

MODELLING OF SOIL ORGANIC CARBON DYNAMIC ON GRASSLAND UNDER DIFFERENT MANAGEMENT AND CLIMATE SCENARIOS

GABRIELA BARANČÍKOVÁ*, ŠTEFAN KOCO, JÁN HALAS, JOZEF TAKÁČ,
JARMILA MAKOVNÍKOVÁ, MIRIAM KIZEKOVÁ

National Agricultural and Food Centre, Slovak Republic

Barančíková, G., Koco, Š., Takáč, J., Makovníková, J., and Kizeková, M. (2023). Modelling of soil organic carbon dynamic on grassland under different management and climate scenarios. *Agriculture (Poľnohospodárstvo)*, 69(3), 105 – 117.

Improperly used farming systems and agrotechnical practices with ongoing climate change can contribute to the reduction of the level of soil organic carbon (SOC) stocks not only in intensively cultivated arable soils but also in grasslands. One of the ways to track changes in the SOC stock is the use of mathematical models. The RothC model was validated at the locality Suchý vrch, which hosts long-term experiments on grassland. The soil type is sandy-loam textured Cambisol. Validation was done for the period 1993 – 2009 on grassland with various applications of mineral and organic fertilisers. Results of validation show that the RothC model appropriately predicts the development of grassland SOC and can be used in forecasting SOC stock in the future. Five different management scenarios, with carbon input 2.3 to 6.4 t/ha and three climate scenarios (RCP 2.6, RCP 4.5, RCP 8.5) of the MPI climate model were used to track the changes of SOC stock on grassland in the period 2009 – 2100. Modelling results of SOC development show, that in the future, a relatively low-temperature increase (RCP 2.6) and a relatively high carbon input into the soil (6.4 t/ha) can ensure moderate carbon sequestration. However, between the low-carbon management scenarios (2.3 and 4.1 t/ha), SOC stocks are continuously decreasing in the RCP 2.6 climate scenario. At a significantly higher temperature (climate scenario RCP 8.5), that is expected in future, it will not be possible to maintain the current level of SOC stock not even at a high carbon input (6.4 t/ha).

Key words: soil organic carbon, grassland, RothC model, climate scenarios, management scenarios

Soil organic matter (SOM) is one of the most important soil parameters, which affects many biological, chemical and physical soil processes (Campbell & Paustian 2015). Soil organic carbon (SOC), the key element of SOM, is considered the primary indicator of soil quality and health in relation to productive and ecological soil functions (Chevalier *et al.* 2016) and also affects all classes of ecosystem

services (Banwart *et al.* 2015). It can be said that SOC is essential to numerous functions delivered by soils (Kopittke *et al.* 2022). The benefits deriving from the strategies that are currently adopted for global SOC sequestration are becoming increasingly relevant to mitigate climate change as well as to improve food production (Moinet *et al.* 2023).

In the soil ecosystem, the accumulation and

Gabriela Barančíková (*Corresponding author), Štefan Koco, Ján Halas, National Agricultural and Food Centre-Soil Science and Conservation Research Institute, Regional Working Place Prešov, Raymannova 1, 08001 Prešov, Slovak Republic. E-mail: gabriela.barancikova@nppc.sk

Jozef Takáč, National Agricultural and Food Centre-Soil Science and Conservation Research Institute, Trenčianska 55, 821 09 Bratislava, Slovak Republic

Jarmila Makovníková, National Agricultural and Food Centre-Soil Science and Conservation Research Institute, Regional working place Banská Bystrica, Mládežnícka 36, 974 04 Banská Bystrica, Slovak Republic

Miriám Kizeková, National Agricultural and Food Centre-Plant Production Research Institute, Grassland and Mountain Agriculture Institute, Mládežnícka 36, 974 04 Banská Bystrica, Slovak Republic

decomposition of SOM is constantly taking place. These processes are influenced by the soil temperature and moisture, the supply of nutrients, soil texture, the soil cover as well climatic factors (Wiesemeier *et al.* 2019). Currently, due to intensive changes in land use and soil management, as well as under the influence of climate change, the SOC stock is the subject of significant changes.

Currently, publications on changes in SOC stock on intensively used arable land are prevalent, and there is significantly less information on SOC stock changes on grassland. Relatively many articles dealing with changes in SOC stock come from Australia, where grasslands/pastures occupy 80% of the area in the wide range of climatic, geographical and land use conditions (Allen *et al.* 2013). As reported by several authors (Cook *et al.* 2010; Witt *et al.* 2011; Dean *et al.* 2012) in Australia, the dominant factors, that affect SOC stock on grassland/rangeland are climate conditions, soil parameters, vegetation characteristics, fires and pasture management. Kirschbaum *et al.* (2017) found, that for grazed pastures, SOC stock depends on four key factors: both total carbon inputs from primary production and additional inputs such as purchased feed, the division of carbon inputs between the amount harvested from the site and the fraction retained on site and made available for the formation of carbon in the soil, the division of carbon between readily mineralized carbon from plant residues and organic carbon (labile carbon) and retained and stabilized carbon (stable carbon), and the biophysical control factors of the specific rate of carbon decomposition.

The distinction between the primary effects determined by biomass inputs and removal and the secondary effects of carbon return through animal manure and the coupling of the carbon and nitrogen cycle have been well described by Sousanna and Lemaire (2014).

Climatic conditions and the way grasslands are managed can also alter the size and relative contributions to changes in SOC stock (Whitehead *et al.* 2018). Overgrazing, biomass burning, land use change, and other unsuitable practices (Lu *et al.* 2017; Abdala *et al.* 2021) can cause soil degradation resulting in increased CO₂ emissions and drastic SOC depletion (Chaplot *et al.* 2016; Abdala *et al.* 2018). Different pasture management strategies,

such as fertiliser application and rotational grazing, can increase biomass production and thus lead to increased SOC sequestration (Conant *et al.* 2017; Abdalla *et al.* 2022). On a global scale SOC stock on grassland can increase, decrease, or remain unchanged, depending on climate conditions and grazing intensity (Pineiro *et al.* 2010). Allen *et al.* (2013) state that main indicators, that affect SOC stock in grassland are climate conditions, soil and vegetation characteristics and grazing intensity.

One way to track changes in SOC stock is by using mathematical models. Long-term field experiments are suitable for testing SOC models, which are extremely valuable for understanding long-term SOC dynamic (Smith *et al.* 2020). There are many different mathematical model approaches (Campbell & Paustian 2015). However, many of them require a large number of input parameters, which are quite difficult to obtain. The well-known and most used for SOC stock changes tracing and SOC sequestration is the RothC model (Coleman & Jenkinson 2005). This model was used on global (Morais *et al.* 2019), European (Smith *et al.* 2005, 2006), regional (Farina *et al.* 2017) and country level (Mondini *et al.* 2012). It was also used at the farm level (Hábová *et al.* 2019; Prokopyeva *et al.* 2021) and currently was used for the creation of a global map of SOC sequestration (Peralta *et al.* 2022). The Rothamsted Carbon Model (RothC) model was successfully used also in Slovak conditions mainly on arable land at the country, regional and farm levels (Barančíková *et al.* 2010; 2012; Skalský *et al.* 2020; Barančíková *et al.* 2014; 2022), however, it was not used on grasslands in Slovak conditions. For this reason, we decided to validate and use this model at prediction of SOC changes on selected Slovak grassland.

This study aims to simulate the effect of agro-technical management practices and climate scenarios on the SOC stock changes in the grassland, on sandy-loam textured Cambisol, at the locality Suchý vrch.

The RothC model has been validated for the period 1993–2009 on grassland long-term experiments with different rates of mineral and organic fertilisers. The prediction of SOC stock was done for the period 2009–2100. Five different management scenarios and three climate scenarios (RCP

2.6, RCP 4.5, RCP 8.5) of the Max-Planck Institute (MPI) climate model were used to track the changes of SOC stock in grassland.

MATERIAL AND METHODS

Basic characteristics of Suchý vrch locality

Suchý vrch is situated in central Slovakia near Banská Bystrica (Figure 1) at an altitude of 480 m, GPS: 48°43'06,43''N, 19°06'13,71''. The soil type is sandy-loam textured Cambisol (FAO, 2015). The average precipitation during the growing season ranges from 270 mm to 630 mm and the mean growing season temperature varies from year to year from 7.5°C to 9.7°C. The Suchý vrch site is in a moderately warm climate zone.

