

1 Article

# 2 Modelling and prediction of organic carbon 3 dynamics in arable soils based on a 62-year field 4 experiment in the Voronezh region, European Russia

5 Ilshat Husniev<sup>1</sup>, Vladimir Romanenkov<sup>1,2</sup>, Olga Minakova<sup>3</sup> and Pavel Krasilnikov<sup>1,\*</sup>

6 <sup>1</sup> Faculty of Soil Science, Lomonosov Moscow State University, 119991, Leninskie Gory 1, building 12,  
7 Moscow, Russian Federation; husniev.ilshat@gmail.com

8 <sup>2</sup> Geographical Network Department, All-Russian Research Institute of Agrochemistry, 127550,  
9 Pryanishnikova street, 31a, Moscow, Russian Federation, [geoset@yandex.ru](mailto:geoset@yandex.ru)

10 <sup>3</sup> All-Russian Research Institute for Sugar and Sugar Beet, 396030, building 86, Ramon', Voronezh Region,  
11 Russian Federation, [olalmin2@rambler.ru](mailto:olalmin2@rambler.ru)

12 \* Correspondence: [krasilnikov@soil.msu.ru](mailto:krasilnikov@soil.msu.ru)

13

14 **Abstract:** Organic carbon (OC) accumulation in soil mitigates greenhouse gases emission and  
15 improves soil health. We aimed to quantify the dynamics of OC stock in soils and to justify  
16 technologies that allow annual increasing OC stock in the arable soil layer by 4‰. We based the  
17 study on a field experiment established in 1936 in the 9-field crop rotation with a fallow on  
18 Chernozem in European Russia. The RothC version 26.3 was used for the reproducing and  
19 forecasting OC dynamics. In all fertilizer applications at FYM background, there was a decrease in  
20 the OC stock with preferable loss of active OC, except the period 1964-71 with 2-5‰ annual OC  
21 increase. The model estimated the annual C input in the arable soil layer as 1,900 kg·ha<sup>-1</sup>. For  
22 increasing OC stocks by 4‰ per year, one should raise input to 2400 kg·ha<sup>-1</sup>. Simulation was made  
23 for 2016-2090 using climate scenarios RCP4.5 and RCP8.5. Crop rotation without fallowing provided  
24 an initial increase of 3‰ and 6‰ of stocks in the RCP8.5 and RCP4.5 scenarios accordingly, followed  
25 by a loss in accumulated OC. Simulation demonstrates difficulties to increase OC concentration in  
26 Chernozems under intensive farming and potential capacity to rise OC stock through yield  
27 management.

28 **Keywords:** soil health; soil organic matter; greenhouse gases; climatic change scenarios;  
29 Chernozems; long-term experiment

30

## 31 1. Introduction

32 Organic carbon (OC) dynamics in the soil is given special attention during the last few decades  
33 [1]. On the one hand, the relevance of these studies is related to the significant role of soil carbon in  
34 the global carbon cycle, which includes the release of greenhouse gases into the atmosphere, which  
35 is believed to have an impact on recent climate changes on Earth [2]. On the other hand, the  
36 importance of soil organic matter (SOM) for the soil health, its fertility, maintaining the species  
37 diversity of soil organisms and providing other ecosystem services related to the soil is being  
38 understood at a new level [3].

39 At the Paris climate conference (COP 21) in 2015, a voluntary action programme was proposed  
40 as part of the Agenda, "Initiative 4 per 1000: Soils for food security and climate", which emphasizes  
41 the role of soil organic matter in addressing a three-level problem: food safety, the adaptation of food  
42 systems to climate change, and mitigation of anthropogenic greenhouse gas emissions [4]. This  
43 initiative calls for fixing C in soils through advanced methods of soil treatment: it is believed that an  
44 increase in the OC content in cultivated soils by 4‰ per year will compensate for all greenhouse gas  
45 emissions associated with agriculture while ensuring soil health [5]. A broader context for the

46 importance of soil OC for mitigating the climatic change was given in the decision on Koronivia Joint  
47 Work on Agriculture at the UN climate conference (COP23) in 2017. However, practical mechanisms  
48 for responding to these initiatives should be developed on the regional and local level [3].

49 There are several limitations for the increase in OC in agricultural soils [6]. One of these  
50 limitations is the reverse dependence of soil potential to accumulate OC on the current SOM  
51 concentration. Generally, soils with low OC concentration may easily increase C stock after  
52 application of organic fertilizers and conservation agricultural practices. In contrary, in soils with  
53 initially high SOM reserves, it is difficult to increase their OC stock; some of these soils even lose C  
54 under intensive cultivation despite the use of manure. Ironically, fertile soils with high SOM  
55 concentration turn to be the most difficult with respect to the increase of OC stock by 4% per year. In  
56 Russia, Chernozems are the most productive soils that stretch from the western borders of the  
57 country to Eastern Siberia in the steppe and forested steppe zones; they contain up to 6% OC in the  
58 topsoil [7,8]. Our previous studies based on the long-term field agrochemical experiments in Russia  
59 showed that just to maintain OC in Chernozem in steppe zone inputs of 2.6–2.9 Mg C ha<sup>-1</sup> yr<sup>-1</sup> were  
60 required [9]. The loss of SOM in soils leads to the reduction in soil health and consequently, to the  
61 depletion of soil-related ecosystem services [10].

62 This work aimed to quantify the long-term dynamics of OC stocks in arable soils of the region  
63 using data on production processes and to justify optimal agricultural technologies that allow  
64 maintaining and increasing organic carbon stock in the arable soil layer by 4% per year, providing  
65 both stabilization of productivity and mechanisms for reproduction of soil health.

