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Carbon and nitrogen balances in soil under SRC willow using the DNDC model

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Abstract

Unsustainable production of agricultural biomass for electricity and heat can increase greenhouse gas emission and nitrates leaching. The DNDC (DeNitrification and DeComposition) model was used to estimate carbon sequestration and field losses of nitrogen, especially N_2O emission in willow production. The model is capable of predicting willow yields with a relatively low error (RRMSE = 11.5%). DNDC estimated a significant carbon sequestration under willow (1.41-4.11 Mg eq. CO_2 ha^{-1} yr^{-1}). The N_2O field emissions generated by the DNDC model were compared with IPCC Tier 1 emission estimates. The average annual N_2O emission generated by the model was 3.7 kg N ha^{-1} (1.35% of nitrogen available for plant); whereas N_2O emission using IPCC methodology was insignificantly lower (3.5 kg N ha^{-1}). Nitrate leaching was at a range of 8.96-21.24 kg N ha^{-1} yr^{-1}. We did not find a statistically significant relationship between the annual soil carbon growth and nitrogen losses from soil. An analysis into the sensitivity of the model indicated a considerable influence of precipitation on NO_3^- leaching (99% of variability) as well as a strong relationship between temperature and precipitation inputs and N_2O emission. The DNDC model is a useful tool in the assessment of carbon and nitrogen balance in soil under SRC willow.

Key words: Willow, DNDC**,** soil carbon, greenhouse gas, nitrous oxide, nitrates leaching.

Introduction

The change in energy production from fossil fuels to agricultural biomass feedstock creates both real opportunities as well as risks. When producing biomass without first considering its impact on the environment, such as a decrease in the soil's health, quality, as well the availability of water, a full investigation must be made in order to avoid minimal or negative greenhouse gas reduction benefits. The production of agricultural crops is subject to mandatory environmental standards and "cross-compliance" in the Common Agriculture Policy [5] and common environmental rules (inter alia the Water Framework Directive [40] and Nitrate Directive [28]). The criteria for sustainable agricultural biomass production for heating and electricity in Europe are suggested in a report from the European Commission [30]. Among the concerns of biomass production are sustainability and in particular, greenhouse gas (GHG) performance. In reference to Directive 2009/28/EC [9], the Commission underlines the protection of carbon stock and emphasises, that quantities of carbon in soil's organic matter can change depending on the crops or trees planted as well as the management regime, such as fertilisation. Consequently, in the paper we focus on greenhouse gas emission simulated on the field scale under willow cultivated in Poland - especially on nitrogen losses as N_2O, which is a very significant greenhouse gas with global warming potentials 296 times larger than CO_2 [17].

The Intergovernmental Panel on Climate Change has developed a procedure for the estimation of greenhouse gas emissions from agriculture [15-17]. Although this method is recommended for national inventories of GHG fluxes, the Tier 1 approach proposed by the IPCC is associated with a high uncertainty range and is not able to differentiate regional conditions and crop management practices. On the other hand, process-based models such as DNDC (DeNitrification-DeComposition) allow improving crop-specific estimates of GHG emissions at a regional level [12, 21, 22].

The species we investigate in this study is short rotation coppice (SRC) willow (*Salix viminalis*). Willow is considered in Poland as one of the best quality biomass crops for power stations. The crop has a perennial nature with an extensive root system, relatively high yields, and has environmental benefits for cultivation due to high uptake of nutrients and sequestration of soil carbon, which makes willow ideal for biomass crops [31, 36, 38]. Furthermore, compared to annual crops, willow is regarded as plants with low requirements for nutrients. In the literature, the requirements range from 180-450 kg N ha^{-1} per three-year rotation. In addition, there is also an internal recycling of nutrients in the leaf litter, roots and shoots [8]. In Poland, we still do not have sufficient long-term data on fertilizer and yield of SRC willow coppice. According to our knowledge, there have not been any data available about the total greenhouse gas balance under SRC willow in the literature also. Hence, there is a demand for modelling exercises, which can be the source of the missing data.

