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Assessment of carbon sequestration as affected by different management practices using the RothC model

Jakub Prudil[1], Lubica Pospíšilová[1], Tamara Dryšlová[2], Gabriela Barančíková[3], Vladimír Smutný[2], Luboš Sedlák[1], Pavel Ryant[1], Petr Hlavinka[2,4], Miroslav Trnka[2,4], Ján Halas[3], Štefan Koco[3,5], Jozef Takáč[3], Kateřina Boturová[1], Soňa Dušková[2], Lubomír Neudert[2], Michal Rábek[2]*

[1]*Mendel University in Brno, Faculty of AgriSciences, Department of Agrochemistry, Soil Science, Microbiology and Plant Nutrition, Brno, Czech Republic*
[2]*Mendel University in Brno, Faculty of AgriSciences, Department of Agrosystems and Bioclimatology, Brno, Czech Republic*
[3]*National Agricultural and Food Centre, SSCRI Bratislava, Bratislava, External Working Place Prešov, Prešov, Slovak Republic*
[4]*Global Change Research Institute, The Czech Academy of Sciences, Brno, Czech Republic*
[5]*University of Prešov, Faculty of Humanities and Natural Sciences, Department of Geography and Applied Geoinformatics, Prešov, Slovak Republic*

**Corresponding author: xprudill@mendelu.cz*

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Abstract. Long-term field experiments provide a valuable dataset for predicting changes in soil organic carbon (SOC) stocks in different agricultural systems. The RothC-26.3 model was used to simulate changes in SOC in the monoculture of spring barley (*Hordeum vulgare* L.) and the Norfolk crop rotation during 1972–2100. The potential of the Gleyic Fluvisol Clayic to sequester organic carbon was investigated. The studied soil was heavily textured, with medium organic carbon content. Four management scenarios in the monoculture and six management scenarios in the Norfolk crop rotation were evaluated. Three different global climate models (MPI, MRI, CMSS) representing the uncertainty of future climate conditions were used. Results showed that carbon stocks were mainly influenced by plant residue inputs and exogenous organic materials application. The projection showed trends of carbon stocks decreasing in the case of monoculture management. Results also documented that management scenario D with straw incorporation and intercrops represented sustainability and carbon stock increase during all modelled climate scenarios. The SOC stock at the end of the century was approximately 66 t/ha. This represents a moderate sequestration of SOC of approximately 0.09 t/ha/year.

Keywords: organic carbon accumulation; crop management and climatic conditions; modelling

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Agrotechnical practices and farming systems amplified by climate change over the past decades have seriously impacted soil carbon sequestration and contributed to the critical level of carbon dioxide (CO_2) in the atmosphere. Moreover, climate change and the rate of carbon sequestration are correlated to the soil type, plant input, crops, and other anthropogenic factors. Understanding how the different factors interact is important for successful management strategy development. The level and balance of soil organic carbon (SOC) are the main criteria of agricultural sustainability. They are also important for maintaining other non-productive ecosystem services such as biodiversity provision, hygienic and environmental functions, etc. SOC is often considered the primary soil quality indicator in agricultural lands (Chevallier et al. 2016). It is also a key factor in all groups of ecosystem services (Banwart et al. 2015). Organic carbon in the soil ecosystem is influenced mainly by natural conditions and human activities (Eckelmann et al. 2006, Tayebi et al. 2021). As quoted by Wiesmeier et al. (2019), natural factors that affect SOC dynamics include soil properties, climate characteristics, and geographic factors. Besides natural indicators, the impact of human activities on SOC stock comes through land use (arable land, meadow, forest) and the case of intensive soil management (Guo and Gifford 2002, Barančíková et al. 2013, Maillard and Angers 2014, Poeplau and Don 2015). Loss of SOC stock after the conversion of natural ecosystems into agricultural land has been confirmed by many authors (Guo and Gifford 2002, Poeplau and Don 2015, Ledo et al. 2020).

In cultivated soils, the SOC stock has also been affected by erosion processes and low-carbon inputs. These can significantly reduce the stabilisation of soil organic matter (SOM) due to deteriorated aggregation, and subsequent mineralisation promoted by increased soil temperature and aeration (Balesdent et al. 2000, Hamza and Anderson 2005). On the other hand, many studies showed that appropriate management practices, which include crop diversity, mulching, supply of organic matter and organic fertilisers to the soil (soil fertility management, cultivation of perennial crops), control of wind and water erosion, the application of soil conservation technologies, and application of biowastes increase the SOC stock in agricultural soils (Poeplau and Don 2015, Kowalska et al. 2020, Ledo et al. 2020, Valkama et al. 2020, Seitz et al. 2022).