## 66 2. Materials and Methods

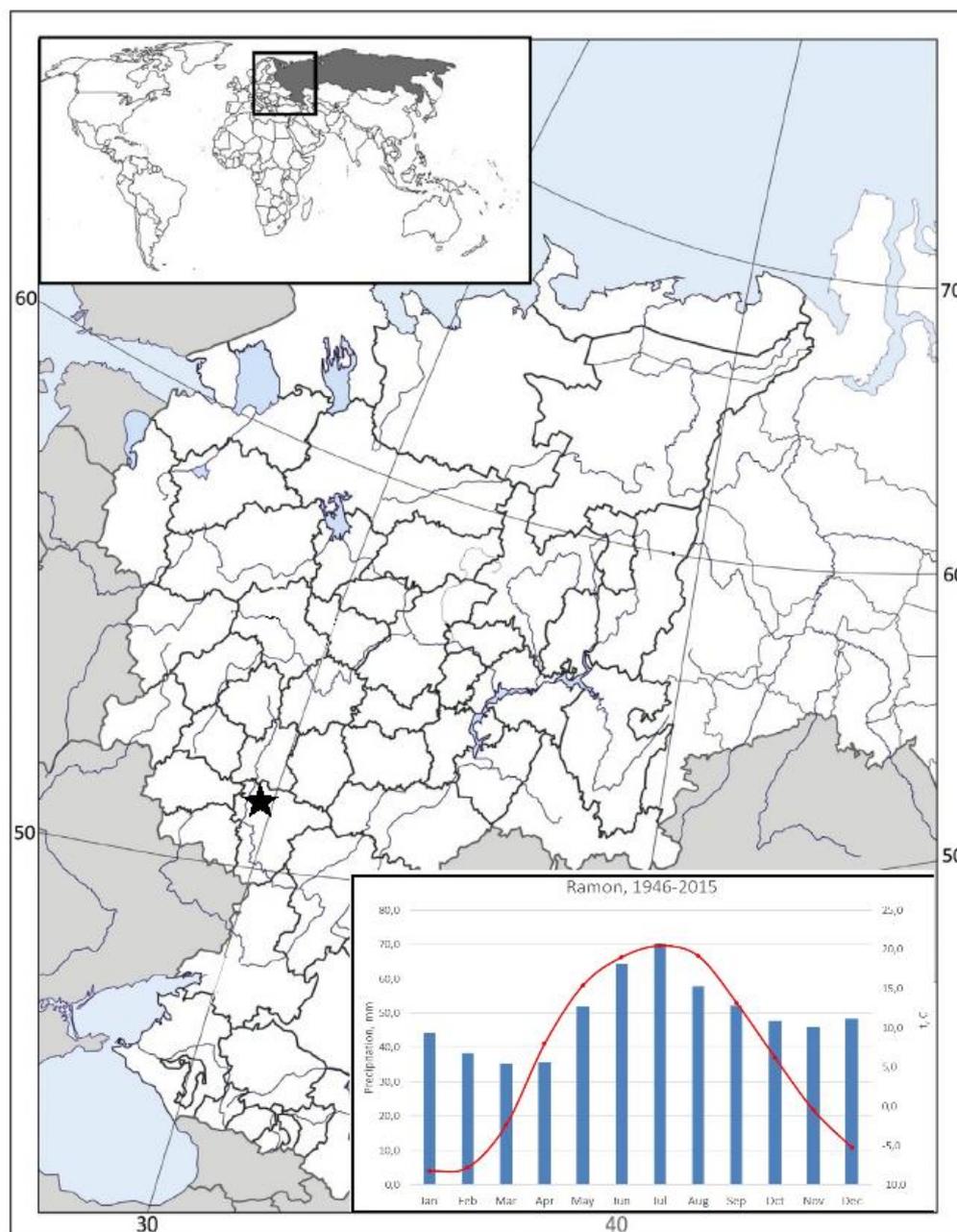
67 The study was based on a long-term field experiment “The System of fertilizers for sugar beet  
68 and other crops in crop rotation with beet” launched in 1935 at the experimental field of the All-  
69 Russian Research Institute of Sugar and Sugar Beet named after A. L. Mazlumov (VNIISS), located in  
70 a typical forest-steppe in the North of the Voronezh region on leached chernozem (Luvic Chernozem  
71 in WRB system). The location of the site and its climatic characteristics are shown in Fig. 1; in the  
72 Köppen system, the climate is Dfb (Snow climate, fully humid with warm summer). The 9-field crop  
73 rotation included black fallow—winter wheat—sugar beet—spring barley with clover—clover—  
74 winter wheat—sugar beet—peas—oats and was studied at nine fields. To simulate the dynamics of  
75 organic carbon stocks, four treatments of the experiment from field No.4 were used (Nos. 36, 39, 31,  
76 32): No. 36 was a control without fertilization; No. 39 with the application 25 t·ha<sup>-1</sup> of organic fertilizer  
77 and one rate of mineral fertilizers (FYM25+N45P60K45); No. 31 with a double rate of mineral  
78 fertilizers (FYM25+N90P120K90); and No. 32 tested the application of a triple rate of mineral  
79 fertilizers (FYM25+N135P180K135) at the same organic fertilizer rate. FYM was applied during  
80 fallowing and mineral fertilizers for sugar beet.

81 For these treatments, 15 measurements of SOC content were available since 1954.

82 The Rothamsted model RothC version 26.3 is used for studying the dynamics of organic carbon.  
83 This mathematical modelling method allows taking into account the entire range of influencing  
84 factors and is widely used in calculating the carbon stock in agricultural and forest automorphic soils  
85 [11]. This model requires monthly climate information (average temperature, precipitation, and  
86 evaporation), and the main characteristics of soils (initial carbon content in the arable layer, clay  
87 content, density) and the input of organic residues into the soil as input data for the period under  
88 review. This model allows calculating the stock of organic carbon on a monthly basis and can be used  
89 for long-term modelling.

90 Verification of the model based on the experimental data with a statistical accuracy assessment  
91 was carried out based on the Modeval model. Some statistical indicators are presented in Table 1.  
92 Based on the data presented in Table 1, we concluded that the calculated data adequately reproduce  
93 the real dynamics of OC stocks. SOC stocks for all the tested treatments demonstrated a steady  
94 decline at the initial period, followed by the period of near-equilibrium and opposite positive trend,  
95 followed by a slow decrease since the mid of 80s. RothC describes the measured data better than the  
96 mean of the measurements, which can be concluded from CD values greater than 1. Despite low

97 RMSE values, the model tended to overestimate SOC stocks, which can be partially attributed to high  
 98 spatial variability of carbon content in plot replications. However, M values did not reveal significant  
 99 bias. For further explanation on the assessment of statistical accuracy, please consult [11].  
 100



101

102

103

**Figure 1.** The location and a climatic diagram for the VNISS experimental field. Ramon, Voronezh region, is the closest meteorological station to the field.

104

105

106

107

108

**Table 1.** Statistical evaluation of the results of modelling the dynamics of organic carbon reserves using the Roth-C model in the long-term experiment of VNISS.

Treatment	$r^1$	RMSE <sup>2</sup>	EF <sup>3</sup>	CD <sup>4</sup>	M <sup>5</sup>
36	0.88	3.92	-2.15	1.37	-1.31
39	0.80	5.20	-3.59	1.62	-2.24
31	0.92	5.43	-4.61	1.10	-3.04
32	0.94	2.75	-2.25	1.02	-1.53

109 <sup>1</sup>Correlation coefficient

110 <sup>2</sup>Root mean square error of the model

111 <sup>3</sup>Modelling Efficiency

112 <sup>4</sup>Coefficient of Determination

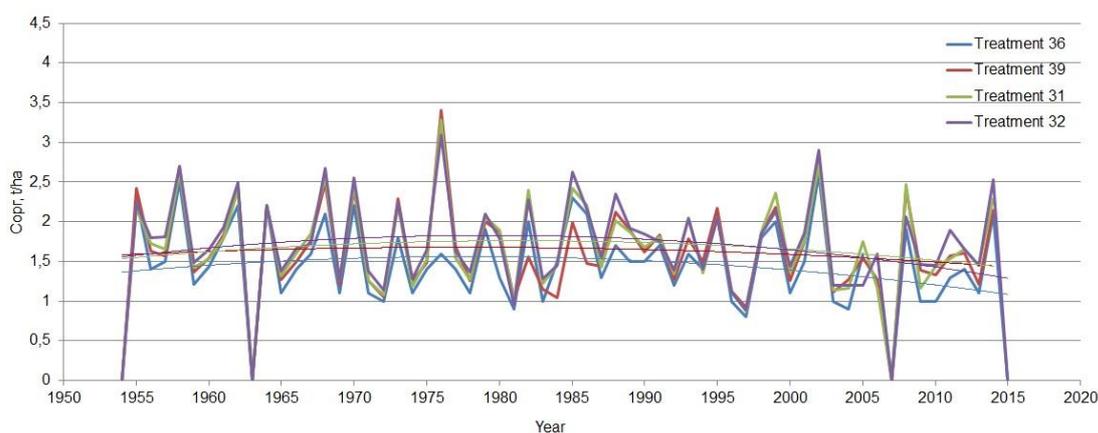
113 <sup>5</sup>Mean Difference

### 114 3. Results

#### 115 3.1. Modelling C intake during the long-term experiment

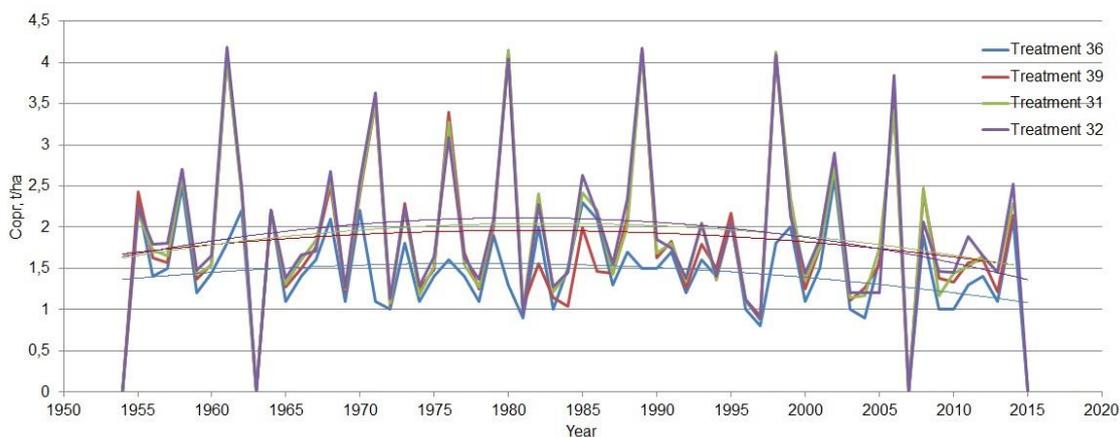
116 To assess the long-term dynamics of organic carbon stocks in the upper 20 cm of arable soils, the  
 117 calculation of organic carbon input was performed. The following figures show the dynamics of  
 118 organic carbon input with plant residues and manure (if any) during the simulation period for the  
 119 treatments.

