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Maps of Soil Organic Carbon Sequestration Potential in the Russian Croplands

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Abstract—Adoption of the farming systems that aim to sequester carbon in agricultural soils is one of the ways to mitigate global climate change. This study focuses on the estimation of organic carbon sequestration potential of the Russian croplands in the upper (0–30 cm) soil layer by creating a set of maps using the data from global and national databases as the input data. The maps are generated within the FAO Global Soil Organic Carbon Sequestration Potential Map (GSOCseq) project according to the unified methodology using the RothC model to predict the rate of carbon sequestration in 2020–2040 under a business as usual scenario (BAU), as well as under sustainable soil management scenarios with additional different C input (+5, +10, and +20%) resulting from the use of sustainable soil management (SSM) scenarios. The total potential sequestration rate by the croplands of the Russian Federation in the 0–30-cm layer under a BAU scenario is assessed at 8.5 Mt/year and the estimate under SSM scenarios, up to 25.5 Mt/year. The carbon sequestration by the cropland of each soil ecological zone (except for the light chestnut (Eutric Cambisols (Protocalcic)) and brown semidesert (Luvic Calcisols) soils, where it is around zero) and on a national scale is positive. The Altai krai, Omsk oblast, Novosibirsk oblast, and Krasnoyarsk krai have the greatest potential for sequestration. Several subjects of the Russian Federation—Krasnodar krai, Republic of Crimea, Rostov oblast, Primorskii krai, Republic of Adygea, and Kaliningrad oblast—demand the adoption of sustainable management of soil resources.

Keywords: resource conservation technologies in agriculture, climate change, RothC model, agricultural lands, carbon balance, "4 per 1000" initiative

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INTRODUCTION

An accurate assessment of the world resources of soil organic carbon and the potential capacity of its sequestration in soil is of great interest for the prediction of global climate change. The CO_2 sequestration from the atmosphere and the subsequent increase in the stock of organic carbon in anthropogenically disturbed sites of soil and vegetation cover are regarded as the most important strategy in mitigating the anthropogenic impact on climate change and improving other soil ecosystem functions [28]. The main advantage of a growth in the scale of carbon sequestration in agricultural soils consists in the corresponding maintenance of soil fertility and its increase; moreover, this approach does not require any changes in land management, for example, afforestation of agricultural lands, and thus will not increase the competition for land resources [16]. It is expected that a positive carbon balance in the soil–vegetation system will be attained via a widespread adoption of conservation agriculture practices [22, 23]. Numerous studies worldwide suggest that croplands during several next decades will be able to considerably enhance the sequestration of atmospheric carbon [15].

The total stock of organic carbon in 100-cm soil layer is 1462–1548 Gt and in 200-cm layer, 2376–2456 Gt [8]. The estimates for the loss of soil organic carbon over the history of farming vary in a wide range from 44 to 537 Gt [13]. According to the latest data, the carbon loss over 12000 years in 200-cm layer amounts to 133 Gt [21]. Adoption of the land sustainable management practices aimed at the carbon sequestration in soil (such as no-till farming to minimize the impact of soil, constant soil mulching with plant residues and cover crops, and a wide use of various biological techniques) can compensate for the two-thirds of the losses. Worldwide data integration demonstrates that the annual rates of organic carbon sequestration can reach 0.2 to 0.5 t C/ha [15]. Theoretically, the maximum carbon amount that can be sequestered in soil from the atmosphere is assessed at 77 Gt C (https://www.ipcc.ch/report/ar6/wg1/#FullReport). The local losses and the rate of organic carbon sequestration depend on the soil type, vegetation, climate, as well as land management type and duration.

The soil cover of the Russian Federation is the most diverse and large, and can be regarded as the greatest "soil carbon reservoir" in the world [4]. The carbon stock in 100-cm soil layer in Russia is estimated at 292 Gt C [26], which accounts for over 15% of the world carbon stock.