The main objectives are here as follows: (1) to predict soil organic carbon (SOC) dynamics for SRC willow crops, (2) to compare the N_2O field emission model outputs with Tier I country-specific emission factor estimates, (3) to verify the hypothesis that SOC accumulation may increase the risk of nitrogen leaching [37].

Material and Methods

DNDC model: The DNDC model was the first used to model N_2O emissions from agricultural soils in the US [24, 25]. Subsequently, it was used and validated extensively by many research groups covering a range of countries and production systems for grassland, cropland and forest [12] where there was good compliance between the measured and modelled results.

DNDC integrates processes describing soil hydrology, plant growth and biogeochemical reactions regulating transport and transformation of C, N and water in the plant-soil-systems. The DNDC model contains five main sub-models [23]: The soil climate sub-model calculates the daily soil temperature and moisture fluxes in one dimension; the crop growth sub-model simulates crop biomass accumulation and partitioning, water and nitrogen uptake by vegetation and root respiration; the decomposition sub-model calculates decomposition, nitrification, NH_3 volatilisation and CO_2 production. Whilst the denitrification sub-model tracks the sequential biochemical reduction from nitrate NO_3^- to NO_2^-, NO, N_2O and N_2 based on soil redox potential and dissolved organic carbon. The model requires input variables where the temperature, rainfall sum and N fertilization level are relatively easy to obtain and the simulation time is short.

In this study, the DNDC model version 9.2 (http://www.dndc.sr.unh.edu) was tested for short rotation coppice crops - willow (Salix viminalis). Atmospheric CO_2, rainfall N and depth of the soil water retention layer were used as a default (Table 1).

DNDC calibration: The model calibration for willow was carried out by using empirical crop-specific data - yields and nitrogen uptakes. Crop yields and the share of nitrogen in the above-ground biomass were measured in two sites - Osiny Experimental Station (51°42'N, 22°04'E) and Grabow Experimental Station (51°21'N, 21°40'E) during 2004-2008. The willow plantations were established in the spring of 2003. The yield per hectare was assessed by weighing the shoots from 5 m^2 net plots in five replications using a field balance. The nitrogen uptake was based on the determination of nitrogen content in leaves and shoots measured using flow spectrophotometry technique. The other physiological and phenology parameters for the model (water requirement, LAI, height and growing degree-days) were assumed on the basis of available literature. The site-specific input-data for DNDC includes climatic data from 2004-2008 (daily maximum and minimum air temperature and daily precipitation), soil properties (texture, bulk density, pH and soil organic carbon (SOC)), crop properties and management activities (applications of fertilizers, tillage and weeding). The input data used for the model calibration are summarised in Table 1. Statistical analysis of the simulation results consisted of calculating the root mean square error RMSE (Equation 1) and the relative root mean square error of prediction RRMSE (Equation 2):

Equation 1

$$RMSE = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(P_j - O_j)^2}$$

Equation 2

$$RRMSE = \frac{RMSE \times 100}{\bar{O}}$$

where O_j and P_j are the observed and predicted values, $\bar{O}$ is the average of observed values and n is number of cases.

Table 1. The inputs summary for the DNDC model.