120 Fig. 2 shows the distribution of organic C input with surface residues and underground biomass  
 121 annually, and figure 3 shows total C input with the amount of organic fertilizers taken into account.  
 122 As can be seen from Fig. 2, C input in the control treatment (36) decreased, reaching a minimum by  
 123 the end of the observation period; in the other treatments (39, 31, 32), C input increased slightly until  
 124 1976, then also decreased by the end of the observation period. A similar relationship is observed in  
 125 Fig. 3, where the relationship is even more pronounced and can be estimated using a polynomial  
 126 curve.



127

128 **Figure 2.** The annual C input in the long-term field experience of VNIISS only with plant residues. On the axis  
 129 of abscissas – the receipt of organic C,  $t \cdot ha^{-1}$ , on the axis of ordinate – the year of receipt. Smoothing was  
 130 performed using second-degree polynomials.



131

132 **Figure 3.** The annual C input in the long-term field experience of VNIISS in total, taking into account the  
 133 application of organic fertilizers. On the axis of abscissas – the receipt of organic C,  $t \cdot ha^{-1}$ , on the axis of  
 134 ordinate – the year of receipt. Smoothing was performed using second-degree polynomials.

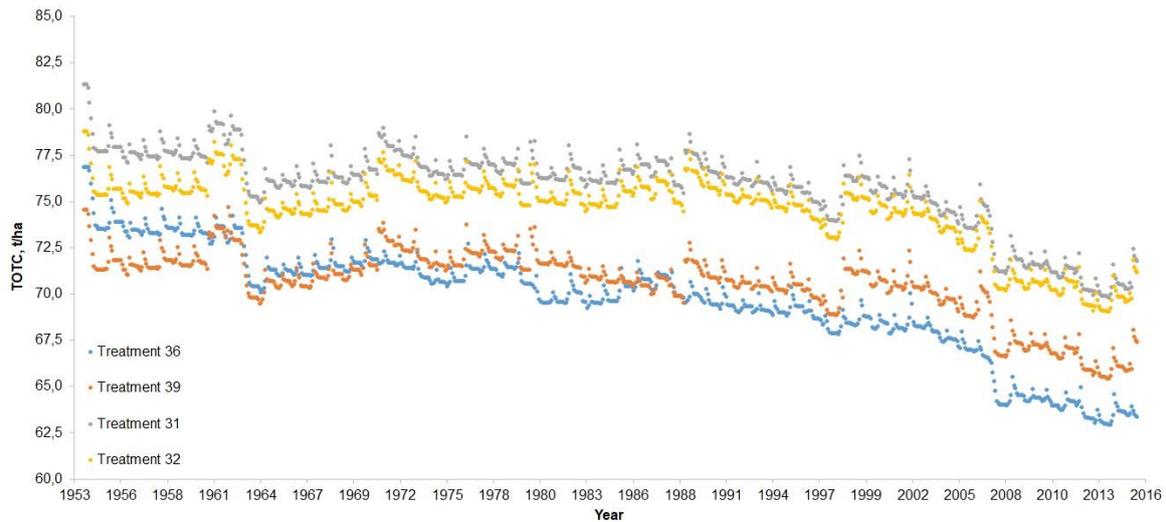
135 The study of the polynomial function shows that in all treatments, the initial annual C input with  
 136 plant residues was on average  $1600-1800 \text{ kg} \cdot ha^{-1}$  of organic C, then reached the maximum values on  
 137 average  $1900-2100 \text{ kg} \cdot ha^{-1}$  in the period from 1977 to 1987, and after 60 years, at the end of the  
 138 observation period, decreased to  $1300-1500 \text{ kg} \cdot ha^{-1}$  of organic C. The dynamics of C input from plant  
 139 residues differed insignificantly for all the treatments with fertilization. For the control treatment, the  
 140 decline continued, reaching a level of about  $1500 \text{ kg} \cdot ha^{-1}$  C per year 60 years after the start of the  
 141 experiment. The difference in the behaviour of the control treatment and treatments with fertilizers  
 142 can be due to both a relatively smaller amount of plant residues in the former case and a smaller ratio  
 143 of underground and aboveground products in the total biomass, which is taken into account in the  
 144 Levin equations [12]. Differences in crop rotation productivity between treatments with different  
 145 rates of mineral fertilizers did not drastically change C input with plant residues, only slightly  
 146 increasing their supply in direct dependence on the rate. The actual changes were caused by organic  
 147 fertilizers regularly applied once per crop rotation, as can be seen from Fig. 3. At the same time, the  
 148 tendency to increase the average value of C input to the soil with an increase mineral fertilizers rate  
 149 becomes more pronounced at the background of organic fertilizers.

150 In all treatments with fertilizer applications, there is a gradual decrease in organic carbon stocks (Fig.  
 151 4). The lowest losses of soil organic carbon, both in absolute and relative terms, are observed in the  
 152 treatment 39 of the experiment with the application of organic fertilizer and one rate of mineral  
 153 fertilizers and reach the maximum values in the control (Table 2).

154 **Table 2.** Simulated changes in SOC stocks in the upper 20 cm of four treatments of the experiment for the  
 155 period from 1954 to 2015

Changes in SOC stocks between 1954 and 2015				
Treatment	36	39	31	32
Absolute losses, $t \cdot ha^{-1}$	11.51	6.25	8.43	6.62
Relative loss, %	-15.35	-8.59	-10.63	-8.61
Relative losses per annum, %	-0.25	-0.14	-0.17	-0.14

156



157

158 **Figure 4.** Simulated changes in organic C stock at four treatments for the period from 1954 to 2015.

159 The correspondence of the dynamics of total organic C stocks for each treatment, calculated from  
 160 the model and experimental values is shown in Fig. 5.