If and how soils can sequestrate more organic carbon requires precise methods for evaluation of SOC. Lorenz and Lal (2005) pointed out that conventional analytical methods for assessing SOC stock are expensive, time-consuming, and not always comparable. The mechanisms for SOC stabilisation can be classified into three categories: physical, chemical, and physico-chemical stabilisation. The authors stated that all the organic carbon forms presented in the soil are still not well studied and monitored. Moreover, the increase in SOC stabilisation and sequestration may cause the C turnover to slow down. Jenkinson et al. (1999) defined inert organic carbon as a fraction of soil organic matter that is biologically inert and has an equivalent radiocarbon age of more than 50 000 years. Besides inert organic carbon, soil organic matter includes relatively stable and labile carbon forms. Some data have also been set from an empirically derived relationship between inert and total SOC (Falloon et al. 1998, 2000, Falloon and Smith 2002). Many mathematical and statistical models were developed for the modelling and prediction of SOC. Today, one of the promising approaches is using carbon isotope data (^{13}C and ^{14}C) that can be coherent with the carbon cycle anthropogenic perturbation time scale (e.g. from years to century). In general, modelling provides valuable information on the development of SOC stock, which can be positive (carbon sequestration) or negative (carbon emission) (e.g. the ORCHIDEE, CENTURY, EPIC, RothC). These models and field measurements would suggest that soil properties and crop management can play a significant role in determining the carbon stocks. Several sites in the Czech Republic and all over the world operate with the EPIC model, and the simulation of crop production and its agro-environmental impact are documented (Pohanková et al. 2015, Viscarra Rossel et al. 2016, Camino-Serrano et al. 2018, Finke et al. 2019, Hábová et al. 2019). In this way, data from SOC long-term field monitoring are regarded as a key factor for quantifying and validating mathematical and statistical models. The selected RothC model was initially developed and parametrised to model the turnover of organic carbon in arable soil from Rothamsted long-term field experiments. Later, it was extended to model turnover in grassland and woodland. It can operate in different soil uses and soil management, different soil types and under different climates (Smith et al. 2007, Van Wesemael et al. 2010, Barančíková et al. 2013, Francaviglia et al. 2019, Wust-Galley et al. 2020, Prokopyeva et al. 2021, Paramesh et al. 2022).

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This article aims to simulate the effect of agrotechnical management practices and climate change on the level of carbon accumulation in the intensively used Gleyic Fluvisol Clayic. The RothC model was validated for 1972–2020 and the prediction of SOC stock was made for 2022–2100. Three climatic scenarios, four management scenarios for monoculture, and six management scenarios for the Norfolk crop rotation were modelled.

MATERIAL AND METHODS

Site and long-term field characteristics. The long-term field experiment was established in the autumn of 1969 in the Field Experimental Station of Mendel University in Žabčice. The place Žabčice is located in the South Moravian region (49°0'42"N, 16°36'9"E; altitude of 180 m a.s.l.). Thirty-year average (1991–2020) annual air temperature is 10.3 °C, and average annual precipitation is 491 mm, indicating the warmest and driest areas in the Czech Republic. The field experiment is focused on spring barley (*Hordeum vulgare* L.) due to the tradition of growing and breeding in the Moravian region. During that time, cultivars were changed according to the demand of breweries and nowadays only cv. Bojos is grown. Details of crops alternating in Norfolk during all assessed periods (1972–2020) are listed in Table 4. There were these crops grown: red clover (*Trifolium pratense* L.), winter wheat (*Triticum aestivum* L.), sugar-beet or silage maize (both with application of farmyard manure (FYM) in dose 35 t/ha), spring barley (*Triticum hordeum* L., the same cultivars like in monoculture). Norfolk crop rotation was modified in the year 2003, and the current rotation consists of these crops: alfalfa (*Medicago sativa* L.), winter wheat (*Triticum aestivum* L.), grain maize (*Zea mays* L.) with application of FYM in dose 25 t/ha and spring barley (*Hordeum vulgare* L.).

In monoculture, three experimental factors are included in long-term field trials (soil tillage, straw management, and nitrogen fertilisation). Norfolk crop rotation is conducted with two experimental factors (without straw management. Soil tillage methods are used: ploughing (0.22 m) and shallow loosening (0.12–0.14 m). All crops, except spring barley, are fertilised with nitrogen in a single dose according to the plant's nutrition needs; for spring barley, differentiated nitrogen fertilisation is implemented (nitrogen doses of 30, 60 and 90 kg/ha in ammonium sulphate).

Other nutrients are applied in a dose of 39.6 kg P and 99.6 kg K (triple superphosphate, and potassium salt) for all fields in the autumn, which corresponds to a dose of 39.24 kg of pure phosphorus and 99.60 kg of pure potassium.

In the monoculture of spring barley, there are three variants of straw management: straw harvested (SH), straw chopping and incorporated (SI), and straw burning (SB). Each experimental variant is carried out in four replications, harvesting plots areas are 20 m^2, and yields of crops were calculated in appropriate units per hectare. Data processing was done by MS Excel v. 2010 (Microsoft, Redmond, USA).

Soil properties. The studied soil was classified as Gleyic Fluvisol Clayic, heavily textured, with medium organic carbon content. The soil type was classified according to the IUSS Working Group WRB (2022) and Němeček et al. (2011). The soil is heavily textured and weakly acidic, with medium cation exchange capacity and SOC content. Basic soil properties are documented in Tables 1 and 2.

Soil sampling and analysis. From 1972–2017, the soil was sampled once a year after harvesting the crops from 0–0.10 m, since 2017, from a depth of 0–0.10, 0.10–0.20, and 0.20–0.30 m. Basic soil characteristics were determined by commonly used standard methods. Soil reaction was determined by the potentiometric method in distilled water and 1 mol/L KCl solution (1:2.5). Particle size analysis was determined by the pipette method. Soil organic carbon content was determined by the oxidimetric titration method (Hábová et al. 2019).

