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Modelling soil organic carbon sequestration under crops for biofuels in Poland

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Abstract. The soil organic carbon (SOC) stocks have become of special importance for sustainable biofuels production. We focused on SOC changes in high activity clay soils in Poland under arable crops for biofuels production. The SOC sequestration values were calculated using a DNDC model with four different tillage systems. The initial SOC stocks in Poland were highly spatially variable with values in the range of 35–97 t C ha^{-1}. The simulated regional SOC sequestration rates in topsoils ranged from -0.17 to 0.32 t C ha^{-1} $year^{-1}$ in full tillage, 0.36–0.73 t C ha^{-1} $year^{-1}$ in reduced tillage, and 1.69–3.22 t C ha^{-1} $year^{-1}$ in no-tillage. For full tillage with straw incorporation the results for SOC sequestration were similar to those of the reduced tillage. The uncertainties of the estimations were provided, in addition to the length of the periods of SOC sequestration. The results for Poland are relatively high comparted to those from literature which might suggest that DNDC overestimated the SOC stocks in our study. Although DNDC was based on long-term tests and proved adequate SOC simulations in many studies, still a comprehensive model validation is required in a field scale with relevant SOC measurements, climatic, soil and crop data.

Key words: soil organic carbon, carbon sequestration, tillage, no-till, modelling, CO_2

INTRODUCTION

Agricultural lands hold large reserves of carbon in the stocks of soil organic carbon (SOC), which is a an important component of the soil organic matter (58%) (Stockmann et al., 2013). Historically, soil organic carbon has been lost from agricultural lands and released to the atmosphere as CO_2. This was primarily caused by the changes in land use in the transition from natural ecosystems (i.e., woodlands and grasslands) into croplands. The conventional cultivation systems used in Europe have further contributed to the decrease in soil organic carbon in the past decades (Mondelaers et al., 2009; Aertsens et al., 2013). Based on a review by Borzęcka-Walker et al. (2011), the commonly used agricultural production methods in Poland caused SOC losses that ranged from -0.31 to -0.47 t C ha^{-1} over the period of 35 years till 2003; which is a very negative situation because of the low levels of soil organic matter in the tillage layer of agricultural soils of Poland (on average 2.2%, equivalent to 1.3% C, compared with 3-6% C in central Europe) (Gobin et al., 2011).

Simultaneously, many agricultural management practices result in an increase in the content of soil organic matter, which leads to the formation of soil organic carbon "sinks" (Lal, 2002). When CO_2 is removed from the atmosphere by plants and eventually stored in the soil, the process is soil organic carbon sequestration (Olson, 2013). Long-term land management practices determine the input-output balance of organic matter and steady levels of SOC. With regard to this, the sequestration of SOC is limited over time till a new steady state is reached in the soil (Olson, 2013; West, Post, 2002).

In the European Union, with the implementation of Directive 2009/28/EC (EC, 2009), which established sustainability criteria for biofuels production, the SOC stocks have become of special importance for calculating the greenhouse gas (GHG) impact of biofuels. For biofuel feedstock the sustainability criteria require preservation of the SOC content through avoiding conversion of high carbon stock areas (i.e., moors, wetlands). Changes of the SOC stocks related to feedstock production must be included in the GHG calculations, both the losses linked to land use conversion as well as carbon savings from SOC accumulation via improved agricultural management.

In our study, we investigated the stocks of SOC in high activity clay soils (HACS) of Poland under arable crops cultivated for biofuels production. The simulations were

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conducted with a grid of 50×50 km. We predicted the changes in the SOC that would occur with different management practices applied for the cultivation of crops used for biofuels. These results could provide support for the decision makers and the stakeholders, i.e., the agronomists and farmers, to establish appropriate regimes for SOC management with regard to GHGs emission reductions from the cultivation of biofuel feedstock.

MATERIALS AND METHODS

Guidelines for the calculations of SOC stocks for biofuels

The requirements in terms of the GHGs emission calculation for biofuels were established in the Directive 2009/28/EC (Annex V) and the Commission Decision on the guidelines for the calculation of land carbon stocks for the purpose of the above mentioned directive (EC, 2010). Among others, these apply for the spatial scale of the analysis, tillage systems, soil types, and the accuracy of the methodologies applied.

The required spatial resolution for the calculations of GHGs emissions from agricultural raw material was at least at level 2 in the nomenclature of territorial units for statistics (NUTS). In our study, we used a higher resolution based on a grid of 50×50 km covering the territory of Poland, which ensured at least three grid-squares per each NUTS-2 region (Figure 1). Our analysis was performed for HACS, which are soils suitable for crops used as a feedstock for biofuels in the agro-climatic conditions of Poland; HACS cover 31.4% of the sown area in Poland. The tillage systems we analysed in our study directly refer to those included in the Commission Decision. For the calculation of land carbon stocks, the IPCC Tier-1 methodology was recommended by the Commission Decision as an appropriate method, however, if resources available, more detailed methods should be used in order to provide improved accuracy and precision of the estimates (IPCC, 2006, EC, 2010). In our study, we used a DNDC model, which is relevant for the IPCC Tier-3 methodology.

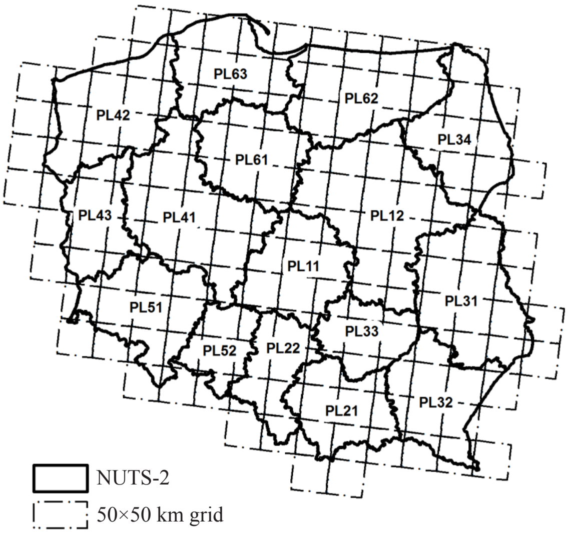

Figure 1. NUTS-2 regions and the 50×50 km grid-squares in Poland.