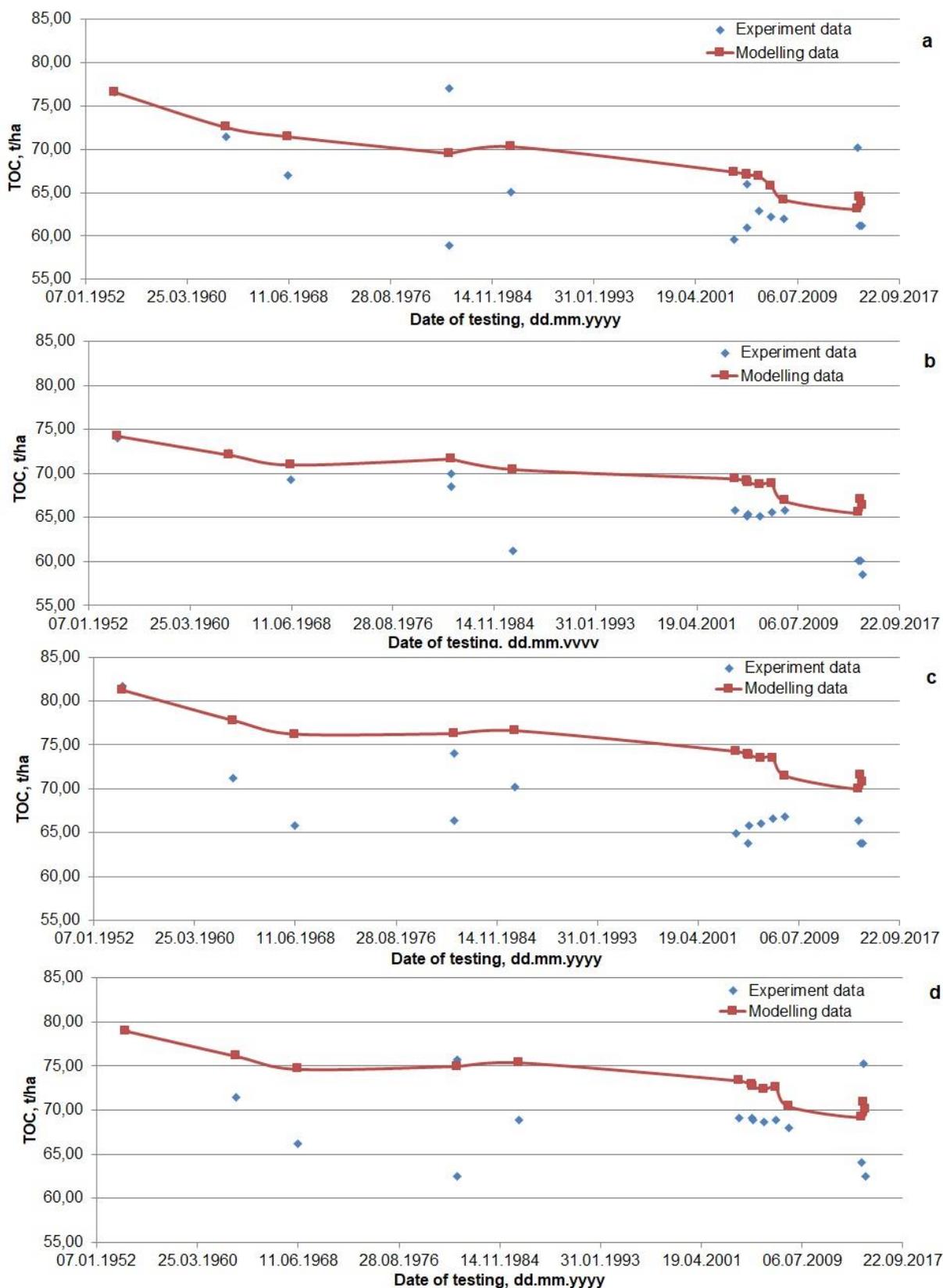
161 If we consider the rate of accumulation or loss of carbon in the soil for 62 years of the experiment  
 162 (Table 2) and the annual C input into the soil with surface residues, underground biomass and  
 163 organic fertilizers (Table 3), the model estimates the average annual amount of C input necessary to  
 164 maintain initial stocks in the arable soil layer as on average 1,900 kg·ha<sup>-1</sup>.

165 If we aim to increase organic C stocks by 0.4% per year, then to achieve this goal, it is necessary to  
 166 increase the input of carbon to the soil to an average of 2400 kg·ha<sup>-1</sup>. Fig. 4 shows that the trend  
 167 towards an increase in SOC stocks was observed only in the period 1964-1971. During this period,  
 168 20% of row crops and 80% of continuous crops were planted in crop rotation. Analyzing the dynamics  
 169 of organic C stocks in this period (Table 4), we can observe an annual increase SOC stocks of 0.4 per  
 170 cent or more in three tested treatments of the experiment (39, 31 and 32), which indicates that the  
 171 above goal can be achieved with crop rotation and agricultural technologies applied at this stage of  
 172 the experiment.

173 **Table 3.** Indicators of organic carbon balance in the long-term VNIISS experiment (1954-2015).

Mean annual value, t · ha <sup>-1</sup>	Treatments			
	36	39	31	32
C input with plant residues, experimental, 1954-2015	1.443	1.590 (88%)	1.637 (88%)	1.680 (89%)
C input with organic fertilizers, experimental, 1954-2015	-	0.218 (12%)	0.218 (12%)	0.218 (11%)
Δ C, 0-20 cm, model, 1954-2015	-0.186	-0.101	-0.136	-0.107
CO <sub>2</sub> flux to the atmosphere	1.687	1.947	2.058	2.071

174



175

176 **Figure 5.** Dependence between experimentally determined and calculated by RothC SOC stocks in a layer of 0-20  
 177 cm of the soil of long-term experiment in the period 1954-2015 for four treatments: a - 36, b - 39, c - 31, d - 32.

178 The average annual loss of CO<sub>2</sub> to the atmosphere during the mineralization of plant residues, organic  
 179 matter and organic fertilizers, calculated according to the RothC model, averaged 1687 kg·ha<sup>-1</sup> for the  
 180 control treatment (36), 1947 kg·ha<sup>-1</sup> for the treatment 39, 2058 kg·ha<sup>-1</sup> for the treatment 31, and 2071

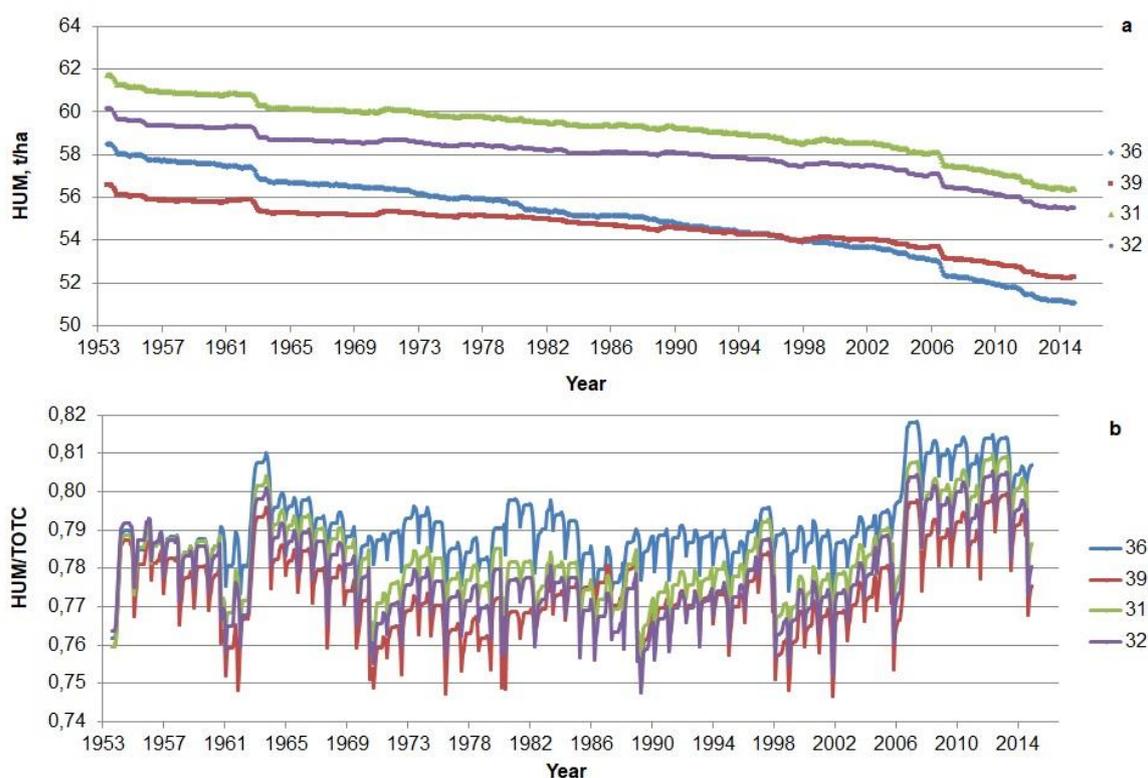
181 kg·ha<sup>-1</sup> for the treatment 32. The total CO<sub>2</sub> emission for the entire period of the experiment of 62 years  
 182 was 104.6 t · ha<sup>-1</sup> for the treatment 36, 120.7 t · ha<sup>-1</sup> for the treatment 39, 127.6 t · ha<sup>-1</sup> for the treatment  
 183 31, and 128.4 t · ha<sup>-1</sup> for the treatment 32.

