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Modelling Soil Organic Carbon Changes on Arable Land under Climate Change – A Case Study Analysis of the Kočín Farm in Slovakia

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Abstract: We have estimated soil organic carbon and crop yield changes under distinct climate change scenarios for the Kočín farm in Slovakia. Two regional climate change scenarios, i.e. the A2 and B2 SRES emission scenarios, and a reference climate scenario have been included into the bio-physical process model EPIC to simulate the effects on the topsoil organic carbon stocks and crop yields for the period of 2010–2050. In addition, we have used the data from several fields of the Kočín farm including the soil data, crop rotational and management data as well as topographical data. The topsoil organic carbon stocks show a decreasing trend for the period of 2010–2050. Among all crop rotation systems and soil profiles, the losses over the period are 9.0%, 9.5%, and 10.7% for the reference, A2, and B2 climate scenarios, respectively. Increasing temperatures accelerate the decomposition of the soil organic carbon particularly when soils are intensively managed. The soil organic carbon changes are crop-rotation specific, which is partly due to the climate scenarios that affect the crop biomass production differently. This is shown by comparison of the crop yields. We conclude that EPIC is capable to reliably simulate effects of climate change on soil organic carbon and crop yields.

Keywords: arable land; climate change; Kočín farm; Slovakia; soil organic carbon

Soil organic carbon (SOC) does not only affect the soil fertility, it also determines many of the environmental soil functions. Since the climate is one of the main forces driving the changes in SOC, the expected climatic change can negatively affect both soil fertility and its non-productive functions. In recent years, SOC has been recognised as an important component in the global carbon cycling, particularly in the context of the climatic change (e.g., Van Camp *et al.* 2004), because it can be a source of carbon dioxide and other greenhouse gases or a sink by sequestering soil organic carbon. The call for reducing carbon emissions from soils and increasing soil carbon sequestration was promoted by the Kyoto Protocol to the United Nations Framework Convention on Climate Change as well as by the associated documents describing the land use, land use change, and forestry activities (Watson *et al.* 2000). Although agricultural ecosystems have a significant potential for carbon sequestration (e.g., Cole *et al.* 1996), the accumulated carbon is usually quickly released back to the atmosphere with a rapid

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export of biomass and increased mineralization in intensively managed soils. That is why agricultural soils have been generally recognised as a source of atmospheric carbon dioxide when considering the net carbon balance (Watson *et al.* 2000). In contrast, several land use measures have been identified for arable land as strategic technologies to support carbon sequestration (e.g., FAO 2004; Smith *et al.* 2008), such as conservation tillage with crop residue mulching. It implies that projecting SOC changes requires a complex modelling approach addressing both the land use and climate change aspects. In this study, we simulate only the effects of climate change assuming that farm land-use management systems (i.e. fertilization rates, crop rotation, tillage) remain constant over time.

The modelling of SOC dynamics has become a stable part of the environmental assessment in agriculture – including the climate change phenomena (e.g., Easterling *et al.* 1992, 1996). Biophysical process models such as CENTURY, DAISY, RothC, EPIC, or DNDC are able to simulate important geo-bio-physical and geo-chemical processes under different site conditions and management regimes. The EPIC model (Williams *et al.* 1984; Jones *et al.* 1991) was originally developed to simulate the erosion effects on soils and crop biomass (Putnam *et al.* 1988), but later it was extended to provide the abilities for integrated environmental impact assessments in agriculture (Williams 1995) including carbon dynamics (Izaurralde *et al.* 2001, 2006). EPIC allows the simulation of numerous crops and tillage operations, and contains other routines to simulate for example hydrological balances, N, P, and C cycling, soil density changes, tillage, wind and water erosion or leaching. It was also modified to simulate the effects of CO_2 changes on the plant growth (Stockle *et al.* 1992). In addition, the EPIC model can include climate change data and simulate the biophysical impacts on agro-ecosystem functions (e.g., Brown & Rosenberg 1999; Huszár *et al.* 1999).

In this article, we use EPIC to simulate SOC changes of alternative crop management systems and fields under climate change for the Kočín farm in Western Slovakia. The simulations include the data of two regional climate change scenarios, which were downscaled from the General Circulation Model scenarios (cf. Lapin *et al.* 2005; Lapin & Melo 2005), and a "reference" climate scenario, which has been modelled stochastically from historical records. The two regional climate change scenarios, namely the A2 and B2 SRES emission scenarios (cf. Nakicenovic & Swart 2000; Lapin *et al.* 2005; Lapin & Melo 2005), and the reference climate scenario are implemented in EPIC. These climate change scenarios cannot be perceived as "prognoses" here, but only as the time series modelling of climatic parameters based on healthy scientific principles (cf. Lapin 2004). The A2 scenario assumes continuously increasing global population and regionally oriented and slower economic growth. The B2 emission scenario assumes continuously increasing population (lower than A2) and intermediate economic development which emphasises on the environmental sustainability (cf. Nakicenovic & Swart 2000). Since we use a constant crop management in our modelling, it is assumed that SOC changes are attributed mainly to the climatic effects.

This case study does not present the classical fine-scaled modelling approach. But it aims at providing a robust farm-level modelling schema, which has a potential to cover Slovakia since it uses sources that are accessible on national scale. Once this modelling framework appears to be scientifically effective, it could be employed as a tool supporting decision making at different levels and could be helpful in environmental assessments including climatic change in agricultural land use and management.

