Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 7 December 2020 doi:10.20944/preprints202012.0133.v1

Article

The effect of crop rotation and cultivation history on predicted carbon sequestration in soils of two experimental fields in the Moscow region, Russia

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Abstract: Soil organic carbon (SOC) sequestration in arable soils is a challenging goal for soil management. Multiple factors should be considered for the prediction of the soil capacity to fix atmospheric carbon. In this study, we focused on the effect of crop rotation and previous land use for future carbon sequestration on two experimental fields with identical soils (Retisols) and input of organic fertilizers. We analyzed the SOC dynamics and used the Roth C model to forecast SOC changes under RCP4.5 and RCP8.5 scenarios. Our experimental and modelling results indicated a consistent increase in SOC stocks and the stable fractions of soil organic matter (SOM). The increase in SOC was higher in the experiment with the crop-grassland rotation that in the experiment with a rotation of row crops and barley. With similar total SOC stocks, the efficiency of soil management differed as reflected by the contrasting composition of SOM, as fields with a long cultivation history showed higher SOM stability. The goal of 4‰ annual increase of SOC stocks may be reached under crop- grassland rotation in 2020-40 and 2080-90 when applying mineral or organic fertilizer system for scenario RCP4.5, and mineral fertilizer system in 2080-2090 for scenario RCP8.5.

Keywords: soil organic carbon; long-term experiments; RothC model; climate change; "4 per 1000" initiative; Retisols

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1. Introduction

During the last decade, the importance of soil organic carbon (SOC) in the global carbon cycle became a vital topic in the climatic change agenda [1,2]. SOC sequestration is a challenging goal for soil management outlined by the '4 per 1000' initiative [3] and Coronivia Joint Work for Agriculture [4]. In this context, the potential SOC accumulation in arable soils is of significant importance. The assessment of this potential is done through modelling, and there were several successful attempts to predict the SOC potential fixation in soils in different scales [5,6]. Land use and the application of mineral and organic fertilizers are believed to be the most important variables affecting the accumulation and stability of SOC. However, various other factors should be considered for the prediction of soil capacity to fix atmospheric carbon. In practice, the assessment of the contribution of multiple factors to carbon accumulation in soils is a challenging task because of the scarcity of data on long-term dynamics of SOC under controlled conditions [7]. Two important gaps in our knowledge on the factors affecting SOC accumulation are the lack of information on the effect of particular crop rotations on different soils and the absence of understanding of the role of the previous land use on the future carbon dynamics in soils. We do not know if previous soil use may be easily smoothed by subsequent management, or it can have a long-term effect. In this research, we had a unique situation with two fields with the same soil and almost identical input of fertilizers, but differing in crop rotations and land use in the starting date of the experiment. The results of SOC dynamics modelling for the past has been presented in our previous publication [8]. Modelling showed that fertilization and modification of crop rotation both could provide a steady increase in the C input and accumulation of soil C in the 0-20 cm layer. However, the gain is finite, and the C stock can be quickly lost with reducing crop rotation productivity. The present study aimed to model the future dynamics of SOM and its fractions under two climatic scenarios for two experimental fields with different crop rotations.

2. Materials and Methods

We based the research on two long-term field experiments of the DAOS – Dolgoprudny agrochemical experimental station (Dolgoprudny town, Moscow region), included in the geographical network of field experiments with fertilizers (Geoset). This territory consists of a cluster of long-term experiments initiated in 30s last century by academician D. Pryanishnikov based mainly on Rothamsted experience [8] The climate is Dfb – humid continental without a dry season and with warm summer. The soil is an Albic Retisol (Loamic, Aric, Cutanic) formed on glaciofluvial "cover loam".

The first experiment was a part of the project "Efficiency of increasing doses of mineral fertilizers" initiated in 1937. The site was under long-term agricultural use before the beginning of the experiment. The four-field fodder crop rotation beet – spring wheat – potato – oats was replaced in 1965 by a three-field rotation with two fields of row crops (beet, potato, sunflower) and a field of barley, and continued until 2011. This experiment is referred below as DAOS 3. The initial SOC concentration in the 0-20 cm layer was 1.0-1.1%, which corresponded to a stock of 28.6-28.8 $Mg{\cdot}ha^{-1}$; organic C content was assessed in the laboratory using wet oxidation with potassium bichromate + sulphuric acid [9]. During the experiment period, the SOC content in the 0-20 cm layer was determined eight times. For modelling, we used the data from the first field for the following treatments: absolute control without fertilizers (control), NPK 1.5 rates with manure application of 40 $Mg{\cdot}ha^{-1}$ per rotation (20 $Mg{\cdot}ha^{-1}$ for potatoes and 20 $Mg{\cdot}ha^{-1}$ for beets) (NPK1,5+FYM), NPK 3 rates without manure application (3NPK), NPK 3 rates with manure application (NPK3+FYM). The single rate of mineral fertilizers for the first seven rotations was $N_{60}P_{75}K_{90}$ for potatoes, $N_{80}P_{100}K_{120}$ for beets and $N_{30}P_{38}K_{45}$ for cereals, later adjusted for PK, remaining unchanged for N. At the end of the experiment in 2006 the topsoil was strongly acid, with pH_{KCl} ranging from 3.7 on the field under 3NPK to 4.8 under control with manure.

The other experiment DAOS 4, "Efficiency of ballast and concentrated forms of mineral fertilizers" was launched in 1933. The site was under natural forest vegetation until 1925; no fertilizers were applied before the experiment. Five-field crop rotation (clover – winter rye – potatoes – fodder beet – oats with grass sowing) was established on five fields. In 1978, starting with the 10th rotation, the scheme was changed to a four-field rotation: clover – winter wheat – potatoes – barley with grass seeding. This experiment is referred below as DAOS 4. The initial carbon content in the 0-20 cm layer was 1.0-1.3%, which corresponded to a stock of 30.3-32.4 $Mg{\cdot}ha^{-1}$. The sampling scheme for SOC monitoring was the same as in the DAOS 3 experiment. For modelling, data from 1935-2011 of the first field were used for the following treatments: absolute control (control); farmyard manure 50 $Mg{\cdot}ha^{-1}$ per rotation, since 1978 – 40 $Mg{\cdot}ha^{-1}$ (FYM); treatment with ballast NPK fertilizers – ammonium sulfate, simple superphosphate, potash salt (NPK1) and equivalent application of diammophos DAP and potassium chloride (NPK2). $N_{90}P_{90}K_{90}$ was added for row crops and winter wheat, $N_{90}P_{90}K_{120}$ for potatoes, $N_{45}P_{45}K_{45}$ for oats and grasses, and $N_{60}P_{80}K_{80}$ for barley. The pH_{KCl} values of the topsoil in 2011 ranged from 4.5 on the field under NPK to 5.0 under manure. Some data on the abovementioned experiments were summarized in the monograph [10].

To assess SOC dynamics, we used the model developed for the Rothamsted experimental station RothC version 26.3, which calculates the organic matter cycle in the arable layer of mineral soils with a monthly step, taking into account the influence of soil taxonomic group, temperature, soil humidity and vegetation cover [11]. In the RothC model, soil organic matter (SOM) is divided into five pools: carbon of rapidly decomposing plant residues DPM, resistant plant material RPM, microbial biomass BIO, humified HUM, and inert IOM organic matter, which have different mineralization rates described by first-order equations. To launch the model, a database of the EuroSOMNET (European Network of Field Experiments on Soil Organic Matter) standard was created, which included the Geonet experiments described above [12].