DNDC modelling

DNDC

DNDC (Denitrification-Decomposition) is a process-based model used for agro-ecosystems for the prediction of soil fluxes of N_2O, CO_2, and CH_4, crop production, NH_3 volatilization and NO_3 leaching (Giltrap et al., 2010). The model is composed of five interacting submodels, i.e., the thermal-hydraulic, aerobic decomposition, denitrification, fermentation, and plant growth (management practices) submodels (Giltrap et al., 2010). These submodels were described in Li et al. (1992, 1994) and Li (2000). The simulations with DNDC were widely used internationally (http://www.globaldndc.net/information/publications-i-3.html), and the model demonstrated adequate predictions of crop yields, carbon fluxes, nitrogen fluxes and the water balance (Beheydt et al., 2007; De Vries, 2007; Giltrap et al., 2010; Li et al., 2005; Sales, 2010). Dedicated DNDC applications for the simulations of SOC dynamics on European cropland included research works by Li et al. (1997), Sleutel et al. (2006 a, b), Leip et al. (2008) and Wattenbach et al. (2010). To our knowledge the model was not used for the simulations of SOC stocks under improved agricultural management as it was defined by the Directive 2009/28/EC and EC (2010) guidelines.

In our study we used the model DNDC 9.2 version to investigate long-term (20 year) carbon fluxes, i.e., SOC sequestration, in different tillage systems with crops that might be used as feedstock for biofuels. We also simulated N_2O emissions that were reported by Syp et al. (2016). The simulations were conducted with a grid of 50×50 km. The model required as input: soil properties, daily weather data, and crop management practices (crop rotation, fertilization, tillage). To simulate SOC sequestration the DNDC model calculated at a daily time step: (i) the turnover of organic matter in the soil, (ii) crop growth, (iii) partitioning of crop biomass into grain, stems and roots, and (iv) soil respiration (Li et al., 1997). In the model, there are four major pools relevant for SOC: litter residue, microbes, humads, and passive humus at surface layer. After defining the total SOC content, the default SOC profile as well the SOC partitioning values for litter, humads and passive humus were automatically determined by DNDC, taking into account the defined cropping system.

The model showed SOC dynamics over time as well as carbon (C) biogeochemistry (all the C pools and fluxes).

However, in our study we focused only on the SOC sequestration values (an aggregate pool of C) relevant for the 0–30 cm topsoil layer. In the DNDC 9.2 version different layers within topsoil were not distinguished with regard to SOC stock predictions.

Soil data

The DNDC required as input following data on the high activity clay soils (weighted averages for the 50×50 km grid-squares): initial content of total SOC in kg C kg^{-1} of soil in the topsoil layer (0–30 cm), clay content (%), bulk density (g cm^{-3}), and pH. The soil data were derived from the measurements of 50 000 benchmark soil profiles located across Poland (IUNG-PIB, 1992). Over 50 soil parameters, including the SOC content in the soil layer 0–30 cm, were specified for each benchmark profile. An algorithm was then developed to assign the soil profiles to polygons on the 1:100 000 agronomic-soil map of Poland (Stuczyński et al., 2007). The data on SOC contents as well as the method of SOC mapping in Poland were applied by Panagos et al. (2013) for the estimations of SOC in Europe. In this study, for the simulations with DNDC only HACS of arable land were selected as most suitable for biofuel crops. Table 1 presents the basic statistics (skewed distribution) on the SOC contents measured in HACS of arable land from the benchmark profiles (12 244 profiles) in Poland. The spatial distribution of HACS was presented in Figure 2.

Table 1. Statistics for the SOC (% weight) from the benchmark profiles of HACS of arable land in Poland.

Number of samples	Median	Min.	Max.	Median absolute deviation
12 244	1.25	0.06	13.92	0.34

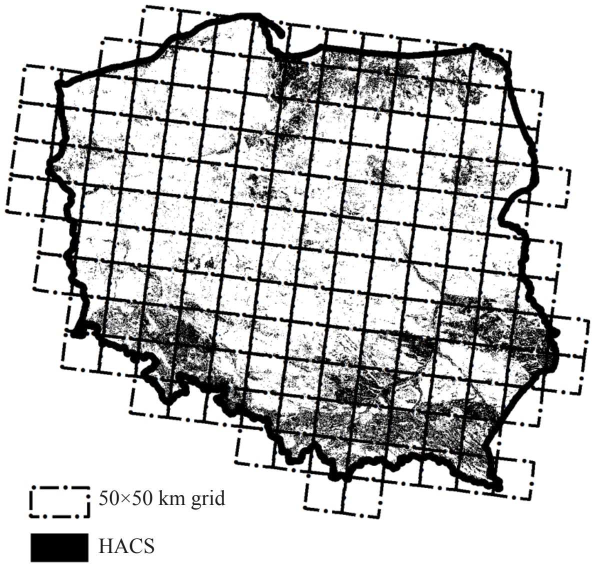

Figure 2. High activity clay soils (HACS) of arable land in Poland and the 50×50 km grid-squares.

The SOC initial content and the other required soil parameters for the DNDC modelling were established for topsoils (0–30 cm) of HACS in a grid of 136 squares 50×50 km that covered the territory of Poland. Using the geographic information system, the SOC levels were estimated for each of the grid-squares with reference to the contours of different soil suitability complexes of HACS and different levels of SOC assigned to them on the 1:100 000 agronomic-soil map. As a result, the SOC values were estimated as weighted averages for each of the grid-squares.