MATERIAL AND METHODS

Study area

The Kočín farm is situated in the western part of the Trnavská pahorkatina Hilly Land in Slovakia (Figure 1). The farm area covers approximately 2420 ha, of which 1048 ha (43%) is used as cropland. In total, 10 fields covering 612 ha, i.e. 58% of the cropland, are analysed: 5301/1, 5501/1, 5601/1, 6501/1, 7302/1, 7401/1, 7602/1, 7603/1, 8301/1 and 8501/1 (numbering according to the Land Parcel Identification System of Slovakia, URL: www.podnemapy.sk/lpis_verejnost/viewer.htm). The field or parcel selection was determined by the soil data availability.

Soil and topography data

In total, 12 soil profiles have been included in the analysis. The soil profile data originates from the Complex Soil Survey database (Linkeš *et al.*

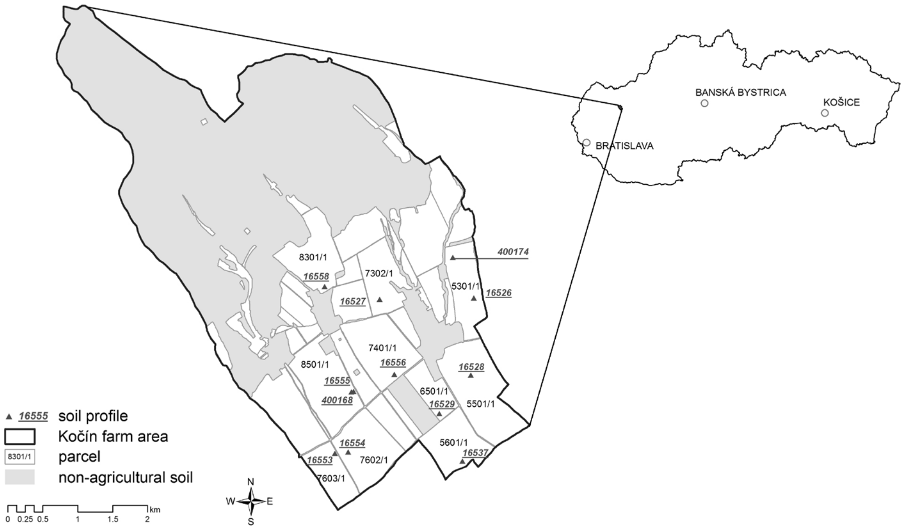

Figure 1. Map of the study area with the location of parcels and soil profiles (triangles with underlined labels)

1988) and the Soil Monitoring System database (Kobza *et al.* 2009). The soils are mainly Haplic Luvisols with loamy to clay-loamy texture, which developed from loess parent material. The selected soil profiles (Figure 1) represent a majority of the soil variability in the study area. Fourteen soil parameters have been derived or measured for each soil horizon and are input to EPIC (Table 1). Water retention properties have been estimated by pedo-transferring functions published by Orfánus *et al.* (2003) using the ROSETA model (Schaap *et al.* 1997). The slope, slope length, and elevation data have been derived from the detailed elevation model (cf. Ilavská 2007). The parcel areas have been obtained from the Land Parcel Identification System.

Climatic data

The following daily weather parameters are used for years 2010 to 2050: sunshine duration (in h per day), maximum and minimum air temperatures (in °C), and precipitation (in mm/day). In addition,

Table 1. List and values of soil parameters

Soil variables	Mean ± SD (topsoil)	Source
Soil reaction in water suspension	7.3 ± 0.5	CCS, SMS
Carbonates (%)	0 (26 in one profile)	CCS, SMS
Sum of base cations (cmol$_+$/kg)	16.4 ± 3.1	CCS, SMS
Cation exchange capacity (cmol$_+$/kg)	17.6 ± 3.3	CCS, SMS
Organic carbon (%)	0.96 ± 0.13	CCS, SMS
Sand (ø 0.05–2 mm) (%)	15.8 ± 6.9	CCS, SMS
Silt (ø 0.002–0.05 mm) (%)	59.8 ± 7.2	CCS, SMS
Nitrogen in organic matter (g/t)	1441 ± 177	PMS
Phosphorus in organic matter (g/t)	181 ± 35	PMS
Bulk density (t/m^3)	1.32 ± 0.04	PMS
Volume of stones (vol. %)	0	CMS, SMS
Wilting point at 1500 kPa (m^3/m^3)	0.102 ± 0.011	Roseta
Filed water capacity at 33 kPa (m^3/m^3)	0.297 ± 0.012	Roseta
Saturated hydraulic conductivity (mm/h)	8.4 ± 0.8	Roseta

CMS – Complex Soil Survey database (Linkeš *et al.* 1988); SMS – Soil Monitoring System database (Kobza *et al.* 2009); Roseta – model by Schaap *et al.* (1997); SD – standard deviation global daily radiation (in MJ/m^2) has been calculated from the sunshine duration. A "reference" climatic scenario (REF) for years 2010–2050 has been prepared with stochastic modelling from the daily data of the Jaslovské Bohunice meteorological station (years 1989–2009) – it is situated about 12 km southward from the study area. The WXGEN weather generator (cf. Nicks *et al.* 1990), which is considered one of the best models for stochastic weather generation (cf. Wallis & Griffiths 1995), has been used to simulate the reference daily weather parameters. In addition to the REF scenario, A2 and B2 climate change scenarios for the Jaslovské Bohunice meteorological station have been adopted (Lapin *et al.* 2005; Lapin & Melo 2005) – also the sequence of daily weather parameters for the years 2010 to 2050. Although the daily A2 and B2 scenario data have been modified according to the observed daily data (for more details on downscaling procedure see Lapin *et al.* 2005), it shall to be treated as areal average.