The monthly amount of C input the soil was calculated using the yield dependence and reference data on the quality of FYM. The initial distribution of C across the pools, which is required to run the model, was modelled for C content under equilibrium conditions. The content of the IOM pool was pre-calculated, as described by Falloon et al. [13]. After calculating the IOM pool, the RothC model was run in the mode of calculating the distribution of C across the pools by selecting the average long-term value of C input to the soil in such a way that the C reserves obtained by modelling corresponded to experimentally determined values. For the DAOS 3 experiment, the average annual amount of calculated C input was 830-840 kg·ha^{-1}, for DAOS 4 – 880-940 kg·ha^{-1}. The configuration of the RothC model was fitted to the control treatments, using the other treatments as independent ones to validate the quality of the configuration. In the process of fitting, the initial RPM content increased by a proportional reduction in HUM, and the input of C with applied FYM decreased.

In our previous research, we modelled and verified the dynamics of SOC in DAOS 3 and DAOS 4 experiments for the period 1935–2011 [14]. In the present study, the forecast of the dynamics of organic carbon stocks under the future climate was made for two climate scenarios: RCP4.5 and RCP8.5 from four Representative Concentration Pathways scenarios used in the IPCC fifth assessment report (AR5). They describe four different 21st-century pathways of changes in greenhouse gas emissions and concentrations as well as in land-use [15]. The selected scenarios correspond to the moderate and the extreme scenario of anthropogenic impact on the Earth's climate system, respectively. CO_2 concentrations by 2100 range from 580-650 ppm CO_2 for RCP4.5 to more than 1000 ppm for RCP8.5. Calculations were based on the regional climate model developed at the Voeikov Main Geophysical Observatory for an ensemble scenario of 31 CMIP5 models [16]. DAOS climate data were calculated based on the "Climate–Soil–Yield" simulation system [17]. The output data were temperature, precipitation, and potential evapotranspiration with a monthly resolution up to 2100.

The obtained climate data were used to make a forecast of crop rotation yield for each of the experiments until 2090. The calculation was carried out separately for each treatment of the experiment. For modelling, Seylyaninov's hydro-thermal coefficient (HTC), which characterizes the degree of moisture availability for plants, was used as the basis for calculating the predicted yield [18]. HTC is calculated according to the formula:

$$HTC = \frac{P}{\sum_{t>10} \frac{T}{10}} \quad (1)$$

where P is the sum of precipitation (mm) and T is the sum of temperature (°C) for the months with the mean temperatures >10°C, which mainly correspond to the vegetation period, namely April–October. This index was calculated at the monthly level, for the same period. The dependence of the relative crop yield U on the moisture availability was approximated with the following expression:

$$U = \frac{Y}{Ymax}; for\ HTC > 1.15\ \ U = -0.20 \cdot h^2 + 0.41 \cdot h + 0.2;$$

$$\text{otherwise}\ \ U = -0.92 \cdot h^2 - 0.36 \cdot h + 0.2; \quad (2)$$

According to (2) the maximum yield value Y_max coincide with HTC = 1.15, which corresponds to slightly humid climate conditions in the range from arid to a very humid climate. Y_max required for calculations was estimated by fitting the average yield obtained in each treatment of the long-term experiment to the average yield values for the first ten years of the forecast period with an Excel spreadsheet. A linear trend was calculated for each crop/treatment during the experiment to take into account the factor associated with technological progress. The predicted crop yield for each crop rotation was used to calculate the carbon input with plant residues using the approach introduced by Levin [19]. The model was adjusted previously using measured SOC concentrations during the experiment. The model found satisfactory convergence between the experimental and calculated data for all the studied treatments [14].

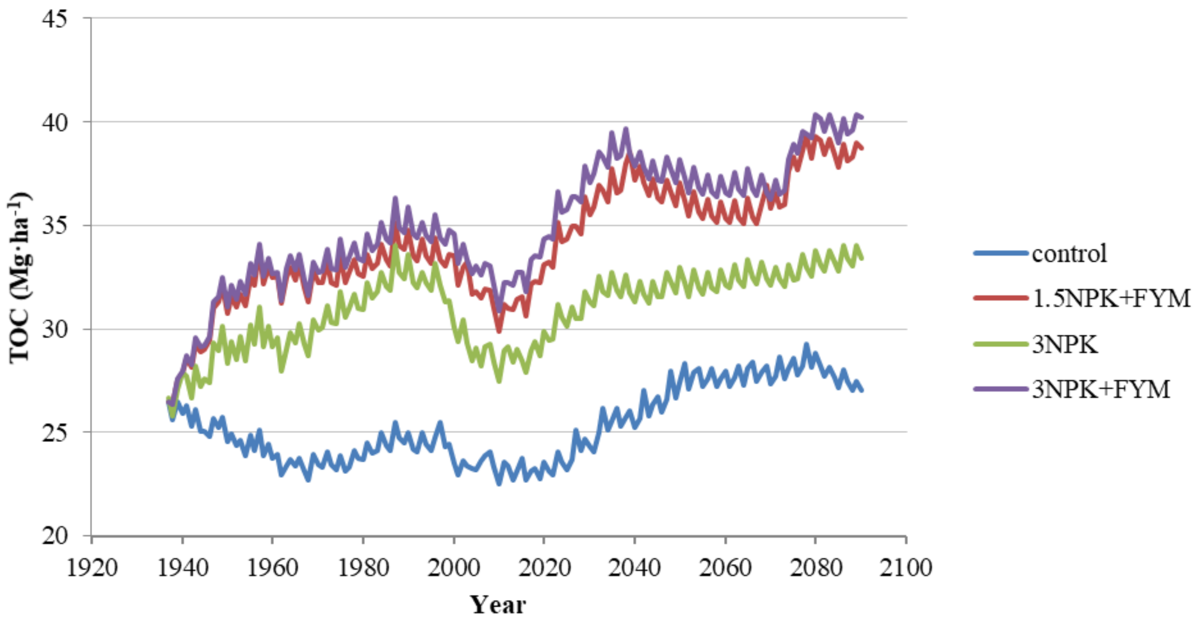
3. Results

3.1. DAOS 3 experiment

Figure 1 shows the dynamics of carbon stocks in the arable soil horizon calculated for two climate scenarios. Starting from 2020, the forecast of C stocks was made over twenty-year periods, with the calculation of the rate of SOC dynamics and C input (Table.1). This period is recommended for evaluating the effectiveness of the 4 per 1000 initiative [3].

Under the RCP4.5 scenario, an increase in SOC stock was detected for all treatments from 2020 to 2090, which, however, was not consistent. A relatively more intensive increase in soil carbon stocks was predicted for the period 2020-40, with a decrease in the growth rate (control and mineral fertilizers) or a loss of up to 2 Mg·ha^{-1} of previously accumulated C (organic plus mineral fertilizers) until 2071-2072. In the treatment with the organic and mineral fertilizers, SOC stock was growing until 2081 and reached 39-40 Mg·ha^{-1} and then decreased 1-2.5 Mg·ha^{-1} over the last decade. Under the RCP4.5 scenario, similar patterns were observed in the 3NPK+manure and 1.5 NPK+FYM treatments. The absolute growth in C stocks in 2020-90 under this scenario was 4-7 Mg·ha^{-1}, decreasing in the series 3NPK+FYM ≈ 1.5 NPK+FYM > NPK > control.