Table 1. Texture classes in the profile of Gleyic Fluvisol Clayic

Horizon	Depth (m)	Clay	Silt	Sand	Texture class
			(%)		
Ap	0–0.15	48.50	44.50	7.00	silty clay
AM	0.15–0.30	44.00	47.25	8.75	silty clay
MG	> 0.30	49.00	48.80	2.20	silty clay

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Table 2. Average values of physico-chemical parameters in the studied Gleyic Fluvisol Clayic

Horizon	Depth (m)	pH_{H_2O}	pH_{KCl}	Conductivity (mS/cm)	CEC ($mmol_+$/kg)	SOC (%)
Ap	0–0.15	6.60	5.60	0.23	219.20	1.22
AM	0.15–0.30	6.40	5.45	0.18	155.00	0.48
MG	> 0.30	6.25	5.35	0.20	150.00	0.22

pH_{H_2O} – active soil reaction; pH_{KCl} – exchangeable soil reaction; CEC – cation exchange capacity; SOC – soil organic carbon content

The RothC Model. The structure of the RothC model (Coleman and Jenkinson 1996, 2005, Coleman et al. 1997) was as follows: soil organic carbon was split into four active compartments (DPM – decomposable plant material; RPM – resistant plant material; BIO – microbial biomass; HUM – humified organic matter) and a small amount of inert organic matter (IOM). Each compartment decomposes by a first-order process with its characteristic rate. The IOM compartment is resistant to decomposition.

Input data

The input data include the following: climate data, soil data and crop management data.

Climate data

- monthly precipitation (mm);
- monthly evapotranspiration (mm);
- average monthly mean air temperature (°C).

Soil characteristics

- clay content (%);
- inert organic carbon;
- initial soil organic carbon stock (C t/ha);
- depth of soil layer considered (cm).

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 (amount of C t/ha);
- residues quality factor (DPM/RPM ratio).

The RothC model for Žabčice locality. Climate data for the baseline period 1972–2020 were obtained from Žabčice meteorological station. The station is situated directly at the experimental site and has been kept following the World Meteorological Organisation Standards.

Soil data. Analytical data on clay content were received from the particle size analysis of disturbed samples collected from the Žabčice locality (Table 1). SOC stock was modelled for 30 cm of soil depth.

At the beginning (in 1972), the initial carbon stock status was calculated for different variants of the monoculture of spring barley and the Norfolk.

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

Where: SOCm – measured soil organic carbon content (%); BD – bulk density (g/cm^3); d – soil depth (0.30 m).

The biologically inert SOC fraction (IOM) is calculated from the initial SOC stock by an exponential equation (Faloon et al. 1998):

$$\text{IOM} = 0.049\text{SOC}^{1.139}$$

The initial SOC content was used for running the RothC model to equilibrium (10 000 years) under constant environmental conditions (Coleman and Jenkinson 1996). The empirically derived relationship was set between inert organic matter and the total stock of organic carbon (Falloon et al. 2002, Barančíková 2013, Hábová et al. 2019). Data of carbon and radiocarbon ages were received in equilibrium mode (initial soil state, initial radiocarbon age) and were applied to run the model in short-term mode (1972–2020), and for prediction in long-term mode (2022–2100). Literature data for RMSE for long-term field experiments modelling were between 2% and 30% (Smith et al. 1997, Falloon and Smith 2002, Guo et al. 2007, Barančíková et al. 2013, Hábová et al. 2019).

Crop management data. Organic carbon inputs of plant residues or farmyard manure were calculated according to Barančíková et al. (2013) and Hábová et al. (2019).

Qr – carbon content in plant input (t/ha),

$$Qr = u \times kc$$

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 – 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).

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Management data set for validation (warm-up) period (1972–2020)

Monoculture of spring barley. Monoculture of spring barley – the influence of straw incorporation, straw burning, and straw harvesting on crop yields was studied in the monoculture of spring barley.

The model validation was performed for each variant. So model validation was performed three times with the different plant residue inputs (k_C – for spring barley + straw incorporated, straw harvested, and straw burnt, for monoculture), and then measured SOC values (1972–2020) were used for RMSE (root mean square error) calculation.

Norfolk crop rotation. Norfolk crop rotation was chosen for calculating C input from plant residues of individual crops according to yields each year and *Kc* value for a given crop in the Norfolk crop rotation from 1972–2020. The C input from organic fertiliser was considered and applied for the year corresponding to the application of organic fertilisation. Nine measured SOC values during the period 1972–2020 were used for RMSE calculation.

Development of SOC stock – forward period (until 2100)

SOC stock was predicted for four (monoculture) and six (Norfolk) management scenarios and three climate scenarios.

Future management scenarios for monoculture

- Management scenario (A) – the current management scenario (using average spring barley yield during the period 1972–2020, variant straw incorporation, *kc* – spring barley);
- Management scenario (B) – the current management scenario (using average spring barley yield during the period 1972–2020, variant straw harvested, *kc* – spring barley);
- Management scenario (C) – the current management scenario (using average spring barley yield during the period 1972–2020, variant straw harvested, yearly intercrops from August, *kc* – spring barley + intercrops);
- Management scenario (D) – the current management scenario (using average spring barley yield from 1972–2020, variant straw incorporated, yearly intercrops from August, *kc* – spring barley + straw + intercrops).