A2 and B2 climatic scenarios show a small increase in average daily minimum temperature compared to the REF scenario (Figure 2a) as well as a small increase in average daily maximum temperature (Figure 2b) during the majority of months. The A2 scenario assumes a higher temperature increase by the end of the simulated time period as compared to the B2 scenario. Both climatic change scenarios show an increase in average precipitation during the winter months, but a small decrease during the spring and summer periods (especially B2 scenario, see Figure 2c). Finally, both A2 and B2 scenarios show an increase in average sunshine duration almost during the year (Figure 2d).

Crop management data

Parcel-specific crop management data have been obtained from the Kočín farm management records. It has been aggregated and three crop rotation (CR) systems and crop specific fertilization regimes have been derived afterwards (Table 2). In addition, a crop management calendar has been projected following the farm management diary, including sowing and harvesting dates, tillage and fertilization dates and other cultivations. Individual crop rotation systems and respective fertilization rates have been applied to all soil profiles, i.e. three variants (CR1 to CR3) have been simulated for each soil profile. Conventional tillage consists of mouldboard ploughing, chisel ploughing (10 cm), regular seeding and two times

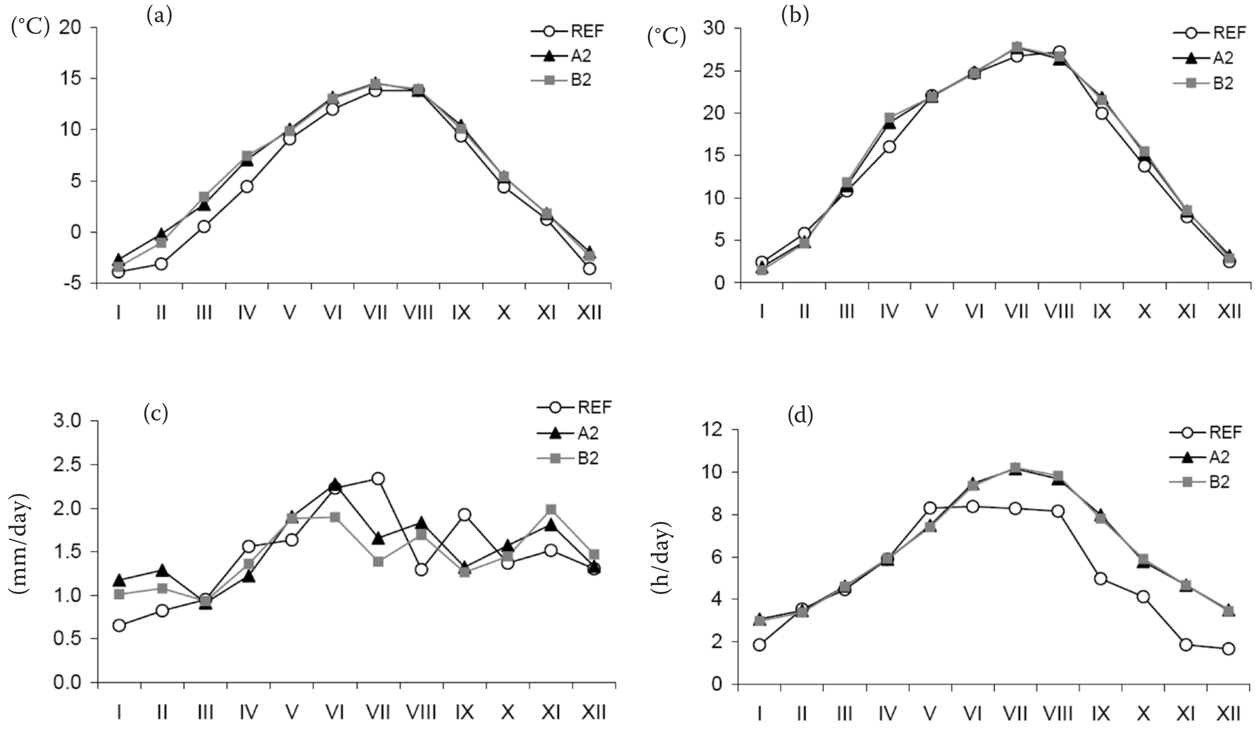

Figure 2. Average values of (a) daily minimum and (b) daily maximum air temperatures, (c) precipitation, and (d) sunshine duration for the reference scenario (REF) and A2 and B2 climate change scenarios for 2010 to 2050

Table 2. Crop rotation (CR) systems and crop fertilization rates

	Crop rotation systems		
Year	CR 1	CR 2	CR 3
1	silage corn	corn	silage corn
2	alfalfa	spring barley	spring barley
3	alfalfa	winter wheat	winter wheat
4	alfalfa	sugar beets	winter rape
5	winter wheat	winter wheat	winter wheat
6	spring barley		

Crop	Crop fertilization rates			
	mineral fertilizers (kg/ha)			manure (t/ha)
	N	P_2O_5	K_2O	
Winter wheat	107	35	30	–
Silage corn	145	9	17	30
Alfalfa	38	10	5	–
Spring barley	32	18	19	–
Corn	152	43	63	–
Sugar beets	96	0	0	40
Winter rape	160	84	50	–

spike harrowing. Irrigation has been omitted in this study to isolate the climatic effects. These scenarios do not represent a true crop management in any parcel, but they are considered to reproduce the likely crop shares and management regimes.