Thus, the dynamics of C in the treatments of the DAOS 3 experiment under the RCP4.5 scenario is expected to be quite contrasting. The most noticeable growth occurred in the first twenty years, decreasing in the series 3NPK+FYM > 1.5 NPK+FYM > NPK > control.



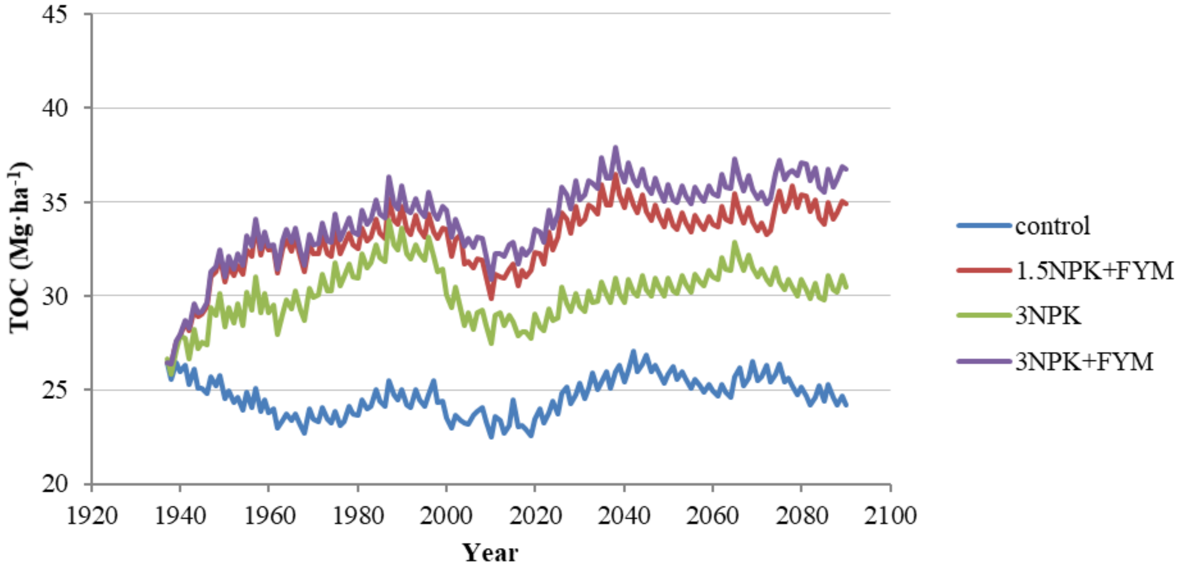


Figure 1. Simulated annual dynamics of total organic carbon (TOC) stocks in DAOS 3 experiment (1937-2090): (a) – RCP4.5, (b) – RCP8.5.

As shown in Table 1, the highest C input is expected in 2020-40 and 2060-80, while in 2040-60 there should be a decrease in C input, which is especially noticeable in the treatments with organic and mineral fertilizer application. Such a decline was not detected in control and was also less pronounced in the treatment with mineral fertilizers in 2040-60 than in the periods mentioned above. This result shows the expected instability of yield in the crop rotation of the experiment under the future climate, which is only partially compensated by additional C input with organic fertilizers. Indeed, for these treatments, the annual increase in the most favourable 20-year periods was 5.1-6.2‰, that is 2-3 times higher than the increase in the treatment with mineral fertilizers. In 2080-90, the decline in SOC stock occurred against the background of continued C input to the soil, which may indicate the predominant effect of climate changes that accelerates the mineralization of previously accumulated SOC. In general, under this climate scenario, to maintain SOC stocks for the entire simulated period, an average of 1.19 $Mg{\cdot}ha^{-1}$ should be applied annually in the soil in DAOS 3 experiment, which is less than the one determined for the experimental period of 1937-2011, when an average of 1.39 $Mg{\cdot}ha^{-1}$ was required.

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Table 1. Annual gain/loss and input of C by treatments.

Period	**Treatments of the DAOS 3 experiment Annual gain/loss, ‰ / C input, Mg·ha^{-1}**			
	Control	**1.5NPK+FYM**	**3NPK**	**3NPK+FYM**
RCP4.5				
2020-2040	3.7/0.99	6.2/1.74	2.3/1.28	5.1/1.77
2040-2060	5.4/1.10	-2.5/1.02	1.3/1.05	-1.7/1.09
2060-2080	1.6/1.06	5.6/1.43	2.6/1.12	5.1/1.43
2080-2090	-6.3/0.88	-1.4/1.39	-1.1/1.19	-0.2/1.49
RCP8.5				
2020-2040	4.2/1.05	3.7/1.47	1.1/1.09	3.8/1.56
2040-2060	-0.8/0.79	-1.3/1.01	2.2/1.05	-0.9/1.09
2060-2080	0.3/0.86	2.3/1.29	-0.2/1.08	2.3/1.39
2080-2090	-3.8/0.79	-1.2/1.40	-1.3/1.21	-0.9/1.51

Period	**Treatments of the DAOS 4 experiment Annual gain/loss, ‰ / C input, Mg·ha^{-1}**			
	control	**FYM**	**NPK1**	**NPK2**
RCP4.5				
2020-2040	6.9/1.27	12.0/2.16	12.3/1.85	13.2/1.90
2040-2060	3.5/1.12	4.7/1.93	5.3/1.62	5.4/1.66
2060-2080	1.1/1.06	2.8/1.83	2.2/1.51	2.6/1.55
2080-2090	7.3/1.31	7.8/2.30	10.3/2.00	11.0/2.07
RCP8.5				
2020-2040	5.6/1.16	8.0/2.04	7.6/1.55	8.4/1.58
2040-2060	1.7/1.16	3.9/1.86	4.6/1.56	4.8/1.58
2060-2080	0.1/1.09	1.2/1.83	0.6/1.52	0.9/1.55
2080-2090	5.5/1.30	5.8/2.18	8.5/1.87	8.9/1.92

Under the RCP8.5 scenario, a less noticeable change in soil C stocks is expected, which leads to a smoother forecast schedule. In the same manner, as for the RCP4.5 scenario, we can distinguish periods of increase and loss of SOC that occur at different rates. Similar dynamics was observed for both treatments of the organo-mineral fertilizer system: intensive growth until 2038 up to 37-38 Mg·ha^{-1}, which is 1-2 Mg·ha^{-1} less than for the RCP4.5 scenario. Further, until 2065, 3-4 Mg·ha^{-1} of previously accumulated C is lost, with relative stabilization at the level of 34-36 Mg·ha^{-1} until the end of the modelling period.

In the case of the NPK experiment, an increase from 28 to 33 Mg·ha^{-1} is expected from 2020 to 2065, less intense after 2040, and then a loss of accumulated stocks with a tendency to stabilization. In control, growth is expected until 2042 from 23 to 27 Mg·ha^{-1}, followed by short periods of growth and losses in the range of 24-27 Mg·ha^{-1} until 2090.

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The absolute C stocks gain in 2020-90 under this scenario is 2-4 Mg·ha^{-1}. Gains increased, and losses decreased in the 3NPK+FYM > 1.5 NPK+FYM > NPK > control series, as in the RCP4.5 scenario.