	Osiny ES	Grabow ES	Units
Climatic data			
Altitude	153	166	m
Longitude	22°04'E	21°40'E	
Latitude	51°28'N	51°21'N	
Average daily max. temp. [A]	13.1	13.4	°C
Average daily min. temp. [A]	2.9	4.6	°C
Yearly accumulate precipitation [A]	515	636	mm
N concentration in rainfall [B]	2.8	2.8	Mg N $litre^{-1}$
Atmospheric CO_2 concentrations [B]	350	350	ppm
Soil properties (0-10 cm depth)			
Bulk density [B]	1.4	1.4	g cm^{-3}
DNDC soil classification [A]	Sandy clay loam	Sandy loam	
Clay fraction [B]	0.27	0.09	
pH [A]	5.5	5.5	
Initial organic C content at soil surface [B]	0.026	0.013	kg C kg
Initial NO_3- concentration at soil surface [B]	10	6	Mg N kg
Initial NH_4+ concentration at soil surface [B]	7	7	Mg N kg
Porosity [B]	0.421	0.435	
WFPS at field capacity [B]	0.52	0.32	
WFPS at wilting point [B]	0.24	0.15	
Depth of water table [B]	9.99	9.99	m
Crop management			
Growth beginning [A]	01.05		
Harvest date [A]	30.12		
Tilling method [A]	Ploughing Slightly, 5 cm		
Nitrogen fertilizer NH_4NO_3 application [A]	75		kg N ha^{-1}

[A] values according to own studies, [B] default DNDC values.

DNDC simulations for Poland: Poland was divided into 137 grid cells (each approximately 50 km x 50 km), for which the climate data from the MARS Database elaborated by Joint Research Centre of European Commission were available. The daily meteorological data (minimum and maximum temperature and precipitation) were obtained for the period of 1986-2004 for 10 grid cells ($a_{1...}a_{10}$) representative for Poland (Fig. 1).

The meteorological data is presented in Table 2. The soil's properties were assumed as sandy loam soil (the properties of the soil were also used as some of input data for calibration and are shown for the Grabow Experimental Station in Table 1). All crop and field management input data are listed in Table 1. The simulation was run for the plantation over a duration of 19 years (1986-2004), where the crop was harvested every three years, starting one year after its establishment. Triennial cutting was assumed for willow, because this option is preferred by the energy industry as it allows for the lowest costs of harvest.

Statistically significant differences between results were calculated using LSD method at p

Figure 1. The grid cells ($a_{1...}a_{10}$) spacing in Poland, for these the simulation in DNDC was run.

Table 2. Range of meteorological input data (1986-2004) used in DNDC for selected grid cells in Poland.

Input parameter	Range for grids
Average minimum daily temperature (^oC)	3.0 - 5.3
Average maximum daily temperature (^oC)	11.3 – 13.5
Average yearly rainfall sum (mm)	423 – 642

= 0.05 (all output DNDC data had a normal distribution). The standard deviation was also calculated.

The N_2O field emissions generated by DNDC model were compared to IPCC Tier 1 emission estimates [17], where following standard factors were used (kg N_2O-N per kg N^{-1}): 0.01325 for N fertilizers, 0.01225 for N in crop residues and 0.01225 for N mineralized.

We also carried out model testing with various changed inputs. The Monte Carlo method was used for a sensitivity analysis in order to identify the input parameters that had the greatest effect on selected outputs of the model. Subsets of temperature and precipitation values deviated maximally by 20% from the real values that were tested. Five hundred runs were performed each year.

Results and Discussion

The results of the conducted calibration for the DNDC model used for willow plantations indicate that RMSE and RRMSE for dry matter were 1.51 Mg ha^{-1} and 11.49%, respectively (Fig. 2). That shows that the prediction error was only slightly higher than the range of the model and fitted well ≤10%. The prediction error for nitrogen uptake was considerably worse. RRMSE amounted to 32% (RMSE=55.93 kg N ha^{-1}). It can be assumed from the previously mentioned fact that the amounts of nitrogen in the ecosystems are usually very labile to change and are dependent on many external factors.

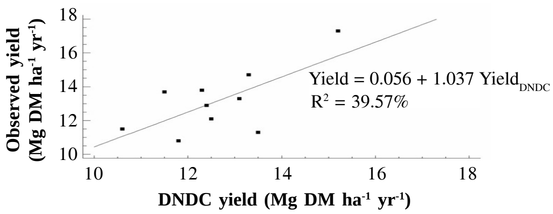

Figure 2. Calibration of observed and predicted yields by DNDC ($Yield_{DNDC}$) yields of *Salix viminalis* (Mg dry matter ha^{-1}).