Croplands and pastures occupy approximately 12% of the area of this country and the organic carbon stock there is assessed at 16.8 Gt C in the upper 30-cm layer and 28.0 Gt C in the upper 100-cm layer. Based on the target value of "4 per 1000", the Russian croplands are capable of accumulating up to 4.4 million tonnes C, which corresponds to an annual sequestration rate of 0.16 t C/ha per year [15]. However, some researchers disagree with this assumption; in particular, Ivanov and Stolbovoi [2] report the calculated estimates demonstrating that the target of "4 per 1000" initiative is unachievable at a full scale in this country because of carbon saturation limit for arable soils. In their paper, the authors suggest to transform this initiative into the national "2 per 1000" initiative to be implemented in 12–15 years. However, the actual potential of Russian soils in carbon sequestration is still vague.

The soil carbon dynamics in arable soils of European Russia and Ukraine was assessed in 2006–2007 based on the RothC (Rothamsted Long Term Field Experiments Carbon) dynamic modeling, described below in more detail [18–20, 24, 25]. Several possible scenarios of the changes in carbon stock for different types of cropland use [18] and global climate change [19] were elaborated. The modeling covered the period of 1990–2070 [25]. A database comprising the necessary parameters of soil management, climate, and soil characteristics was created for RothC model [20]. A specific feature of the studies of 2006–2007 was that the database was not formed according to regular grids but rather several hundreds of mapping units distinguished in the European Russia. These test plots mapping units were separated according to the uniformity of the structure of soil cover taking into account the administrative boundaries [5]. Any more detailed information at that time was unavailable.

In 2020–2022, the FAO (Food and Agriculture Organization of the United Nations) Global Soil Organic Carbon Sequestration Potential Map (GSOCseq) project was implemented (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/global-soil-organic-carbon-sequestration-potential-map-gsocseq/en/); the applied methods are described in Technical specifications and country guidelines (https://www.fao.org/3/cb0353en/cb0353en.pdf) [27]. According to the project, 29 maps were constructed based on a unified methodology, RothC model for each country of the world [9]. RothC describes the turnover of organic carbon in the topsoil of automorphic mineral soils and takes into account the effects of soil type, temperature, moisture, and plant cover on soil C turnover with a monthly step [9]. RothC model is based on a quantitative description of soil processes. The soil organic carbon in this model is partitioned into four active pools, namely, decomposable plant material, stable plant material, microbial biomass, and humified organic matter, which differ in the rate of transformation, and one inactive pool, comprising inert matter. In this project, the sequestration of soil organic carbon in croplands was forecasted for 20 years according to four scenarios: business as usual (BAU) and three variants of sustainable soil management (SSM) for the increase in organic matter resulting from conservation agriculture practices, guaranteeing the organic carbon intake by soils (https://www.fao.org/3/cb0353en/cb0353en.pdf) [27]. It is assumed that a 20-year period is sufficient for the soil carbon stock to reach the new equilibrium state.

The goal of this work was to construct a set of maps for the territory of the Russian Federation assessing the organic carbon sequestration potential in 30-cm arable soil layer according to the guidelines for the FAO Global Soil Organic Carbon Sequestration Potential Map project [27]. We considered the croplands because they are to a greater degree susceptible to the depletion of organic carbon stock. The open sources data from national and global databases were used in the work.

OBJECTS AND METHODS

Main modeling principles. The maps of *soil organic carbon* (hereinafter, soil carbon) sequestration potential were created according to the Technical specifications and country guidelines for Global Soil Organic Carbon Sequestration Potential Map (GSOCseq) partnership [3].

The modeling comprised three phases:

(1) *Initialization–spin up phase* is aimed at bringing the carbon stock and pools to equilibrium depending on climate, soil, plant, and agricultural characteristics using RothC. The equilibrium stock has to match the values given in Global Soil Organic Carbon Map in 0–30-cm soil layer (GSOC17) [7, 10]. The annual modeling cycle was repeated 500 times [27] until this value was reached. Modeling was performed for unchanging weather conditions taking the long-term average annual values in 1980–2000 as such. The total annual carbon input with plant residues was initially set as 1 t C/ha per year. The performed simula-

tion gave the "*initial*" average annual carbon input for BAU scenario until the year of 2000 [27].