Since the beginning of the 1990s, the Suchý vrch locality has been used for long-term field experiments in which the effects of different management treatments on grassland ecosystems are monitored. Over 1993–2002, the effect of mineral fertilisers on dry matter yield, nutritive value, and botanical com-

position on semi-natural grassland (G), over-sown grassland (S) and temporary grassland (T) was evaluated. The N, P, K fertiliser rates were (kg/ha/year): V-1: control; V-2: P30, K60; V-3: N90, P30, K60; V-4: N180, P30, K60. Subsequently, in the period 2007–2009, the effect of organic fertiliser–manure on grassland production and soil-biological properties was monitored. Treatments received nitrogen (N, kg/ha/year) and manure (M t/ha/year) as follows: V-1: control; V-2: N40, MH7; V-3: N80, M14; V-4: N120, M21.

RothC model

The model enables determination of the turnover of organic carbon and this allows for the effects of important parameters i.e. soil type effects, temperature, humidity, and vegetation cover on the rotation process, with a monthly interval (Coleman & Jenkinson 1996).

In the RothC model, organic carbon is divided into four compartments (decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified organic mat-

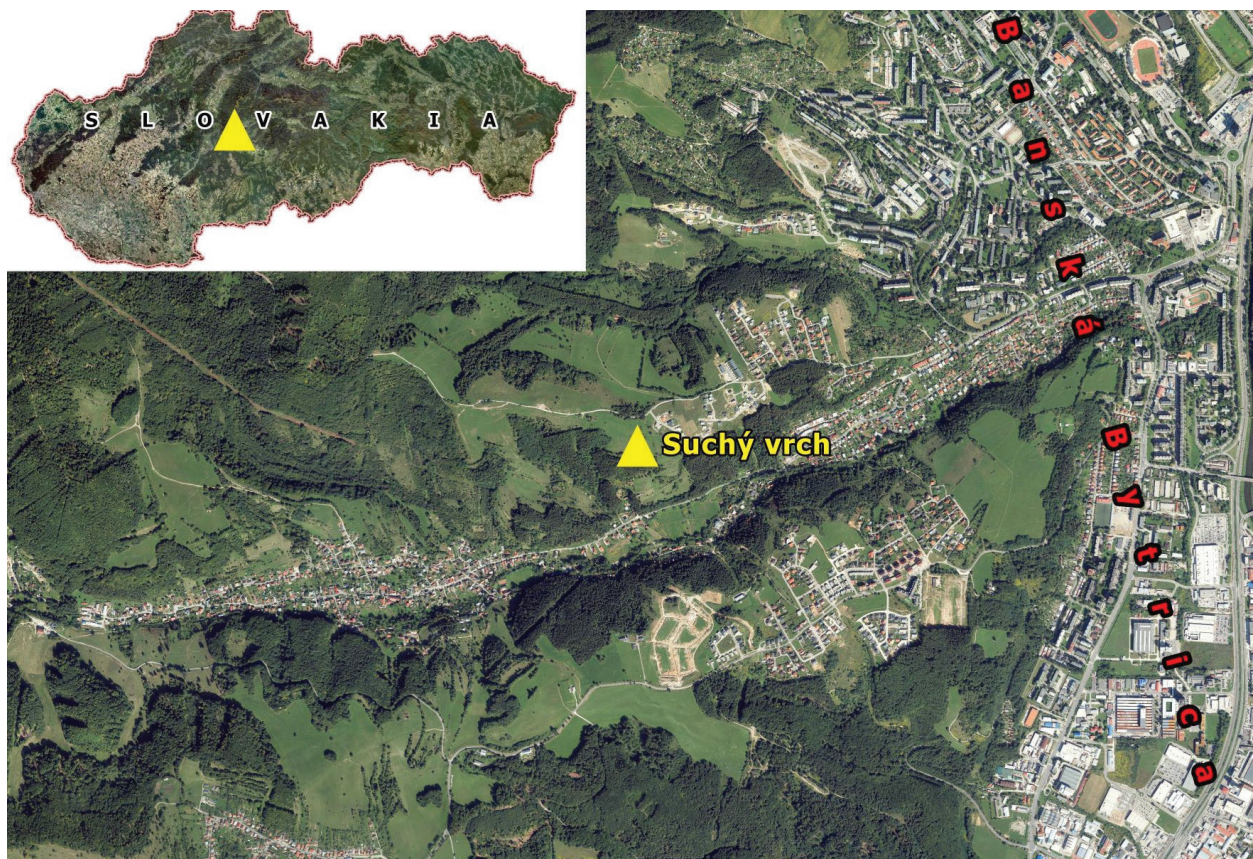


Figure 1. Suchý vrch locality.

ter (HUM)), and a small amount of inert organic matter (IOM). Each of these compartments breaks down by a process defined as first-order (Coleman & Jenkinson 2005).

The input is given by three groups of data to allow a correct use.

Climate data:

- monthly precipitation [mm],
- monthly evapotranspiration [mm],
- average monthly mean air temperature [°C]

Soil characteristics:

- clay contents [%],
- inert organic carbon (IOM),
- initial soil organic carbon (SOC) stock (C t/ha),
- depth of soil layer considered [m].

Crop management data:

- soil cover (soil surface with or without vegetation cover),
- monthly input of plant residues (amount of C t/ha),
- monthly input of farmyard manure (FYM) (amount of C t/ha),
- residues quality factor (DPM/RPM ratio).

Detailed information about the RothC model is available at the Rothamsted Carbon Model (ROTHC) : <https://www.rothamsted.ac.uk/rothamsted-carbon-model-rothc>.

Input data of RothC model for Suchý vrch locality

Validation of the RothC model (warm-up phase) was carried out for the 1993–2009 period.

Climate parameters for this period were sent by the meteorological station Banská Bystrica.

Soil depth was 0.30 m. Measured data of clay content and SOC concentration were received from Suchý vrch long-term experiments. Initial SOC stock and SOC stock of measured SOC concentration during the period 1993–2009 were calculated by the following formula:

$$\text{Initial SOC stock} = \text{SOCm} \times \text{BD} \times d$$

where: SOCm – measured soil organic carbon content [%]; BD – bulk density [g/cm³]; d – soil depth (0.30 m).

The biologically inert SOC fraction (IOM) is cal-

culated from the initial SOC stock by an exponential equation (Falloon *et al.* 1998):

$$\text{IOM} = 0,049\text{SOC}^{1,139}$$

Inputs of organic carbon from plant residues or livestock manure were calculated as suggested by Bielek and Jurčová (2010):

$$Q_R - \text{carbon content in plant input [t/ha],}$$

$$Q_R = u \times kc$$

where: u – yield [t/ha]; kc – coefficient of carbon content in plant input according to predicted yield (amount of C t/ha yield) for a given crop;

$$Q_H - \text{carbon content in organic manure [t/ha],}$$

$$Q_H = D_H \times C_H$$

where: D_H – dose of organic fertiliser, C_H – coefficient of conversion of the organic fertiliser dose to the amount of carbon [t/ha].

The mean square error determined the total differences between simulated and measured values (RMSE) (Loague and Green, 1991) and the STATGRAPHICS Centurion XVI program was used for data analysis and visualization.

Prediction of SOC stock (forward phase) was realized in the period 2009–2100.

Climate scenarios

The values of climate parameters of scenarios RCP (Representative Concentration Pathways) 2.6, RCP 4.5 and RCP 8.5 of climate model MPI were received from the Slovak Hydrometeorological Institute. In Table 1 average values of measured climate parameters (2000–2020) and values of climate parameters of each scenario for the period (2020–2100) are given.

Management scenarios

In all management scenarios (MS), the Kc coefficient in the fourth year of temporary grass cultivation was used to calculate the plant carbon inputs into the soil (Q_R). We do not consider the application of farmyard manure, because manure application on grasslands is not a common practice in Slovakia. In *scenarios MS3 to MS5* we assume different grazing intensities. Carbon inputs from grazing an-

imals' excrements (Q_H) were calculated according to Tarasovičová and Barančíková (Tarasovičová & Barančíková, 2011).

Management scenario I (MS1) represents grasslands mown 3 times a year. In this scenario, we consider the mean yearly dry matter yield for the period 2006–2009 under climate conditions typical for the Suchý vrch locality.

Management scenario II (MS2) also represents grasslands mown 3 times a year. However, in this scenario, we consider an average annual dry matter yield lower, than that recorded in the dry period 2000–2002, in the locality Suchý vrch.