Modelling, validation, and statistical evaluation

The EPIC model version EPIC0509 has been used in this case study analysis. The model outputs of interest are (i) SOC stocks in the topsoil 0–30 cm (OCPD in t/ha) and (ii) dry matter crop yields (in t/ha), which are statistically compared between A2, B2, and REF climate change scenarios for the years 2010 to 2050. The crop yields are used to indirectly validate and evaluate the modelling outputs with the observations.

The modelling has been preceded with some pre-run simulations. It comprises the simulations of 20 years with the observed daily weather data (1990 to 2009, Jaslovské Bohunice meteorological station) using the crop rotations and soil profiles aiming to initialize the management-specific input variables, such as OCPD for example (Schmid *et al.* 2007; Sobocká *et al.* 2007). The pre-run outputs are used as the input for simulating the years 2010 to 2050. Afterwards, EPIC has been applied for all combinations of crop rotations, soil profiles, and climate scenarios. Changes in outputting such as OCPD and crop yields have been compared between the climate scenarios and statistically evaluated using the *t*-test in the Statistica software package (StatSoft 2001).

This modelling framework requires an indirect validation procedure since no time series of SOC are available. The validation procedure is based on testing whether EPIC can appropriately simulate the crop yields. We have validated whether the reference modelling (incl. reference climate) produces the crop yields that are consistent with the values originating from the Kočín farm statistical bulletin (years 1989 to 2005 for some parcels). Since we have not enough historical data to provide a statistically sound validation, we have simulated the crop yields using the historical records for winter wheat, spring barley, sugar beet and alfalfa (no sufficient data exists for other crops). The following fractions of water in the yield have been used to recalculate the dry matter yields: 14% for winter wheat and spring barley, 15% for alfalfa hay, and 84% for sugar beet, respectively. Student's *t*-test for unequal sample sizes and Levene's test for homogeneity in variances have been applied in this analysis.

RESULTS

Initialization of EPIC simulations

Topsoil organic carbon content (OCPD) has been initialized, along with other soil variables, with the pre-run simulations. EPIC has been applied for all combinations between the crop rotations and soil profiles and each soil profile has been initialized with average OCPD. The evolution of OCPD (Figure 3) shows a decreasing trend in the course of time (averaged in all soil profiles and crop rotations) until it reaches some kind of equilibrium by the end of the initialization period. This illustrates the idea of autonomous initialization of OCPD so that further changes (beyond 2010) can be attributed mainly to the climatic differences.

Crop yield comparison for reference modelling

The comparison of average crop yields between EPIC simulations (incl. referential climate scenario and conventional crop management) and statistical records indicates that EPIC slightly overestimates winter wheat (about 9%) and sugar beet yields (about 17%) and underestimates alfalfa yields (about 21%). The modelled spring barley yields are about 4% lower compared to the statistical data on average, but this difference is not statistically significant at the 95% confidence level (Table 3). The EPIC model produces significantly lower variances in winter wheat yields, but for the other tested crops these variances do not significantly differ from those obtained from statistical records. Maize and rape have not been analysed since we do not have enough statistical records available for the farm. We must also perceive that the water content coefficients, which are used to convert to dry matter yields, may vary within some intervals and this may contribute to the uncertainty of this comparison.

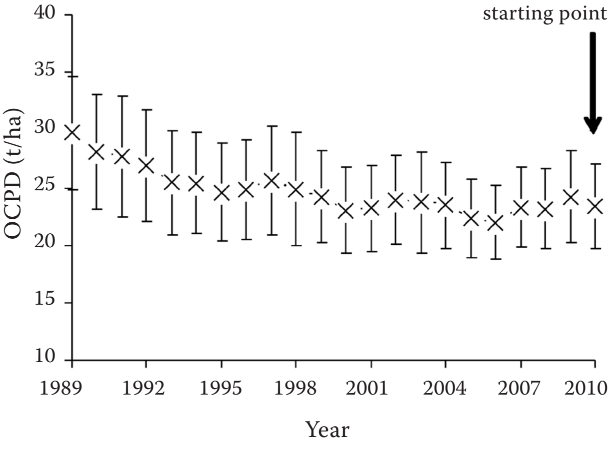

Figure 3. Simulation of SOC in the topsoil 0–30 cm (OCPD in t/ha, average ± SD) between 1989 and 2010 (average of all soil profiles and crop rotations)

It is indirectly shown that our SOC simulations may contain uncertainties coming from over- or underestimating biomass of individual crops. Although there is not a perfect fit with observed data, we can state that EPIC simulates likely crop yields and their variability.