Future management scenarios for the Norfolk crop rotation

- Management scenario (A) – the current management scenario (2000–2020, grain maize, spring barley, alfalfa, winter wheat. Maize bark is incorporated, but barley and wheat straw are harvested. Farmyard manure is applied before barley in a dose of 25 t/ha, *Kc* – grain maize + maize bark + spring barley + winter wheat + FYM 25 t/ha);
- Management scenario (B) – the current management scenario (2000–2020, grain maize, spring barley, alfalfa, winter wheat. Maize bark is incorporated, but barley and wheat straw are harvested. FYM in a dose of 40 t/ha, *Kc* – grain maize + maize bark + spring barley + winter wheat + FYM 40 t/ha);
- Management scenario (C) – the current management scenario (2000–2020, grain maize, spring barley, alfalfa, winter wheat. Maize bark, barley and wheat straw are incorporated, with no organic fertilisation, *Kc* – grain maize + maize bark + spring barley + straw + winter wheat + straw);
- Management scenario (D) – the current management scenario (2000–2020, grain maize, spring barley, alfalfa, winter wheat. Maize bark, barley and wheat straw are incorporated, with no organic fertilisation, yearly intercrops after winter wheat in August, *Kc* – grain maize + maize bark + spring barley + straw + winter wheat + straw + intercrops);
- Management scenario (E) – the current management scenario (2000–2020, grain maize, spring barley, alfalfa, winter wheat. Maize bark is incorporated, but barley and wheat straw are harvested, FYM 40 t/ha, yearly intercrops after winter wheat in August, *Kc* – grain maize + maize bark + spring barley + winter wheat + intercrops + FYM 40 t/ha);
- Management scenario (F) – the current management scenario (2000–2020, grain maize, spring barley, alfalfa, winter wheat. Maize bark is incorporated, barley straw is harvested, wheat straw is incorporated, FYM 40 t/ha, yearly intercrops after winter wheat or spring barley in August, *Kc* – grain maize + maize bark + spring barley + winter wheat + straw + intercrops + FYM 40 t/ha).

Climate scenarios

The soil organic carbon stock simulation was calculated with emission and socioeconomic scenario RCP 585, i.e., assuming no coordinated global climate change mitigation increases the global

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anthropogenic forcing of 8.5 W/m^2. At the same time, this scenario was selected due to its stronger climate signal, with the change expected for the next three decades being relatively similar to other SSP scenarios. Three climatic scenarios were applied with the model MRI-CGCM3 (Meteorological Research Institute, Japan), representing the smallest rate of temperature change and virtually unchanged precipitation over the main vegetation season. The MPI-ESM 1.2 (Max Planck Institute, Germany) projects a smaller rate of temperature increase by 2050 compared to MRI and almost unchanged precipitation compared to the baseline over the April–September period. Finally, the CMCC-ESM (Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy) climate estimate leads to a considerably higher temperature increase with a marked precipitation reduction of up to 20% over the warm half-year. The selected scenarios varied from warm-dry to hot-dry scenarios, and the variability of temperature and precipitation during 1981–2100 is presented in Table 3.

RESULTS AND DISCUSSION

Crop yields evaluation

The average crop yields are presented in Table 4. The obtained results showed that the lowest yields were on the straw harvested variant (SH) compared to straw incorporation (SI) and straw burnt (SB).

The RothC modelling

The modelling of SOC stock was realised for the depth of 0.30 m, according to European global levels (IPCC 2006, Panagos et al. 2013, Lugato et al. 2014, Yigini et al. 2017, Peralta et al. 2022).

In the monoculture of spring barley, a good fit between modelled and measured data was observed in all studied variants (Figure 1). When the straw was incorporated, the measured SOC stock was between 55 and 63 t/ha (RMSE = 7.6). When the straw was harvested, the measured SOC stock was 50–60 t/ha (RMSE = 14.0). When the straw was burnt, the modelled SOC stocks were between 58 to 70 t/ha (RMSE = 8.8) (Figure 1). The Norfolk crop rotation (Figure 2) also showed a good match between the measured and modelled data (RMSE = 8.7). The development of SOC from 1972–2020 was almost the same as for monoculture, straw burnt. In the case of the Norfolk crop rotation, SOC stock was between 60–70 t/ha. It should also be mentioned the model for straw-harvested treatment (Figure 1B) underestimated the SOC content by approx. 20%, similarly for the variant with straw burning. The modelling uncertainty may be significant and affect the predictions. Dataset evaluation only according to RMSE may not always be accurate.

Prediction of climate conditions

The climatic scenario CMCC-ESM predicts the highest temperature increase with reduced precipitation during 2040–2100. On the other hand, the difference between the average temperature in MPI_ESM1.2 and MRI-CGCM3 is negligible. The development of temperature increases during 2020–2100 differs in all selected scenarios, as is evident from Figure 3; the highest temperature increase has MRI during 2020–2040.

Prediction of SOC for monoculture of spring barley

Monoculture farming was modelled in four management scenarios (A, B, C, D) during three climatic scenarios (MPI, MRI, CMSS) and temperature increase in 2022–2100. The projected development of SOC stock under the monoculture of spring barley with straw incorporation (management scenario A) and with straw incorporation and intercrops (management scenario D) during three different climate scenarios

Table 3. Temperature (°C) and precipitation (mm) during the vegetation season for three used GCMs as estimated for the baseline (1981–2010) and individual decades up to 2100

Decade	T MRI × T		T MPI		T CMSS	
	T	P	T	P	T	P
1981–2010	16.6	316	16.6	316	16.6	316
2022–2030	18.5	300	17.5	317	17.8	270
2031–2040	19.0	320	18.1	314	18.9	271
2041–2050	19.2	322	18.5	316	19.5	261
2051–2060	19.6	321	19.2	314	20.9	248
2061–2070	19.8	304	19.6	311	21.6	243
2071–2080	20.1	296	20.4	314	22.5	243
2081–2090	20.8	301	21.2	322	23.3	248
2091–2100	21.3	310	21.9	304	23.9	261