The resulting negative values of carbon dioxide emission under willow indicate a soil sequestration of carbon that is derived from leaf litters and dead roots. Willow mitigated the CO_2 emission at an average of 2.86 Mg ha^{-1} yr^{-1} which is equal to 0.76 Mg ha^{-1} yr^{-1} of sequestrated C (Table 3). The yields of SRC willow varied considerably between the years from 4.36 to 5.62 Mg C ha^{-1} yr^{-1} (Table 3). Smith [34] estimated that the replacement of cropland area with biomass energy crop plantations would result in a carbon sequestration range of 0.14-0.43 Mg C ha^{-1} yr^{-1}, on average by approximately 50% greater than the estimated sequestration potential of the no-till cultivation. In another publication, sequestration under permanent crops was assessed at 0.62 Mg C ha^{-1} yr^{-1} at ±50% deviation [33]. Styles and Jones [35] calculated C sequestration at 1.15 Mg C ha^{-1} yr^{-1}, when the SRC was displaced as set-aside. Matthews and Grogan [26] estimated the net sequestration level under willow at 0.41 Mg C ha^{-1} yr^{-1}. In the studies of Hellebrand *et al.* [14] the C sequestration rate under SRC was 0.34 Mg C ha^{-1} yr^{-1}. Sequestration estimates obtained by Bradley and King [4] for the conversion of fields from arable to willow were 0.25-0.38 Mg C ha^{-1} yr^{-1}. Considering the question about C soil more precisely, the litter and dead root fractions are partitioned here into three pools: very labile fraction of litter, labile humads, and passive humus. Our studies showed that carbon inputs were incorporated mainly into the soil as

Table 3. Average annual yields, GHG emissions and their mitigation for willow in selected grid cells.

Grid cell number ($a_1 \ldots a_{10}$)	Yield* (Mg C ha^{-1} y)	CO_2 emission (Mg eq. CO_2 ha^{-1})	CH_4 emission (Mg eq. CO_2 ha^{-1})	N_2O emission (Mg eq. CO_2 ha^{-1})	Net GHG emission (Mg eq. CO_2 ha^{-1})	$U_{C\ Net\_GHG}$
58076	5.55 ab (0.19)	-2.68 bc (0.42)	-0.02 ns (1.71)	1.40 bcd (0.64)	-1.30 abcd	1.87
59068	4.42 b (0.23)	-1.41 a (0.93)	-0.02 ns (9.37)	2.17 ab (0.51)	-0.10 a	9.43
60072	4.59 b (0.21)	-2.75 bc (0.45)	-0.02 ns (9.86)	1.63 abc (0.61)	-1.15 abcd	9.89
60077	5.23 ab (0.21)	-3.11 bcd (0.40)	-0.02 ns (9.91)	2.41 a (0.55)	-0.72 abc	9.36
62068	4.36 b (0.22)	-2.37 ab (0.49)	-0.02 ns (9.62)	1.95 ab (0.56)	-0.44 ab	9.64
63065	5.17 ab (0.15)	-2.47 ab (0.51)	-0.02 ns (9.86)	0.67 d (0.57)	-1.82 bcd	9.89
64070	4.44 b (0.22)	-2.67 bc (0.46)	-0.02 ns (9.87)	2.32 a (0.53)	-0.36 a	9.89
64076	4.70 ab (0.22)	-4.11 d (0.32)	-0.02 ns (11.65)	2.20 ab (0.48)	-1.93 cd	11.66
66067	5.62 a (0.18)	-3.22 bcd (0.42)	-0.02 ns (10.48)	0.91 cd (0.52)	-2.32 d	10.50
66073	4.88 ab (0.21)	-3.77 cd (0.35)	-0.02 ns (10.92)	2.45 a (0.44)	-1.33 abcd	10.94
μ ($a_1 \ldots a_{10}$)	4.90	- 2.86	- 0.02	1.81	- 1.15	

In each column, the means followed by the same letter are not significantly different at $P \le 0.05$. Symbol $U_{c\ Net\_GHG}$ indicates the cumulated standard deviation for emissions of CO_2, CH_4 and N_2O; a, b, c, ... homogenous groups, ns non-significant difference. The value between the brackets is the relative standard deviation. *The term "Yield" is the average values (calculated per year per hectare) of willow yield, which is harvested every third year.

microbiological humads (they ranged regionally 0.34-0.57 Mg C ha^{-1} yr^{-1}), while the share of humus was slight (0.01-0.11 Mg C ha^{-1}).

