Application of RothC Model to Predict Soil Organic Carbon Stock on Agricultural Soils of Slovakia

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Abstract: Soil organic matter (SOM) takes part in many environmental functions and, depending on the conditions, it can be a source or a sink of the greenhouse gases. Presently, the changes in soil organic carbon (SOC) stock can arise because of the climatic changes or changes in the land use and land management. A promising method in the estimation of SOC changes is modelling, one of the most used models for the prediction of changes in soil organic carbon stock on agricultural land being the RothC model. Because of its simplicity and availability of the input data, RothC was used for testing the efficiency to predict the development of SOC stock during 35-year period on agricultural land of Slovakia. The received data show an increase of SOC stock during the first (20 years) phase and no significant changes in the course of the second part of modelling. The increase of SOC stock in the first phase can be explained by a high carbon input of plant residues and manure and a lower temperature in comparison with the second modelling part.

Keywords: agricultural land; RothC; Slovakia; soil organic carbon

One of the most important indicators of soil quality is soil organic matter (SOM), which is an important building block for the soil structure, formation of stable aggregates, and is able to improve the infiltration rates and the storage capacity for water (Jones *et al*. 2005). SOM presents a major pool of carbon in the biosphere and can act both as a source and a sink for carbon dioxide and other greenhouse gases. Agricultural intensification and cultivation in general results in a serious decrease in SOM as compared to that in the natural vegetation. Presently, the protection of soil organic matter is one of the main tasks, because SOM in addition to its soil fertilizing function can act in the elimination of the soil contamination and carbon sequestration. Under steady state conditions, each soil reaches equilibrium carbon content, depending on a number of factors such as the land use, land management, soil type, and climate. This equilibrium can be disturbed by the land use and land management changes or climatic changes. Generally, each soil type is characterized by its specific content of organic carbon. It is also clear that the cropland soils are characterized by a lower soil organic carbon (SOC) content as compared to similar soils under native forest or grassland on the same soil type (Guo & Gifford 2002). The changes of soil organic matter in Slovakia are observed on the national level by SOC monitoring running from 1993, which is a part of Complex Soil Monitoring of Slovakia. Even though the sampling is realized only every 5th year, it is possible to evaluate the changes in SOM in the past period on the basis of these data. Nevertheless, the prediction of soil organic carbon stock as a consequence of climatic changes and rapid changes in the land use and land management is a very important task for the future. One of the most promising tools for the estimation of SOC stock is modeling. There are several types of models for the estimation of soil organic carbon stock (SOMM, ITE, Verberne, RothC, CANDY, DNDC, CENTURY, DAISY, NC-SOIL). RothC and CENTURY are two of the most widely used and tested SOM models. The CENTURY model is a general ecosystem model for C, N, P, S cycling in the soil-plant system (Parton *et al.* 1992). At present, the CENTURY model was used for modelling SOC stock on one of the representative Slovak cropping farm (Sobocká *et al.* 2007). However, this model needs very detailed input data whose acquisition is a problem with all agricultural soils in a specific region or country. RothC-26.3 (Colleman & Jenkinson 2005) was originally developed and parameterised to model the turnover of organic C in arable topsoils from the Rothamsted Long Term Field Experiments. RothC-26.3 was tested in long term experiments on a range of soils and climatic conditions in Western and Central Europe. In a majority of cases, this model was tested on long-term experimental sites with detailed descriptions of the sites conditions and treatments (Coleman *et al.* 1997; Smith *et al.* 1997; Falloon & Smith 2002; Barančíková 2007; Ludwig *et al.* 2007). The CENTURY and RothC models are applied to the prediction of soil organic carbon stock on regional and national scales (Falloon *et al.* 1998, 2002; Falloon & Smith 2003; Smith *et al.* 2005, 2007; van Wesemael *et al.* 2005; Easter *et al.* 2007).