184 **Table 4.** The simulated increase in SOC stocks in at the VNIISS experiment for the period 1964-1971

The increase in SOC stock for the period 1964-1971				
Treatment	36	39	31	32
Absolute values, t · ha <sup>-1</sup>	1.1	2.6	2.3	2.5
Relative values, %	1.5	3.7	3.0	3.3
Relative values per annum, %	0.2	0.5	0.4	0.4

185

186 The RothC model allows us to track the dynamics of individual SOC pools. Fig. 6 shows the dynamics  
 187 of the fraction of humified organic matter carbon (HUM), which is characterized by the highest  
 188 stability in comparison with other pools (except for the inert one, the content of which does not  
 189 change during the experiment) in relation to the dynamics of the total C stock (MRT is 50 years).



190

191 **Figure 6.** The dynamics of humified organic matter carbon HUM pool (a) and the proportion of humified C to  
 192 its total soil stock, (b) calculated using the RothC model with monthly data.

193 As can be seen from Fig. 6, changes in the stocks of humified organic matter has the same trend as  
 194 the change in the stocks of total organic carbon (Fig. 4). The dynamics of the ratio of the pool of  
 195 humified C to its total stock in the soil is different. The percentage of humified C in all treatments at  
 196 the beginning of the experiment was 76% of the total SOC stock. With a decrease in the input of fresh  
 197 organic matter after the 1970s, the proportion of humified C tended to increase in all treatments, most  
 198 intensively in the treatments with the application of organic and mineral fertilizers. This tendency is  
 199 explained by the large losses of organic C from more dynamic pools – RPM and BIO. The maximum  
 200 increase in the proportion of humified organic matter at the end of the experiment was observed in  
 201 the control treatment (36) - 81%.

202 During the experiment, the HUM pool decreased by 12% in treatment 36, 7% in treatments 39 and 32,  
203 and 8% in treatment 31. Thus, all treatments showed a tendency to decrease the reserves of organic  
204 matter resistant to mineralization of the soil over the 62 years of the experiment.

205 Such dynamics of organic C reserves is characterized by the behaviour of a system that does not reach  
206 an equilibrium state in the course of the experiment. Indeed, if we look at the dynamics of recalcitrant  
207 plant material pool (RPM, Fig. 7b), the MRT of which is 3.3 years. All treatments demonstrate its  
208 decline after each following year without recurrent trend during the next rotation.

209 Similar trends were detected by the dynamics of microbial biomass (BIO) pool (MRT of 1.5 years),  
210 with a smaller range of variation (Fig. 7b). The content of decomposable plant material (DPM)  
211 changes most actively and does not reveal any regularities (Fig. 7a). This fraction is the most dynamic  
212 since its MRT is minimal compared to other fractions (0.1 years). There are almost no differences  
213 between the treatments.

214 The same regularities are observed in the dynamics of humified organic matter carbon (HUM),  
215 recalcitrant plant material (RPM) and microbial biomass (BIO) pools as in the dynamics of total  
216 organic carbon reserves of the pilot site. The highest C losses were observed during the period of  
217 fallow, which especially affected the control treatment (36).

### 218 3.2. Forecast of C fixation in soil for the period 2016-2090

219 After identifying the model based on data from 62 years of research, forecast calculations for the  
220 period 2016-2090 were performed using simulation modelling. Two climate variability scenarios  
221 (RCP) were used for subsequent predictive modelling, namely RCP4.5 and RCP8.5, which  
222 correspond to the possible range of radiation exposure values in 2100 (4.5 and 8.5 W/m<sup>2</sup>, respectively).  
223 The convergence of the results of calculations based on the model and experimental data allows to  
224 set crop rotation options with different proportions of cereals and row crops and explore the  
225 possibility of ensuring a deficit-free C balance in alternative crop rotations. The simulation  
226 experiment for 2016-2090 conditions included the following crop rotations:

227 1. Business-as-usual (BAU) with the application of 25 t · ha<sup>-1</sup> of FYM per crop rotation (20% row crops,  
228 10% fallow);

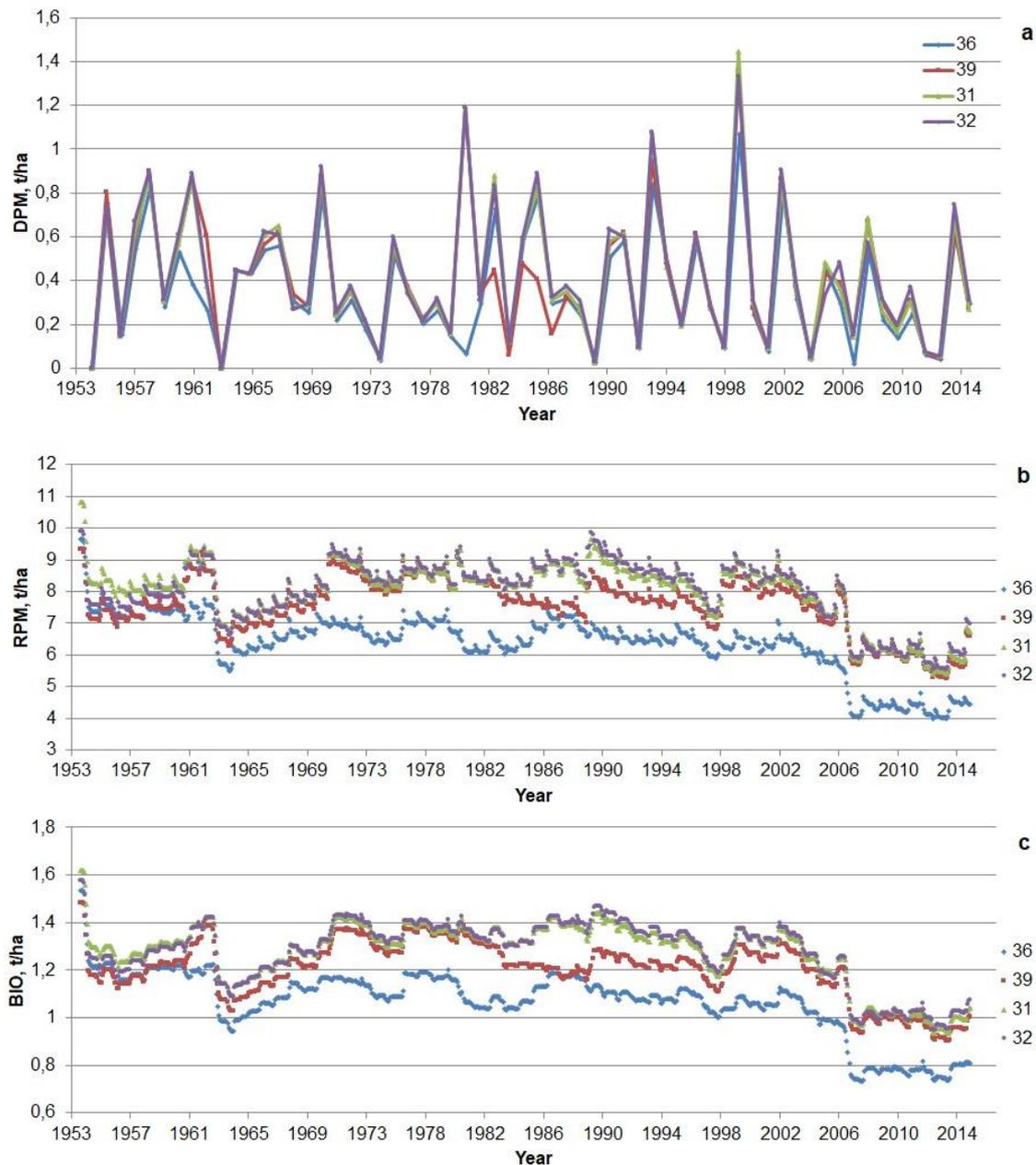
229 2. BAU with the application of 52 t · ha<sup>-1</sup> of FYM for crop rotation (20% row crops, 10% fallow);