Weather data

The model required long-term (20-year) daily weather data on the maximum temperature, minimum temperature and precipitation. These data were derived from the JRC Crop Growth Monitoring System (http://mars.jrc.ec.europa.eu/mars/About-us/AGRI4CAST/Models-Software-Tools/Crop-Growth-Monitoring-System-CGMS). The data were interpolated for the 136 grid-squares that covered Poland. At least one weather station was allocated to three neighbouring squares. Therefore, for each square, a 30-year meteorological series was derived for the period of 1975–2004. Then, to fit the 20-year time series required by the DNDC model, the JRC dataset was verified for annual precipitation because this parameter had large spatial variability, and the SOC simulations could be strongly influenced by the precipitation (Tum et al., 2012). The verification was based on a national model developed by Górski (unpublished) that was based on over 1000 weather stations located throughout Poland.

Crop rotations and tillage systems

The SOC simulations with DNDC were performed with the data (i.e., crop rotations, fertilization, tillage methods, harvest modes) derived from crop production farms, which were the main suppliers of crops for biofuels in Poland. These farms (without livestock) were 40.7% of the total number of farms and covered 36.4% of the arable land in Poland. Under research were 275 farms with maize grain, 272 with winter wheat, and 1218 with winter rapeseed. Two crop rotation systems with crops suitable for biofuel production were chosen for the DNDC modelling (N-fertilization amount in parentheses, kg N ha^{-1}):

1. Maize grain (140)/winter wheat (120)/winter rapeseed (180)/winter wheat (100).
2. Winter rapeseed (180)/winter wheat (100)/winter wheat (120)/winter triticale (100).

These crops are representative for Poland with winter wheat covering 2,00 Mha (19% of current sown area in 2014), winter triticale 1,31 Mha (13%), maize grain

0,68 Mha (7%), and winter rapeseed 0,99 Mha (9%), respectively (GUS, 2015).

With reference to the guidelines for the calculation of land carbon stocks (EC, 2010), the DNDC simulations were performed for tillage systems that were defined as follow:

- Full tillage (FT, the reference system) – A system with substantial soil disturbance following full inversion and/or frequent (within the year) tillage operations; and at planting time, little (*e.g.* <30%) of the surface is covered by residues;
- Reduced tillage (RT) – A system with primary and/or secondary tillage but with reduced soil disturbance (typically shallow tillage and without full soil inversion); and at planting, the surface is typically covered with >30% residues;
- No-tillage (NT) – A system with direct seeding without primary tillage and with minimal soil disturbance only in the seeding zone; and herbicides are typically used for weed control.

One additional management system was investigated, which was considered representative of crop production farms in Poland:

- Full tillage with ploughed straw (FTS) – A system with full tillage with all crop residues left in the field for ploughing into the soil (representative of medium inputs of organic matter, as defined in the EC guidelines).

In the DNDC libraries we defined the management systems as follows: FT – ploughing with moldboard and 30% of the above-ground crop residue is left in the field, FTS – ploughing with moldboard and all crop residue is left in the field, RT – ploughing with disk or chisel (10 cm) and at least 30% of residue is left in the field, NT – no till, i.e. only mulching (0 cm) and all residue left in the field.

DNDC recalibration against experimental data and validation of the recalibrated model

In our study the calibration and validation was done with crop data only as no relevant long-term SOC measurement were available for Poland in order to perform a spin-up simulation and verify how the model predict the initial SOC levels. For modelling SOC dynamics with DNDC it was crucial to adequately simulate the crop biomass production. Crop growth plays an important role in regulating the soil C, N and water regimes, which further affect a series of biochemical or geochemical processes occurring in the soil. Therefore, adequately simulated crop yields determine the accordance of the simulations of other processes, and are crucial for the quality of the model predictions of C in the soil-plant-atmosphere system.

The data from three crop production experiment stations located in different parts of Poland were used for the DNDC model calibrations with crops: a 23-year experiment with full tillage, and a 16-year and 17-year experiments, both with full tillage, reduced tillage and no-tillage. All established with crops that could be used for biofuels, i.e. winter wheat, winter rapeseed, maize grain.

By default, the DNDC 9.2 version included coefficients for C and N fluxes, which were adequate for crops cultivated in the US. In our study we applied the coefficients recalibrated by the JRC for crops in the EU-15 as used for regional simulations with DNDC by Leip et al. (2008). Further, based on the data derived from the crop experiment stations in Poland, dedicated model recalibration for Poland was conducted for the crop C coefficients (biomass allocation to grain/straw/roots). The relative root mean square errors (RRMSE) were used to check the consistency of the simulated results with the field experimental data, and the optimum model calibrations had the smallest RRMSEs. In our study, a RRMSE that approximated 20% was accepted as an indication of suitable model accuracy. The simulation errors (RRMSE) for the selected crops were as follow: 19% for maize grain, 20% for winter wheat, and 20% for winter rapeseed.

The recalibrated model was then verified (validated) with the crop yields from commercial crop farms, which are the primary suppliers of feedstock for biofuels in Poland (see section above). In the validation process, the simulation errors (RRMSE) for crop yields were as follow: 26% for maize grain, 21% for wheat, and 9% for rapeseed. Thus, the recalibrated and validated DNDC model was justified for use in the simulations of yields and C fluxes in our study.

Estimation of soil organic carbon changes

The net changes in SOC (sequestration or loss) were calculated as the difference between the DNDC cumulative results (20 year-time) for each improved tillage system (FTS, RT, NT) and the cumulative results for the reference full tillage system (FT). The SOC changes were predicted for each of the 136 squares in the 50×50 km grid. The cumulative values for the improved tillage systems were expressed with a second-degree polynomial regression, or when the square effect was not significant statistically, with a linear regression for the 20-year period. Finally, the SOC sequestration in tonnes per hectare per year (t C ha^{-1} $year^{-1}$) was determined as the result of the regression function for the year 20 divided by 20. The uncertainty was calculated as the square error of the estimation as a percentage (%). Because the sequestration of SOC is limited over time till a new steady state is reached in the soil, the sequestration was estimated with the second-degree polynomial regression function: $y = ax^2 + bx + c$, with vertex coordinates, and the formulas $\Delta = b^2 - 4ac$, $p = -b/2a$ and $q = -\Delta/4a$. The maximum possible SOC sequestration in the long-term was characterized by q ($f(x)max$) as t C ha^{-1}, whereas the sequestration time was in years (p).