For SOC stock modelling on agriculture lands of Slovakia, it was decided to use RothC-26.3 model because of its simplicity and the availability of the data to run the model. The validation of this model in Slovak conditions was done on selected key monitoring localities (Barančíková 2007). RothC-26.3 model was used also for the estimation of SOC stock on particular Slovak agricultural farms in the future (Barančíková & Halás 2008).

In this paper, we present the testing of the RothC model usefulness for the prediction of the SOC in agricultural soils of Slovakia on the country level.

MATERIAL AND METHODS

Sites selection

No monitoring exists of the long-term SOC dynamics in Slovakia. Regarding this fact, it was necessary to combine the existing soil profile data from two separate datasets and thus to obtain both the initial soil carbon values and the validation dataset for the testing of the RothC modelling outputs for the time period of 1970–2006.

The complex soil survey database (Linkeš *et al.* 1988) contains the soil profile descriptions and analytical data collected in 1961–1970 time period. The database of soil monitoring (Kobza *et al.* 2009) contains the time series of the soil profile analytical data for the period from 1993 to 2002.

The sites represented by two spatially and semantically corresponding soil profiles, coming from the Complex soil survey database and the Database of soil monitoring, were selected based on several criteria:

- Minimal distance between the soil profiles
- Same or very similar genetic soil types of the soil profiles
- Same or very similar clay contents of the soil profiles
- Same land cover/land use (arable land or grassland) reported for the soil profiles
- Availability of relevant long-term meteorological data for the site

From the set of all possible sites, the final set of 32 sites in total was selected so that it could sufficiently represent the soil cover and agro-climatic conditions of Slovakia. The localisation of the selected sites can be seen in Figure 1.

RothC-26.3 model

The RothC-26.3 model splits SOC into four active compartments and a small amount of inert organic matter. The active compartments are the Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). Inert organic matter (IOM) content in RothC model is defined as a fraction of soil organic matter that is biologically inert and has an equivalent radiocarbon age of more than 50 000 years. The IOM compartment is resistant to decomposition and it was calculated

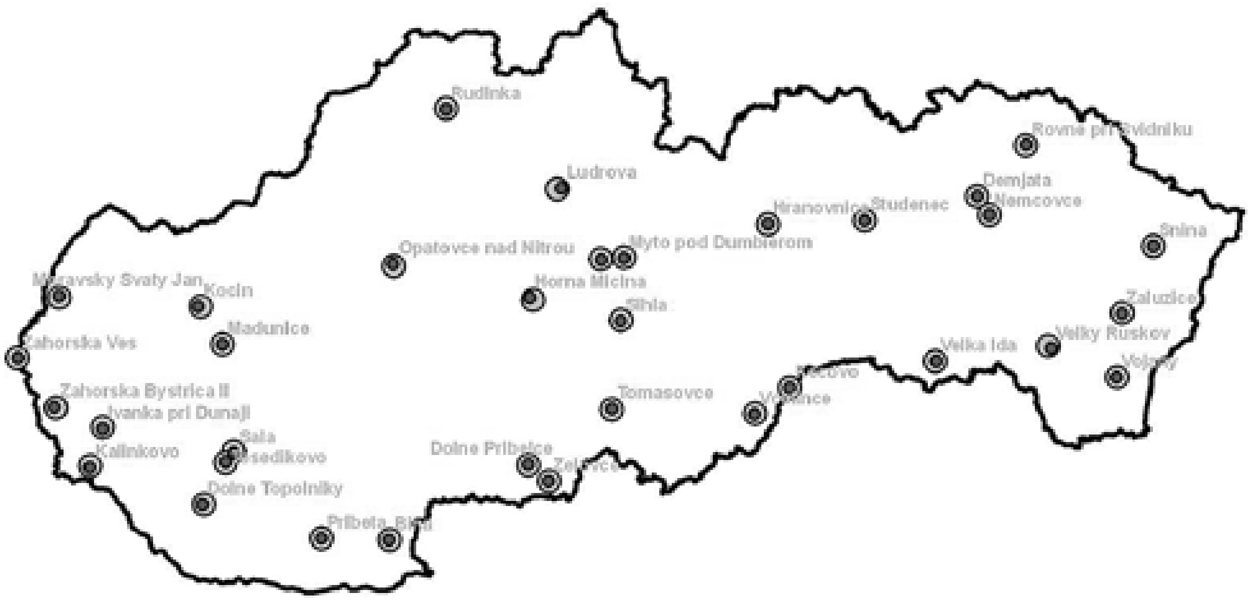

Figure1. Localisation of the selected sites for the modelling of SOC stock on agricultural land