(2) *Warm up* phase consists in data harmonization because the carbon stock in the FAO map was compiled on the data of different types over 1960–2000. The soil carbon stock according to GSOC17 map in the guidelines [10] is conventionally assumed to represent the carbon stock 20 years before the current period coinciding with the initial modeling time point, that is, 2000. The model in the warm up phase is run taking into account the real weather conditions of 2000–2020 and the change in the annual carbon input with plant residues.

(3) *Forward* phase aims at the estimation of the change in soil carbon stock and its rate over the next 20 years, that is, 2020–2040 depending on the scenarios proposed in the guidelines. The first scenario of business as usual, BAU, implies that carbon input to soil with plant residues is the same each year and corresponds to the current level. As for three SSM scenarios, the sustainable soil management should lead to a certain increase in the organic carbon input to soil as compared with the current level depending on particular scenario: by 5% for SSM1, 10% for SSM2, and 20% for SSM3. These scenarios are a sort of hypothetical ones because particular resource-saving practices and the ways of achievement are not discussed.

Predictive modeling was based on the climate parameters of 2000–2020 and the land use maps of 2020. The absolute sequestration of soil carbon was assessed as the difference between the stock simulated for 2040 for different scenarios and the calculated basic stock for 2020. The relative soil carbon accumulation was estimated as the difference between the corresponding soil carbon stock predicted for 2040 for the SSM scenarios and the modeled soil carbon stock for 2040 under the BAU scenario.

Initial data. The maps were created with a spatial resolution of 1 km; the carbon stock was computed for the 0–30-cm soil layer. Only croplands among different land use types were selected for construction a set of maps. The algorithm and the sources of initial data used for simulations are described below.

Algorithm for generation the mask of croplands in Russia. Any mask of cropland over entire territory of the Russian Federation that would comprise the intensively used fields and exclude the abandoned fields is absent. The map of Russian croplands relevant as of 2020 is generated by integrating two masks for the regions of active land use in Russia created using two different principles:

(1) *The mask for Global Food Security-Support Analysis Data at 30 m (GFSAD30) cropland-extent data* (https://www.usgs.gov/centers/western-geographic-science-center/science/global-food-security-support-analysis-data-30-m). The GFSAD30 project comprises the global data on croplands and water use with a resolution of 30 m. The field areas are based on the time series with a step of 2–4 months of the Landsat-8 images over 3–4 years. The spectral images were separately generated for each of the 74 agroecological zones based on the reflectance in all Landsat-8 spectral channels and two most widespread vegetation indices: NDVI (normalized difference vegetation index) and ENVI (enhanced vegetation index). The latter is a refined vegetation index elaborated by improving NDVI via optimization of the vegetation signal in the regions with a high leaf area index (LAI). In addition, the Shuttle Radar Topographic Mission (SRTM) data were used, as well as the basic topography indices computable with the help of SAGA GIS (https://saga-gis.sourceforge.io/en/): slope gradient, slope aspect, horizontal and vertical curvatures, convergence index, total catchment area, and topographic wetness index. Training involved 100000 points and testing, 19171 points. The overall recognition rate for this mask was 91.7%; and

(2) *The mask of used croplands and the overgrowing croplands* was generated as one of the layers of the abandoned croplands potentially suitable for reforestation [1]. Creation of this map relied on the integration of some other products (masks of forest cover, residential lands, and bogs) and the threshold oscillation of the normalized difference water index (NDWI) calculated by analyzing the available sets of Landsat images [1]. The threshold values for distinguishing between the used and abandoned fields were determined by expert analysis.

Both masks have their own disadvantages first and foremost appearing in the areas with a considerable decrease in agricultural activity over the last 30 years as false positive solutions. A 30-m resolution is considerably higher as compared with the resolution of modeled organic carbon sequestration maps and allows the mapping of these masks onto a working resolution of 1 km to be regarded as a probabilistic process [3]. Each pixel of the new mask consisted of approximately 1110 pixels of the masks with a resolution of 30 m. The number of pixels marked in these maps as a field determined the probability of ascribing a particular pixel of the new 1-km mask to the class of field. Correspondingly, the scores of 1 to 10 were ascribed to all pixels of the new mask, where the score of 1 indicates that the fields occupy 10% of the area and the score of 10, 100%.