230 3. Sustainable (SUS) grain-row crop rotation with the application of 25 t · ha<sup>-1</sup> of FYM per crop rotation  
231 (20% row crops, 80% crops of continuous sowing);

232 4. SUS rotation with the application of 52 t · ha<sup>-1</sup> of FYM for crop rotation (20% row crops, 80% crops  
233 of continuous sowing).

234 Thus, the analysis of the predicted SOC stocks dynamics reveals the effect of such factors as climate,  
235 crop rotation and the rate of organic fertilizers on the ability of the studied soils to accumulate organic  
236 matter and the ability to achieve an annual increase of 0.4% from the initial values, which can  
237 potentially compensate greenhouse gas emissions associated with agricultural activities.

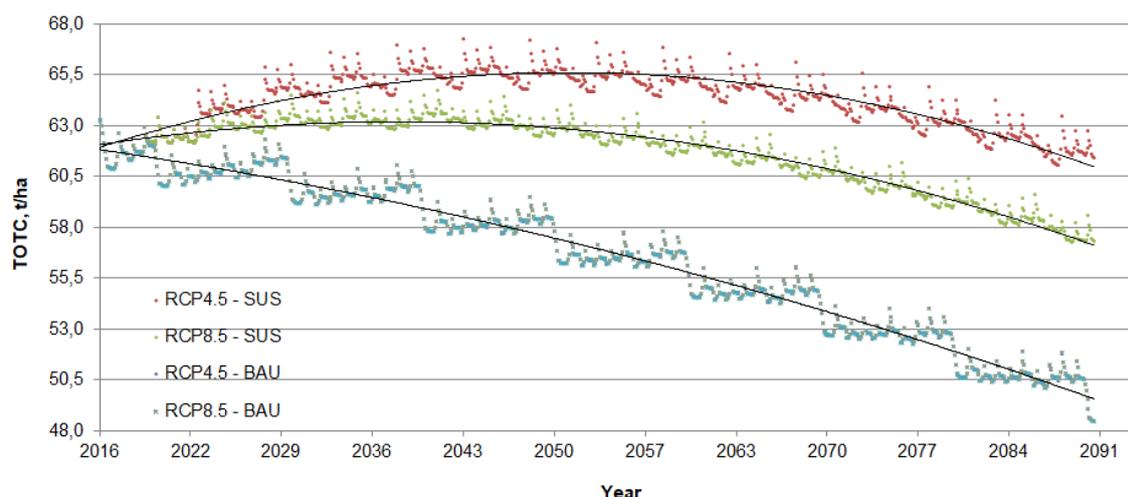
238



239

240 **Figure 6.** The dynamics of decomposable plant material (DPM) (a), recalcitrant plant material (RPM) (b) and  
 241 microbial biomass (BIO) (c) pools calculated from the RothC model. The graph (a) uses annual model data for  
 242 July, (b) and (c) use monthly model data

243 As can be seen from Fig. 8, which shows the dynamics of SOC stocks under various climate scenarios  
 244 and crop rotations for the control treatment (36), the actual crop rotation in both the RCP4.5 and  
 245 RCP8.5 scenarios predicts a gradual, uniform annual 3% decrease down to  $49.5 \text{ t} \cdot \text{ha}^{-1}$ . Change in  
 246 crop rotation to the variant 39 provides a consistent annual increase of 3% of SOC stocks from 2016  
 247 to 2041 under the RCP8.5 scenario, and rise of 6% of SOC stocks from 2016 to 2055 under the RCP4.5  
 248 scenario, and then, there is a tendency to gradually lose the accumulated C under both scenarios  
 249 (Fig.9,10).



250

251 **Figure 8.** The dynamics of total SOC stocks for various crop rotations calculated using the RothC model for  
 252 2016-2090 (treatment 36) under the RCP4.5 and RCP8.5 climate scenarios. The trend line is a polynomial of the  
 253 second degree.

#### 254 4. Discussion

##### 255 4.1. Long-term trends in SOC stock in soils under intensive farming

256 The results of SOC dynamics simulation during more than 60 years allow linking periods of C loss  
 257 with annual C inputs less than  $1,900 \text{ kg}\cdot\text{ha}^{-1}$  (Figure 4). To control or increase SOC stock  $70\text{-}80 \text{ t}\cdot\text{ha}^{-1}$  in  
 258 the upper 20 cm of the soil higher C inputs are necessary, which demonstrated by the increase of C  
 259 stock during 1964-71 and coincide with the highest C input  $1900\text{-}2100 \text{ kg}\cdot\text{ha}^{-1}$  during this  
 260 experimentation period. One of the problems for effective management of C level in the experiment  
 261 is a small increase of C input because of increasing fertilizer rates: in average 10, 13 and 16% growth  
 262 for 1954-2015 with ordinary, double and triple fertilization rates compared to the control,  
 263 respectively. With modest input of C from FYM application (11-12% from total C, Table 3), FYM  
 264 addition did not prove effective in maintaining the C stock, at least at the rate applied. However, the  
 265 rapid change of SOC trend and 2- 5‰ annual SOC increase in 1964-71 demonstrates relevance in  
 266 management crop yields and crop residues returned to the soil. The rate of SOC accumulation  
 267 increased 2-2.4 times under fertilization. The effect was most pronounced in the treatment with  
 268 ordinary fertilization rate mainly as it has the smallest SOC stock among fertilization treatments in  
 269 1964.

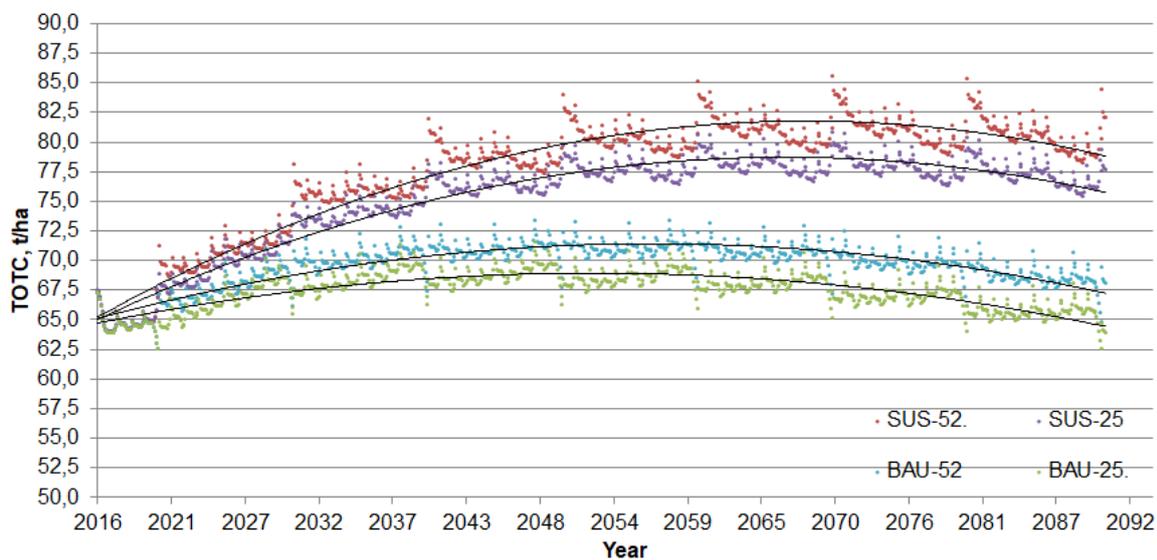
270 A tendency to decrease the reserves of SOC resistant to mineralization of the soil over the 62 years of  
 271 the experiment resulted in 8-15% SOC decline which was coincided with 4-6% growth in the  
 272 proportion of humified organic matter, mainly in the control treatment (Fig.6). Tracing of losses  
 273 during fallow periods show that RPM pool decline was almost twice higher than that of HUM pool  
 274 (Fig. 6a and 7b) which illustrates comparatively higher losses of more active pools. During 1954-2015  
 275 RPM and BIO pools reduced by almost half. The same figures demonstrate that during the period of  
 276 SOC increase, 1964-71, HUM pool remains practically constant (treatments 39,32) or has a slight  
 277 decline (treatments 36,31). All SOC growth is connected with the increase of more active RPM and  
 278 BIO pools, which indicates the viability to monitor active C fractions as indicators of maintaining  
 279 SOC stock in the studied soils.