Soil organic carbon and crop yield changes in 2010 to 2050

The simulation outputs have been compared at different levels. The levels of comparison include (i) by soil profiles and crop rotation system separately, (ii) by all soil profiles and crop rotation systems, and (iii) separately for individual crops. The first level of comparison enables the evaluation of OCPD and crop yields under different site conditions and various crop rotation systems. The second level of comparison allows a trend analysis of the SOC pools over the years 2010–2050, and the third level of comparison enables the crop yield comparisons between different climatic scenarios.

The first comparison results (Appendix 1) indicate that neither of the two climate change scenarios (A2 and B2) affects the average yields per crop rotation systems significantly. However, some crops are affected in a positive way while the others negatively. Nevertheless, both A2 and B2 scenarios show a statistically significant decrease in the topsoil SOC stocks for all studied parcels and crop rotation systems in comparison with the reference climate scenario. The average OCPD decreases between 1.7% and 6% (3.5% on average over all parcels) when A2 is compared to the reference climate scenario. The highest decrease in OCPD is shown on parcel 5501/1 (crop rotation systems 2 and 3). The modelling results of the B2 scenario also indicate a decrease in topsoil SOC stocks as compared to the reference scenario. The average OCPD decreases between 0% and

Table 3. Comparison between modelled average crop yields and average crop yields from statistical sources (farm statistical bulletin) in t_{DM}/ha; Student's *t*-test for unequal sample sizes and Levene's test are used for testing differences between means and standard deviations respectively

	Crop	Crop yield statistics		Modelled crop yields		*P*-value
		N	mean	N	mean	
Analysis of mean	Winter wheat	35	4.57	360	4.99	< 0.001
	Spring barley	28	4.16	252	3.99	0.315
	Alfalfa	25	5.26	372	4.17	< 0.001
	Sugar beets	21	8.34	144	9.79	0.036
		N	SD	N	SD	
Analysis of standard deviation	Winter wheat	35	0.89	360	0.58	0.002
	Spring barley	28	0.86	252	0.74	0.183
	Alfalfa	25	1.19	372	1.09	0.853
	Sugar beets	21	1.33	144	1.91	0.163

N – number of observations, DM – dry matter, SD – standard deviation

6.6% (4.5% on average over all parcels). Again, parcel 5501/1 (crop rotation systems 2 and 3) is identified as the most vulnerable. On the other hand, smaller changes are simulated on parcels 8301/1 (A2 scenario and CR 1) and 5301/1 (B2 scenario, CR 1). On average, the smallest OCPD losses are simulated for the crop rotation system one (CR1).

The topsoil organic carbon stocks show a decreasing trend for the years 2010–2050 with all climate scenarios (Figure 4). The OCPD losses are about 9% (1.8 t/ha), 9.5% (2.1 t/ha) and 10.7% (2.4 t/ha) for REF, A2 and B2 climate change scenarios, respectively. Furthermore, OCPD seems to reduce more slowly under A2 than B2 climate change scenario, which might be explained with an increased biomass production by some crops and higher organic residue inputs.

The third level of comparison (Table 4) shows that the crop yield changes significantly vary with the crop. In the A2 climate scenario, the model simulates an increase in corn yields (about 17% for corn, and 8% for silage corn), sugar beet yields (about 9%) and winter rape yields (about 14%). In contrast, decreases in winter wheat (about –2%) and spring barley (about –11%) yields are simulated. No significant change in the yield has been simulated for alfalfa between the A2 and REF climate scenarios. In the B2 climate change scenario, only the decreases in winter wheat (about –2.6%) and alfalfa yields (about –7%) are statistically significant.

DISCUSSION

The average topsoil organic carbon stocks show a decreasing trend over the years 2010–2050 in all climate scenarios. The SOC trends of the B2 and A2 climate change scenarios are more declining than that of the reference climate scenario. Based on these simulations, we could expect that the increasing temperature, which is here associated with the climate change, accelerates the decomposition of the soil organic carbon as expected by Smith *et al.* (2005). However, it is worth noticing that carbon-favourable management practices can highly influence SOC dynamics (e.g. FAO 2004; Smith *et al.* 2008) so as to stabilise the SOC depletion even under global warming. Therefore, we see our simulation results as a climate-related threat to the topsoil organic carbon stocks provided that adequate crop adaptation measures are not adopted.

We show that the changes in the SOC stocks are crop-rotation specific. This is due to different sediment losses by crops and tillage as well as due to the crop biomass and residue yields under the different climate change scenarios. The first crop rotation system (CR1) includes three consecutive years of alfalfa cultivation, which appears to be the most effective in stabilizing SOC depletion. The two other crop rotation systems lead to substantial losses in SOC stocks.

The simulations show that the climate change scenarios affect crop yields significantly. Statistically significant changes are simulated for the

Appendix 1. Statistical evaluation of crop yields and topsoil organic carbon stocks (OCPD 0–30 cm) effects from the A2 and B2 climate change scenarios for individual crop rotations and land parcels/profiles