according to Falloon formula (Falloon *et al.* 1998). The incoming plant carbon is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming material. These pools in turn decompose exponentially to form CO_2 and BIO+HUM. The clay content of the soil (in percentage) is one of the input parameters and is used to calculate how the topsoil can hold the water available for plants and it also affects the way in which the organic matter decomposes. The clay content determines the ratio between the CO_2 and BIO+HUM produced. The decomposition rate is modified as a function of temperature, soil moisture deficit, and the presence of the plant cover (Colemam & Jenkinson 2005).

Further details of the RothC model and the model itself can be obtained from the GCTE SOMNET website.

Input data

The RothC-26.3 model requires three types of data:

(a) Climatic data – monthly rainfall (mm), monthly evapotranspiration (mm), average monthly mean air temperature (°C);

(b) Soil data – clay content (%), inert organic carbon (IOM), initial soil organic carbon (SOC) stock (t C/ha), depth of the soil layer considered (cm);

(c) Land use and land management data – soil cover, monthly input of plant residues (t C/ha), monthly input of farmyard manure (FYM) (t C/ha), residue quality factor (DPM/RPM ratio).

(a) Climatic data

Meteorological stations network (individual meteorological stations) data coming from the Slovak Hydro-meteorological Institute were analysed and interpreted to obtain the input climatic data for the RothC modelling.

The minimal distance between the meteorological station and the corresponding modelling site, the similarity of the environmental conditions compared to the corresponding site, and weather data accessibility and completeness were applied as the decisive criteria in the process of the relevant meteorological station selection. For each meteorological station, the monthly rainfall (mm) and average monthly mean air temperature (°C) were calculated based on daily data. The monthly potential evapotranspiration (mm) was calculated on the basis of Pennmann equation. The missing monthly weather data were complemented in the final data processing with the data observed at the same weather station and identical month in preceding or following year.

(b) Soil data

Initial SOC stock (t C/ha) was calculated according to Eq. (1) from the available topsoil data coming from the Complex soil survey database:

Table 1. Basic soil data, meteorological stations, average annual carbon input of plant residues (C PR) and manure (C MR) on the selected sites