RESULTS

The actual soil organic carbon content in the topsoils (0–30 cm) of the 136 grid-squares was presented in Figure 3. The lowest value was 35 t C ha^{-1}, whereas the highest value in Poland was 97 t C ha^{-1}. The mean SOC content was 59 t C ha^{-1} (median = 58, standard deviation = 12, variance = 144). Most of the grid-squares were in the classes of 54.1–60.0 t ha^{-1} (37 units) and 60.1–67.0 t ha^{-1} (28 units).

In the descriptions of simulated SOC sequestration, the ranges of values are provided below, which represent the lowest and the highest values calculated for the 136 squares in the grid that covered the territory of Poland. The basic statistics are presented in Tables 2 and 3.

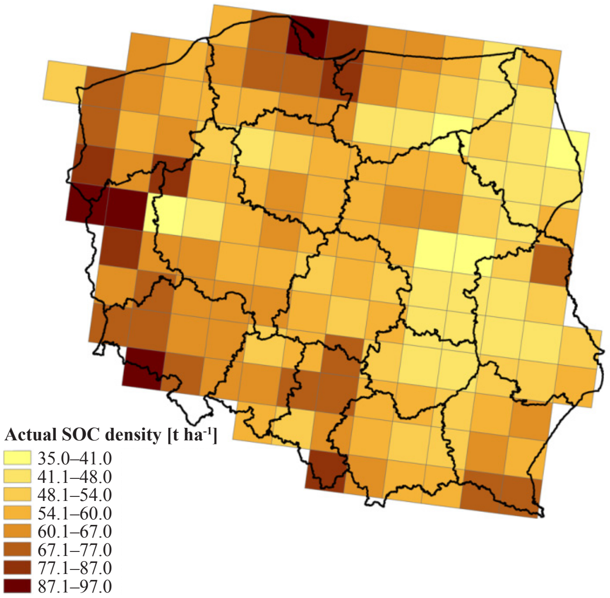

Figure 3. Actual SOC density in topsoils of arable land (HACS) for squares of the 50×50 km grid.

For the first crop rotation, the SOC sequestration in the reference full tillage systems (FT) ranged from -0.11 to 0.32 t C ha^{-1} year^{-1}. For the reduced tillage systems (RT), the SOC sequestration was in the range of 0.41–0.73 t C ha^{-1} year^{-1}, with levels of uncertainty that ranged from 17–36%. The no-tillage systems (NT) were characterized with SOC sequestration in the range of 1.69–3.22 t C ha^{-1} year^{-1}, with levels of uncertainty of 3–14%. The full tillage systems with ploughed straw (FTS) had levels of SOC sequestration and uncertainty that were similar those in the reduced tillage systems, *i.e.* 0.43–0.74 t C ha^{-1} year^{-1}, with levels of uncertainty of 16–43%. Thus, for the accumulation of soil C, the RT systems were not a better cultivation system than the FTS.

The SOC sequestration in reduced tillage system (RT) was estimated at 15–30 years and would increase the SOC by 9–15 t C ha^{-1}, which amounts 11–28% of the initial SOC level in topsoil. Similar values were recorded for the full tillage system with ploughed straw. For a no-tillage system (NT), the SOC sequestration was calculated at 28–97 years and would result in SOC gain of 50–146 t C ha^{-1}, which was an increase of 62–325% of the initial SOC level. The estimation of the period of SOC sequestration and the maximal SOC levels was not possible for each of the grid-squares, with regard to nonhomogenous time series of SOC contents.

In the second crop rotation, the SOC sequestration in the reference full tillage system was in the range of -0.17–0.20 t C ha^{-1} year^{-1}. The SOC storage increased in the RT systems and was 0.36–0.60 t C ha^{-1} year^{-1}, with the uncertainty of estimation at the level of 16–33%. In the no-tillage systems, the SOC sequestration was in the range of 1.81–3.07 t C ha^{-1} year^{-1}, with the uncertainty at the level of 1–9%. As it was also observed in the first crop rotation, the reduced tillage systems (RT) did not increase the gains in SOC storage compared with the full tillage systems with ploughed straw (FTS), which had SOC sequestration in the

Table 2. Statistics for soil SOC sequestration (t C ha^{-1} year^{-1}) in topsoils (HACS) of arable land – the first crop rotation.

Tillage system#	Number of observations	Mean	Median	Min.	Max.	Variance	Standard deviation	Skewness
FT	136	0.17	0.17	-0.11	0.32	0.01	0.08	-0.76
FTS	136	0.56	0.55	0.43	0.74	0.00	0.06	0.40
RT	136	0.55	0.55	0.41	0.73	0.00	0.07	0.28
NT	136	2.40	2.41	1.69	3.22	0.09	0.30	0.08

FT – full tillage; FTS – full tillage with ploughed straw; RT – reduced tillage; NT – no-tillage

Table 3. Statistics for soil SOC sequestration (t C ha^{-1} year^{-1}) in topsoils (HACS) of arable land – the second crop rotation.

Tillage system#	Number of observations	Mean	Median	Min.	Max.	Variance	Standard deviation	Skewness
FT	136	0.05	0.06	- 0.17	0.20	0.01	0.08	0.20
FTS	136	0.47	0.47	0.30	0.59	0.00	0.04	0.59
RT	136	0.49	0.49	0.36	0.60	0.00	0.04	0.60
NT	136	2.48	2.49	1.81	3.07	0.05	0.21	3.07

see Table 2

Table 4. Initial SOC stock (t C ha^{-1}) and simulated SOC sequestration values (t C ha^{-1} year^{-1}) with the uncertainty of the estimates (%) for NUTS-2 level in HACS in Poland – the first crop rotation.