Parcel (soil profile)	Crop rotation	Climatic scenario	Yield (t_{DM}/ha)			OCPD (t/ha)			Parcel (soil profile)	Crop rotation	Climatic scenario	Yield (t_{DM}/ha)			OCPD (t/ha)		
			mean	SD	% change to REF	mean	SD	% change to REF				mean	SD	% change to REF	mean	SD	% change to REF
5301/1 (16526)	CR 1	REF	5.94	3.39	–	23.75	1.53	–	7602/1 (16554)	CR 1	REF	5.92	3.44	–	26.06	1.61	–
		A2	5.87	3.66	−1.20	23.15	1.28	−2.54***			A2	5.86	3.70	−0.95	25.46	1.35	−2.29***
		B2	5.75	3.63	−3.25	23.75	1.35	0			B2	5.74	3.67	−3.03	25.04	1.49	−3.90***
	CR 2	REF	5.97	2.40	–	21.61	0.85	–		CR 2	REF	6.08	2.50	–	23.75	1.00	–
		A2	6.22	2.82	4.26	20.7	0.81	−4.20***			A2	6.34	2.87	4.18	22.83	1.01	−3.91***
		B2	5.85	2.36	−1.88	20.38	0.92	−5.72***			B2	5.92	2.37	−2.71	22.53	1.16	−5.16***
	CR 3	REF	5.66	3.63	–	20.65	0.51	–		CR 3	REF	5.68	3.65	–	22.62	0.74	–
		A2	5.84	4.20	3.23	19.77	0.71	−4.25***			A2	5.9	4.25	3.82	21.75	0.95	−3.84***
		B2	5.5	3.64	−2.76	19.65	0.86	−4.84***			B2	5.52	3.64	−2.83	21.64	1.13	−4.33***
7302/1 (16527)	CR 1	REF	5.63	3.02	–	19.38	1.37	–	8501/1 (16555)	CR 1	REF	5.84	3.22	–	22.3	1.44	–
		A2	5.58	3.26	−0.91	18.94	1.20	−2.24***			A2	5.77	3.51	−1.14	21.63	1.28	−2.97***
		B2	5.5	3.42	−2.38	18.55	1.13	−4.24***			B2	5.65	3.51	−3.18	21.36	1.34	−4.19***
	CR 2	REF	5.49	2.12	–	17.3	0.67	–		CR 2	REF	5.98	2.50	–	20.18	0.90	–
		A2	5.74	2.43	4.53	16.67	0.57	−3.62***			A2	6.2	2.81	3.79	19.19	1.00	−4.89***
		B2	5.44	2.16	−0.93	16.42	0.58	−5.10***			B2	5.81	2.33	−2.83	19.03	1.07	−5.71***
	CR 3	REF	5.33	3.25	–	16.48	0.34	–		CR 3	REF	5.55	3.46	–	18.99	0.62	–
		A2	5.46	3.76	2.48	15.85	0.41	−3.82***			A2	5.76	4.01	3.61	18.14	0.86	−4.48***
		B2	5.22	3.32	−2.10	15.79	0.53	−4.22***			B2	5.43	3.50	−2.20	18.05	1.10	−4.95***
5501/1 (16528)	CR 1	REF	5.83	3.16	–	24.71	1.61	–	7401/1 (16556)	CR 1	REF	5.72	3.21	–	20.87	1.38	–
		A2	5.77	3.41	−1.15	23.94	1.43	−3.11***			A2	5.67	3.51	−0.73	20.41	1.17	−2.19***
		B2	5.67	3.47	−2.82	23.44	1.53	−5.14***			B2	5.57	3.55	−2.52	20.2	1.15	−3.22***
	CR 2	REF	5.87	2.31	–	21.93	0.97	–		CR 2	REF	5.75	2.33	–	19.11	0.78	–
		A2	6.11	2.64	4.09	20.67	1.05	−5.75***			A2	6.01	2.69	4.43	18.49	0.66	−3.24***
		B2	5.77	2.30	−1.74	20.48	1.24	−6.65***			B2	5.65	2.26	−1.75	18.28	0.66	−4.35***
	CR 3	REF	5.55	3.42	–	20.98	0.71	–		CR 3	REF	5.47	3.45	–	17.95	0.53	–
		A2	5.71	3.93	2.85	19.73	0.96	−5.93***			A2	5.65	3.96	3.27	17.51	0.61	−2.46***
		B2	5.43	3.48	−2.19	19.63	1.22	−6.40***			B2	5.34	3.47	−2.48	17.57	0.52	−2.12***