280 In the next 60 years of simulation for the control treatment, a steady decline is expected, but the rate  
 281 of SOC loss is twice less than in the first 60-year period. Absolute annual loss during fallowing may  
 282 be as high as  $2.5 \text{ t}\cdot\text{ha}^{-1}$ , and this dynamics is practically the same under both climate scenarios. The  
 283 omission of the fallow field is enough to maintain the current  $61 \text{ t}\cdot\text{ha}^{-1}$  SOC stock. This measure can

284 be more potentially attractive under the RCP4.5 scenario. In comparison with RCP8.5 scenario, it is  
 285 twice more effective in increasing SOC stock, the effect is sustainable during a longer period, and  
 286 even a decline of accumulated SOC stock after 2055 allows to maintain in 2090 the same SOC level as  
 287 in 2015. Under RCP8.5 all accumulated SOC will be lost before 2060. This simulation is confirming  
 288 the importance of fallowing factor on SOC dynamics, which is more pronouncing than the effect of  
 289 climate change.

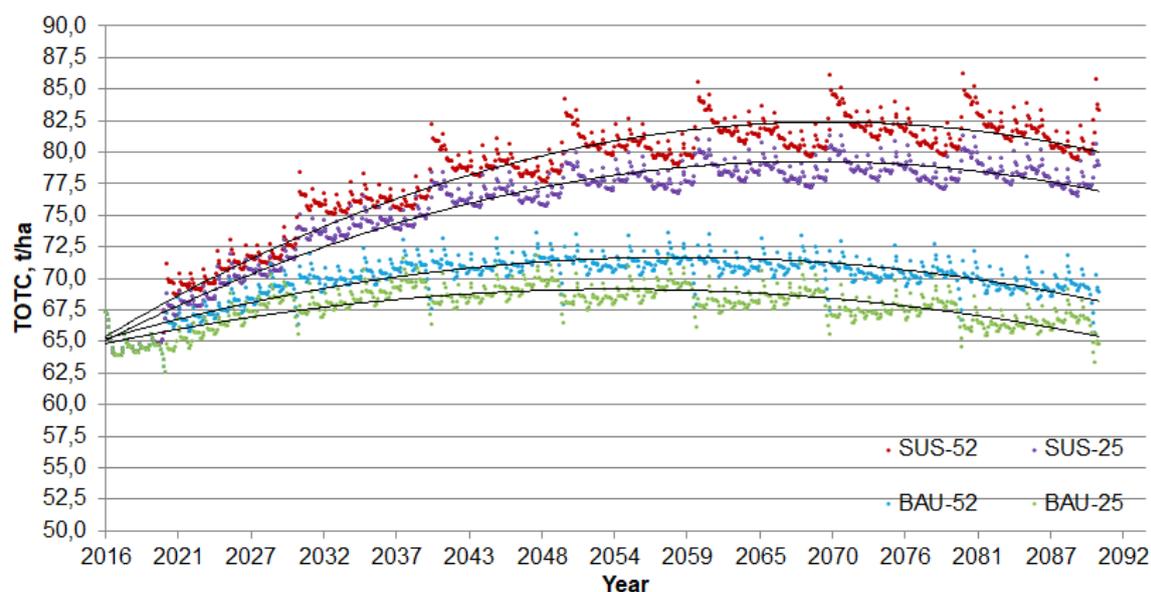
290 Investigating the effect of crop rotation on SOC dynamics under fertilization is illustrated by Fig.9  
 291 and 10 for treatment 39 with one rate of fertilizers at FYM background. Under both RCP4.5 and 8.5  
 292 scenarios accumulation of SOC is expected with >4‰ annually until 2050 and increasing FYM rate  
 293 up to 52 t·ha<sup>-1</sup> can provide additional 2.5 t·ha<sup>-1</sup> SOC accumulation after 35 years since increasing  
 294 organic fertilization rates. Introduction of SUS instead BAU crop rotation without fallowing allows  
 295 to accumulate additionally up to 10 t·ha<sup>-1</sup> SOC in the next 45 years, initial 1954 SOC level 74 t·ha<sup>-1</sup> can  
 296 be reached within 25 and 20 years after crop rotation change for RCP4.5 and 8.5 scenarios,  
 297 respectively. SOC dynamics is close for both climate scenarios, but RCP 8.5 seems slightly more  
 298 favourable for SOC accumulation. Increasing FYM rate will have potentially the same effect in SUS  
 299 rotation as in BAU. After 2060 in BAU rotation and 2070 in SUS rotation part of the previously  
 300 accumulated SOC will be lost under more unfavourable climate conditions. This loss can be as high  
 301 as 4 t·ha<sup>-1</sup> SOC in BAU rotation and 2.5-3 t·ha<sup>-1</sup> SOC in SUS rotation. It is worth to note that withdrawal  
 302 of fallowing needs to be compensated by changes in management practices that allow sustaining high  
 303 crop yields and additional chemicals load to prevent the spreading of weeds and pathogens.  
 304 Important that the first half of the century, according to both climate scenarios is the most promising  
 305 period for introduction adaptation measures for the additional accumulation of SOC in the studied  
 306 soils.

307



308

309 **Figure 9.** The dynamics of total SOC stocks for various crop rotations calculated using the RothC model for  
 310 2016-2090 (treatment 39) under the RCP4.5 climate scenario. The trend line is a polynomial of the second  
 311 degree.



312

313 **Figure 10.** The dynamics of total SOC stock for various crop rotations calculated by the RothC model for 2016-  
 314 2090 (treatment 39) under the RCP8.5 climate scenario. The trend line is a polynomial of the second degree.

315 *4.2. SOM and soil health under climatic change*

316 Soil health is believed to reflect its ability to contribute to the soil-related ecosystem services, and thus  
 317 it may act as a measure of soil value [10]. In agricultural systems, soil health is under the intense  
 318 pressure of human activities, and thus the maintenance of soil health should be specially addressed  
 319 [13]. Its decline may be associated with the degradation of the physical and chemical properties of  
 320 soils, reduction in biodiversity and biological activity [14]. SOC stock is one of the main indicators of  
 321 soils health, and its preservation is an indispensable condition for the sustainability of  
 322 agroecosystems. The “4 per mille” initiative stresses the double benefit of carbon sequestration in  
 323 agricultural soils: on the one hand, carbon fixation mitigates global warming, and on the other hand,  
 324 it favours the improvement of soil health [4]. In this respect, we should consider the long-term  
 325 variation in SOC pools as the temporal fluctuation of soil health and related ecosystem services. This  
 326 work allows quantifying the impact of changes in technology under intensive agriculture in the  
 327 ability to control the carbon stocks of arable Chernozems in the forest-steppe zone, as well as  
 328 evaluating the effect of optimization of mineral nutrition of plants during the processes for solving  
 329 the above problems.