NUTS-2	SOC initial level	Tillage system$^{\#}$						
		FT	FTS		RT		NT	
		SOC seq.	SOC seq.	Uncert.	SOC seq.	Uncert.	SOC seq.	Uncert.
PL11	56	0.20	0.57	24	0.58	25	2.30	5
PL12	52	0.19	0.53	23	0.54	25	2.41	6
PL21	57	0.19	0.65	21	0.64	21	2.67	5
PL22	49	0.11	0.63	24	0.64	25	2.60	5
PL31	51	0.20	0.53	26	0.52	26	2.46	6
PL32	61	0.14	0.60	24	0.61	25	2.72	5
PL33	69	0.20	0.59	23	0.59	23	2.39	6
PL34	49	0.26	0.54	23	0.56	25	2.53	4
PL41	59	0.14	0.51	23	0.49	26	2.07	8
PL42	69	0.12	0.57	24	0.56	22	2.24	6
PL43	81	0.00	0.47	23	0.46	24	1.93	10
PL51	69	0.11	0.54	21	0.52	23	2.24	7
PL52	60	0.14	0.61	23	0.61	27	2.37	6
PL61	55	0.18	0.51	24	0.51	25	1.97	8
PL62	60	0.20	0.56	26	0.54	27	2.67	5
PL63	70	0.13	0.59	26	0.58	29	2.53	5

see Table 2

Table 5. Initial SOC stock (t C ha^{-1}) and simulated SOC sequestration values (t C ha^{-1} year^{-1}) with the uncertainty of the estimates (%) for NUTS-2 level in HACS in Poland – the second crop rotation.

NUTS-2	SOC initial level	Tillage system$^{\#}$						
		FT	FTS		RT		NT	
		SOC seq.	SOC seq.	Uncert.	SOC seq.	Uncert.	SOC seq.	Uncert.
PL11	56	0.09	0.48	22	0.50	23	2.40	3
PL12	52	0.08	0.44	25	0.46	27	2.37	4
PL21	57	0.03	0.50	22	0.51	24	2.60	3
PL22	49	- 0.01	0.50	22	0.51	23	2.65	3
PL31	51	0.08	0.45	22	0.48	23	2.53	3
PL32	61	0.00	0.48	23	0.50	25	2.68	3
PL33	69	0.08	0.46	22	0.46	24	2.48	3
PL34	49	0.18	0.47	23	0.50	24	2.50	2
PL41	59	0.04	0.47	22	0.47	23	2.32	5
PL42	69	0.00	0.50	22	0.51	22	2.47	4
PL43	81	- 0.07	0.46	19	0.46	19	2.30	5
PL51	69	- 0.02	0.47	21	0.47	23	2.38	4
PL52	60	0.05	0.46	24	0.46	24	2.37	3
PL61	55	0.09	0.45	23	0.44	24	2.27	4
PL62	60	0.03	0.49	22	0.51	23	2.69	2
PL63	70	- 0.00	0.49	21	0.48	23	2.61	3

see Table 2

range of 0.30–0.59 t C ha^{-1} year^{-1}, with the uncertainty of 13–33%.

In the second crop rotation for the reduced tillage systems, the soil SOC sequestration time was estimated at 17–25 years, which would increase the SOC by 8–10 t C ha^{-1}, an increase of 13–16% of the initial SOC stock in the topsoil layer (0–30 cm). For the full tillage systems with ploughed straw, the values of 15–55 years and 7–14 t C ha^{-1} were determined. In the no-tillage systems, the sequestration of SOC was longer than that for reduced-tillage and was 29–99 years, which would result in gains in the SOC of 38–148 t C ha^{-1}, an increase of 71–257% of the initial SOC content. The estimation of the period of SOC sequestration and the maximal SOC levels for each of the squares was not possible, the same as in the first crop rotation.

The simulations produced the widest range of results for the no-tillage systems in both crop rotations; however, the uncertainty of the results was relatively low for the no-tillage management. In general, the second crop rotation produced lower results for SOC sequestration than the first rotation for FTS and RT systems, however an opposite tendency was observed for no-tillage.

The simulated SOC values for 136 grid-squares were aggregated to NUTS-2 level as weighted averages (Table 4 and 5). As such, they could be used to calculate the GHGs emission reductions from biofuels (actual values) in Poland as specified in Directive 2009/28/EC (Annex V).

DISCUSSION

Mosaic pattern of initial SOC contents

The arable land (HACS) in Poland was highly variable for the contents of SOC. The mosaic pattern of SOC content could be explained primarily by the variation in the pedogenesis of HACS, water conditions, climatic regions and historical cropland management regimes. According to the guidelines for the calculation of land carbon stocks (EC, 2010), the standard SOC values for HACS were 95 t C ha^{-1} for a cold temperate moist climate and 50 t C ha^{-1} for a cold temperate dry climate. The climate classification (http://eusoils.jrc.ec.europa.eu/projects/RenewableEnergy) is presented in Figure 4. In our study, the maximal value of the SOC for Poland was 97 t C ha^{-1}, which was very close to the standard SOC value of 95 t C ha^{-1} for the cold temperate moist zone. The generally lower values of the SOC in the grid-squares than the standard values resulted from the effects of climate and agriculture land management.

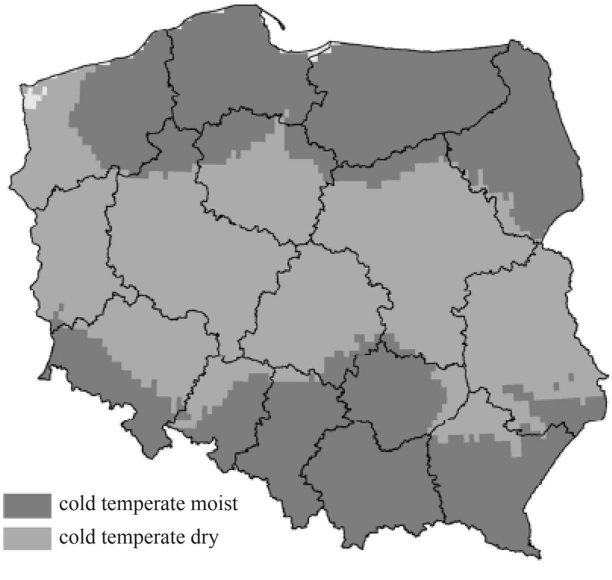

Figure 4. Climatic zones in Poland according to IPCC classification and NUTS-2 regions.