To identify the areas with active agricultural use, it was necessary to distinguish the territorial invariants of the solar energy conversion by surface. This was assessed based on the time series of 2018–2020 of the MODIS products: MOD13A1.006 Terra Vegetation Indices (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD13A1) and MOD17A2H.006 Terra Gross Primary Productivity (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD17A2H/-2022). The areas under intensive agricultural use should display a sharp oscillation regime of functioning (high variation in vegetation indices and gross primary productivity), whereas the areas withdrawn from use should be more inert (small changes are observable). Data dimensionality was reduced using the principal component method for each year of observation (2018, 2019, and 2020) to reveal the pattern of dynamics. The retention of 75% variance of principal components was used as the criterion. Thus, the invariants of agroecological states were identified. The integral index for 3 years was computed based on the determined invariants, for which the score values (1–10) obtained by geographic pooling of the two above-described masks was discriminated.

Thus, we got the probabilistic map showing the share of cropland in each 1-km pixel. The pixels with this value exceeding 50% were used in the further analysis. In this way, we created the relevant mask of the Russian croplands as of 2020. The croplands identified while examining the *mask of the Russian croplands* occupy 110.9 million hectares, accounting for 6.5% of the Russian lands (1712.5 million hectares).

Climatic data. The high-resolution dataset CRU (Climatic Research Unit) TS v. 4.05 for 1901–2020 (University of East Anglia, United Kingdom) was the source of climatic data [12]. This is a public dataset with a spatial resolution of about 50 km^2 (0.5 × 0.5 degrees; https://crudata.uea.ac.uk). The values are obtained by the interpolation of observation data of almost all public land-based weather stations. The average monthly temperatures (°C), precipitation (mm), and evapotranspiration according to Penman–Monteith (mm) over two periods, 1980–2000 and 2001–2020, were calculated using the daily climatic data for 1980–2020 extracted from CRU database.

Soil data. The National Soil Organic Carbon Stock Map in the 0–30-cm soil layer (t C/ha) was used as the starting point for modeling the carbon stock of 2000 [7, 10]. The data on cropland were obtained by matching the cropland mask without the adjustment for the decrease in carbon stock in cropland as compared with the native land.

Data on the content of clay fraction (particles with a size of <0.002 mm) were extracted from the repository of global spatial predictions of soil properties and classes at a 250-m resolution (SoilGrids250m) v. 2.0 [17].

Data on vegetation cover. The presence and distribution of vegetation cover were assessed on a monthly basis with the help of the Google Earth Engine based on 2013–2020 time series of MOD13A1.006 Terra Vegetation Indices (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD13A1), products, which gives the NDVI values for each pixel with a resolution of 500 m. The time series of satellite images makes it possible to assess the share of images with the NDVI values exceeding a specified threshold, which indicates an active growth of vegetation. The threshold value of 0.5, recommended for Europe [27], was used for construction of sequestration maps.

Estimating the amount of input plant residues. The computations are based on the assumption that the changes in carbon input to soil are associated with the changes in net primary production (NPP) [25]. With the knowledge of NPP for the target years and the amount of organic residues input in the initial period, it is possible to calculate the amount of input organic residues for any period assuming the proportionality between the amount of organic residues and NPP under the BAU scenario:

$$C_t = \frac{C_{t-1}\,\mathrm{NPP}_t}{\mathrm{NPP}_{t-1}}, \quad (1)$$

where C is the annual carbon input, t; NPP, net primary production, t C/ha; t, target year; and $t-1$, previous year. In the first modeling phase, C is the "*initial*" average annual carbon input under the BAU scenario for 2000.

The NPP for 2001–2020 was calculated using the data on temperature, precipitation, and duration of active vegetation according to the MIAMI model [11, 14]:

$$\mathrm{NPP} = \min\left(\mathrm{NPP}_T, \mathrm{NPP}_P\right), \quad (2)$$

$$\mathrm{NPP}_T = \frac{3000}{1 + e^{1.315-0.119T}}, \quad (3)$$

$$\mathrm{NPP}_P = 300 \times 1 - e^{-0.000664P}, \quad (4)$$

where is shown in g(dry matter)/m^2/year; T, annual mean temperature (°C); and P, annual mean precipitation (mm). Initially, NPP is determined according to temperature; then, according to precipitation; and the minimum value is regarded as the final value. The resulting NPP value is recalculated into t C/ha via multiplying by the coefficient of 0.0048.