Table 1 shows that the dynamics of C input to the soil is expected to be similar to the RCP4.5 scenario. At the same time, in the periods 2040-60 and 2080-90, the absolute values were identical in the fertilization treatments. In the remaining periods, which were relatively more favourable for the realization of yield, it was less than in the RCP4.5 scenario by 3-18% for the treatments with fertilization, and for the control in all periods except 2020-40, it remained by 11-39% less. As in the previous climate scenario, the maximum annual increase in C stocks was observed for the organo-mineral treatments (except for the 2020-40 period for the control treatment, where the increase was 4.2‰), amounting to 3.7-3.8‰, which is about half the increase under the RCP4.5 scenario. The period 2080-90, as for the previous scenario, was very unfavourable. With a slight increase in C inputs compared to the previous period, the drop in stocks occurred at a faster rate than with RCP4.5, which is especially noticeable in the 3NPK+FYM treatment. On average, 1.14 Mg·ha^{-1} of C should be applied annually for the entire simulated period to maintain C stocks, which is close to the results obtained for the RCP4.5 scenario. For both scenarios, the most favourable period for C accumulation is 2020-40, and among the treatments is the organo-mineral fertilizer system. An increase in the rate of mineral fertilizer against the background of organic did not significantly affect the increase in C input. Therefore the dynamics of both options are predicted to be similar. The accumulated stock of C is not stable and may be partially lost in the next period when crop rotation productivity decreases.

3.2. DAOS 4 experiment

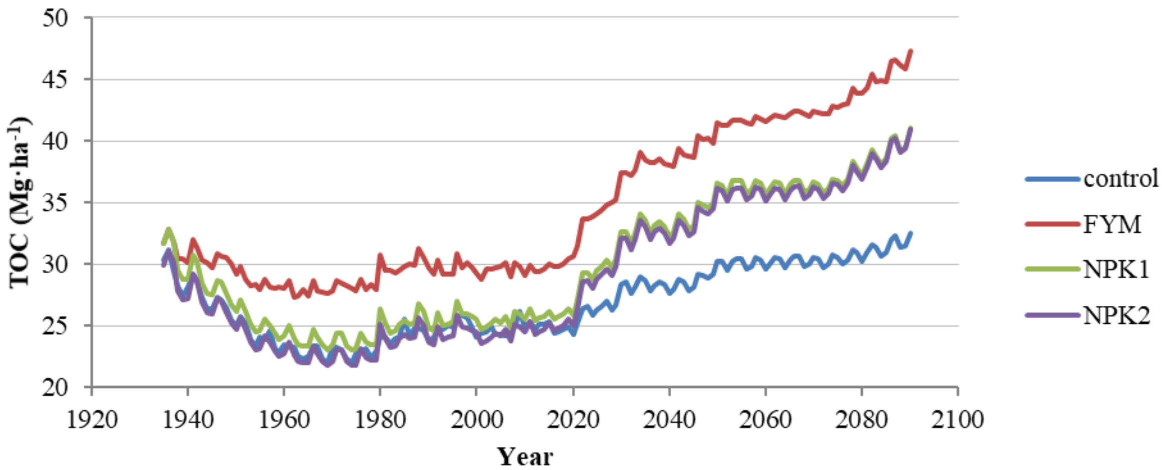
The forecast based on the DAOS 4 experiment shows similar trends for both climate scenarios, except for the last period (Fig. 2). From 2020, all treatments of the RCP4.5 scenario experience an intensive increase in soil C stocks until 2050. Further, there is a trend towards stabilization (mineral fertilizer system and control) or slight growth (organic system) until 2073-2075 and a new increase until 2090. In the control, all these periods are weakly expressed. Total expected increase in C stocks from 2020-90 is 8-15 Mg·ha^{-1} in the RCP4.5 scenario and 5-11 Mg·ha^{-1} in the RCP8.5 scenario. This growth is 2-3 times higher than the increase in C stocks expected in the DAOS 3 experiment over the same period, with close initial C stocks to date.

Absolute stocks will stabilize in 2050-79 at 36 and 34 Mg·ha^{-1} for mineral fertilizer systems under RCP4.5 and RCP8.5 scenarios, respectively. During the same period, the C stock in the organic fertilizer system increased from 41 to 42 Mg·ha^{-1} and from 37 to 41 Mg·ha^{-1} for the same climate scenarios.

Under the RCP8.5 scenario of the experiment, an increase is observed until 2066. Further, a stable state in the control and a weak increase in other treatments until the end of the modelling period. In the RCP4.5 scenario, C accumulation of up to 47 Mg·ha^{-1} is also observed, while in RCP8.5, the maximum value does not exceed 43 Mg·ha^{-1}.

The highest rate of increase in C content is observed in the first twenty years – 2020-40 (12-13‰), under the climate scenario RCP4.5 and 8‰ in the climate scenario RCP8.5. The increase was approximately equal for organic and mineral fertilizer systems. The second period of maximum accumulation of C in 2080-90 was characterized by maximum growth rates of annual C content of 10-11 and 9‰ for the RCP4.5 and RCP8.5 scenarios, respectively, while it was approximately 50% higher for the mineral fertilizer system. Comparison of predicted C inputs in 2020-90 with the period 1935-2011 shows that under the considered climate scenarios, the expected productivity of crop rotation will increase. This increase for fertilizer treatments is 6-7% higher for RCP4.5 compared to RCP8.5 in 2040-90 and increases to 20% for mineral fertilizer treatments in 2020-40. In the period 2060-80, with a relatively lower accumulation of C, ranging from 1 to 3%, the decrease in C inputs was in most cases less than 10%. It can be assumed that clover cultivation allows more efficient use of climate resources in the DAOS 4 crop rotation compared to the crop rotation without grasses and the predominance of row crops in the DAOS 3 experiment. In particular, this leads to a more significant increase in C stocks in favourable years and a relatively smaller drop in unfavourable ones. If the increased mineralization of organic C is compensated by a corresponding increase in the biomass of plant residues, the overall effect of climate change can be positive for fulfilling the conditions for accumulation of C in arable soil. This result is consistent with the previously obtained conclusions about the prospects of the territory of the non-Chernozem zone of Russia for the accumulation of additional stocks of C in the future climate conditions [20].

To maintain the C stocks for the entire simulated period, an average of 1.31-1.38 Mg·ha^{-1} must be applied annually, which is significantly less than that determined for the experimental period 1935-2011, when an average of 2.13 Mg·ha^{-1} was required. This result reflects the loss of approximately 15% of the initial SOC stock in the control treatment and with the mineral fertilizer system during the experimental period. However, in the case of the DAOS 3 experiment, it also indicates more favourable opportunities for sequestration with arable soil in the future climate compared to the current one.