330 As shown by the results of the experiment, in most cases it was difficult to increase SOC concentration  
 331 in Chernozems that fits well with the general opinion that it is difficult to expect carbon sequestration  
 332 in soils initially rich in SOC. The application of high rates of organic fertilizers was a necessary  
 333 component for the maintenance and increase of SOC pools in soils. The demand for manure may be  
 334 a challenge in the future because even now, many farms in the south of Russia face a deficiency of  
 335 organic fertilizers. Further research is required to find out if green manure, biochar and other  
 336 alternative carbon sources may replace traditional manure-based soil amendments.

337 **Author Contributions:** Conceptualization, Pavel Krasilnikov and Vladimir Romanenkov; methodology,  
 338 software, Vladimir Romanenkov; investigation, Olga Minakova; data curation, Ilshat Husniev; writing—original  
 339 draft preparation, Ilshat Husniev; writing—review and editing, Pavel Krasilnikov and Vladimir Romanenkov;  
 340 visualization, Ilshat Husniev; supervision, project administration, funding acquisition, Pavel Krasilnikov. All  
 341 authors have read and agreed to the published version of the manuscript.

342 **Funding:** The research was a part of the activities of the Horizon 2020 project Coordination of International  
 343 Research Cooperation on soil CARbon Sequestration in Agriculture (CIRCASA). The financial support for the  
 344 research was obtained from the project “Management of atmospheric carbon sequestration in arable soils of

345 Russia" of the Federal Task Program "Research and development in priority areas of development of Russia's  
346 scientific and technological complex for 2014–2020", unique project identifier RFMEFI61618X0105.

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

## 350 References

- 351 1. Smith, J.; Smith, P.; Wattenbach, M.; Gottschalk, P.; Romanenkov, V.A.; Shevtsova, L.K.; Sirotenko, O.D.;  
352 Rukhovich, D.I.; Koroleva, P.V.; Romanenko, I.A.; Lisovoi, N.V. Projected changes in the organic carbon  
353 stocks of cropland mineral soils of European Russia and the Ukraine, 1990-2070. *Glob. Chang. Biol.* 2007,  
354 13, 342–356.
- 355 2. Rumpel, C. Soils linked to climate change. *Nature* 2019, 572, 442-443.
- 356 3. Vermeulen, S.; Bossio, D.; Lehmann, J.; Luu, P.; Paustian, K.; Webb, C.; Augé, F.; Bacudo, E.; Baedeker, T.;  
357 Havemann, T.; Jones, C.; King, R.; Reddy, M.; Sunga, I.; Von Unger, M.; Warnken, M. A global agenda for  
358 collective action on soil carbon. *Nature Sustainability* 2019, 2.1, 2-4.
- 359 4. Soussana, J. F.; Lutfalla, S.; Ehrhardt, F.; Rosenstock, T.; Lamanna, C.; Havlík, P.; Richards, M.; Wollenberg,  
360 E.; Chotte, J.-L.; Torquebiau, E.; Ciais, P.; Smith, P.; Lal, R. Matching policy and science: Rationale for the '4  
361 per 1000-soils for food security and climate' initiative. *Soil and Tillage Research* 2019, 188, 3-15.
- 362 5. Minasny, B.; Malone, B.P.; McBratney, A.B.; Angers, D.A.; Arrouays, D.; Chambers, A.; Chaplot, V.; Chen,  
363 Z.-S.; Cheng, K.; Das, B.S.; Field, D.J.; Gimona, A.; Hedley, C.B.; Hong, S.Y.; Mandal, B.; Marchant, B.P.;  
364 Martin, M.; McConkey, B.G.; Mulder, V.L.; O'Rourke, S.; Richer-de-Forges, A.C.; Odeh, I.; Padarian, J.;  
365 Paustian, K.; Pan, G.; Poggio, L.; Savin, I.; Stolbovov, V.; Stockmann, U.; Sulaeman, Y.; Tsui, C.-C.; Vågen,  
366 T.-G.; van Wesemael, B.; Winowiecki, L. Soil carbon 4 per mille. *Geoderma* 2017, 292, 59-86.
- 367 6. Poulton, P.; Johnston, J.; Macdonald, A.; White, R.; Powlson, D. Major limitations to achieving "4 per 1000"  
368 increases in soil organic carbon stock in temperate regions: evidence from long-term experiments at  
369 Rothamsted Research, United Kingdom. *Glob. Chang. Biol.* 2018, 24, 2563–2584
- 370 7. Krasilnikov, P.; Sorokin, A.; Golozubov, O.; Bezuglova, O. Managing Chernozems for advancing SDGs. In  
371 *Soil and Sustainable Development Goals*; Lal, R., Horn, R., Kosaki, T., Eds.; Publishers: Catena-Schweizerbart  
372 Stuttgart, 2018; *GeoEcology Essays*, pp. 175–188.
- 373 8. Sorokin, A.; Owens, P.; Láng, V.; Jiang, Z.-D.; Michéli, E.; Krasilnikov, P. "Black soils" in the Russian soil  
374 classification system, the US Soil Taxonomy and the WRB: Quantitative correlation and implications for  
375 pedodiversity assessment. *Catena* 2021, 196, paper 104824.
- 376 9. Romanenkov, V.; Belichenko, M.; Petrova, A.; Raskatova, T.; Jahn, G.; Krasilnikov, P. Soil organic carbon  
377 dynamics in long-term experiments with mineral and organic fertilizers in Russia. *Geoderma Regional*  
378 2019, 17, paper e00221.
- 379 10. Doran, J. W.; Zeiss, M. R. Soil health and sustainability: managing the biotic component of soil quality.  
380 *Applied Soil Ecol.* 2000, 15, 3-11.
- 381 11. Smith, P.; Smith, J.U.; Powlson, D.S.; McGill, W.B.; Arah, J.R.M.; Chertov, O.G.; Coleman, K.; Franko, U.;  
382 Frolking, S.; Jenkinson, D.S.; Jensen, L.S.; Kelly, R.H.; Klein-Gunnewiek, H.; Komarov, A.S.; Li, C.; Molina,  
383 J.A.E.; Mueller, T.; Parton, W.J.; Thornley, J.H.M.; Whitmore, A.P. A comparison of the performance of nine  
384 soil organic matter models using datasets from seven long-term experiments. *Geoderma* 1997, 81, 153–225.
- 385 12. Levin J.J. Resolvents and bounds for linear and nonlinear Volterra equations. *Trans. Amer. Math. Soc.* 1977,  
386 228, 207-222.
- 387 13. Kibblewhite, M.G.; Ritz, K.; Swift, M.J. Soil health in agricultural systems. *Philosoph. Transact. Royal Soc.*  
388 B: Biol. Sci. 2007, 363, 685-701.
- 389 14. Montanarella, L.; Pennock, D. J.; McKenzie, N.; Badraou, M.; Chude, V.; Baptista, I.; Mamo, T.; Yemefack,  
390 M.; Aulakh, M. S.; Yagi, K.; Hong Suk, Young; Vijjarnsorn, P.; Zhang, G.; Arrouays, D.; Black, H.;  
391 Krasilnikov, P.; Sobocká, J.; Alegre, J.; Henriquez, C.R.; Mendonça-Santos, M.L.; Taboada, M.; Espinosa-  
392 Victoria, D.; Alshankiti, A.; AlaviPanah, S.K.; EL\_Mustafa Elsheikh, E.A.; Hempel, J.; Arbestain, M.C.;  
393 Nachtergaele, F.; Vargas, R. World's soils are under threat. *SOIL* 2016, 2, 79-82.