^{-1}. The largest share in the increase of C was humus (1,062 kg C ha^{-1}), the lowest humates (116 kg C ha$^{-1)}$. The SOM pool of litter showed an increase of 264 kg C ha^{-1} (Fig. 2a). In the A1 rotation, where manure was applied, the increase was 7,203 kg C ha^{-1}. Humates caused an increase of 5,330 kg C ha^{-1}, humus 1,679 kg C ha^{-1} and litter only 194 kg C ha^{-1}. In the B2 cropping system with mixed grasses, the highest rates of C sequestration was 12,051 kg C ha^{-1}. Cumulative SOM pools consist of humates 7,297 kg C ha^{-1} , litter 2,996 kg C ha^{-1}and humus 1,719 kg C ha^{-1} (Fig. 2b).

A DNDC model also allows for predicting the accumulation of N kg ha^{-1} in the SOM pool. In our simulation after 16 years, the A0 rotation total accumulation of N was 115 kg ha^{-1} (Fig. 3a). The quantity of N accumulation broken down by fraction to humus and humates was 106 and 11 kg N ha^{-1}, respectively. The value for the litter was 3 kg N ha^{-1}. The negative value indicates that litter collected all the supplied N. The manure application in the A1 rotation resulted in an increase of N to 700 kg N ha^{-1}. In humates the fraction increase was raised to 533 kg N ha^{-1}, but in humus it only increased to 167 kg N ha^{-1}. The value of N in litter was 0, which shows that there was an offset balance between the accumulation and collection of N. Fig. 3b presents the accumulations of N in B1 and B2 crop rotations. Heavy rates of manure in B2 rotations resulted in an accumulation of 977 kg N ha^{-1}. The rates of N accumulation were: humates 719, humus 719

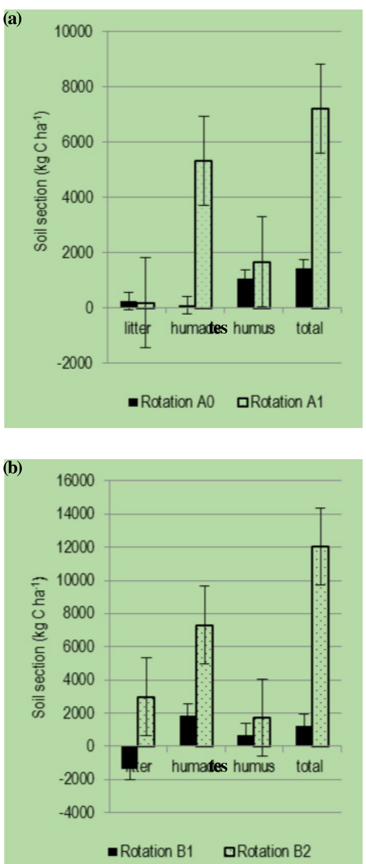

Figure 2. Accumulation of C (and standard errors) in kg ha^{-1} in SOM pool after 16 years simulations for A0 - A1 (a), and B1 –B2 (b) crop rotations.

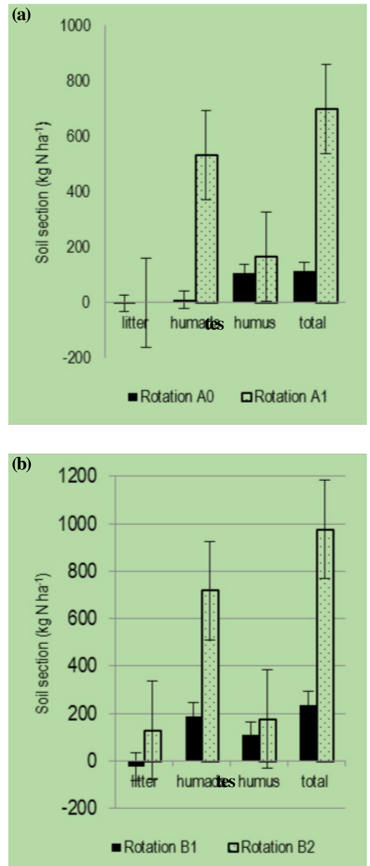

Figure 3. Accumulation of N (and standard errors) in kg ha^{-1} in SOM pool after 16 years simulations for A0 - A1 (a), and B1 –B2 (b) crop rotations.

and litter 128 kg N ha^{-1}. Our simulations show that a treatment of manure increases the accumulation of N and C in SOM pools. The highest rates were displayed in humate fraction.