In other management scenarios, in addition to plant residues, excrements from grazing cattle were considered as carbon input. Under these management scenarios, carbon inputs from plant residues are significantly lower, than in *scenario MS1*, depending on the length of the grazing season.

In *management scenario III (MS3)*, the grasslands are mown in May and grazed by cattle from June to the end of October. The grazing period lasts 123 days. We consider 2 cattle units per hectare as it is eligible for subsidies.

In *management scenario IV (MS4)*, grasslands are grazed by cattle during the growing season from April to October (214 days).

At *management scenario V (MS5)* grasslands are mown twice a year (May and August): carbon inputs from plant residues are the same as in *scenario MS1*. At the end of the growing season from September to the end of October (61 days) grasslands are grazed by cattle.

The carbon inputs for each management scenario are shown in Table 2.

RESULTS AND DISCUSSION

Validation of RothC Model

During the period 1993–2009, SOC stock was determined on each treatment, but not every year. The dataset included 8 measured data of SOC stock.

The RMSE values ranged from 8 to 15, indicating that the modelled and measured SOC stock values of the fertilised treatments on all grassland types (G, S, T) were in good agreement.

The literature reports RMSE values on long-term field experiments in the range of 2–30% (Smith *et al.* 1997; Fallon & Smith 2002; Guo *et al.* 2007).

For all grassland types, a comparison of measured and modelled SOC stock values is illustrated on treatment V-4 (Figures 2–4).

According to the t-test, the sign test and the signed test were not found statistically significant

T a b l e 1

Average values of climate parameters, temperature (T °C) and precipitation (w mm), measured (2001–2020) and each climatic scenario (2020–2100)

Time period	T RCP2.6	T RCP4.5	T RCP8.5	w RCP2.6	w RCP4.5	w RCP8.5
2001–2010	8.33	8.33	8.33	801	801	801
2011–2020	9.35	9.35	9.35	822	822	822
2021–2030	6.14	6.74	6.66	984	835	908
2031–2040	6.71	7.01	7.50	895	864	918
2041–2050	7.00	6.87	7.41	867	869	941
2051–2060	6.92	7.74	7.86	802	840	816
2061–2070	7.07	7.90	8.39	910	919	938
2071–2080	6.81	7.50	8.34	942	891	891
2081–2090	6.56	8.16	9.72	945	853	788
2091–2100	6.95	7.41	9.80	847	929	886

RCP – representative concentration pathways.

differences between the measured and modelled SOC stock values.

When comparing individual ecosystems (T, G, S), we set the model to the initial mean SOC value stock of all treatments. Carbon input data of plant residues and manure represent average carbon inputs of all treatments and all grassland types. As can be seen in Figure 5, the development of SOC stock on each grassland type was significantly different.

On the temporary grassland (T) was found a con-

tinuous decrease of SOC stock during the modelled period. On over-sown grassland (S) and semi-natural grassland (G), a decrease of SOC stock was recorded in the middle of the modelled period while from 2003 SOC stock for S and G grasslands show a slight increase (Figure 5). The significant decrease in the SOC stock recorded in the middle of the modelling period for all grasslands may be due to the drought period 2000–2003, which resulted in very low grass yield. As reported by several authors (Job-

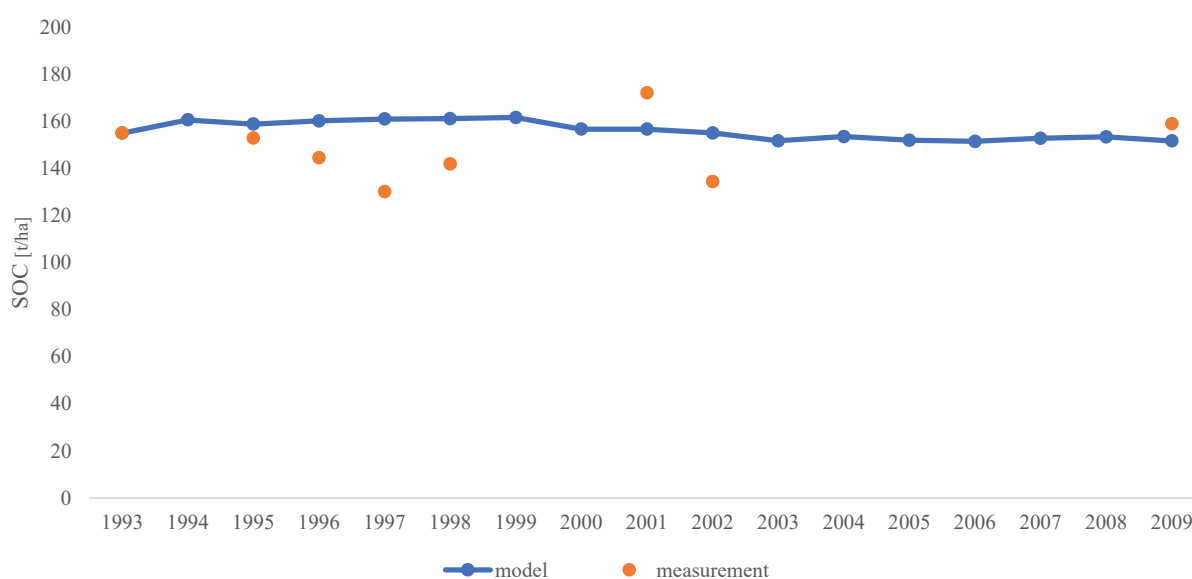


Figure 2. Comparison of modelled and measured values of SOC (soil organic carbon) stock on treatment V-4 on seminatural grassland (G).

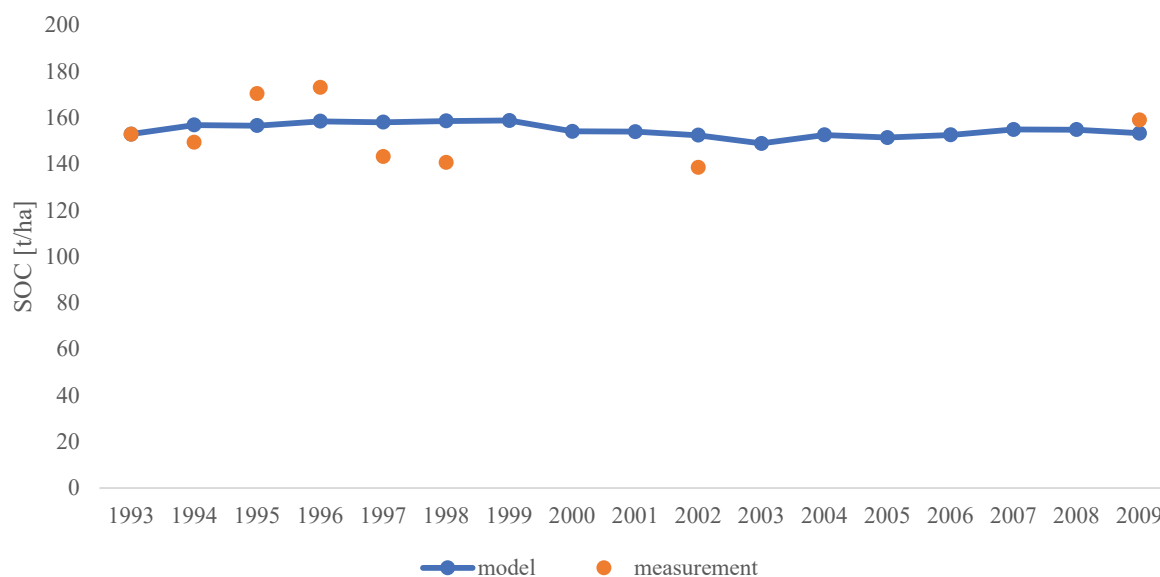


Figure 3. Comparison of modelled and measured values of SOC (soil organic carbon) stock on treatment V-4 on over-sown grassland (S).

