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Assessing the impact of management practices on gas emissions and N losses calculated with denitrification-decomposition model

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ABSTRACT

The study presents the impact of management practices on greenhouse gas emissions (GHG) and nitrogen (N) losses calculated with a denitrification-decomposition model. Two cropping systems were analysed. The first rotation (A) consisted of potato, winter wheat, spring barley and corn. The second (B) included potato, winter wheat, spring barley and clover with grasses mixture. In A1 and B1 scenarios, fluxes were estimated on the basis of mineral fertilizers input, whereas in A2 and B2 scenarios the assessment of emissions was made with regards to manure. The results indicated that the application of manure in A rotation led to the increase of nitrous oxide (N_2O) emission, N leaching, N surplus, crop yields, and the decrease of nitrogen use efficiency higher than in B rotation. Additional doses of manure in A2 scenario increased the potential of the accumulation of soil organic carbon (SOC) and global warming potential (GWP) by 157%. In B2 scenario, SOC augmented more than three-fold but GWP increased only by 10%. The N losses and GHG emissions could be minimised by controlling N application through the implementation of nutrient management plan in which N doses are defined based on the crop needs and soil quality.

Keywords: crop rotation; modelling; agricultural practice; carbon dioxide; macronutrient

The field observations show clear trends that the management practices, especially fertilizer application rates, have significant effects on carbon dioxide (CO_2) and nitrous oxide (N_2O) fluxes from the soil (Li et al. 2010). Nitrogen (N) applied in fertilizer and manure is not always used efficiently by crops (Smith et al. 2008). A great portion of N is lost in the soil through denitrification, nitrate leaching, ammonia volatilisation or the run-off to surface water (Tilman et al. 2002). Strict limitation of the N dose is deemed as one of the best management strategies to minimise N losses (D'Haene et al. 2014). Many researchers focus on the prediction of the impact of alternative management practices on the environment (Ouyang et al. 2013). Reduction of greenhouse gas (GHG) emissions through the cultivation management practices is one of the most cost-effective methods (Babu et al. 2006). Most studies present the influence of only singular crops (Beheydt et al. 2008) or two-crop rotations on the environment (Ludwig et al. 2011). Impact assessment of crops cultivation on environment should be analysed in long-term experiments and in multi-annual rotations. In our study we have chosen two 4-year cropping systems which are typical for Poland. Suitable crop patterns are expected to decrease negative effects of crop cultivation. The results from the long-term experiments are a valuable source of information about the influence of different management options on GHG emissions (Syp et al. 2012). However, it is almost impossible to collect data covering all possible conditions. Models provide an alternative method of assessment for agricultural practices with low time requirements and cost (Smith et al. 2010). At present, the denitrification-decomposition

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(DNDC) model is one of the most precise carbon-nitrogen simulation models, and a useful tool for modelling the assessment of management practices impact on the environment (Ouyang et al. 2013). The model was originally developed for the estimation of carbon sequestration and trade gas emissions from soils in USA. Since its development, the model has been expanded and applied by many researchers to a wide range of production systems at a regional and national scale, i.e. Belgium (Beheydt et al. 2008), Poland (Syp et al. 2011), Canada (Smith et al. 2010) and China (Ouyang et al. 2013). However some of them suggested that pedotransfer functions and denitrification sub-model may need further improvement (Ludwig et al. 2011). This model was selected due to the fact that it was applied by the European Commission to estimate N_2O emissions in accordance with the Renewable Energy directive (Directive 2009/28/EC). The objective of the present study was: to assess environmental indicators such as N surplus, N leaching, nitrogen use efficiency (NUE), N_2O and CH_4 emissions, soil organic carbon sequestration (SOC) and global warming potential (GWP) from arable soils in Poland which receive N from mineral fertilizers and manure. All simulations were performed under different cropping systems using the DNDC model.

MATERIAL AND METHODS

The data used in the calculation were from a field experiment conducted from 1980–2008 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, Puławy (IUNG-PIB). The soil was classified as heterogeneous sandy loam and loam (Cambisols), with pH of 6.8 for the first crop rotation and 5.7 for the second. The others parameters were: soil bulk density of 1.4 g/cm^3, clay fraction of 0.09%, initial value of SOC 0.01 kg C/kg soil at the depth 5 cm, and average precipitation of 614 mm. All these parameters were used as input data for the DNDC model (version 9.2; http://www.dndc.sr.unh.edu). The experiment was conducted as a two factor system. The first factor were A and B crop rotations, the second factor was autumn application of wet manure. The A cropping system consisted of plants depleting the soil from organic carbon: potato, winter wheat, spring barley and corn silage (called P-W-B-C). B rotation included crops enriching soil with humus: potato, winter wheat and mustard as an after-crop for ploughing, spring barley and mixture of clover with grasses (called P-W-G-B). Two scenarios were simulated for each crop rotation; A1, A2 and B1, B2 for A and B crop rotations, respectively. A2 and B2 scenarios differed from A1 and B1 only by additional application of fresh manure for potato at 80 t/ha which corresponded to the rate of 325 kg N/ha, 184 kg phosphorus (P)/ha, and 472 kg potassium (K)/ha. Table 1 presents the amounts of applied N, P, K fertilizers and manure. In our research, the ammonium nitrate fertilizer was applied. The experiment was established using a randomised split-plot layout in two cycles offset in one year. The 4-year cropping system was repeated in seven cycles. In all management scenarios, we simulated