DNDC simulations for Poland compared with other studies

Our simulations with DNDC model for Poland were compared with carbon accumulation rates reported in the literature (Table 6). For full tillage, which is the most common practice for crop production farms in Poland we received medians indicating SOC sequestration of 0.06 t C ha^{-1} year^{-1} for the first rotation and 0.17 t C ha^{-1} year^{-1} for the second crop rotation, respectively. Other studies suggest SOC losses under the current agricultural management in Europe. Leip et al. (2008) who used DNDC for EU-15 regional simulations presented losses of organic carbon for a 98-year spin-up simulation (the whole variety of soils and crops with constant weather data of year 2000) with an average rate of 0.5 t C ha^{-1} year^{-1} during the first decade slowing down to 0.1 t C ha^{-1} year^{-1} during the last decade. Sleutel et al. (2006b) in regional simulations with DNDC for Flemish (Belgium) cropland with intensive agriculture showed SOC stock decrease by 0.15 t C ha^{-1} year^{-1} during period 2006–2012 compared with 0.48 t C ha^{-1} year^{-1} in the 1990s. Vleeshouwers and Verhagen (2002) used CESAR model to calculate SOC loss of 0.84 t C ha^{-1} year^{-1} for cropland in Europe.

Our estimates for SOC sequestration for full tillage with straw ploughed under were close to those estimated by Gobin et al. (2011). They used simple statistical relationships for the yield of cereals and the carbon sequestration (humified organic carbon) and showed that leaving all of the straw in the field resulted in SOC sequestration in Poland in the range of 0.31–0.45 t C ha^{-1} year^{-1}. Our simulations with the DNDC model produced values in the ranges of 0.43–0.74 and 0.30–0.59 t C ha^{-1} year^{-1} for the two crop rotations. Notably, the statistical cereal yields used by Gobin et al. (2011) were lower than the yields simulated by the DNDC model in our study (yields from commercial crop production farms), which could explain the higher values that were simulated. Sleutel (2006a) who validated DNDC for field experiments in Flandria (Belgium) suggested a flaw in the ability of DNDC to simulate straw decomposition under temperate conditions, which resulted in SOC stock overestimation. In a recently published study by Lugato et al. (2014) the pan-European simulations with CENTURY model for ploughing with 100% straw incorporation showed median values of 0.1 and 0.04 t C ha^{-1} year^{-1} by 2020 and 2050, respectively. Smith et al. (2008) and Vleeshouwers and Verhagen (2002) simulated SOC sequestration of 0.15 t C ha^{-1} year^{-1} for this management system. These results are significantly lower compared to our simulations for Poland.

Table 6. Comparison of simulated SOC stock accumulation rates under different management options, results in t C ha^{-1} year^{-1}.

Management option	DNDC simulated results, Poland[#]	Literature	Reference
Full tillage (FT)	0.17 and 0.06	-0.50 slowing down to -0.10	Leip et al., 2008
		-0.48 slowing down to -0.15	Sleutel et al., 2006b
		-0.84	Vleeshouwers and Verhagen, 2002
Full tillage with straw incorporation (FTS)	0.55 and 0.47	0.31–0.45	Gobin et al., 2011
		0.10 slowing down to 0.04	Lugato et. al., 2014
		0.15	Smith et al., 2008
		0.15	Vleeshouwers and Verhagen, 2002
Reduced tillage (RT)	0.55 and 0.49	<0.4	Smith et al., 2000
		0.06[##]	Frank et al., 2015
		<0.10	Lugato et al., 2014
		0.10	Aertsens et al., 2013
No-tillage (NT)	2.41 and 2.49	0.30–0.40	Smith et al., 2000
		0.57±0.14	West and Post, 2002
		0–1.30	Soane et al., 2012
		0.16	Oorts et al., 2007
		0.10[##]	Frank et al., 2015

[#] medians for two crop rotations
[##] recalculated from t CO_2 ha^{-1} year^{-1}

Experimental data from Europe for reduced tillage and in particular for no-tillage are scarce; this is primarily because these management systems are not commonly used in Europe (Soane et al., 2012). The SOC simulations with DNDC for reduced tillage in Poland (0.41–0.73 t C ha^{-1} year^{-1} and 0.36–0.60 t C ha^{-1} year^{-1} for the two crop rotations) are similar to those reported by Smith et al. (2000 in Freibauer et al., 2004), who calculated the mean SOC sequestration in the EU-15 for reduced tillage at <0.4 t C ha^{-1} year^{-1} (uncertainty >50%) and at 0.3–0.4 t C ha^{-1} year^{-1} (uncertainty >50%) for no-tillage. Our results for reduced tillage are close or within the range provided for Europe with 50% uncertainty, but for no-tillage, we estimated higher sequestration rates.

The analysis of global meta-data for no-tillage (67 long-term experiments) showed that the change from conventional tillage to no-tillage, using best management practices, resulted in an average SOC sequestration rate of 0.57±0.14 t C ha^{-1} year^{-1} (West, Post, 2002). The review of 11 European studies on no-tillage found only 16 experiments of which only two continued for more than 20 years (Soane et al., 2012). These experiments showed that the SOC sequestration ranged from 0 to 1.3 t C ha^{-1} year^{-1}, with the high range of values reported for Spain. For France (32 year experiment) SOC sequestration was 0.16 t C ha^{-1} year^{-1} (Oorts et al., 2007). Recently published studies with model simulations for Europe presented modest SOC sequestration values for reduced and no-tillage practices. For example, Frank et al. (2015) used GLOBIOM-EU model for European cropland to simulate average savings of 0.06 t C ha^{-1} year^{-1} for reduced tillage and 0.10 t C ha^{-1} year^{-1} for no-tillage (recalculated from t CO_2 ha^{-1} year^{-1}). Lugato et al. (2014) used CENTURY model and received a slightly lower medians than 0.1 t C ha^{-1} year^{-1} for reduced tillage by 2020. Also Aertsens et al. (2013) estimated for EU-27 values close to 0.1 t C ha^{-1} year^{-1} for no/low tillage.