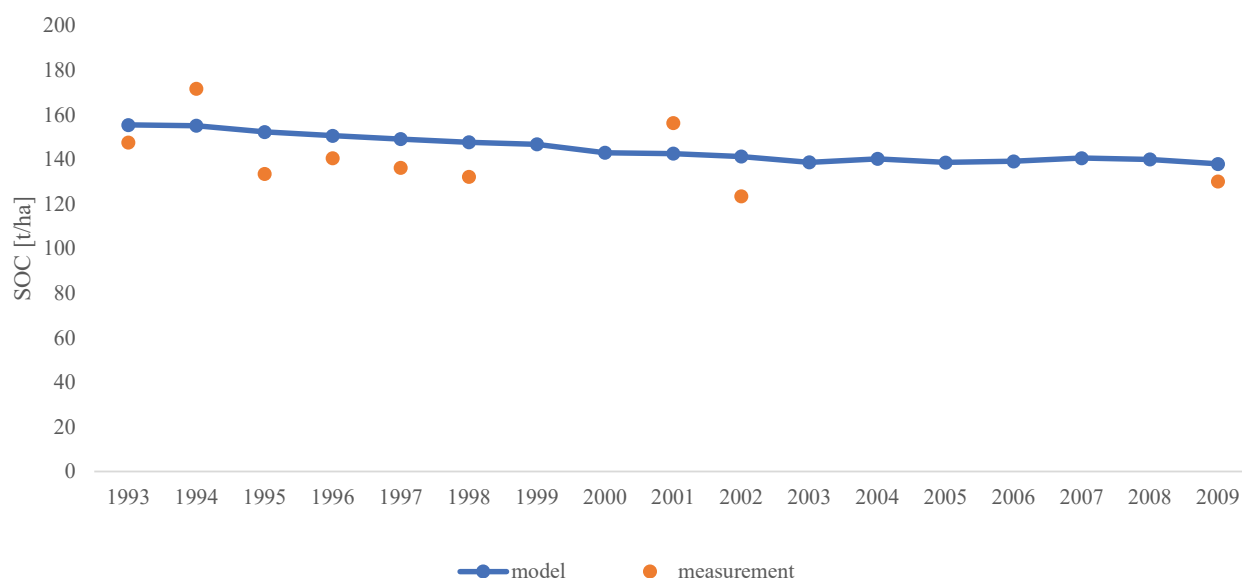


Figure 4. Comparison of modelled and measured values of SOC (soil organic carbon) stock on treatment V-4 on temporary grassland (T).

bágy & Jackson 2000; Honley *et al.* 2015; Koven *et al.* 2017), the amount of precipitation can be a limiting factor that affects SOC stock on grassland. SOC stock is significantly influenced also by the carbon input from plant residues (Schulp & Verbung 2009; Allen *et al.* 2013; Banwart *et al.* 2015). It can therefore be said that a considerable decrease in plant biomass due to the dry season, was also reflected in a decrease in the stock of SOC. The reversal of the downward trend of SOC stock in all types of pasture (T, G, S) may also be a consequence of the contribution of external organic matter in the form of manure in the period 2006–2009. The positive effect of manure on SOC stock has been reported by several authors (Maillard & Angers 2014; Whitehead *et al.* 2018; Kuhnel *et al.* 2019; Bolinder *et al.* 2020).

Prediction of SOC stock in the period 2009–2100 for different climate scenarios and different grassland management

According to the measured values, the average value of SOC stock at the beginning of the modelled period on Suchý vrch grassland was 110 t/ha. It can be said that this value of SOC stock is relatively high since, on the basis of monitoring data (sampling 2007), the SOC stock ranges from 32 to 165 t/ha and the average value of Slovak grassland is 72 t/ha.

As can be seen from Figure 6, the development

of SOC stock depends on carbon input to soil (Table 2). The highest value of carbon input occurs in the *MS5 management scenario*, which is mowed twice a year at the beginning of the growing season and where at the end of the growing season (September–October) cattle graze. At the RCP 2.6 climate scenario, where lower temperatures are expected than the current ones (Table 1), the current management can slightly increase the SOC stock in the future period (Figure 6) but the sequestration is very low (0.02 t/ha/year).

The same stock of SOC from the beginning of the modelled period, recorded in the RCP 2.6 climate scenario is also maintained in *management scenarios MS1* (mowing 3 times a year) and *MS3* (mowing once a year and subsequent grazing). However, in *MS4* (grasslands are grazed by cattle during the growing season) and mainly at *MS2* (mown 3 times, very low dry matter yields due to dry season), SOC stock continuously decreases (Figure 6). These scenarios have the lowest carbon input to soil (Table 2).

The RCP 4.5 climate scenario also predicts lower temperatures in the future period than the current ones. The predicted temperatures in the RCP 4.5 climate scenario are higher than in the RCP 2.6 climate scenario (Table 1). The higher temperatures predicted for the climate scenario RCP 4.5 compared to RCP 2.6 scenario are reflected in the development of the SOC in the future period (Figure 7). At the

T a b l e 2

Carbon inputs from plant residues (C PR) and cattle excrements (C E) for each management scenario

Scenarios	C PR [t/ha/year]	C E [t/ha/year]
MS1	5.99	0.00
MS2	2.24	0.00
MS3	4.67	0.86
MS4	2.55	1.50
MS5	5.99	0.43

Note: MS – management scenario.

RCP 4.5 climate scenario, in contrast to RCP 2.6, even with the highest soil carbon input (*MS5*) the SOC stock cannot increase in the future, but only be maintained at the same level as at the beginning of the modelled period (Figure 7).

At management scenarios *MS1* and *MS3* at the beginning of the modelled period SOC stock is maintained at the same level, however in the next period SOC moderately decreases (Figure 7). As well as in the case of climate scenario RCP 2.6, at climate scenario RCP 4.5, SOC stock decreases for *MS2* and *MS4*. As the same as with climate scenario RCP 2.6, also RCP 4.5, the decrease in SOC stock was higher for *MS2* than *MS4* (Figure 7). Compared to climate scenario RCP 2.6., at *MS2* and *MS4* the decrease was greater at the RCP 4.5 climate scenario (Figure 7).

At climate scenario RCP 8.5 on all management scenarios, during the modelled period, SOC stock continually decreases compared to the beginning level (Figure 8). At *MS5*, with the highest SOC input, the initial values of SOC are maintained until 2050. In the following period, also for this management scenario, a decrease in the SOC stock was recorded (Figure 8).

At climate scenario RCP 8.5, the lowest decrease of SOC stock during the modelled period, i.e. about 9%, at *MS5 management scenario* and the highest decrease about 56% at *MS2 management scenario* (Figure 8) were registered.

Based on the obtained results it is clear that organic carbon inputs and climate parameters have a fundamental influence on SOC stock development, which is also by the literature (Allen *et al.* 2013; Banwart *et al.* 2015; Koven *et al.* 2017; Whitehead *et al.* 2018; Funes *et al.* 2019; Ledo *et al.* 2020; FAO, 2021; Kizeková *et al.* 2022). In general, it can be said, that a higher carbon input into the soil, is reflected in a higher SOC stock, and also, that SOC stock is positively affected by a cooler and wetter environment.

Achieved results also showed, that in modelling SOC stock by the RothC model, carbon inputs to the soil have a dominant influence, as even small differences in carbon inputs to soil, can fundamentally affect SOC stock (Table 2, Figure 6–8).

Our results also show a non-negligible effect of

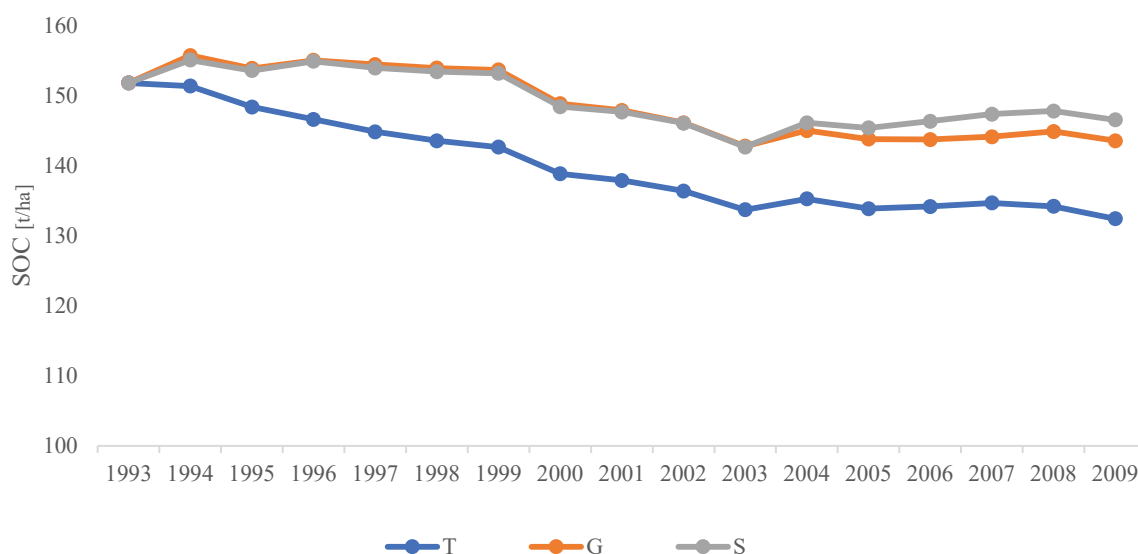


Figure 5. Comparison of SOC (soil organic carbon) development on grassland types (T, G, S) by RothC model.