MRI – warm-dry scenario; MPI – warm-dry scenario; CMSS – hot-dry scenario

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Table 4. Average crop yields in the monoculture of spring barley (*Hordeum vulgare* L.) and in the Norfolk crop rotation (Žabčice 1972–2020)

Year of experiment	Monoculture grain yield of spring barley (t/ha)				Norfolk crop rotation yield of crops (t/ha)	
	straw harvested	straw incorporated	straw burnt	average yield	crop in rotation	yield of crops (t/ha)
1972	3.93	4.06	4.18	4.06	red clover	11.34
1973	3.42	3.61	4.16	3.73	winter wheat	2.64
1974	4.36	5.52	5.31	5.06	spring barley	5.78
1975	4.69	5.04	5.21	4.98	maize for sillage	22.09
1976	5.29	5.76	5.20	5.42	spring barley	6.54
1977	5.06	4.40	4.15	4.54	red clover	5.28
1978	5.06	5.11	5.04	5.07	winter wheat	3.75
1979	4.60	4.75	4.79	4.71	sugar beet	49.41
1980	6.48	6.55	6.43	6.49	spring barley	7.47
1981	5.06	5.16	5.26	5.16	red clover*	7.22
1982	5.36	5.57	5.77	5.57	winter wheat	5.41
1983	5.38	5.85	5.77	5.67	spring barley	4.93
1984	5.13	5.22	5.95	5.43	sugar beet	45.67
1985	4.89	4.79	5.23	4.97	spring barley	6.29
1986	4.77	5.21	5.08	5.02	red clover*	8.44
1987	4.50	4.76	4.82	4.69	winter wheat	5.40
1988	4.64	4.77	5.39	4.93	sugar beet	37.56
1989	6.02	6.31	6.54	6.29	spring barley	6.08
1990	5.26	5.16	6.17	5.53	red clover*	13.11
1991	4.75	4.92	5.49	5.05	winter wheat	7.87
1992	5.04	4.85	6.11	5.33	spring barley	6.67
1993	2.64	3.40	4.73	3.59	sugar beet	41.20
1994	4.25	4.28	5.09	4.54	spring barley	6.14
1995	5.10	5.77	5.91	5.59	red clover*	11.57
1996	4.73	4.82	5.08	4.88	winter wheat	6.33
1997	4.40	4.72	5.08	4.73	sugar beet	44.15
1998	5.52	5.78	5.10	5.47	spring barley	5.93
1999	5.01	4.82	4.87	4.90	red clover*	12.80
2000	5.01	5.45	4.95	5.14	winter wheat	4.90
2001	3.97	4.35	4.24	4.19	spring barley	4.02
2002	4.04	4.75	5.14	4.64	maize for sillage	41.38
2003	5.46	5.53	5.60	5.53	spring barley	6.34
2004	7.05	6.97	7.26	7.09	red clover	5.44
2005	5.65	6.39	6.35	6.13	winter wheat	9.68
2006	2.89	3.08	3.35	3.11	grain maize	12.20
2007	2,99	3.07	3.37	3.14	spring barley	3.27
2008	8.06	8.27	8.47	8.27	red clover	2.63
2009	5.69	6.16	6.37	6.07	winter wheat	9.05
2010	6.32	7.14	7.18	6.88	grain maize	7.77
2011	7.75	8.02	8.19	7.99	spring barley	8.06
2012	3.21	3.49	3.93	3.54	Alexandrian clover	3.38
2013	6.95	6.96	6.99	6.97	winter wheat	7.87
2014	7.48	7.79	7.73	7.67	grain maize	12.80
2015	7.40	7.89	7.76	7.68	spring barley	7.32
2016	5.73	6.00	6.01	5.91	incarnate clover	2.60
2017	6.85	7.04	6.95	6.95	winter wheat	8.26
2018	4.68	4.86	4.75	4.76	grain maize	7.45
2019	6.66	6.92	6.33	6.64	spring barley	6.63
2020	7.56	7.58	7.38	7.51	alfalfa	11.50

Cereals – spring barley, winter wheat and maize for grain were harvested by a small plot combine harvester from the defined harvest area and the grain yield was recalculated to 14% moisture. The sugar beetroot, maize for silage and clovers – were harvested from the defined harvest area by manual sampling; the yield was recalculated – for sugar beetroot to t/ha, for mays for silage to harvest maturity for silage (t/ha), clovers yield was recalculated to dry matter (t/ha), *i.e. that red clover was harvested with cereal cover crop like mix of both

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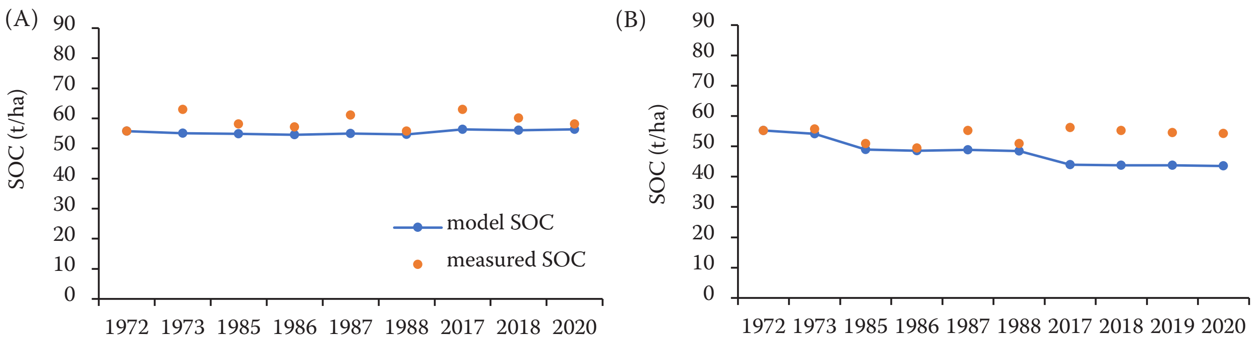