The carbon input under SSM scenarios was computed as a percent increase as compared with the initial BAU data, that is, the carbon input with plant residues increased by the corresponding percent.

Ability to decompose the input plant material. The model utilizes the coefficient of 1.44, recommended by the FAO for crops and improved meadow–pasture lands [27], to assess the ratio of decomposed plant material to its recalcitrant part.

Calculating summary soil carbon sequestration maps and maps of uncertainty. The performed modeling resulted in the map of carbon stock showing the equilibrium states of pools for 2020 (Fig. 1), 18 prognostic maps, and 10 maps assessing the prediction uncertainty. Four maps of the **soil carbon absolute sequestration rate,** ASR, (t C/ha/year) [27] were computed as the difference between the soil carbon stocks in 2040 and 2020 divided by 20 years according to the BAU scenario and with an increase in the organic matter input by 5% (SSM1), 10% (SSM2), and 20% (SSM3):

$$\mathrm{ASR}_i = \frac{\mathrm{SOC}_{i,2040} - \mathrm{SOC}_{i,2020}}{20}, \quad (5)$$

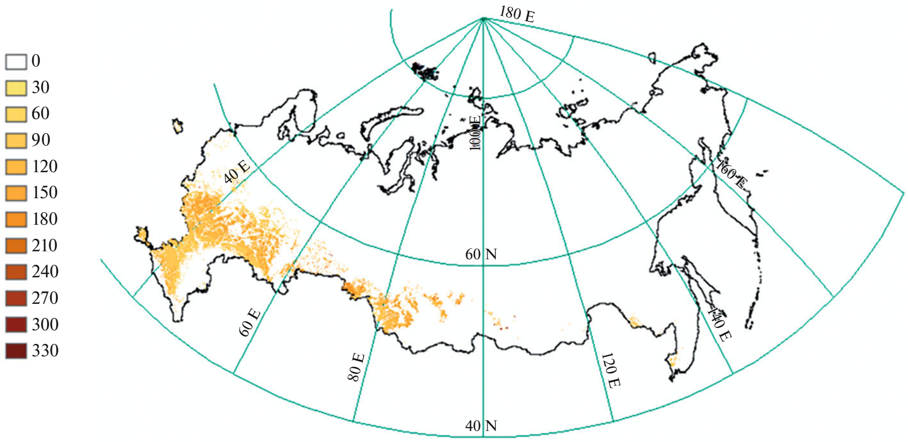

Fig. 1. Carbon stock in the 0–30-cm soil layer of the croplands in the Russian Federation as of 2020 corresponding to the equilibrium state of organic carbon pools, t/ha.

where *i* is one of the scenarios (BAU, SSM1, SSM2, or SSM3); ASR_i is the absolute sequestration rate for one of the scenarios; $SOC_{i,2040}$ and $SOC_{i,2020}$ are the soil carbon stock in 2040 and 2020 for the corresponding scenario, respectively.

Then, we constructed three maps of the **relative soil carbon sequestration rate,** RSR computed as the difference in ASR over 2020–2040 under scenarios SSM1–SSM3 and the values under the BAU scenario [27]:

$$RSR_j = ASR_j - ASR_{BAU}, \quad (6)$$

where *j* is one of the scenarios (SSM1, SSM2, or SSM3); RSR_j is the relative sequestration rate for one of the scenarios; and ASR_j and ASR_{BAU} are the absolute sequestration rates for the corresponding scenario *j* and BAU, respectively.

In addition, a set of auxiliary maps was constructed as well: four maps of the soil carbon stock (t/ha) in 2040 for all scenarios, four maps of absolute differences in the soil carbon stock (t/ha) in 2040 for all scenarios; and three maps of relative differences in the soil carbon stock (t/ha) for SSM scenarios.