Note: T – temporary grassland; S – over-sown grassland; G – seminatural grassland.

temperature on SOC stock development. Modelling results show that in the future moderate sequestration (0.02 t/ha/year) can only be achieved at lower temperatures as assumed by the RCP 2.6 climate scenario and with sufficiently high carbon inputs. This is especially possible with *MS5*, where an optimal dry matter yield is assumed to be achieved. All this occurs through significant carbon inputs into the soil from plant residues, but also from additional

carbon input from the manure of grazing cattle and limited to the end of the growing season (Table 1, Figure 5). According to the RothC model, in *MS5* of the RCP 8.5 climate scenario, SOC stocks are expected to decrease (Figure 8) due to the significantly higher temperatures in this scenario compared to RCP 2.6 (Table 1). These results are consistent with the literature data. Hobley *et al.* (2015) found that precipitation positively and temperature negatively

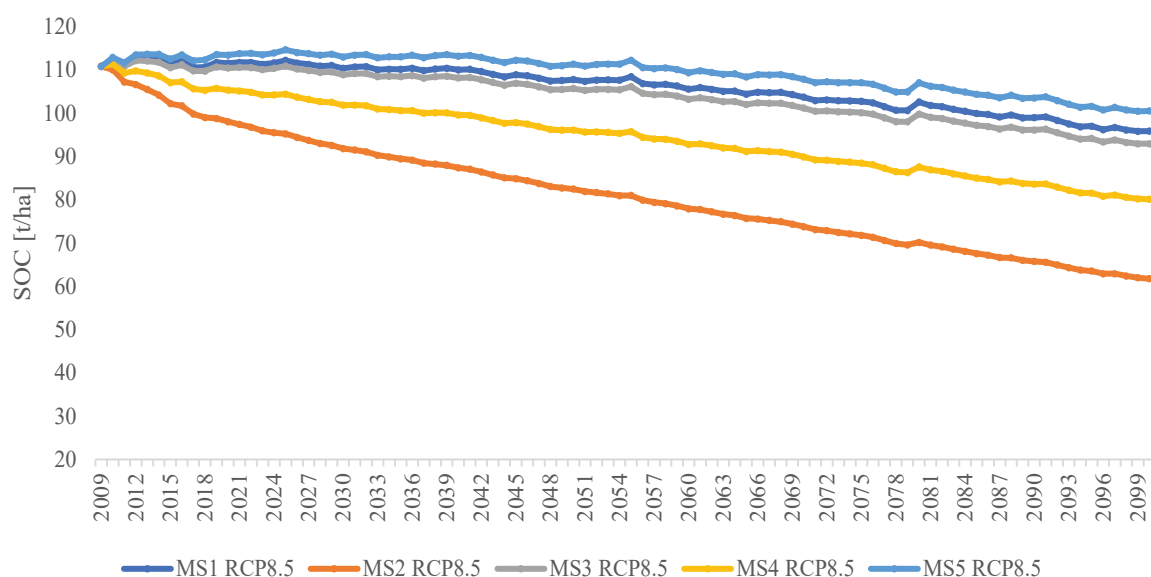


Figure 6. Development of SOC (soil organic carbon) stock at climate scenario RCP 2.6 and different management scenarios. Note: MS 1 RCP2.6 – management scenario I, climate scenario RCP2.6; MS 2 RCP2.6 – management scenario II, climate scenario RCP2.6; MS 3 RCP2.6 – management scenario III, climate scenario RCP2.6; MS 4 RCP2.6 – management scenario IV, climate scenario RCP2.6; MS 5 RCP2.6 – management scenario V, climate scenario RCP2.6.

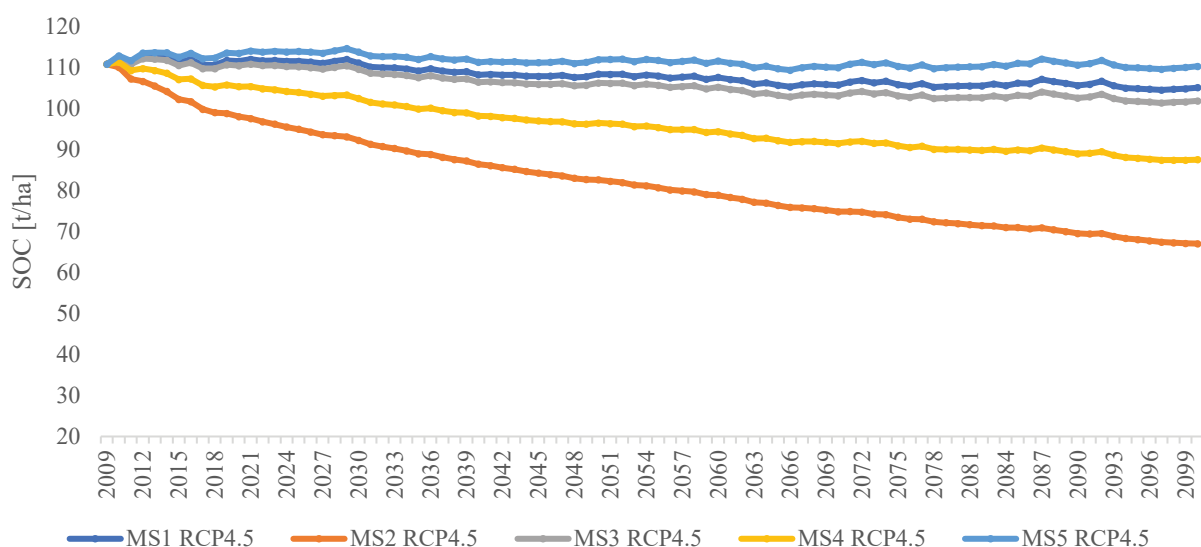


Figure 7. Development of SOC (soil organic carbon) stock at climate scenario RCP 4.5 and different management scenarios. Note: MS 1 RCP4.5 – management scenario I, climate scenario RCP4.5; MS 2 RCP4.5 – management scenario II, climate scenario RCP4.5; MS 3 RCP4.5 – management scenario III, climate scenario RCP4.5; MS 4 RCP4.5 – management scenario IV, climate scenario RCP4.5; MS 5 RCP4.5 – management scenario V, climate scenario RCP4.5.

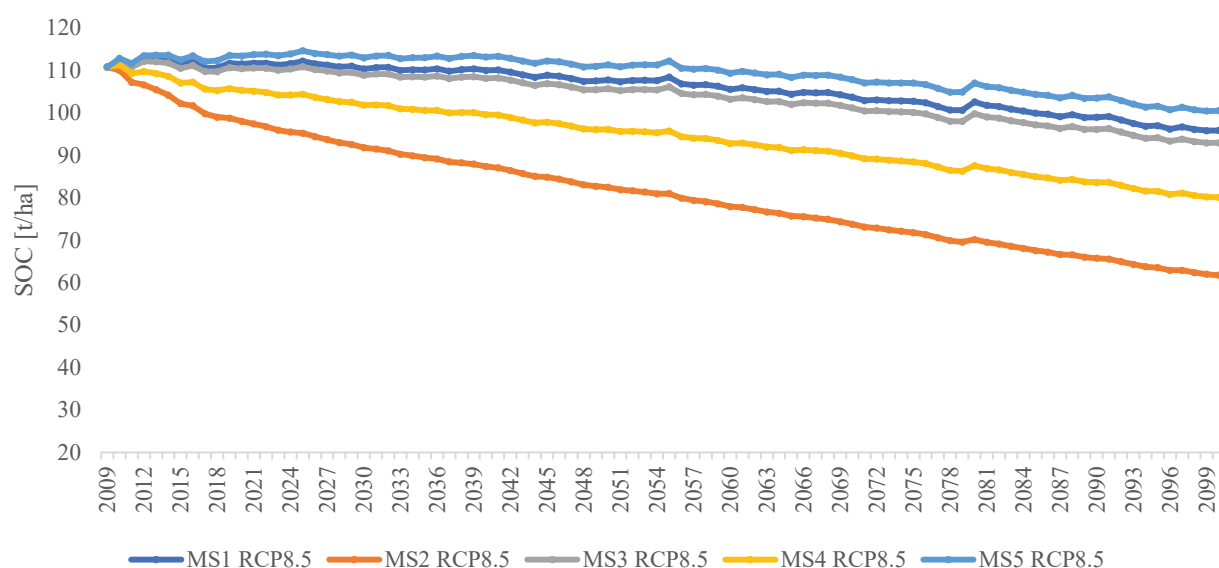


Figure 8. Development of SOC (soil organic carbon) stock at climate scenario RCP 8.5 and different management scenarios. Note: MS 1 RCP8.5 – management scenario I, climate scenario RCP8.5; MS 2 RCP8.5 – management scenario II, climate scenario RCP8.5; MS 3 RCP8.5 – management scenario III, climate scenario RCP8.5; MS 4 RCP8.2 – management scenario IV, climate scenario RCP8.5; MS 5 RCP8.2 – management scenario V, climate scenario RCP8.5.