Luo et al. (2010) and Baker et al. (2007) showed that no-tillage did not significantly increase the total SOC stock, but rather changed distribution of C in the soil profile. Based on a global meta-data base of 69 paired experiments Luo et al. (2010) reported that in no-tillage systems the SOC increased by 3.15±2.42 t C ha^{-1} (mean±95% confidence interval) in the surface 10 cm of soil, although a decline was observed by 3.30±1.61 t C ha^{-1} in the 20–40 cm soil layer. It should be emphasized that the DNDC model (version 9.2) we used for Poland simulated total SOC stocks in the topsoil (0–30 cm) with no information on the SOC distribution at different levels, which could be very essential for no-tillage system as it was discussed here.

In summary this review, the simulated SOC sequestration values in Poland from our study were higher than data from field trials and model simulations from other studies. In particular our results for no-tillage might indicate that DNDC model overestimated the SOC sequestration rates for Poland.

Possible explanation of DNDC overestimation for Poland

As it was stated in the method section, the DNDC model was used in numerous studies and simulated adequate predictions of SOC dynamics. By receiving comments and suggestions it continued to be modified and improved after almost two decades of development (Giltrap et al., 2010). With regard to that we had confidence in DNDC as a reliable and capable modelling tool to simulate adequate SOC predictions. In our study the model was first feed with crop C coefficients relevant for EU regional simulations (Leip et al., 2008) and then calibrated and validated with crop yields in Poland, finally producing reasonable simulations. We used the default distribution of SOC pools in the DNDC which was based on many long-term tests worldwide and worked well for most simulations. However, any local calibration in terms of total SOC partitioned into different pools should improve the model predictions. In our case relevant data on long-term SOC measurements were not available.

The comparison with other studies suggested that our regional simulations with DNDC of SOC stocks in Poland might be overestimated. A possible explanation is that the model was not sufficiently validated or calibrated in terms of SOC changes. Sleutel et al. (2006a) urged caution with the application of SOC models at regional scales after limited validation or calibration at the field scale. They calibrated the DNDC model with two field experiments in Flanders including crop yields, mineral N inputs and dry matter inputs and validated the model simulations with measured SOC levels. They adjusted the crop and soil parameters in the DNDC 8.1 model to local conditions before they made a large-scale validation. There is a hypothesis that an adjustment of the default coefficients for partitioning the initial SOC stock into DNDC's SOC pools (litter = 8%; microbial biomass + humads = 12%; passive humus = 80%) could improve the model availability to predict SOC stocks in Poland. This could be supported by the model validation done by Sleutel et al. (2006a) who used a large data set of SOC medium-term measurements to establish the initial SOC levels.

CONCLUSIONS

We used a DNDC 9.2 model to predict SOC stock changes in Poland under two crop rotations with crops that could be used for biofuel production. We simulated SOC stocks (an aggregate pool) in the topsoil (0–30 cm) with no information on the SOC distribution at different soil levels. The simulations showed that the change in tillage system from ploughing to those of reduced and no-tillage lead to increased concentrations of SOC in topsoils, with the highest levels of SOC storage for no-tillage. No significant difference was found between the reduced tillage system and the full tillage system with straw left in the field. The uncertainty associated with simulated regional values should encourage careful use of these values. The simulated sequestration of soil organic carbon was limited in time till a new equilibrium was achieved in the soil. Our results compared with literature might suggest overestimated SOC sequestration values received with DNDC for Poland. Although DNDC was based on long-term tests and proved good simulated results in many studies worldwide, still a special care is required with model validation. In our study DNDC calibration and validation with crop data was not sufficient itself for the model to prove good SOC predictions in regional scale. This implied that model validation with relevant long-term SOC measurements is a necessary condition for a dynamic model such as DNDC to prove adequate SOC stock simulations.

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REFERENCES

Aertsens J., De Nocker L., Gobin A., 2013. Valuing the carbon sequestration potential for European agriculture. Land Use Policy, 31: 584-594.

Baker J.M., Ochsner T.E., Venterea R.T., Griffis T.J., 2007. Tillage and soil carbon sequestration – What do we really know? Agriculture, Ecosystems & Environment, 118(1-4): 1-5.

Beheydt D., Boeckx P., Sleutel S., Li C., Van Cleemput O., 2007. Validation of DNDC for 22 long-term N_2O field emission measurements. Atmospheric Environment, 41: 6196-6211.

Borzęcka-Walker M., Faber A., Mizak K., Pudełko R., Syp A., 2011. Soil Carbon Sequestration Under Bioenergy Crops in Poland. In: Principles, Application and Assessment in Soil Science (ed. E. Burcu Özkaraova Güngör), InTech.

De Vries W., Leip A., Reinds G.J., Kros J., Lesschen J.P., Bouwman A.F., 2011. Comparison of land nitrogen budgets for European agriculture by various modeling approaches. Environmental Pollution, 159: 3254-3268.

EC, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union, 140: 16-62.

EC, 2010. Commission Decision of 10 June 2010 on guidelines for the calculation of land carbon stocks for the purpose of Annex V to Directive 2009/28/EC. Official Journal of the European Union, 151: 19-41.

Frank S., Schmid E., Havlík P., Schneider U.A., Böttcher H., Balkovič J., Obersteiner M., 2015. The dynamic soil organic carbon mitigation potential of European cropland. Global Environmental Change, 35: 269-278.

Freibauer A., Rounssevell M.D.A., Smith P., Verhagen J., 2004. Carbon sequestration in agricultural soils of Europe. Geoderma, 122: 1-23.