Locality	Soil type (WRB)	Meteorological stations	Clay content (%)	SOC (t/ha)	IOM (t/ha)	C PR (t/ha)	C MR (t/ha)
Opatovce nad Nitrou	haCM(ca)	Prievidza	29.6	27.1	2.1	1.40	0.66
D. Topoľníky	haFL	Zihárec	3.4	30.6	2.4	1.64	0.70
Tešedíkovo	moFL	Zihárec	34.2	65.3	5.7	1.07	0.86
Šaľa	haFL	Zihárec	13.3	25.5	2.0	1.14	0
Ivánka pri Dunaji	haFL	Bratislava-letisko	5.4	22.7	1.7	1.53	0.58
Záhorská Ves	haFL	Moravský Sv. Ján	32.3	18.9	1.4	1.21	0.76
Kalinkovo	haFL(ar)	Bratislava-letisko	16.1	38.5	3.1	1.70	0.66
Madunice	haFL	Piešťany	4.8	37.8	3.1	1.35	0
Kočín	ccctLV	Piešťany	25.4	23.6	1.8	1.37	0.38
Moravský Svätý Ján	haAR	Mor.Sv.Ján	2.6	22.3	5.9	0.83	0.6
Záhorská Bystrica	rzLP	Stupava	9.1	31.6	2.5	4.88	0.2
Biňa	haFL	Želiezovce	15.5	32.7	2.6	1.91	0.69
Horná Mičina	haCaM(ca)	B. Bystrica	24.2	57.5	4.9	1.43	0.33
Príbeta	glnCH	D. Plachtince	16.0	27.0	2.1	1.64	0.21
Želovce	haFL	D. Plachtince	22.6	29.8	2.3	1.17	0.58
Mýto pod Ďumbierom	haCM	Brezno	4.2	50.7	4.3	1.52	0.23
Sihla	haCM	Lomnica n. Rimavicou	5.2	86.0	7.8	4.79	0.02
Horná Lehota	haCM(ca)	Brezno	11.3	54.4	4.6	2.81	0.39
Rudinka	haFL	Žilina	10.5	27.8	2.2	1.03	0.57
Tomášovce	stabctLV	Bolkovce	17.2	28.9	2.3	1.9	0
Včelince	glnCH	Rimavská Sobota	20.9	40.6	3.3	1.17	0.75
Ludrová	rzLP	Ružomberok	13.3	67.4	5.9	1.44	0.85
Nemcovce	lvST	Prešov	21.2	29.5	2.3	1.07	0.09
Kecovo	ctLV(cr)	Silica	40.0	27.1	2.1	1.2	0.31
Veľká Ida	moGL	Košice	25.4	49.4	4.2	0.7	0.37
Snina	lvST	Kamenica n. Cirochou	7.2	29.7	2.3	1.12	0.48
Rovné	stCM	Stropkov-Tisinec	5.4	26.5	2.0	2.67	0
Veľký Ruskov	glnPH	Milhostov	31.0	39.4	3.2	1.48	0.25
Vojany	lvST	Vysoká n. Uhom	12.1	9.2	0.6	1.1	0.81
Studenec	glPH	Spišské Vlachy	13.6	22.0	1.7	1.26	0.66
Hranovnica	haCM	Ganovce	18.6	49.9	4.2	0.78	0.66
Zalužice	stabctLV	Michalovce	9.8	35.1	2.8	0.83	0.59

SOC – initial soil organic carbon stock; IOM – inert organic carbon

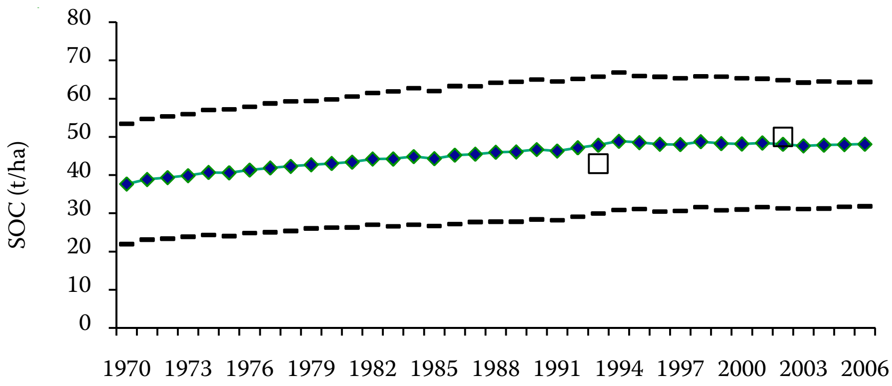

Figure 2. Observed and simulated data of the SOC stock on the selected sites on agricultural land in Slovakia

---- confidence limits of the simulated data
—◆— modelled SOC
—□— observed SOC

$$\text{Intial SOC Stock} = \text{SOC} \times \text{BD} \times \text{SD} \tag{1}$$

where:

SOC – concentration of soil organic carbon (%)
BD – bulk density (g/cm^3) calculated from the available soil texture and SOC data by the pedotransfer function published by Linkeš *et al.* (1989)
SD – topsoil depth (cm)

The initial SOC content is used for running the RothC model to equilibrium under constant environmental conditions. Because of the lack of climatic data before 1960, the constant climatic conditions were taken as the average of the climatic data from 1960–1990. For each locality, first of all RothC was run to equilibrium (10 000 years), iteratively fitting carbon inputs to match the initial SOC stock and thus the distribution in compartments (DPM, RPM, BIO, HUM) with different decomposition rates. The data of carbon and radiocarbon ages in all these compartments received in equilibrium mode (initial soil state, initial radiocarbon ages) were used to run the model in short term mode (for the modelling of SOC in the time period from 1970–2006).