affected SOC stocks in Australian grasslands. A significant influence of climatic factors on the SOC stock in the pastures of Australia is also reported by Allen *et al.* (2013). Kuhnel *et al.* (2019) found, that seasonal changes in climatic parameters had a dominant influence on the SOC stock in Bavaria pastures. An increase in autumn precipitation led to a decrease, while an increase in spring and summer led to an increase in SOC stocks.

Our results also show a wide range of SOC stock changes in different management scenarios. Significant SOC sequestration was detected only with MS5 and climate scenario RCP 2.6. For the other management and climate scenarios the RothC model predicts the elimination of organic carbon from soil (Figure 5–8). Using the RothC model on pastures in Switzerland, Wust-Galley (2020) reports annual changes in SOC stocks during the period 1990–2017 ranging from -0.64 to $+0.67$ t/ha depending on land management. The relatively low sequestration of SOC stocks at the Suchý vrch locality may be a consequence of the considerably high initial value of the SOC stock (110 t/ha) stated by Hassink (1997) and Cotrufo *et al.* (2019) the soil has only a certain capacity for stabilizing organic carbon in organo-mineral complexes.

Regarding the effect of grazing intensity on SOC stock, the results of individual studies are not con-

sistent (Whitehead *et al.* 2018), however Abdalla *et al.* (2021) report, that rotational grazing can significantly increase SOC stock compared to traditional free cattle grazing. Soussana *et al.* (2006) and Ward *et al.* (2016) found that moderate levels of grassland management intensity (N fertiliser application and mowing time) were associated with higher SOC stocks on extensively but also intensively managed grasslands. Whitehead *et al.* (2018) mention grazing intensity as one of the criteria for increasing SOC stocks in grasslands but it depends on the species composition in grassland and seasonal climatic conditions. Our results show that mowing twice a year and grazing at the end of the grazing season (MS5) can provide a moderate increase of SOC stock under climate scenario RCP 2.6. At an extremely increase in temperature, as assumed at climate scenario RCP 8.5, in the first period of modelling the SOC stock level can stabilize at the initial level, but in the following period, SOC stock starts to decrease even at management scenario V (Figure 8).

CONCLUSIONS

This work represents the first attempt to predict development changes of SOC stock at different climate and management scenarios for Slovak grass-

lands. Validation of the RothC model on grassland long-term experiment of Suchý vrch locality was done. Based on our results it can be concluded that the model appropriately predicts the development of SOC stock on grassland and can be used in forecasting SOC stock in the future period. The results of modelling the development of SOC in three climate scenarios and five management scenarios show that with a relatively low-temperature increase (RCP 2.6 climate scenario) and relatively high carbon inputs into the soil (MS5) in sandy loam textured Cambisol with relatively high SOC content, moderate carbon sequestration can be achieved in the future. However, according to the RothC model results, in management scenarios with low carbon inputs into the soil, mainly with MS2 and MS4, also at lower temperature increases (climate scenario RCP 2.6) SOC stock continually decreases. Significantly higher temperature increases in the future (climate scenario RCP 8.5) will not ensure sequestration or maintenance of initial SOC stock level even with high carbon inputs into the soil (MS5).

Acknowledgement: This work was done as a part of the project “Towards climate-smart sustainable management of agricultural soils” (EJP-SOIL, grant agreement ID: 862695, project CarboSeq) funded by the European Union’s Horizon 2020 research and innovation program and is also the result of the project implementation: „Scientific support of climate change adaptation in agriculture and mitigation of soil degradation” (ITMS2014+ 313011W580) supported by the Integrated Infrastructure Operational Program funded by the ERDF.

REFERENCES

- Abdalla, K., Mutema, M., Chivenge, P., Everson, C., and Chaplot, V. (2018). Grassland degradation significantly enhances soil CO₂ emission. *Catena*, 167, 284–292. DOI: 10.1016/j.catena.2018.05.010.
- Abdalla, K., Chivenge, P., Ciaia, P., and Chaplot, V. (2021). Long-term (64 years) annual burning lessened soil organic carbon and nitrogen content in a humid subtropical grassland. *Global Change Biology*, 27(24), 6436–6453. DOI:10.1111/gcb.15918.
- Abdalla, K., Mutema, M., Chivengas, P., and Everson, C. (2022). Grassland rehabilitation significantly increases soil carbon stocks by reducing net soil CO₂ emissions. *Soil Use and Management*, 28(2), 1250–1265. DOI:10.1111/sum.12790.
- Allen, D., Pringle, M.J., Bray, S., Hall, J., O'Reagain, P.O., Phelps, D., Cobon, D.H., Bloesch, P.M., and Dalal, R.C. (2013). What determines soil organic carbon stocks in the grazing lands of north-eastern Australia? *Soil Research*, 51(8), 695–706. DOI:10.1071/SR13041.
- Banwart, S.A., Black, H., Cai, Z., Gicheru, P.T., Joosten, H., Victoria, R.L., Milne, E., Noellemeyer, E., and Pascual, U. (2015). The global challenge for soil carbon. In Banwart, S.A., Noellemeyer, E., Milne, E. (Eds.), *Soil Carbon*. Scope Series volume 71, Cabi International, Boston, pp. 1–9. Available at: <https://www.cabi.org/Uploads/CABI/Open-Resources/45322/chapter-1.pdf>.
- Barančíková, G., Halás, J., Gutteková, M., Makovníková, J., Nováková, M., Skalský, R., and Tarasovičová, Z. (2010). Application of RothC model to predict soil organic carbon stock on agricultural soils of Slovakia. *Soil and Water Research*, 5(1), 1–9. DOI:10.17221/23/2009-SWR.
- Barančíková, G., Makovníková, J., Skalský, R., Tarasovičová, Z., Nováková, M., Halas, J., Gutteková, M., and Koco, Š. (2012). Simulation of soil organic carbon changes in Slovak arable land and their environmental aspects. *Soil and Water Research*, 7(2), 45–51. DOI:10.17221/38/2011-SWR.
- Barančíková, G., Skalský, R., Koco, Š., Halas, J., Tarasovičová, Z., and Nováková, M. (2014). Farm-level modelling of soil organic carbon sequestration under climate and land use change. In Halldórsson, G., Bampa, F., Þorsteinsdóttir, A.B. (Eds.) *Soil carbon sequestration for climate food security and ecosystem services*. Luxembourg: Publications Office of the European Union, 94–100. Available at: <https://op.europa.eu/en/publication-detail/-/publication/bb316319-9bb0-41a2-875f-97ea183dced2/language-en>.
- Barančíková, G., Skalský, R., Koco, Š., Halas, J., and Takáč, J. (2022). Monitoring of soil organic carbon (SOC) in Slovakia and the use of modelling in the balance of carbon changes. In Menšík L., Kunzová E., Madaras, M. (Eds.) *Book of Abstracts from the Webinar: Current Management of Agricultural Land in Changing Environmental Conditions – SOM (Soil Organic Matter). 2nd Volume* [Monitoring pôdneho organického uhlíka (POC) na Slovensku a využitie modelovania pri bilancii jeho zmien. Zborník abstraktov z webinára: Současné hospodárenie na zemědělské půdě v měnících sa podmínkách prostředí – SOM (půdní organická hmota) 2. ročník]. Praha: Crop Research Institution, pp. 12–13. Available at: <https://op.europa.eu/en/publication-detail/-/publication/bb316319-9bb0-41a2-875f-97ea183dced2/language-en>.
- Bielek, P. and Jurčová, O. (2010). *Methodology of soil organic matter balance and determining the need for organic fertilization of agricultural soils* [Metodika bilancie pôdnej organickej hmoty a stanovenie potreby organického hnojenia poľnohospodárskych pôd]. Bratislava: Soil Science and Conservation Research Institute, 145 p.
- Bolinder, M.A., Crotty, F., Elsen, A., Frac, M., Kismányoky, T., Lipiec, J., Tits, M., Tóth, Z., and Kätterer, T. (2020). The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: a synthesis of reviews. *Mitigation and Adaptation Strategies for Global Change*, 25, 929–952. DOI:10.1007/s11027-020-09916-3.
- Campbell, E.E. and Paustian, K. (2015). Current developments in soil organic matter modeling and the expansion of model applications: a review. *Environmental Research Letters*, 10(12), 123004. DOI:10.1088/1748-9326/10/12/123004.
- Chaplot, V., Dlamini, P. and Chivenge, P. (2016). Potential of grassland rehabilitation through high density-short duration grazing to sequester atmospheric carbon. *Geoderma*, 271, 10–17. DOI:10.1016/j.geoderma.2016.02.010.