Table 5 presents the average annual fluxes of three major greenhouse gases (e.g. CO_2, N_2O and CH_4). The net GWP is presented as a result of those simulations. All crop rotations are a net sink of CO_2. The manure amendment increases SOC which provides more substrates to increase the N_2O emissions through nitrification and denitrification in the soil. Different management practices have enhanced the N_2O emissions, as CO_2 equivalents, while the change in CO_2 equivalents of CH_4 absorption was insignificant (Table 5). The average annual increases in N_2O emissions, which were converted into carbon dioxide (CO_2) equivalent emissions with 100-year global warming potential (GWP) multipliers, offset by 56-144% of carbon sequestration, depended on the management option. In our study, we observed an increase of net GWP per ha with higher rates of manure in B2 rotation compared to B1. The difference was not statistically significant ($p \leq 0.61$; $\alpha = 0.05$). The high level of the applied N increased the net GWP by 11.6 kg CO_2 eq. kg ha $^{-1}$ but lowered average emission by 0.20 kg CO_2 eq. of kg biomass. This was due to an increase in the average annual crop biomass by 9% and grain by 10%. An application of 325 kg N in manure in A1, every four years under potato, resulted in the absorption of GHG. The high value of carbon sequestration in soil outweighs the emissions of N_2O.

Table 5. Estimated (means and standard deviation) annual net GWP for a 4 year complete crop rotation cycle for different management practices.

GWP	A0*	A1*	B1*	B2*
CO_2 (kg CO_2 eq. ha^{-1})	-322±2175a	-1640±11107a	-697±81a	-2346±13576a
N_2O (kg CO_2 eq. ha^{-1})	377±260a	922±457b	3975±5280a	5726±6622a
CH_4 (kg CO_2 eq. ha^{-1})	-17±1.44a	-22±2.26b	-18±1.37a	-21±2.26b
Net GWP(kg CO_2 eq. ha^{-1})	38±2078a	-740±10785a	3260±8447a	3359±16341a
Net GWP (kg CO_2 eq. kg $biomas^{-1}$)	0.09±0.5a	-0.03±2.7a	0.79±4.2a	0.59±4.1a
Net GWP (kg CO_2 eq. kg $grain^{-1}$)	0.19±1.3a	0.46±5.0a	-1.9±34.6a	9.7±39.8a

*Values with different letter in a same row indicate significant differences between the cropping systems at $p<0.05$ (Tukey HSD, test). Positive values indicate a net emission of GHGs, while the negative values indicate a net uptake.

Conclusions

The DNDC model is very useful for simulating the impact of different management options in processes occurring in the soil. The data required as an input to the model are easy to obtain. In this study, we tested the DNDC model against our observations. The calibrations of the DNDC model for both crop rotations have indicated that the RRMS error was between 10 and 20%, which indicated that model was calibrated correctly. The results of our study indicated positive effects for a higher rate of the applied FYM as an increase to the amount of SOC, but there was a negative effect of an increase of N_2O emissions. Higher N_2O fluxes have increased the GWP, therefore, there is a strong recommendation to control N application in manure. The European Union has issued the Nitrate Directive [3], which aims to protect water quality across Europe by preventing nitrates from agricultural sources. One of the steps of the directive was to establish limitations of fertilizers which could be applied by taking into account a crop needs. Setting up rates of N fertilizer application to the needs of crops and the availability of N in soil supply should be considered. The maximum amount of the applied animal manure cannot exceed 170 kg N per hectare. In Poland, farmers are obliged to prepare a fertilisation plan. Such a procedure helps to reduce GHG emissions.

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