The SOC stock for the validation set was calculated from the Soil monitoring database topsoil data by Eq. (1).

The data of topsoil clay content (clay fraction < 0.001 mm) were obtained from the available topsoil data coming from the Complex soil survey database were used.

The depth of the soil layer for modelling was set to 20 cm.

(c) Management data

The management data were obtained on the basis of universal questionnaires which had been addressed to all users of the selected sites. The questionnaire contained the data about crops cultivated in the time period of 1970–2007, tillage practices during this period, organic fertiliser application rates and crop yields for all years and crops yields. The missing data for the beginning of the (1970–1980) of the modelling period were completed by an expert estimation from the survey reports. The missing data for the time period up to 1989 were completed with the crop specific data on the yields and crop share data coming from regional or national statistics. The missing data for the time period 1989–2007 were completed with statistic data available on a district level. The missing data of organic manure doses were completed by an expert estimation. Organic carbon input of plant residues or farmyard manure was calculated according to Eq. (2) (Jurčová & Bielek 1997):

Table 2. Average annual plant (C PR) and manure (C MR) carbon input and temperature (*T*) over the decades

Decades	C PR (t/ha)	C MR (t/ha)	*T* (°C)
1970–1980	1.72	0.50	8.5
1981–1990	1.85	0.52	8.3
1991–2000	1.76	0.50	8.8
2000–2007	1.74	0.50	9.2

$$Q = u \times K_C \quad (2)$$

where:

Q – organic carbon of plant residues or farmyard manure (t C/ha)

u – crops yields or manure dose (t/ha)

K_C – amount of carbon of plant residues or manure adequate to 1 tone of the main product yield or 1 tone of manure.

All basic soil data, meteorological stations, annual carbon input of plant residues and manure on the selected sites can be found in Table 1.

Statistical methods

The total differences between the simulated and measured values were calculated as root mean square error (RMSE) (Loague & Green 1991). Student's two-tailed t-test and nonparametric Wilcox-test for comparing the observed and modelled data (for year 1993 and for year 2002) were used. Wilcoxon-test is an alternative to the t-test when the data are not normally distributed (Meloun & Militký 1994).

RESULTS AND DISCUSSION

The short term modelling period represents 36 years with the initial point of 1970. On almost all sites, the organic carbon stock increased. The highest rate was observed in the first 20 years (Figure 2). In the next decades, the increase of SOC was slower, and in the last 6 years no changes in SOC stock were observed. The highest rate of SOC stock increase in the first two decades of the modelling period (1970–1990) can be explained by an intensive application of manure. Later, mainly after 1990, a decrease of the ma-

Table 3. Summary statistics of observed and simulated data of the SOC stock of the selected sites on agricultural land of Slovakia

Year	SOC stock data	Summary statistics				
		average	median	geometric mean	SD	*CV*
Arable land and grassland						
1993	modelled	46.39	42.50	44.01	16.75	36.11
	observed	43.41	38.35	39.91	21.76	50.12
2002	modelled	46.60	42.74	44.55	15.07	32.33
	observed	50.49	43.60	45.73	25.97	51.42
Arable land						
1993	modelled	43.81	41.00	42.17	12.49	28.51
	observed	38.48	36.41	37.04	10.78	28.01
2002	modelled	44.51	42.00	43.00	11.83	26.57
	observed	46.95	43.20	43.35	22.12	47.08

SD – standard deviation; *CV* – coefficient of variations

Table 4. Student's t-test and Wilcox test criteria for comparing the observed and modelled data

	Year	Data of SOC stock	t-test criteria	Wilcox test Z-value
Arable land and grassland	1993	modelled/observed	0.21	0.84
	2002	modelled/observed	0.61	0.05
Arable land	1993	modelled/observed	0.52	0.91
	2002	modelled/observed	0.26	0.05

nure production took place and the level of soil organic matter management was limited with a decrease in the crop production. The average annual carbon input related to the decades can be seen in Table 2.