- Chevallier, T., Hamdi, S., Gallali, T., Brahim, N., Cardinel, R., Bounouara, Z., Cournac, L., Chenu, C., and Bernoux, M. (2016). Soil carbon as the indicator of Mediterranean soil quality. In Haité, H., Yazami, D. (Eds.), *The Mediterranean Region under Climate Change: A scientific update*, Sub-chapter 3.5.3., Marseille, pp 627–636. Available at: https://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers16-11/010068463.pdf.
- Coleman, K., Jenkinson, D.S. (1996). RothC-26.3 - A Model for the turnover of carbon in soil. In Powlson, D.S., Smith, P., Smith, J.U. (Eds.) *Evaluation of Soil Organic Matter Models*. NATO ASI Series, vol. 38. Berlin, Heidelberg: Springer. DOI:10.1007/978-3-642-61094-3_17.
- Coleman, K. and Jenkinson, D.S. (2005). *ROTHC-26.3 A model for the turnover of carbon in soil. Model description and windows users guide*, November 1999 issue (modified April, 2005), 45 pp. Available at: https://www.rothamsted.ac.uk/sites/default/files/RothC_guide_WIN.pdf.
- Conant, R. T., Cerri, C.E.P., Osborne, B.B., and Paustian, K. (2017). Grassland management impacts on soil carbon stocks: a new synthesis. *Ecological Applications*, 27(2), 662–668. DOI:10.1002/ecap.1473.
- Cook, G.D., Williams, R.J., Stokes, C.J., Hutley, L.B., Ash, A.J., and Richards, A.E. (2010). Managing sources and sinks of greenhouse gases in Australia's rangelands and tropical savannas. *Rangeland Ecology and Management*, 63(1), 137–146. DOI:10.2111/08-101.1.
- Cotrufo, M.F., Ranalli, M.G., Haddix, M.L., Six, J., and Lugato, E. (2019). Soil carbon storage informed by particulate and mineral-associated organic matter. *Nature Geoscience*, 12, 989–994. DOI:10.1038/s41561-019-0484-6.
- Dean, C., Wardell-Johnson, G.W. and Harper, R. (2012). Carbon management of commercial rangelands in Australia: Major pools and fluxes. *Agriculture, Ecosystems & Environment*, 148, 44–64. DOI:10.1016/j.agee.2011.11.011.
- Falloon, P., Smith, P., Coleman, K., and Marshall, S. (1998). Estimating the size of the inert organic matter pool from total soil organic carbon content for the use in the Rothamsted carbon model. *Soil Biology and Biochemistry*, 30(8–9), 1207–1211. DOI:10.1016/S0038-0717(97)00256-3.
- Falloon, P. and Smith, P. (2002). Simulating SOC changes in long-term experiments with RothC and CENTURY: model evaluation for a regional scale application. *Soil Use and Management*, 18(2), 101–111. DOI:10.1111/j.1475-2743.2002.tb00227.x.
- FAO and ITPS (2021). *Recarbonizing Global Soils – A technical manual of recommended sustainable soil management*. Volume 4: Cropland, grassland, integrated systems and farming approaches – Case studies. Rome, FAO. DOI: 10.4060/cb6598en.
- FAO (2015). World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. Update 2015. Available at: <https://www.fao.org/3/i3794en/i3794en.pdf>
- Farina, R., Marchetti, A., Francaviglia, R., Napoli, R., and DiBene, C. (2017). Modeling regional soil C stocks and CO₂ emissions under Mediterranean cropping systems and soil types. *Agriculture, Ecosystems & Environment*, 238, 128–141. DOI:10.1016/j.agee.2016.08.015.
- Funes, I., Savé, R., Rovira, P., Molowny-Horas, R., Alcaniz, J.M., Ascaso, E., Herms, I., Herrero, C., Boixadera, C., Boixadera, J., and Vayreda, J. (2019). Agricultural soil organic carbon stocks in the north-eastern Iberian Peninsula: Drivers and spatial variability. *Science of the Total Environment*, 668, 283–294. DOI:10.1016/j.scitotenv.2019.02.317.
- Guo, L., Falloon, P., Zhou, B., Li, Y., Lin, E., and Zhang, F. (2007). Application of the RothC model to the results of long-term experiments on typical upland soils in northern China. *Soil Use and Management*, 23(1), 63–70. DOI: 10.1111/j.1475-2743.2006.00056.x.
- Hábová, M., Pospíšilová, L., Hlavinka, P., Trnka, M., Barančíková, G., Tarasovičová, Z., Takáč, J., Koco, Š., Menšík, L., and Nerušil, P. (2019). Carbon pool in soil under organic and conventional farming systems. *Soil and Water Research*, 14(3), 145–152. DOI:10.17221/71/2018-SWR.
- Hassink, J. (1997). The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant Soil*, 191, 77–87. DOI:10.1023/A:1004213929699.
- Hobley, E.U., Wilson, B.R., Wilkie, A., Gray, J.M., and Koen, T. (2015). Drivers of soil organic carbon storage and vertical distribution in Eastern Australia. *Plant and Soil*, 390 (1–2), 111–127. DOI:10.1007/s11104-015-2380-1.
- Jobbagy, E.G. and Jackson, R.B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, 10(2), 423–436. DOI: 10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2.
- Kirschbaum, M.U.F. (2006). The temperature dependence of organic matter decomposition – still a topic of debate. *Soil Biology and Biochemistry*, 38(9), 2510–2518. DOI:10.1016/j.soilbio.2006.01.030.
- Kizeková, M., Čunderlík, J., Dugátová, Z., Jančová, Ľ., Kanianska, R. and Makovníková, J. (2021). Carbon sequestration in grasslands [Sekvestrácia uhlíka v trávnych porastoch]. *Náše Pole*, 2, 50–53.
- Kopittke, P.M., Berhe, A.A., Carrillo, Y., Cavagnaro, T.R., Chen, D., Chen, Q.-L., Román Dobarco, M., Dijkstra, F.A., Field, D.J., Grundy, M.J., He, J.-Z., Hoyle, F.C., Kögel-Knabner, I., Lam, S.K., Marschner, P., Martinez, C., McBratney, A.B., McDonald-Madden, E., Menzies, N.W., and Minasny, B. (2022). Ensuring planetary survival: The centrality of organic carbon in balancing the multifunctional nature of soils. *Critical Reviews in Environmental Science and Technology*, 52(23), 4308–4324. DOI:10.1080/10643389.2021.2024484.
- Koven, C., Hugelius, G., Lawrence, D.M., and Wieder, W. (2017). Higher climatological temperature sensitivity of soil carbon in cold than warm climates. *Nature Climate Change*, 7, 817–822. DOI:10.1038/nclimate3421.
- Kuhnel, A., Garcia-Franco, N., Wiesmeier, M., Burmeister, J., Hobley, E., Kiese, R., Dannenmann, M. and Kögel-Knabner, I. (2019). Controlling factors of carbon dynamics in grassland soils of Bavaria between 1989 and 2016. *Agriculture Ecosystems and Environment*, 280(1), 118–128. DOI:10.1016/j.agee.2019.04.036.
- Ledo, A., Smith, P., Zerihun, A., Whiteker, J., Vincente-Vincente, J.L., Qin, Z., McNamara, N.P., Zinn, Y., Liorente, M., Liebig, M., Kuhnert, M., Dondini, M., Don, A., Diaz-Pines, E., Datta, A., Bakka, H., Aguilera, E., and Hillier, J. (2020). Changes in soil organic carbon under perennial crops. *Global Change Biology*, 26(7), 4158–4168. DOI:10.1111/gcb.15120.
- Loague, K. and Green, E.E. (1991). Statistical and graphic methods for evaluating solute transport models: overview and application. *Journal of Contaminant Hydrology*, 7(1–2), 51–73. DOI:10.1016/0169-7722(91)90038-3.
- Lu, X., Kelsey, K.C., Yan, Y., Sun, J., Wang, X., Cheng, G., and Neff, J.C. (2017). Effects of grazing on ecosystem structure and function of alpine grasslands in Qinghai-Tibetan Plateau: a synthesis. *Ecosphere*, 8(1), e01656. DOI:10.1002/ecs2.1656.
- Maillard, E. and Angers, D. (2014). Animal manure application and soil organic carbon stocks: a meta-analysis. *Global Change Biology*, 20(2), 666–679. DOI:10.1111/gcb.12438.
- Moinet, G.Y.K., Hijbeek, R., van Vuuren, D.P., and Giller, P.