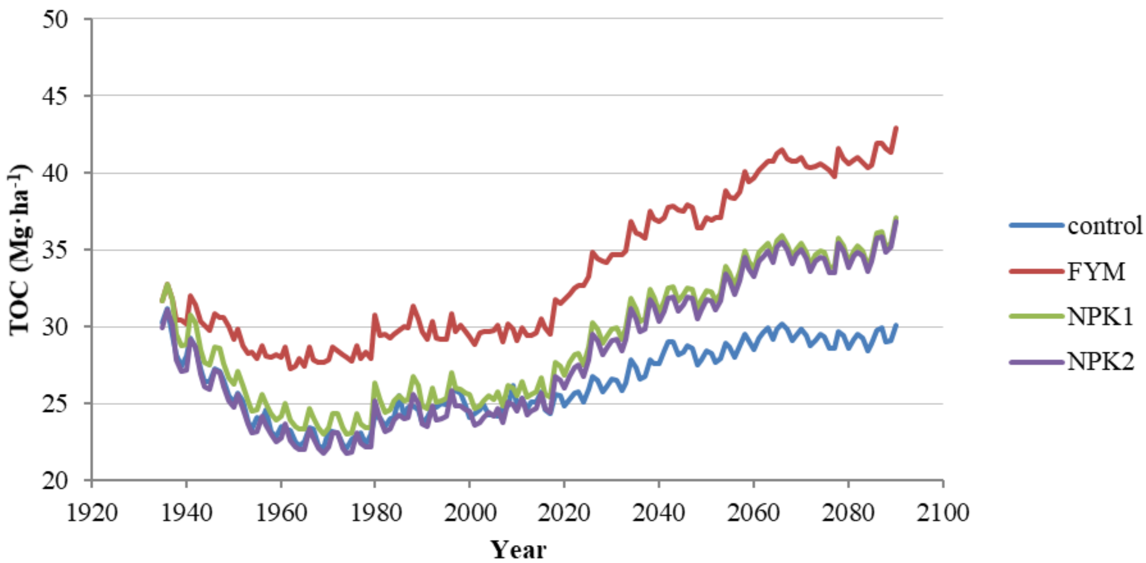


Figure 2. Simulated annual dynamics of total SOC stocks in DAOS 4 experiment (1933-2090): (a) – RCP4.5, (b) – RCP8.5.

Analysis of the RPM and HUM pools dynamics shows that during the experiment as well as during the forecast period, in both experiments, a consistent increase of C stocks also coincide with stabilization of organic C (Fig. 3-6). This stabilization is evident from the constant growth of the HUM pool in the total C. In the DAOS 4 experiment, this increase occurs almost linearly, which leads to an increase in the absolute size of this pool by 1.5-2 times compared to the initial one. The expected increase in C in the 21st century will lead to an increase of 3 times for the organic system, 2.5 times for the mineral system, and more than twice for the control. In the DAOS 3 experiment, the initial increase in SOC stock is followed by some equalization in 1995-2011, during which up to 4-5 Mg·ha^{-1} of previously accumulated C was lost, and then new growth is predicted for both climate scenarios. As a result, the expected size of HUM pool increases approximately 2 times in the organic-mineral fertilizer system, 1.7 times in the mineral system, and 1.3 times in the control. For the RCP8.5 scenario, the absolute increase of this pool is expected approximately 2 Mg·ha^{-1} lower than for the RCP4.5 scenario.

Stabilization tendency C is also quite revealing in the dynamics of the RPM pool, which characterizes the active C fraction. In the DAOS 3 experiment, almost all the losses of C stocks in the period 1995-2010 are associated with a decrease in the size of this pool. The forecast of C stock changes shows the possibility of the rapid growth of this pool – by 2.0-2.3 times over 2010-2040. At the same time, in the organic-mineral fertilizer system, such an increase for the RCP4.5 climate scenario allows reaching the level of 1975-1995, when the stock of C in the RPM fraction was 8 Mg·ha^{-1}, while for the mineral fertilizer system it remains at the level of 6 Mg·ha^{-1}. In the DAOS 4 experiment, where the C stock in this pool is stabilized at 4-6 Mg·ha^{-1} by 1980-90, the increase under future climate conditions can reach two or more times, with the most significant increase occurring in the period 2020-40. In this experiment, the relatively large role of the active fraction of organic C in increasing or decreasing the rate of C stocks growth is noticeable. It can be assumed that with an increase in the absolute amount of sequestered carbon for this system, we get a relatively higher amount of C accumulated in the active fraction, which will be more susceptible to C loss processes under changing external conditions.

Since the '4 per 1000' initiative considers a layer of 0-40 cm, the absolute increase only in the upper horizon should be higher than 4‰. Based on the results of [link] long-term experiments at Rothamsted, it is proposed to use a value >7‰ in the 0-23 cm layer as equivalent to 4‰ in the upper 40 cm layer. In this case, it is clear that the accumulation of C in the future climate will occur, but will remain below the standard indicators. It is only achieved in the experiment DAOS 4 in 2020-40 and 2080-90. when applying mineral or organic fertilizer system for scenario RCP4.5, and mineral fertilizer system in the last period for scenario RCP8.5.

In both experiments, a tendency was revealed that the gain is increased and losses are reduced in a series of organo-mineral fertilizer>organic fertilizer> mineral fertilizer>control. In DAOS 3 treatments form the following series: 3NPK+FYM > 1.5 NPK+FYM > 3NPK > control. In DAOS 4: manure > NPK1 > NPK2 > control.