Appendix 1 to be continued

Parcel (soil profile)	Crop rota- tion	Climatic scenario	Yield (t_{DM}/ha)			OCPD (t/ha)			Parcel (soil profile)	Crop rota- tion	Climatic scenario	Yield (t_{DM}/ha)			OCPD (t/ha)		
			mean	SD	% change to REF	mean	SD	% change to REF				mean	SD	% change to REF	mean	SD	% change to REF
6501/1 (16529)	CR 1	REF	5.72	3.11	–	20.75	1.46	–	8301/1 (16558)	CR 1	REF	5.76	3.27	–	23.84	1.63	–
		A2	5.66	3.37	–0.99	20.23	1.24	-2.49^{***}			A2	5.72	3.56	–0.72	23.43	1.35	-1.70^{***}
		B2	5.56	3.47	–2.80	19.8	1.24	-4.59^{***}			B2	5.6	3.57	–2.76	23.13	1.46	-2.96^{***}
	CR 2	REF	5.67	2.21	–	18.56	0.77	–		CR 2	REF	5.83	2.34	–	21.28	1.15	–
		A2	5.92	2.56	4.47	17.82	0.71	-3.98^{***}			A2	6.12	2.75	4.84	20.73	1.08	-2.61^{***}
		B2	5.6	2.25	–1.24	17.58	0.82	-5.32^{***}			B2	5.74	2.28	–1.68	20.47	1.16	-3.83^{***}
	CR 3	REF	5.43	3.34	–	17.67	0.48	–		CR 3	REF	5.53	3.49	–	20.24	0.95	–
		A2	5.58	3.85	2.83	16.93	0.59	-4.17^{***}			A2	5.72	4.02	3.42	19.71	1.02	-2.64^{***}
		B2	5.31	3.39	–2.10	16.86	0.75	-4.59^{***}			B2	5.38	3.51	–2.63	19.61	1.13	-3.14^{***}
5601/1 (16537)	CR 1	REF	5.89	3.28	–	29.76	1.75	–	8501/1 (400168)	CR 1	REF	5.85	3.20	–	26.28	1.46	–
		A2	5.82	3.56	–1.16	28.9	1.57	-2.91^{***}			A2	5.78	3.47	–1.15	25.39	1.29	-3.39^{***}
		B2	5.7	3.55	–3.23	28.51	1.82	-4.20^{***}			B2	5.67	3.50	–2.95	25.01	1.39	-4.83^{***}
	CR 2	REF	6.03	2.46	–	26.89	1.22	–		CR 2	REF	6.04	2.47	–	24.52	0.94	–
		A2	6.27	2.79	4.01	25.67	1.34	-4.54^{***}			A2	6.28	2.74	3.96	23.3	0.98	-4.97^{***}
		B2	5.87	2.34	–2.62	25.45	1.50	-5.35^{***}			B2	5.86	2.31	–2.89	23.09	1.08	-5.83^{***}
	CR 3	REF	5.61	3.52	–	25.2	0.92	–		CR 3	REF	5.57	3.44	–	23.1	0.63	–
		A2	5.82	4.09	3.67	24.14	1.17	-4.18^{***}			A2	5.77	3.98	3.56	22.07	0.83	-4.45^{***}
		B2	5.47	3.56	–2.47	23.96	1.48	-4.89^{***}			B2	5.47	3.49	–1.94	21.99	1.15	-4.79^{***}
7603/1 (16553)	CR 1	REF	5.94	3.44	–	24.24	1.63	–	5301/1 (400174)	CR 1	REF	5.64	2.97	–	27.4	1.83	–
		A2	5.88	3.71	–0.91	23.63	1.39	-2.54^{***}			A2	5.58	3.20	–1.08	26.78	1.67	-2.23^{***}
		B2	5.75	3.68	–3.13	23.23	1.50	-4.17^{***}			B2	5.51	3.39	–2.43	26.45	1.85	-3.47^{***}
	CR 2	REF	6.08	2.48	–	21.82	1.00	–		CR 2	REF	5.76	2.20	–	24.71	1.53	–
		A2	6.33	2.88	4.07	20.89	1.03	-4.25^{***}			A2	5.98	2.52	3.87	23.78	1.62	-3.76^{***}
		B2	5.92	2.39	–2.59	20.62	1.17	-5.51^{***}			B2	5.62	2.24	–2.27	23.61	1.72	-4.44^{***}
	CR 3	REF	5.69	3.67	–	20.74	0.79	–		CR 3	REF	5.38	3.19	–	23.46	1.30	–
		A2	5.91	4.28	3.75	19.86	0.95	-4.27^{***}			A2	5.56	3.70	3.37	22.63	1.44	-3.55^{***}
		B2	5.53	3.68	–2.84	19.73	1.16	-4.89^{***}			B2	5.28	3.30	–1.86	22.48	1.70	-4.19^{***}

SD – standard deviation, DM – dry matter, REF – reference climatic scenario

Table 4. Statistical evaluation of crop yields in the reference climate scenario (REF) and the A2 and B2 climate change scenarios

Crop name	Climatic scenario	*N*	Crop yield (t_{DM}/ha)		
			mean	SD	% change to the REF scenario
Winter wheat	REF	528	5.05	0.61	–
	A2	528	4.94	0.78	–2.1**
	B2	528	4.91	0.86	–2.6***
Corn	REF	108	6.49	1.58	–
	A2	108	7.59	1.07	16.9***
	B2	108	6.09	1.94	–6.2
Sugar beets	REF	108	9.49	2.08	–
	A2	108	10.30	1.32	8.6***
	B2	108	9.12	2.11	–3.8
Winter rape	REF	108	1.86	0.31	–
	A2	108	2.12	0.38	14.2***
	B2	108	1.92	0.35	2.9
Silage corn	REF	204	12.01	1.84	–
	A2	204	12.99	1.92	8.1***
	B2	204	11.93	2.95	–0.7
Spring barley	REF	336	3.96	0.60	–
	A2	336	3.52	0.98	–11.2***
	B2	336	3.98	0.81	0.5
Alfalfa	REF	264	4.30	1.16	–
	A2	264	4.21	1.05	–1.9
	B2	264	4.01	0.91	–6.6***

N – number of observations, DM – dry matter, SD – standard deviation, **statistically significant at $P < 0.05$, ***statistically significant at $P < 0.01$

A2 climate change scenario, where some crops show a small decrease in the yield (wheat and barley) and others an increase (corn and silage maize, sugar beet and winter rape). The crop yield changes associated with the B2 climate change scenario are not statistically significant except for winter wheat and alfalfa, showing lower yields. The changes in the crop yields correlate with the crop residue dynamics, which partially explains SOC changes. These model results demonstrate only a potential climate-related threat since the crop yields can be effectively managed by the crop management practices.