- K.E. (2023). Carbon for soils, not soils for carbon. *Global Change Biology*, 29(9), 2384–2398. DOI:10.1111/gcb.16570.
- Mondini, C., Coleman, K. and Whitmore, A. (2012). Spatially explicit modelling of changes in soil organic C in agricultural soils in Italy, 2001–2100: Potential for compost amendment. *Agriculture, Ecosystems & Environment*, 53, 24–32. DOI:10.1016/j.agee.2012.02.020.
- Morais, T., Teixeira, R. and Domingos, T. (2019). Detailed global modelling of soil organic carbon in cropland, grassland and forest soils. *PLoS One*, 14(9), e0222604. DOI:10.1371/journal.pone.0222604.
- Peralta, G., Di Paolo, L., Luotto, I., Omuto, C., Mainka M., Viatkin, K., and Yigini, Y. (2022). *Global soil organic carbon sequestration potential map (GSOCseq v1.1)* – Technical manual. Rome: FAO. DOI:10.4060/cb2642en.
- Piñeiro, G., Paruelo, J.M., Oesterheld, M., and Jobbágy, E.G. (2010). Pathways of grazing effects on soil organic carbon and nitrogen. *Rangeland Ecology and Management* 63(1), 109–119. DOI:10.2111/08-255.1.
- Prokopyeva, K., Romanenkov, V., Sidorenkova, N., Pavlova, V., Siptits, S., Krasilnikov, P., and (2021). The effect of crop rotation and cultivation history on predicted carbon sequestration in soils of two experimental fields in the Moscow region, Russia. *Agronomy*, 11(2), 226. DOI:10.3390/agronomy11020226.
- Rothamsted Carbon Model. Version 2.1 (7 April 2009): Available at: <https://www.rothamsted.ac.uk/rothamsted-carbon-model-rothc>.
- Schulp, C.J.E. and Verburg, P.H. (2009). Effect of land use history and site factors on spatial variation of soil organic carbon across a physiographic region. *Agriculture, Ecosystems and Environment*, 133(1–2), 86–97. DOI:10.1016/j.agee.2009.05.005.
- Skalský, R., Koco, Š., Barančíková, G., Tarasovičová, Z., Hałas, J., Koleda, P., Makovníková, J., Gutteková, M., Tobiášová, E., Gömöryová, E., and Takáč, J. (2020). Land cover and land use change-driven dynamics of soil organic carbon in North-East Slovakian croplands and grasslands between 1970 and 2013. *Ekológia (Bratislava)*, 39(2), 159–173. DOI:10.2478/eko-2020-0012.
- Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Froking, S., Jenkinson, D.S., Jensen, L.S., Kelly, R.H.M., Klein-Gunnewiek, H., Komarov, A.S., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thorney, J.H.M. and Whitmore, A.P. (1997). A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. *Geoderma*, 81(1), 153–225. DOI:10.1016/S0016-7061(97)00087-6.
- Smith, J., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R., Montanarella, L., Rounsevell, M.D.A., Reginster, I., and Ewert, F. (2005). Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. *Global Change Biology*, 11(12), 2141–2152. DOI: 10.1111/j.1365-2486.2005.001075.x.
- Smith, J., Smith, P., Meyer, M., Wattenbach, M., Meyer, J., Lindner, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M., Register, I., and Kankaanpää, S. (2006). Projected changes in mineral soil carbon of European forests, 1990–2100. *Canadian Journal of Soil Science*, 86, 159–169. DOI:10.4141/S05-078.
- Smith, P., Soussana, J.F., Angers, D., Schipper, L., Chenu, C., Rasse, D., Batjes, N., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J.E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., and Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, 26(1), 219–241. DOI:10.1111/j.1365-2486.2012.02689.x.
- Soussana, J.-F., Loiseau, P., Vuichard, N., Ceschia, E., Balesdent, J., Chevallier, T., and Arrouays, D. (2006). Carbon cycling and sequestration opportunities in temperate grasslands. *Soil Use and Management*, 20, 219–230. DOI: 10.1111/j.1475-2743.2004.tb00362.x.
- Soussana, J.F. and Lemaire, G. (2014). Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agriculture, Ecosystems and Environment*, 190, 9–17. DOI:10.1016/j.agee.2013.10.012.
- Tarasovičová, Z. and Barančíková, G. (2011). A new approach to the formation of carbon inputs from permanent grasslands of Slovakia for the RothC model [Nový prístup pri tvorbe vstupov uhlíka trvalých trávnych porastov Slovenska pre model RothC]. In *Proceedings of the Soil Science and Conservation Research Institute, Bratislava*, 33, 184–193. Available at: https://www.vupop.sk/dokumenty/vedecke_prace_2011.pdf.
- Ward, S.E., Smart, S.M., Quirk, H., Tallowin, J.R.B., Mortimer, S.R., Shiel, R.S., Wilby, A., and Bardgett, R.D. (2016). Legacy effects of grassland management on soil carbon to depth. *Global Change Biology*, 22(8), 2929–2938. DOI:10.1111/gcb.13246.
- Wiesmeier, M., Urbanski, L., Hobbey, E., Lang, B., von Lutzow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Lies, M., Garcia-Franco, N., Wollschlaeger, U., Vogel, H.J., and Kogel-Knabner, I. (2019). Soil organic carbon storage as a key function of soils – A review of drivers and indicators at various scales. *Geoderma*, 333, 149–162. DOI:10.1016/j.geoderma.2018.07.026.
- Whitehead, D., Schipper, L., A., Pronger, J., Moinet, G.Y.K., Mudge, P.L., Calvelo Pereira, R., Kirschbaum, M.U.F., McNally, S.R., Beare, M.H., and Camps-Arbestain, M. (2018). Management practices to reduce losses or increase soil carbon stocks in temperate grazed grasslands: New Zealand as a case study. *Agriculture, Ecosystems and Environment*, 265, 432–443. DOI:10.1016/j.agee.2018.06.022.
- Witt, G.B., Noël, M.V., Bird, M.I., Beeton, R.J.S., and Menzies, N.W. (2011). Carbon sequestration and biodiversity restoration potential of semi-arid mulga lands of Australia interpreted from long-term grazing exclosures. *Agriculture, Ecosystems & Environment* 141(1–2), 108–118. DOI:10.1016/j.agee.2011.02.020.
- Wust-Galey, C., Keel, C.G. and Leifeld, J. 2020. *A model based carbon inventory for Switzerland's mineral agricultural soils using RothC*. Agroscope Science, No.105, 110 p. Available at: https://www.agroscope.admin.ch/agroscope/fr/home/themes/programmes-recherche/programmes-recherche-2014-2018/biodiversite-microbienne/publikationen-peer-reviewed/_jcr_content/par/external-content.bitexternalcontent.exturl.html/aHR0cHM6Ly9p-cmEuYWdyb3Njb3B1LmNoL210LUNIL3B1Ym9pY2/F0aW9uLzQ1Nzg5.html.

Received: October 10, 2023
Accepted: December 14, 2023