Table 1. The amount of N, P, K fertilizers (kg/ha/year) and manure (kg N, P, K/ha/year) applied in A1, A2, B1 and B2 scenarios. The root mean square error (RMSE) and model efficiency (ME) for A1, A2, B1 and B2 scenarios

Item		P-W-B-C		P-W-B-G	
		A1	A2	B1	B2
Manure	N	–	325-0-0-0	–	325-0-0-0
	P	–	184-0-0-0	–	184-0-0-0
	K	–	472-0-0-0	–	472-0-0-0
Fertilizer	N	90-80-80-135	90-80-80-135	90-160-80-180	90-160-80-180
	P	24-24-24-24	24-24-24-24	24-24-24-24	24-24-24-24
	K	133-71-100-83	133-71-100-83	133-71-96-83	133-71-96-83
RMSE (dt/ha)		1.09	1.44	1.32	1.69
ME		0.85	0.93	0.83	0.57

P – potato; W – winter wheat; B – spring barley; C – corn silage; G – clover-grass mixture

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the annual net N_2O emissions, N-leaching, N surplus, CH_4 emissions, SOC changes, and net GWP. Net N_2O, CH_4 and CO_2 fluxes were converted to kilograms of carbon dioxide equivalents (kg CO_2 eq. per ha) using the 100-year horizon of GWP (298, 25 and 1 for N_2O, CH_4 and CO_2, respectively). The N surplus was calculated as the difference between N input sources and the N losses through plant uptake (Follador et al. 2011). The N gains include the sum of input synthetic fertilizer, manure, N from biological fixation, and crop residues. NUE was calculated as a ratio of the grain yield expressed in kg of C with N applied. The model accuracy and performance were evaluated by the calculation of the root mean square error (RMSE) and model efficiency (ME). The analyses were carried out using Microsoft Office Excel 2010 software packages (Redmond, USA).

RESULTS AND DISCUSSION

In our study, the DNDC calibration was performed on the observed yields, as the other data were not available. During the calibration process, all the parameters related to physiological and phenology parameters were adjusted. The simulations matched the field fertilizing practices. A comparison of the RMSE and ME values of both scenarios indicated that DNDC described A crop rotation better than B (Table 1). Differences in clover-grass mixture crops resulted in higher values of RMSE in B rotation. Ludwig et al. (2011) reported a similar DNDC ME for calibration of the observed yields using literature data of crop properties for rotation which included field bean and winter wheat. The two rotations, A and B, responded differently to the addition of manure. The environmental difference between scenario 1 and 2 was observed not only in the year of manure application but also in whole rotation. In A2 and B2 scenarios, the DNDC output showed that the application of manure resulted in an increase of N_2O emissions, N leaching, N surplus and yields in every rotation and in cumulative values (Table 2). All these increases were higher in A rotation compared to B. The NUE in all rotations of A2 and B2 scenarios were lower than in those of A1 and B1. The values of NUE of A rotation were higher than in B rotation. This shows that crops in A2 and B2 scenarios were over-supplied with N, and the N surpluses in B rotation were higher than in A. The doses of applied manure in both scenarios were too high with respect to the plant nutritional requirements. In A rotation, over 28 years, the additional dose of N in manure increased potential of SOC accumulation from 9424–24 124 kg C/ha, whereas in B rotation it was from 4209–16 156 kg C/ha. An increase of CH_4 emissions due to manure was of similar level in the two rotations (Table 2). In our simulations, the rotation including potato, winter wheat, spring barley and corn silage (A) accumulated more C compared to the rotation without corn (B). The additional application of N in manure increased the changes in SOC, which provided more substrates for increasing the N_2O emissions through the process of nitrification and denitrification in the soil. The application of manure every four years resulted in the changes of net GWP. A rotation positively influenced the environment because net GWP had negative values. In A2 scenario, the additional application of manure-N resulted in an increase in net GWP from 21 337–54 904 kg eq. CO_2 (+157%). The rotation B negatively affected the environment because GHG emissions occurred. In B2 scenario, high dose of manure increased net GWP only by 10%. In our study, emissions of N_2O from manure-treated soils exceeded the emissions from the soil subject only with mineral fertilization. This confirms that the fertilizer sources affect N_2O flux. Kaiser and Ruser (2000) reported that organically fertilized soil is characterised by higher N_2O emissions compared to mineral fertilizer-treated plots. It is due to higher microbiological activities and the accessibility of C suitable for mineralization. As manure application adds C and N to the soil system, it develops the carbon turnover process with a higher rate of oxygen consumption and thus an increased probability of the existence of anaerobic micro-sites, which favours the production of N_2O (Leip et al. 2011). According to Li et al. (2001), SOC is the most sensitive factor for N_2O emissions. In our simulation, the increase in N_2O flux in A2 scenario was almost five-fold compared to B2 scenario. It confirms that the crop selection affects N_2O emissions (Freibauer and Kaltschmit 2003). According to some researchers the timing of application of manure may influence N losses (Follador et al. 2011). The autumn dose of manure augmented N leaching, N surplus, and CH_4 uptake from the soils where manure was applied compared