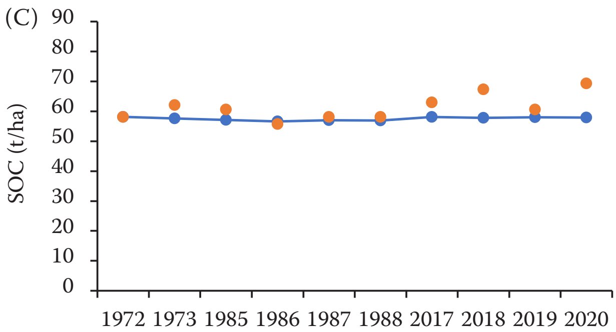

Figure 1. Modelled and measured soil organic carbon (SOC) stock for the monoculture of spring barley, variant (A) straw-incorporated; (B) straw-harvested and (C) straw-burnt (1972–2020)

(MPI, MRI, CMSS) is documented in Figure 4. The average spring barley yields for the straw harvested (SH) and straw incorporated (SI) were used as C input data for the RothC model. Management scenario A with current agrotechnical measures (= monoculture of spring barley with straw incorporation) showed that predicted SOC stock at first increased and, after 2065, gradually decreased. SOC stock did not exceed 62 t/ha. Considering sequestration dynamics (quantification of increases/decreases), it is clear that after the year 2065, this type of management will not be sustainable. Management scenario D with straw incorporation and intercrops represented sustainability during three climate scenarios (MPI, MRI, CMSS). When comparing A and D scenarios, SOC stock was approximately 56 t/ha (A) and 66 t/ha (D) at the end of the century (Figure 4). As it was calculated, the D management scenario with straw incorporation and intercrops represented a moderate SOC sequestration of approximately 0.09 t/ha/year. Considering sequestration dynamics in the D management scenario, it was concluded that this type of management will be sustainable even after 2065. SOC prediction models for the B and C management scenarios are given in Figure 5. The management scenario B with straw harvesting showed that SOC stock has rapidly decreased, and after 2065, the C stock was less than 45 t/ha. Considering sequestration dynamics, this management was the worst and unsustainable. The soil became a source

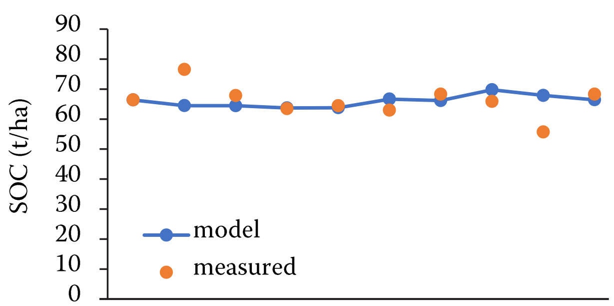

Figure 2. Modelled and measured soil organic carbon (SOC) stock for the Norfolk crop rotation (1972–2020)

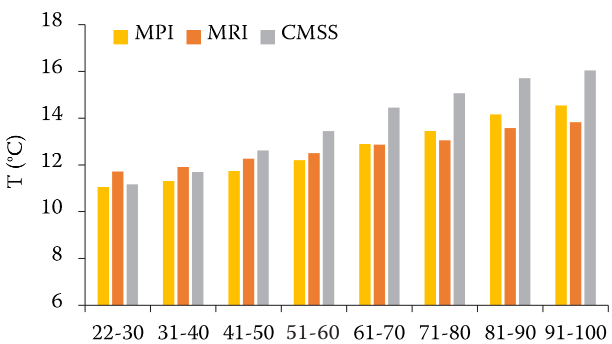

Figure 3. Predicted climatic scenarios (MPI – warm-dry scenario; MRI – warm-dry scenario; CMSS – hot-dry scenario) and temperature (T) increase during the period 2022–2100