The assumed values of nitrogen inputs for willow are shown in Table 1. Perennial energy crops are usually efficient at taking up nitrates due to their long growing season, as well as their permanent and extensive root system; moreover, there is an unchanged soil cover, which can reduce surface run-off and infiltration of nutrients [2, 10, 18, 20, 27]. Willow also has a high nitrogen removal efficiency from soils [3, 19, 29], although low N off-take (150-400 kg N ha^{-1} per three years rotation based on 10-12 Mg DM ha^{-1} yr^{-1} [8] and its seasonal translocation in plant suggests careful application of N fertilizers under this crop. We assumed a value of N translocation as 50 kg ha^{-1} based on own studies of nitrogen share in leaves [3] and calculations of nitrogen pool and losses in SRC [6, 32, 39]. Simulated in DNDC nitrogen uptake from soil by willow aboveground biomass (Table 4) under growing conditions close to the quoted above, averaged 120 kg ha^{-1} yr^{-1}.

N_2O emissions from soils are variable and dependant on fertilizer application rate (the main driver), fertilizer type, crop type, soil type and climate - especially temperature and precipitation, so the emissions are usually highly site-specific. Generally, annual N_2O emission rates from arable soils are lower than 5 kg N ha^{-1} [11], while the emissions from European cropland soils are usually below 3 kg N ha^{-1}. IPCC [17] estimates that emitted N_2O ranges between 1 and 3% of the N added, whereas Crutzen *et al.* [7] revealed that the total N_2O emission should be 3-5% of the reactive nitrogen production. Average production of N_2O in willow cultivation was estimated by DNDC as 3.7 kg N ha^{-1} yr^{-1} and was higher than Tier 1 estimate (3.5 kg N ha^{-1} yr^{-1}) (Table 4). This is equal to 1.35% of nitrogen available for plant in fertilizers and roots and shoots residues. The estimates using IPCC methodology indicated that the contribution of N_2O-N in this part of nitrogen pool was lower (1.25%).

To compare the distribution of DNDC and IPCC N_2O emission data samples, Kolmogorov-Smirnov test was used (Fig. 3). There was no statistical difference between the two distributions at the 95% confidence level ($p = 0.16$).

Both IPCC and DNDC N_2O emission values were higher than available in literature. Kavdir *et al.* [20] calculated that mean annual N_2O emissions on sandy soil from cereals and rape were nearly two times greater at the N application 75 kg ha^{-1} yr^{-1} and more than two fold greater at the N fertilization rate 150 kg ha^{-1} yr^{-1} than for willow (1.93 kg ha^{-1} vs. 1.10 kg ha^{-1} and 3.1 kg ha^{-1} vs.

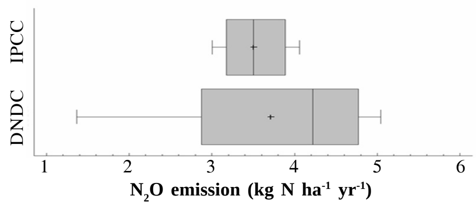

Figure 3. Box-and-whisker plot comparing distributions of N_2O emission values estimated using IPCC Tier1 assessment method and using DNDC model.

1.0 kg ha^{-1}, respectively). Similar rates were reported from loamy sand, where for annual crops fertilised with 75 kg N ha^{-1}, N_2O-N emission rates were 1.60-2.62 kg N ha^{-1}, while for Salix with undersown grass 0.94 kg N ha^{-1} [14].