The model validation reveals that the simulated crop yields are in the range of the crop yields originating from the farm statistical sources. Although it is not possible to validate directly the SOC changes, we assume that the likely crop yields lead to the likely SOC changes when aggregated by parcels and crop rotations. Since the crop management remains constant over the parcels and time, we assume that the majority of the SOC changes can be attributed to the climate change. We can conclude that the presented farm modelling approach has the potential to be used for the national assessment in Slovakia. Similar modelling framework and data are available for any management and administration units, such as farms or districts for example.

We must comment other sources of uncertainty in this study. Firstly, the soil erosion events are loaded

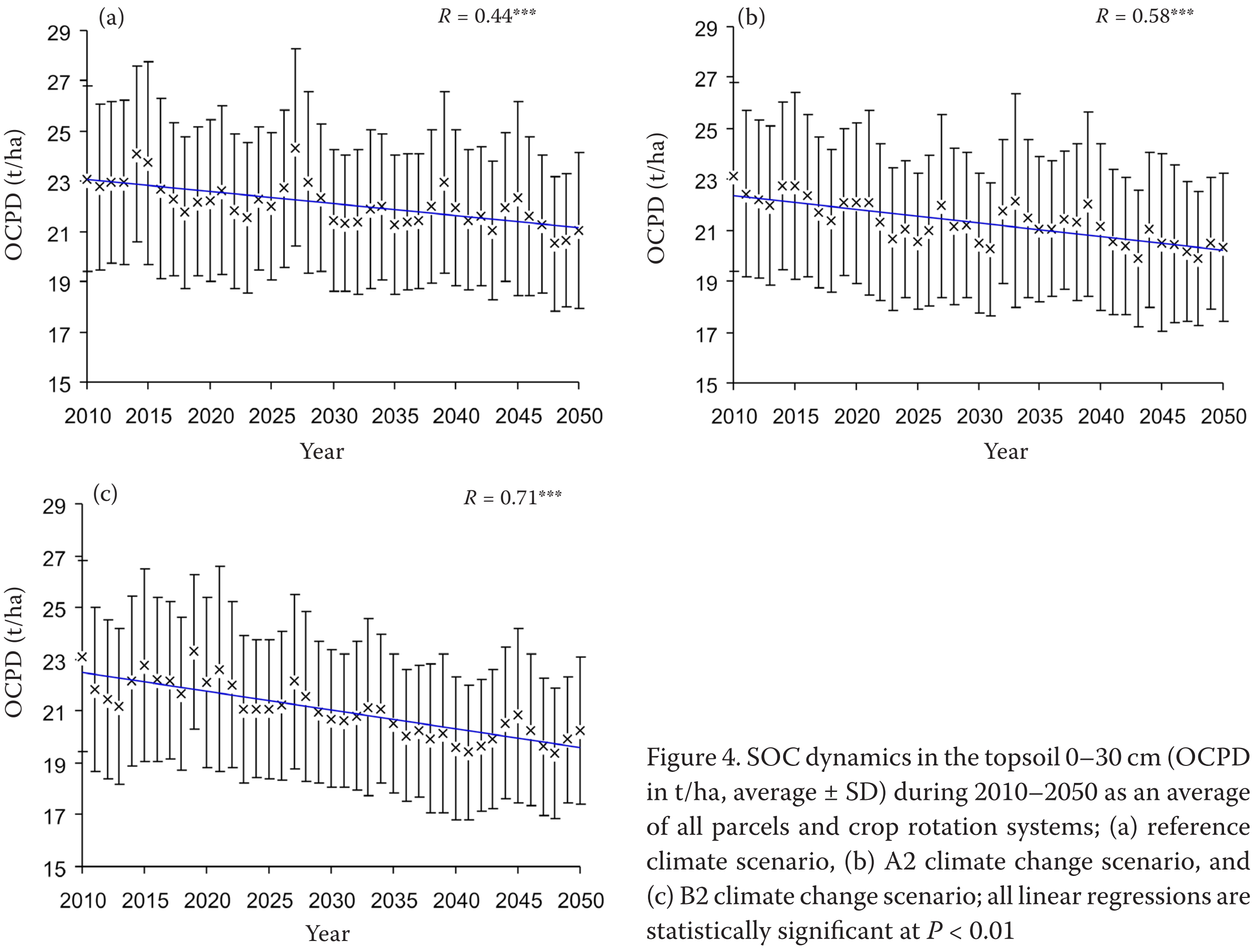

Figure 4. SOC dynamics in the topsoil 0–30 cm (OCPD in t/ha, average ± SD) during 2010–2050 as an average of all parcels and crop rotation systems; (a) reference climate scenario, (b) A2 climate change scenario, and (c) B2 climate change scenario; all linear regressions are statistically significant at $P < 0.01$

with serious uncertainties by the climatic scenarios, which do not provide an adequate distribution of rainfall events on the daily basis. Considering the fact that the study area is highly vulnerable to water erosion (Ilavská 2007), true SOC losses may deviate from our simulations. Secondly, the trends in CO_2 concentrations are not specifically addressed in this study and shall be explicitly considered in the following analyses.

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