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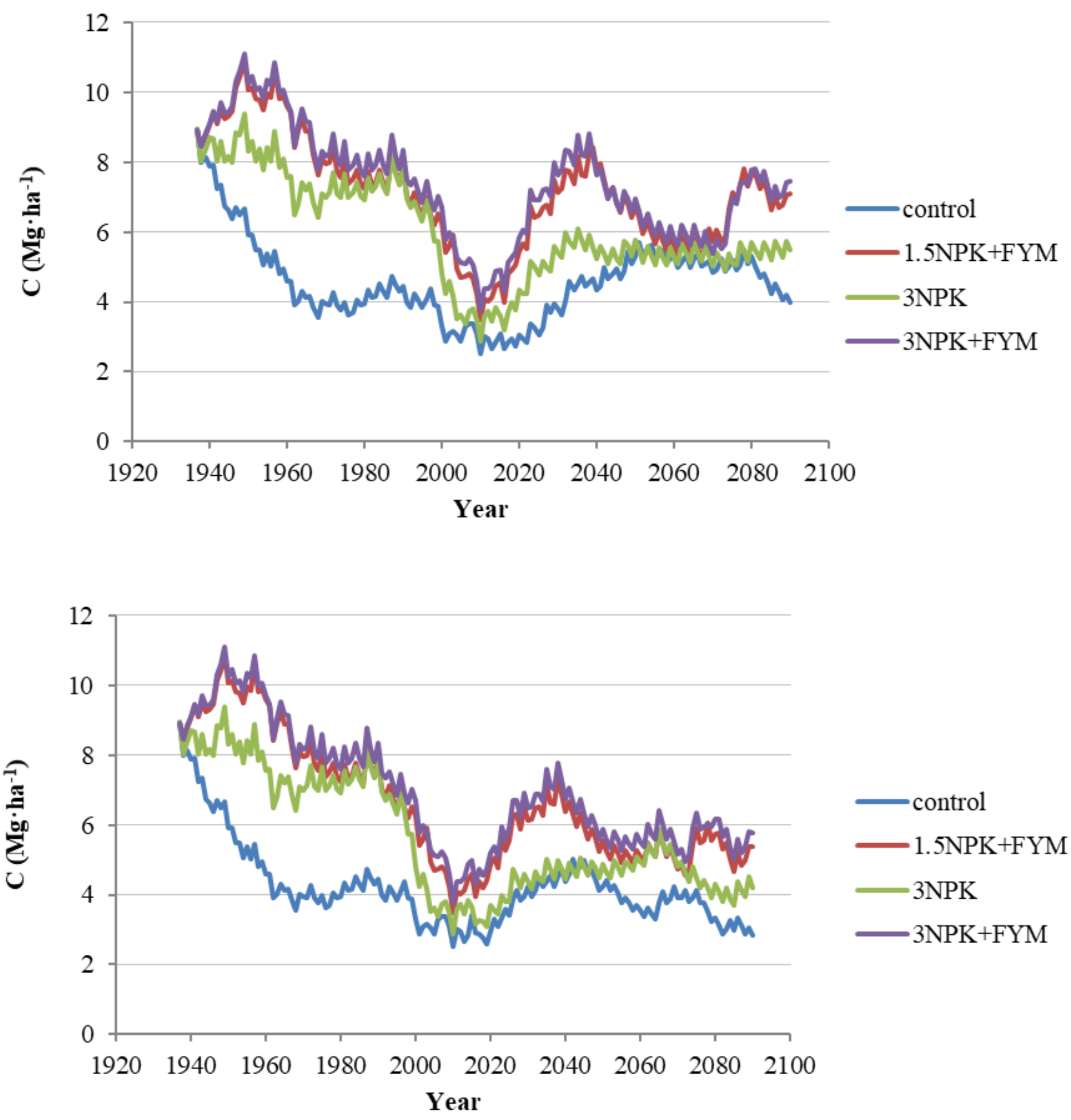
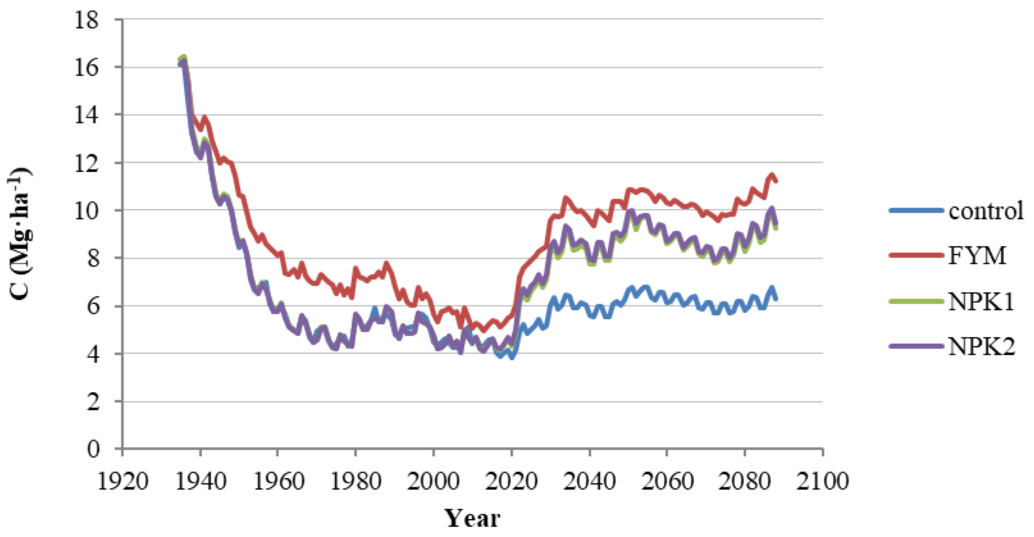


Figure 3. Simulated annual dynamics of C in resistant plant material (RPM) pool in DAOS 3 experiment: (a) – RCP4.5, (b) – RCP8.5.



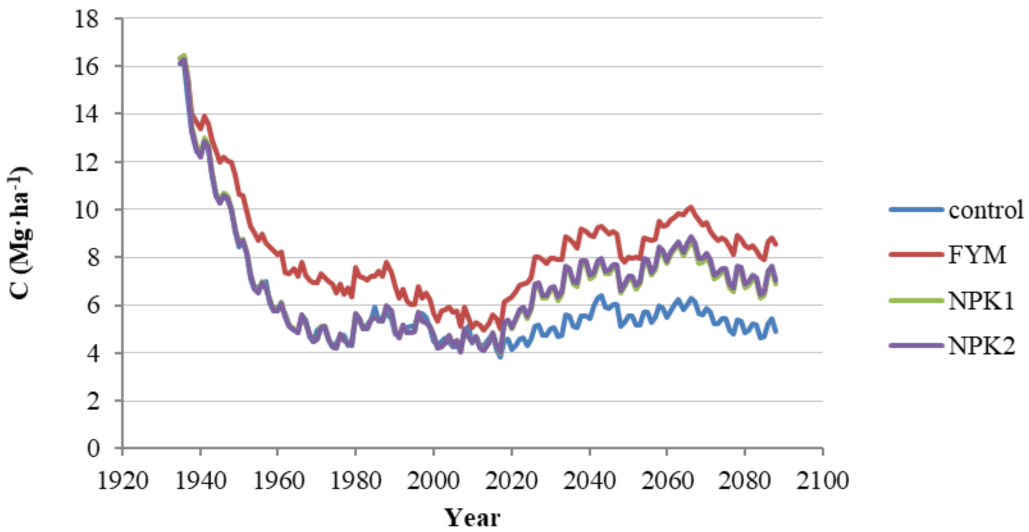


Figure 4. Simulated annual dynamics of C in resistant plant material (RPM) pool in DAOS 4 experiment: (a) – RCP4.5, (b) – RCP8.5.

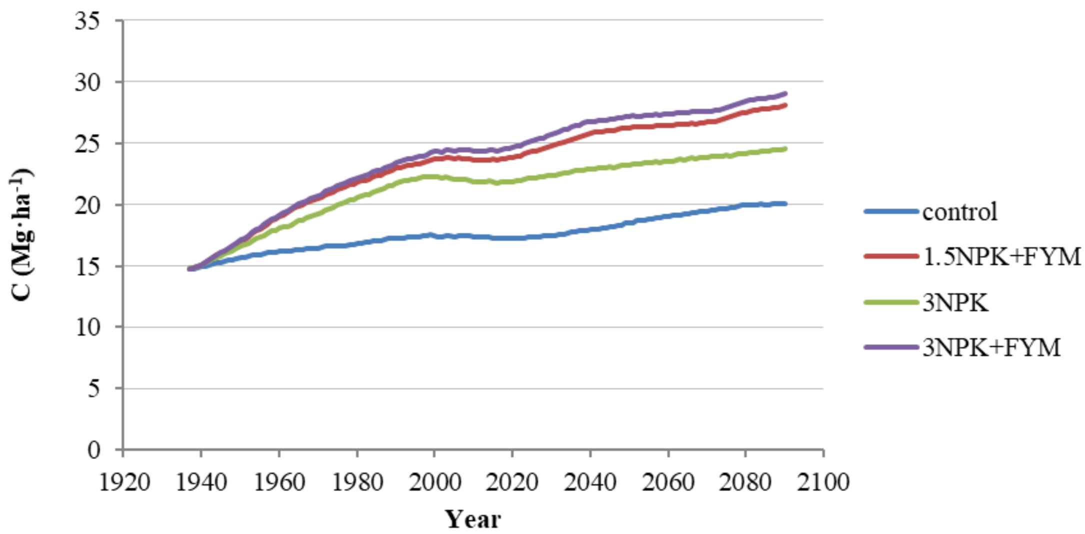
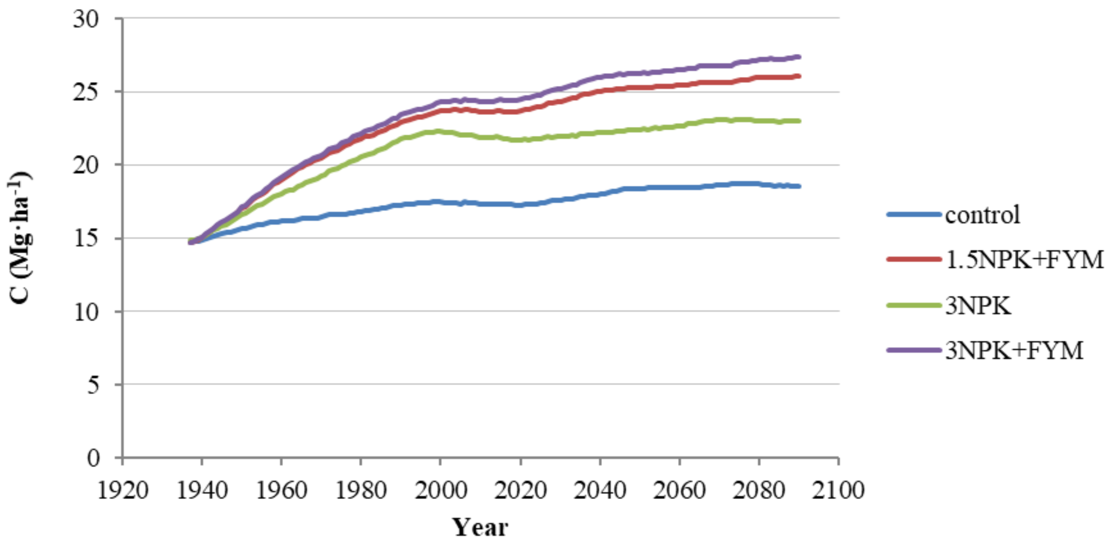