N_2 emission was larger than N_2O (5.04 kg ha^{-1} yr^{-1}) although it depended mostly on similar factors like N_2O emission. Production of CH_4 and N gases - NO and NH_3 was not significant.

From among permanent soil losses of nitrogen, the NO_3 leaching had the largest share, because it averaged 13.5 kg N ha^{-1} yr^{-1} and was most varied between grid cells and years (Table 4). The increase of nitrate application rate to 220-240 kg N ha^{-1} yr^{-1} causes maximum losses in the third year of only 9.7 kg N ha^{-1} yr^{-1} [1]. Similarly, in the range of fertilization application rates 90-127 kg N ha^{-1} yr^{-1}, nitrates were leached at the level 1.6 kg N ha^{-1} yr^{-1} [2]. Nitrate leaching under established SRC will be low and comparable to unfertilized grassland. The overall nitrate leaching in wetter parts of Great Britain is lower than 15 kg N ha^{-1} yr^{-1} and in drier places most likely lower than 5 kg N ha^{-1} yr^{-1} [13].

A relationship between nitrogen losses and soil carbon accumulation is presented in the report of Association of German Agricultural Investigation and Research Centers [37]. Authors of the report indicated that SOC humus balance larger than 300 kg C ha^{-1} yr^{-1} may increase the risk of nitrogen losses. The relationship between annual soil carbon growth and nitrate losses was not statistically significant at the 95% confidence interval ($p = 0.12$) (Fig. 4). The model explained 27.9% of the variability in nitrates leaching values. The correlation coefficient 0.53 indicated a moderately strong relationship between variables. The relationship between N_2O emission and soil carbon variables explained 8.28% of the variability in emission at 0.29 correlation coefficient (Fig. 5).

Sensitivity analysis of the model input parameters - temperature and precipitation on selected model outputs were investigated (Table 5). Precipitation has the greatest influence on the prediction of NO_3 leaching from soil (99.6 % of variability). Temperature explained 45.2% of the variability in N_2O emission and the precipitation factor increased variability to 91.7%. The increasing temperature resulted in increased N_2O emissions as a consequence increased microbial activity[23]. Independent variables which were taken into consideration explained 98.9% of variability in CH_4 emission, whereas precipitation factor was responsible for 54% of emission variability. Moreover, multiple regression between

Table 4. Average annual relevant N fluxes for willow. The last column shows values obtained using IPCC method.

Grid cell number ($a_1 \ldots a_{10}$)	N uptake (kg N ha^{-1})	N leaching (kg N ha^{-1})	N_2O emission (kg N ha^{-1})	N_2O emission (IPCC) (kg N ha^{-1})
58076	134.76 ab (1.19)	9.20 d (7.18)	2.88 abc (14.16)	3.61 abc (6.84)
59068	108.16 b (1.46)	9.49 cd (8.37)	4.45 ab (11.18)	3.01 c (7.60)
60072	112.01 ab (1.33)	16.18 abc (4.75)	3.36 abc (13.58)	3.29 bc (6.90)
60077	127.85 ab (1.31)	8.96 d (8.13)	4.94 a (12.15)	3.65 abc (6.68)
62068	107.27 b (1.39)	11.93 bcd (6.15)	4.01 abc (12.30)	3.00 c (7.31)
63065	126.71 ab (0.97)	13.07 bcd (4.79)	1.36 d (12.60)	3.40 abc (5.71)
64070	108.97 ab (1.43)	13.10 bcd (6.67)	4.78 a (11.80)	3.17 c (7.04)
64076	115.51 ab (1.41)	17.39 ab (6.08)	4.52 ab (10.85)	3.96 ab (6.10)
66067	138.29 a (1.14)	21.24 a (4.25)	1.87 cd (11.43)	4.06 a (6.13)
66073	120.00 ab (1.36)	14.80 abcd (4.85)	5.04 a (9.69)	3.89 ab (6.64)
μ ($a_1 \ldots a_{10}$)	119.96	13.50	3.70	3.50

In each column, means followed by the same letter are not significantly different at $P \leq 0.05$. Symbols a, b, c,... mean homogenous groups, ns - non-significant difference. Value between brackets is the relative standard deviation.