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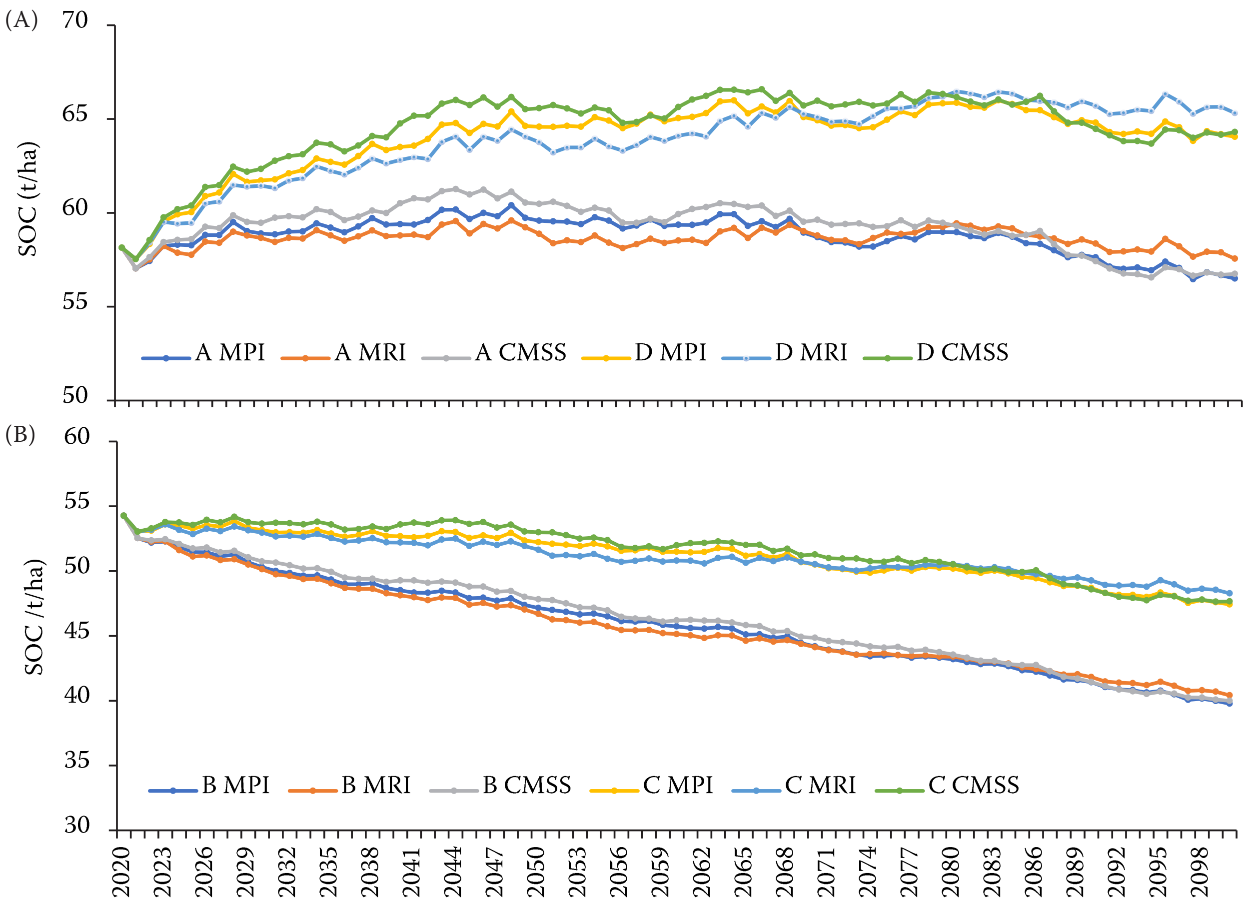

Figure 4. Projected development of soil organic carbon (SOC) stock under monoculture of spring barley with (A) straw incorporation (management scenario A) and with straw incorporation and intercrops (management scenario D) and (B) straw harvesting (management scenario B) and with straw harvesting and intercrops (management scenario C) during three different climate scenarios (MPI – warm-dry scenario; MRI – warm-dry scenario; CMSS – hot-dry scenario)

of carbon, and deterioration is taking place. With straw harvesting and yearly intercrops incorporation, management scenario C indicated the gradual decrease of SOC stock to the value of 50 t/ha. When comparing B and C scenarios, higher SOC stock had intercrop incorporation (scenario C). Considering the effect of different climatic conditions on SOC stock, it was found that the highest SOC stock was under the MRI-CGCM3 (Meteorological Research Institute, Japan) scenario, representing the smallest rate of temperature change and virtually unchanged precipitation over the main vegetation season. The MPI and CMSS scenarios showed a decrease in SOC stock. Many authors documented that the highest carbon accumulation is in warm and wet climatic conditions and the lowest in dry and hot climatic conditions (Yigini et al. 2017, Wiesmeier et al. 2019, Ledo et al. 2020). According to Wang et al. (2021), intercrops may also positively affect SOC stock (Poeplau and Dan 2015, Valkama et al. 2020, Seitz et al. 2022). As it is evident, the current soil carbon status, agricultural management and climate changes are widely discussed today because of removing carbon dioxide (CO_2) from the atmosphere through the natural system and sequestering it in soil (Campbell and Paustian 2015, Rogers et al. 2019, Valkama et al. 2020). According to Web et al. (2003), the increase in air temperature can affect the mineralisation rate and slow down humification processes. The influence of carbon sequestration on SOC stock has been confirmed by other authors (Allen et al. 2013, Koven et al. 2017, Ledo et al. 2020). Whether arable soil is a sink or source of organic carbon depends on various factors, including soil type and texture, existing organic carbon levels, agricultural practices, crop rotations over a period, tillage systems, soil depth, amount and quality of crop residues and organic matter sources, fertilisation practices and climatic