Figure 5. Simulated annual dynamics of C in HUM pool in DAOS 3 experiment: (a) – RCP4.5, (b) – RCP8.5.



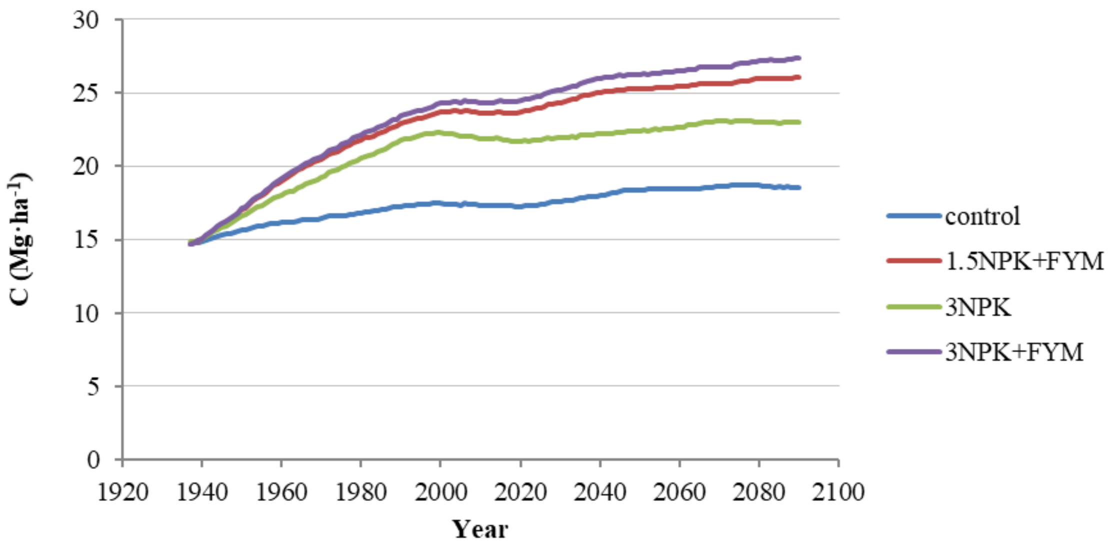


Figure 6. Simulated annual dynamics of C in HUM pool in DAOS 4 experiment: (a) – RCP4.5, (b) – RCP8.5.

4. Discussion

4.1. The importance of the land use history

Simulation of SOC dynamics in the two adjacent fields of the same experimental station with RothC model demonstrates the ability of Retisols to maintain or increase current soil C stocks even if C input is less than 2.0 Mg·ha^{-1}·yr^{-1}. This figure was discussed in a global meta-analysis of published data on the responses of OC to fertilizer managements in 1741 field experiments of Han et al. [21]. Wang et al. [22] estimated with RothC the critical carbon input rate to maintain current SOC level in Russia as 1.9 Mg·ha^{-1}·yr^{-1} with current average and potential inputs 1.3 and 2.8 Mg·ha^{-1}·yr^{-1}, respectively. Earlier, we had demonstrated that for long-term experiments on Chernozem soil the average annual amount of C 1.9 Mg·ha^{-1}·yr^{-1} is sufficient to maintain initial stock 70 Mg·ha^{-1} in the arable soil layer. In contrast, for initial stock 89 Mg·ha^{-1} annual C input level 2.9 Mg·ha^{-1}·yr^{-1} will be necessary [23]. At the same time, for Retisols of different texture with initial C stock, 19-32 Mg·ha^{-1} C input 1.5 Mg·ha^{-1}·yr^{-1} was needed, but C input was estimated as high as 2.0 Mg·C·ha^{-1} ·yr^{-1} for maintaining sustainable C stock 41–43 Mg·ha^{-1} [24]. The present results demonstrate that for DAOS 3 with 28.6-28.8 Mg·ha^{-1} initial C stock an average current input of 1.39 Mg·ha^{-1}·yr^{-1} C was required, while for

DAOS 4 with 30.3-32.4 Mg·ha^{-1} C stock at the beginning of the experiment an average input need to be 0.74 Mg·ha^{-1}·yr^{-1} higher. This fact illustrates higher C rates to keep higher soil C stocks but does not explain the level of required C input for DAOS 4 field. For example, calculated C input for equilibrium model run was 0.83-0.84 Mg·ha^{-1}·yr^{-1} for DAOS 3 and very close 0.88-0.94 Mg·ha^{-1}·yr^{-1} for DAOS 4 at the beginning of both experiments. It reflects the necessity of re-qualification of critical C input for developing site-specific management strategies of soil C sequestration with more detailed information both of temporal and spatial resolution [22].

We can assume that in the case of DAOS 3 and DAOS 4 fields, different land use history has a strong effect on SOC stock temporal dynamics. DAOS 3 plot was used as an arable field for more than 200 years before the experimentation. In contrast, DAOS 4 plot was clear-felled from the forest only in 1926 and before the foundation was used as test sowing field without any fertilization. Comparison of RPM dynamics of different treatments at DAOS 3 it represents other steady-state conditions around initial 8 Mg·ha^{-1} for NPK treatment in the first 20 years after launching the experiment, the same level around 1960-90 for all fertilization plots and loss of a half the initial RPM pool at control during first 25 years of experimentation with a steady-state 4 Mg·ha^{-1} after this period (Fig. 3). At the same time, RPM pool was much higher at DAOS 4, and during first 20 years 10-12 Mg·ha^{-1} C was lost, after that, it was within 4-6 Mg·ha^{-1} for the control and mineral treatments and slightly more for FUM treatment with a slight loss trend until current period (Fig. 4). It demonstrates that the effect of land-use change, despite the initial period of about 25 years, can be traced in the long term. It made it impossible to achieve any C sequestration in DAOS 3 until the 1980s when C stock was as low as 24-31 Mg·ha^{-1}. For fertilization plots of DAOS 4 with a consistent gain of C, it was 5-8 Mg·ha^{-1} higher, even though annual C input was 1.54-1.70 for DAOS 3 and 1.88-2.10 Mg·ha^{-1}·yr^{-1} for DAOS 4 (Figs. 1 and 2).