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Table 2. The comparison between scenarios – average per rotation, average per year and cumulative values – over 7 rotation cycles of nitrogen (N) leaching, N surplus, N_2O emissions, yields, nitrogen use efficiency (NUE), CH_4 emissions, changes in soil organic carbon (SOC) and net global warming potential (GWP)

Scenario	Rotation	N leaching (kg N/ha)	N surplus (kg/N)	Yields (kg C)	NUE	N_2O emission (kg N/ha)	CH_4 emission	Change in SOC	Net GWP (kg CO_2 eq.)
							(kg C/ha)		
A1	I	13	7	2754	50	1.33	–0.51	904	–2684
	II	6	20	2517	42	1.49	–0.53	734	–1977
	III	7	15	2313	47	1.09	–0.60	367	–832
	IV	7	19	2284	46	1.01	–0.59	340	–770
	V	8	13	2334	51	0.55	–0.62	–148	794
	VI	13	20	2014	45	0.87	–0.64	71	147
	VII	10	19	2213	48	0.69	–0.67	89	–12
Average		9	16	2347	47	1.00	–0.59	337	–762
Cumulative I–VII		254	454	65 714	–	28.09	–16.64	9424	–21 337
A2	I	16	59	2907	34	2.03	–0.55	1762	–5491
	II	12	90	2731	27	4.73	–0.61	1562	–3440
	III	14	82	2659	30	3.18	–0.71	917	–1834
	IV	13	73	2710	30	1.93	–0.73	914	–2433
	V	14	65	2808	32	1.50	–0.77	–99	1073
	VI	20	75	2449	29	2.33	–0.82	566	–966
	VII	20	84	2467	29	1.82	–0.87	409	–636
Average		16	75	2676	30	2.5	–0.72	862	–1961
Cumulative I–VII		436	2110	74 923	–	70.03	–20.20	24 124	–54 904
B1	I	18	49	1926	35	6.52	–0.51	383	1757
	II	23	81	1958	29	6.41	–0.53	815	116
	III	59	85	1623	27	12.60	–0.64	–907	9448
	IV	50	157	1896	19	6.57	–0.60	671	723
	V	27	37	2013	39	10.07	–0.63	–180	5546
	VI	35	123	1558	21	6.35	–0.65	192	2370
	VII	67	63	1652	31	9.66	–0.68	79	4400
Average		40	85	1804	29	8.31	–0.60	150	3480
Cumulative I–VII		1115	2375	50 501	–	232.67	–16.93	4209	97 439
B2	I	18	94	2039	26	7.31	–0.56	1210	–891
	II	29	152	1960	20	9.20	–0.60	1448	–844
	III	79	166	1620	18	16.64	–0.75	–568	10 165
	IV	75	234	2097	15	10.08	–0.71	1345	–45
	V	40	95	2383	26	12.72	–0.76	249	5260
	VI	48	200	1658	15	9.78	–0.81	572	2644
	VII	95	169	1653	17	14.45	–0.86	393	5575
Average		55	159	1916	20	11.45	–0.72	664	3123
Cumulative I–VII		1343	4154	51 698	–	310.65	–18.45	16 156	91 577

Positive values indicate a net emission of greenhouse gases (GHGs), while the negative values indicate a net uptake

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to the soils where mineral fertilizers were used. The simulated increase of net GWP was for a large part due to the increase of SOC stock. The results from this research indicate an important interaction that exists between C sequestration in agricultural soils and GHG emissions. As the capacity of soil to store C is limited, all sequestered C will be released again to the atmosphere unless proper soil management is maintained. Our study shows, that the N losses and GHG emissions could be minimalised on farms by controlling N application through the implementation of nutrient management plan in which N doses are defined based on the crop needs and soil quality. The combination of manure application with winter cover cropping systems could be a very efficient option to reduce GHG emissions.

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