Giltrap D.L., Li C., Saggar S., 2010. DNDC: A process-based model of greenhouse gas fluxes from agricultural soils. Agriculture, Ecosystems and Environment, 136: 292-300.

Gobin A., Campling P., Janssen L., Desmet N., van Delden H., Hurkens J., Lavelle P., Berman S., 2011. Soil organic matter management across the EU – best practices, constraints and trade-offs. Final Report for the European Commission's DG Environment, http://ec.europa.eu/environment/soil/pdf/som/full_report.pdf (accessed: 18.06.2015).

GUS 2015. Statistical Book of Agriculture 2015. Central Statistical Office of Poland.

IPCC, 2006. Draft 2006 IPCC guidelines for national greenhouse gas inventories. Overview chapter. Intergovernmental Panel on Climate Change. Available at: https://www.ipcc.ch/meetings/session25/doc4a4b/doc4a.pdf (accessed 29.03.2016)

IUNG-PIB, 1992. Data on soil characteristics from 50 000 soil profiles in Poland. Department of Soil Science, Erosion and Land Conservation. Institute of Soil Science and Plant Cultivation – State Research Institute. Poland.

Lal R., 2002. Soil carbon dynamics in cropland and rangeland. Environmental Pollution, 116: 353-362.

Leip A., Marchi G., Koeble R., Kempen M., Britz W., Li C., 2008. Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen and carbon losses from arable soils in Europe. Biogeosciences, 5: 73-94.

Li C., 2000. Modeling trace gas emissions from agricultural ecosystems. Nutrient Cycling in Agroecosystems, 58: 259-276.

Li C., Frolking S., Crocker G.J., Grace P.R., Klír J., Körchens M., et al., 1997. Simulating trends in soil organic carbon in long-term experiments using DNDC model. Geoderma, 81: 45-60.

Li C., Frolking S., Frolking T.A., 1992. A model of nitrous-oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. Journal of Geophysical Research – Atmospheres, 97: 9759-9776.

Li C., Frolking S., Harriss R., 1994. Modeling carbon biogeochemistry in agricultural soils. Global Biogeochemical Cycles, 8: 237-254.

Li C., Frolking S., Xiao X., Moore B., Boles S., Qiu J., Huang Y., Salas W., Sass R., 2005. Modeling impacts of farming management alternatives on CO_2, CH_4, and N_2O emissions: a case study for water management of rice agriculture of China. Global Biogeochemical Cycles 19: GB3010. dot:10.1029/2004GB002341.

Lugato E., Bampa F., Panagos P., Montanarella L., Jones A., 2014. Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. Global Change Biology, 20(11): 3557-3567.

Luo Z., Wang E., Sun O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agriculture, Ecosystems and Environment, 139: 224-231.

Mondelaers K., Aertsens J., Van Huylenbroeck G., 2009. A meta-analysis of the differences in environmental impacts between organic and conventional farming. British Food Journal, 111: 1099-1120.

Oorts K., Bossuyt H., Labreuche J., Merckx R., Nicolardot B., 2007. Carbon and nitrogen stocks in relation to organic matter fractions, aggregation and pore size distribution in no-tillage and conventional tillage in northern France. European Journal of Soil Science, 58: 248-259.

Olson K.R., 2013. Soil organic carbon sequestration, storage, retention and loss in U.S. croplands: Issues paper for protocol development. Geoderma, 195-196: 201-206.

Panagos P., Hiederer R., Liedekerke M.V., Bampa F., 2013. Estimating soil organic carbon in Europe based on data collected through an European network. Ecological Indicators, 24: 439-450.

Sales W., 2010. Agriculture strategies for mitigating GHG emission: DNDC model and case studies. http://www.arb.ca.gov/research/seminars/salas/salas.pdf (accessed: 18.06.2015)

Sleutel, S., De Neve, S., Beheydt, D., Li, C., Hofman, G. 2006a. Regional simulation of long-term organic carbon stock changes in cropland soils using the DNDC model: 1. Large scale model validation against a spatially explicit dataset. Soil Use and Management, 22: 342-351.

Sleutel, S., De Neve, S., Beheydt, D., Li, C., Hofman, G. 2006b. Regional simulation of long-term organic carbon stock changes in cropland soils using the DNDC model: 2. Scenario analysis of management options. Soil Use and Management, 22: 352-361.

Smith P., Powlson D.S., Smith J.U., Falloon P., Coleman K., 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. Global Change Biology, 6: 525-539.

Smith P., Martino Z., Cai D., Gwary H., Janzen P., Kumar B. et al., 2008. Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences 363(1492): 789-813.

Soane B.D., Ball B.C., Arvidsson J., Basch G., Moreno F. J., Estrade R., 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil, Tillage Research, 118: 66-87.

Stockmann U., Adams M.A., Crawford J.W., Field D.J., Henakaarchchi N., Jenkins M. et al., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems and Environment, 164: 80-99.

Stuczyński T., Kozyra J., Łopatka A., Siebielec G., Jadczyszyn J., Koza P., Doroszewski A., Wawer R., Nowocień E., 2007. Przyrodnicze uwarunkowania produkcji rolniczej w Polsce. Studia i Raporty IUNG-PIB, 7: 77-115.

Syp A., Faber A., Kozak M., 2016. Assessment of N_2O emissions from rapeseed cultivation in Poland by various approaches. International Agrophysics, 30: 501-507.

Tum M., Strauss F., McCallum I., Günther K., Schmid E., 2012. How sensitive are estimates of carbon fixation in agricultural models to input data? Carbon Balance and Management, 7: 3.

Vleeshouwers L.M., Verhagen A., 2002. Carbon emission and sequestration by agricultural land use: a model study for Europe. Global Change Biology, 8: 519-530.

Wattenbach M., Sus O., Vuichard N., Lehuger S., Gottschalk P., Li L. et al., 2010. The carbon balance of European croplands: A cross-site comparison of simulation models. Agriculture, Ecosystems and Environment, 139: 419-453.

West T.O., Post W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation. Soil Science Society of America Journal, 66: 1930-1946.

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