Eglin et al. [25] used ORCHIDEE simulation results for determining the relative importance of land cover change for regional soil C stocks. They found that in the former Soviet Union, forest clearing, which took place during the first half of the 20th century, has impacted the SOC balance in the second half of the same century. This founding indicates that land cover change still affects SOC stocks, unlike in Europe, where no significant change in forest area took place during the 20th century. These results are consistent with our data about the long-term effect of deforestation visible in different SOC dynamics in the long-term field experiments. Morais et al. [26] simulated with RothC model changes in the annual SOC stock in 2014-2100 (without climate change effect) globally for all land use classes. They demonstrated that the conversion of forest to cropland in general result in SOC loss, and, SOC loss is typically faster than SOC recovery. For DAOS 4 SOC gain to reach the initial C level was expected to take 60 years for mineral fertilization plots and about 50 years for FYM fertilization. In contrast, losses take place mainly in the initial 25 year period (Fig.2). Koso et al. [27] and Skalsky et al. [28] found that application RothC for modelling SOC stock in 1970-2020 for different regions of Slovakia would require detailed information on where land cover changes occurred both in the space and time, as it has a strong effect on SOC stock temporal dynamics. However, in a study of the spatial evolution of topsoil SOC driven by climate change and land use change for France up to the year 2100 Meersmans et al. [29] concluded that climate change would have a much more significant influence on future SOC losses in mid-latitude mineral soils than land use change dynamics.

4.2. The effect of crop rotation

For Moscow Region, with the abundance of Retisols, mainly on loam and heavy loam sediments, traditional rotations include alternation of spring (barley and oats) and winter (primarily wheat) cereals, row crops (potatoes, fodder beet and silage corn) and perennial grass [20]. In this paper sustainability of intensive management technologies under future climate conditions was discussed as well as the comparatively more significant effect of changes in the crop rotation system than FYM rates change in additional C sequestration. Our data for RCP4.5 and RCP8.5 also demonstrate the importance of perennial grass in the crop rotation structure. Under future climate conditions, with calculated smaller necessary C annual input for DAOS 3 and significantly less for DAOS 4, the highest gain of C is expected for NPK treatments of DAOS 4 experiment, which are 2-2.5 times higher than in DAOS 3 (Table 1). This fact corresponds with potential effective management of SOC stocks on Retisols with alternating cereals and row crops, but also much higher effect on fodder crop rotations with grasses. Interestingly, FYM treatment of DAOS 4 has average C inputs 0.3-0.5 Mg·ha^{-1}·yr^{-} higher than C inputs of NPK treatments, but the latter more frequently demonstrate higher C gain (Table 1). This contradiction can be attributed to a 5 Mg·ha^{-1} smaller C stock in 80s last century in NPK in comparison with FYM treatment which indicates more rapid C gain in C-depleted arable soil.

Based on the metadata paper of Han et al. (2016) [link] with the potential C increase in arable topsoil by 1.7 and 3.4 g·kg^{-1} for mineral and organic –mineral fertilization, respectively, our TOC stocks before 2100 are within this range. The additional C gain under FYM fertilization for DAOS 3 in a future climate was 5-7 Mg·ha^{-1}, more pronounced under RCP4.5 scenario. Application of 3 rates of NPK at FYM background is expected to have a small additional effect on C sequestration in comparison with 1.5 NPK rate. For DAOS 4 only FYM fertilization is expected to provide 7-8 Mg·ha^{-1} further accumulation when applied at NPK equivalent rates for both future climate scenarios so that we can expect even higher C accumulation under organic-mineral fertilization. Another advantage of DAOS 4 sequestration potential that it is assumed to have a consistent C gain, with visible more and less intensive periods. Duration of C gain is 60-70 years for both mineral and organic fertilization treatments.

In contrast, for DAOS 3, which demonstrates an average increase of C stock for all fertilization treatments during 155 years it represents periodic gains and losses, which alternate each other. These changes are connected with comparatively more or less favourable climate conditions, which affect crop yield, C input and, in the end, change C stocks. It is easier to maintain C accumulation when perennial grass field is present in crop rotation, as in the experiment DAOS 4. Han et al. [21] estimated duration of C sequestration in cool temperate climate as 72-117 years under organic-mineral and less, for example, 46-73 years for mineral fertilization with straw addition. Our data demonstrate higher potential duration for Retisols for both fertilization regimes, which stresses the importance of this region in future C sequestration by arable soil.

The simulation results demonstrate the vital role of crop rotation selection as a measure of adaptation to climate change. In particular, grass cultivation allows for more efficient use of climate resources compared to crop rotation, which reflects an increase in the intensification of agricultural production with a focus on the cultivation of only row crops and cereals. The use of grasses leads to a more considerable increase in C stocks in favourable years and a relatively smaller drop in unfavourable ones.

5. Conclusions

The results of SOC stock modelling under the future climate show the prospects for using the non-Chernozem zone as an area where significant sequestration of C in arable soils may be achieved over several decades, provided that crop rotation productivity remains at the level corresponding to current farming systems. For both climate scenarios, the most favourable period for the accumulation of C is 2020-40, and organic-mineral or organic fertilizer systems would be options that allow a partial compensation of the expected instability of crop yields under the future climate through adding C with organic fertilizers.

At the same time, we showed that even if the total SOC stocks are similar, the efficiency of their management may differ significantly, reflecting the different qualitative composition of organic C. With a standard increase of 4‰ or higher, the role of active C fractions increases in the considered long-term experiments, which will be relatively more susceptible to SOM decomposition processes as a result of climate changes that accelerate the mineralization of previously accumulated C stocks compared to stable fractions of soil humus.

In general, proper management of fertilizer systems and crop rotations is expected to be more important than the uncertainty associated with the implementation of various climate scenarios, which shows the promise of timely adaptation measures. However, the simulation results show that as the accumulation of arable soil increases, the long-term management of its stocks becomes an increasingly difficult practical task.

Author Contributions: Conceptualization, Pavel Krasilnikov and Vladimir Romanenkov; methodology, software, Vladimir Romanenkov; investigation, Nadezhda Sidorenkova, Vera Pavlova, and Stanislav Siptits; data curation, Kristina Prokopyeva; writing—original draft preparation, Kristina Prokopyeva; writing—review and editing, Pavel Krasilnikov and Vladimir Romanenkov; visualization, Kristina Prokopyeva; supervision, project administration, funding acquisition, Pavel Krasilnikov. All authors have read and agreed to the published version of the manuscript.

Funding: The research was a part of the activities of the Horizon 2020 project Coordination of International Research Cooperation on soil CArbon Sequestration in Agriculture (CIRCASA). The financial support for the research was obtained from the project "Management of atmospheric carbon sequestration in arable soils of Russia" of the Federal Task Program "Research and development in priority areas of development of Russia's scientific and technological complex for 2014–2020", unique project identifier RFMEFI61618X0105.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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