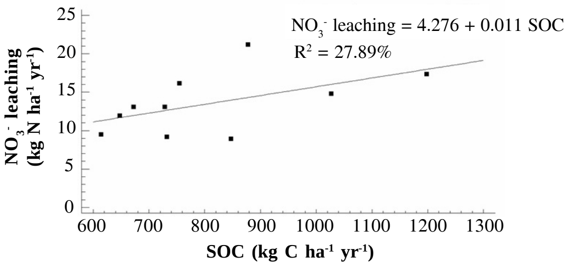

Figure 4. Regression between simulated NO_3- leaching values and simulated Soil Organic Carbon (SOC) values.

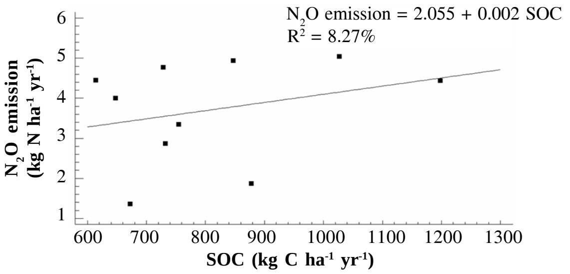

Figure 5. Regression between simulated N_2O emission values and simulated Soil Organic Carbon (SOC) values.

Table 5. Multiple regression models describing relationship between dependent variable (SOC, N_2O, N_{leach}, CH_4) and two independent variables (Temp, P).

Regression model	R^2 (%)	SE (%)
ΔSOC = 729.069 – 5.967Temp + 22.596P	72.21	0.96
N2O = 0.170 + 0.047Temp + 0.042P	91.70	0.00
N_{leach} = 12.716 + 20.102P + 0.61Temp	99.55	0.09
CH_4 = -0.628 – 0.063Temp + 0.062P	98.95	0.00

ΔSOC means Soil Organic Carbon change (kg C ha^{-1} a^{-1}), N_2O (kg N ha^{-1} a^{-1}), $N_{leaching}$ - nitrates leaching (kg N ha^{-1} a^{-1}), CH_4 - CH_4 emission (kg C ha^{-1} a^{-1}), Temp - temperature (°C), P - precipitation (mm). R^2 means coefficient of determination, SE - standard error of estimation.

soil organic carbon growth and two independent variables was performed, which explained 72.2% of the variability in carbon, where precipitation had an influence on 68.7% of variability.

It is necessary to validate the obtained outputs for other experimental sites through measurements especially measured fluxes of greenhouse gases at different levels of nitrogen fertilization under different global warming scenarios. Predictions of the model will need to be performed for long-term period taking into account the removal of old willow plantation.

Conclusions

Calibration of DNDC model for willow crops has indicated, that relative root mean square error of prediction was only 11.49%, what is only slightly greater than range of model good-fitness ≤10%. Simulations carried out in DNDC for willow cultivated in Poland show appreciable greenhouse gas mitigation, due to high level of carbon sequestration in soil, although share of humus is slight. Average nitrogen uptakes by willow crop in the country were at the level of 107-138 kg N^{-1} ha^{-1} yr^{-1}. N_2O emission from sandy clay soil was in the range of 1.36-5.04 kg N ha^{-1} yr^{-1}. Losses of nitrogen through leaching seem generally low, but the model gives much higher estimates than these reported in the literature. Implications of willow cultivation on soil water balance were strictly related to climate conditions, especially rainfall sums. Mean annual actual evapotranspiration was estimated by DNDC in the range of 345-408 mm for grids. To summarize, DNDC model seems to be useful for assessing the most important environmental effects on a field scale, connected directly with willow SRC cultivation.

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