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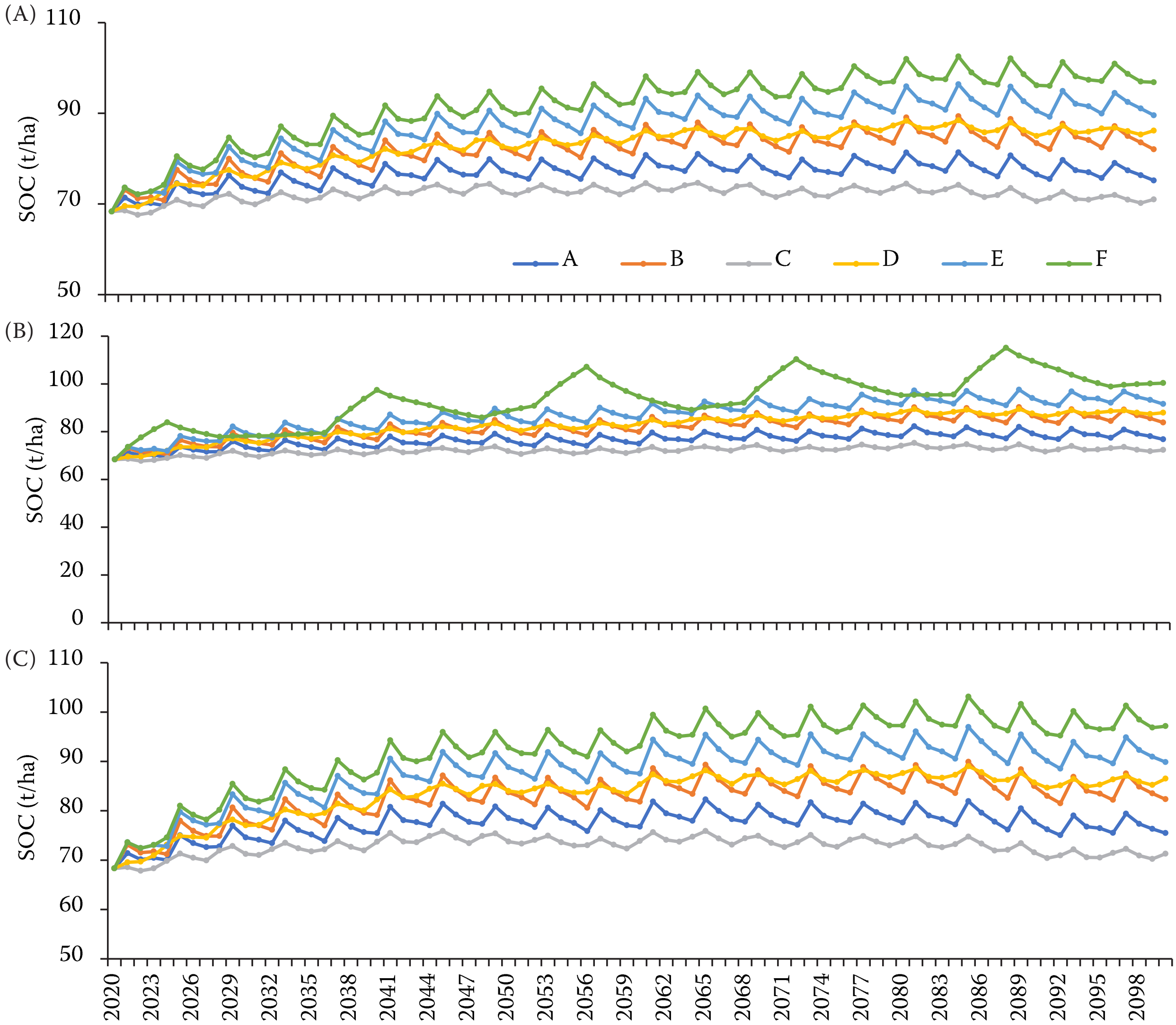

Figure 5. Projected development of soil organic carbon (SOC) stock in Norfolk crop rotation under 6 management scenarios (A–F) and (A) MPI (warm-dry scenario); (B) MRI (warm-dry scenario) and (C) CMSS (hot-dry scenario) climatic scenario

conditions etc. (Baldock and Skjemstad 1999, Song et al. 2014, Banwart et al. 2015, Kunlanit et al. 2019).

The Norfolk crop sequence was modelled in six scenarios (A, B, C, D, E, F) and three different climate scenarios (MPI, MRI, CMSS) (Figure 5). Management scenario (A) – maize grain, spring barley, alfa-alfa, and winter wheat. Furthermore, grain maize bark and FYM 25 t/ha were incorporated, but barley straw and wheat straw were harvested. The SOC stock was lower compared with the B scenario with the same management but FYM 40 t/ha. The lowest stock was in the case of scenario (C) with straw incorporation but no FYM input. Management scenario (D) with the straw and intercrops incorporation showed higher SOC stock compared with the (A), (B), and (C) scenarios. Management scenario (E) with grain maize and intercrops incorporation, FYM 40 t/ha application, but barley and wheat straw harvesting showed higher SOC stock compared with the (A), (B), (C), and (D) scenarios. Management scenario (F) with grain maize bark, FYM 40 t/ha, intercrops, and wheat straw incorporation showed the highest SOC stock. The average SOC stock in Europe varies from 40 to 600 t/ha, depending on soil type, texture, and land use (Dechow et al. 2019). Obtained results for the monoculture of spring barley were lower (40–66 t/ha). The Norfolk crop rotation showed higher carbon sequestration at approximately 70–100 t/ha (Figure 5). In Switzerland, SOC stock in arable soil at above 50 t/ha (Wust-Galey et al. 2020), in Belgium at about

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55 t/ha (Chartin et al. 2017), and in Germany at about 60 t/ha (Dechow et al. 2019). It should be stressed that (E) and (F) management scenarios for Norfolk represented during all selected climate scenarios (MPI, MRI, CMSS) the highest future sustainability. On the other hand, low sustainability showed (A) and (C) management scenarios during all selected climate scenarios (MPI, MRI, CMSS). The carbon accumulation potential of studied Gleyic Fluvisol Clayic was depending mainly on crop management, crop residues and organic matter inputs. Carbon sequestration in studied soil was less influenced by climate change and more by agrotechnical practices. All modelled management scenarios confirmed that increased carbon sequestration is impossible without exogenous organic materials application, an appropriate crop rotation, and an effective straw management strategy. The application of RothC-26.3 was also useful for carbon stock projection in the long- and short-term modes under different management and climatic scenarios.

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