Another reason may be the climatic change, mainly the rise in temperature over the last years. The increasing temperature will speed up the decomposition of soil organic matter and will tend to increase the loss of SOC in the future as reported by Smith *et al.* (2005). As can be seen from Table 2, during the last two decades a substantial growth of the average temperature could be observed on all the selected climate stations.

The average values of SOC stock for a short term modelling period can be seen in Figure 2. The model data of SOC stock predicted by the RothC model were compared to the SOC data for 1993 and 2002 sampling as provided by the monitoring data of the observed period received from Soil Monitoring database (Tables 3 and 4).

According to t-test criteria (t-values were lower than the critical tabulated t-value 2.04), it can be concluded, that the differences (for year 1993 and for year 2002) between the observed and simulated data were not statistically significant at the level of significance $P = 0.05$. According to Wilcox Z-values criteria (Z-values lower than 0.05 means that the difference between two samples is statistically significant) is it clear that the differences in year 1993 between the observed and modelling data were not statistically significant. The differences in year 2002 between the observed and simulated data were not statistically significant, this value, however, belongs to a limit.

As seen in Figure 2, the agreement between the modelled and measured data is satisfactory and RMSE value for arable land (1993) is 29% and for year 2002 14%. Literature data of RMSE values in long-term experiments with RothC model are reported in the range of 2–30% (Smith *et al.* 1997; Falloon & Smith 2002; Guo *et al.* 2007).

Two sources of uncertainties between the measured and modelled data can be recognised and one further represents the input data. The first uncertainty represents the values of the initial carbon stock. The data of SOC stock were modelled for 20 cm soil depth and the initial concentration of soil organic carbon was sampled in the range of 5–20 cm depending on the depth of genetic horizons. For the calculation of the SOC stock, bulk density is also needed. These values were not measured, only calculated according to the model equation published in a previous paper (Linkeš *et al.* 1989). In this model, the clay content (lower than 0.001 mm) and humus content (%) were used as two main soil parameters.

The second uncertainty represents the input of plant residues and manure carbon. These values were calculated according to the formula of Jurčová (Jurčová & Bielek 1997) where the data are needed of the average yields of crops or the amount of manure input and K_C coefficient (expressed as the amount of the plant remains carbon in t C/ha, adequate to 1 tone of the main product yield) for a particular plant. As described in the previous chapter, receiving such data for some selected sites represented a great problem and the application of expert assessment was necessary.

Third source of uncertainty is represented by the measured data of SOC. Mainly on grasslands, great heterogeneity of soil organic carbon concentration can be observed in the input datasets (concentrations of soil organic carbon in 1970, 1993 and 2002 sampling). Moreover, for the calculation of the SOC stock, the calculated values of bulk density were used. Likewise in the calculation of the initial SOC stock, combining of measured and calculated values was used to receive the initial and observed SOC stock.

CONCLUSION

The modelling approach represents one of the most promising method for the estimation of the stock and changes of SOC. RothC model is one of the most widely used models for the estimation and prediction of SOC stock on agricultural land. Because of its simplicity and the generally good availability of the input data required, this model was used also for the estimation of the SOC stock on the selected localities on Slovak agricultural land. On the basis of our results, it can be concluded that RothC 26.3 model is suitable for the estimation of SOC stock changes on Slovak agricultural land and can be used for the modelling of SOC stock changes on the whole territory of agricultural land of Slovakia. The results also show that the model is sufficiently sensitive to the carbon input and temperature. A lower carbon input and an increase of temperature have a negative effect on the stock of soil organic carbon in natural conditions of Slovakia.

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Received for publication July 2, 2009
Accepted after corrections October 22, 2009

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