The uncertainty of mapping was computed by Monte Carlo method. For prognostic maps, we calculated the expected value of soil organic carbon stock for different scenarios and 95% confidence interval. The uncertainty was assessed in percentage as a half confidence interval divided by the mean value:

$$\varepsilon = \frac{t_{95\%} s}{\bar{x}} \times 100\%, \quad (7)$$

where ε is the relative uncertainty of modeling, %; *s*, standard deviation; $t_{95\%}$ is Student's test for 95% confidence level; and $\bar{x}$, mean value.

Computing statistics characterizing soil carbon sequestration potential. The above-described maps were used to compute the statistical characteristics of ASR and RSR for the overall Russian territory, each soil ecological zone of Russia [6], and all subjects of the Russian Federation. Mountain provinces were united into one region of mountain territories. The results are listed in Tables 1 and 3.

In addition, we calculated the values of the summary absolute (SASR) and summary relative (SRSR) sequestration rates (t C/year) for each natural zone and subzone under different scenarios of sustainable soil management:

$$SASR_k = ASR_k \times S_k, \quad (8)$$

$$SRSR_k = RSR_k \times S_k, \quad (9)$$

where $SASR_k$ and $SRSR_k$ are the summary absolute and summary relative soil carbon sequestration rates, respectively, over contour *k*; ASR_k and RSR_k are the mean absolute and mean relative soil carbon sequestration rates, respectively, over contour *k;* and S_k is the area of contour *k*. The results are listed in Tables 2 and 4.

RESULTS AND DISCUSSION

Predicting soil carbon sequestration rate in Russian croplands. The mean soil carbon ASR in 0–30-cm layer of the Russian croplands amounts to 0.05 t C/ha per year for the BAU scenario and can reach 0.11, 0.16, and 0.27 t C/ha per year, respectively, for the three SSM scenarios (Tables 1–4, Figs. 1 and 2). As for the soil carbon RSR, a positive effect is observable in any of three carbon-saving practices (SSM1–SSM3) as compared with BAU scenario: over 20 years, the soil carbon stock can potentially increase by 1.0 t C/ha under SSM1, 2.0 t C/ha under SSM2, and 4.2 t C/ha under SSM3 scenarios.

In total for the overall territory of Russia, the carbon sequestration rate in arable soils amounts to 8.5 Mt C/year and to 12.9, 17.0, and 25.5 Mt C/year, respectively, under the scenarios SSM1, SSM2, and

Table 1. Mean absolute (ASR) and relative (RSR) soil carbon sequestration rates in the croplands of soil ecological zones and subzones of Russia under different sustainable soil management scenarios, t C/ha per year

Zone or subzone	S, km^2	ASR				RSR		
		BAU	SSM1	SSM2	SSM3	SSM1	SSM2	SSM3
D Subzone of gley-podzolic soils, gleyzems, and podzols of northern taiga	14	0.076	0.094	0.120	0.171	0.0186	0.0443	0.0951
E Subzone of podzolic soils of middle taiga	260	0.057	0.062	0.074	0.098	0.0134	0.0198	0.0440
F Zone of soddy-podzolic soils of southern taiga	51432	0.044	0.069	0.084	0.116	0.0191	0.0340	0.0636
K Zone of gray forest soils of deciduous forests	112554	0.068	0.097	0.124	0.177	0.0300	0.0545	0.1058
L Zone of podzolized, leached, and typical chernozems and gray forest soils of forest-steppe	399015	0.068	0.117	0.160	0.247	0.0466	0.0921	0.1818
M Zone of ordinary and southern chernozems of steppe	438178	0.024	0.057	0.092	0.170	0.0390	0.0783	0.1573
N Zone of dark chestnut and chestnut soils of dry steppe	65759	0.018	0.048	0.078	0.136	0.0320	0.0604	0.1182
O Zone of burozems and podzolic burozem soils of coniferous–broadleaved and broadleaved forests	14654	0.037	0.046	0.098	0.194	0.0159	0.0614	0.1584
P Zone of light chestnut and brown soils of semidesert	5257	−0.002	0.042	0.073	0.139	0.0379	0.0678	0.1333
Mountainous areas	10215	0.075	0.117	0.170	0.278	0.0416	0.0899	0.1906

Median was taken as the estimate of the mean; *S,* cropland area.

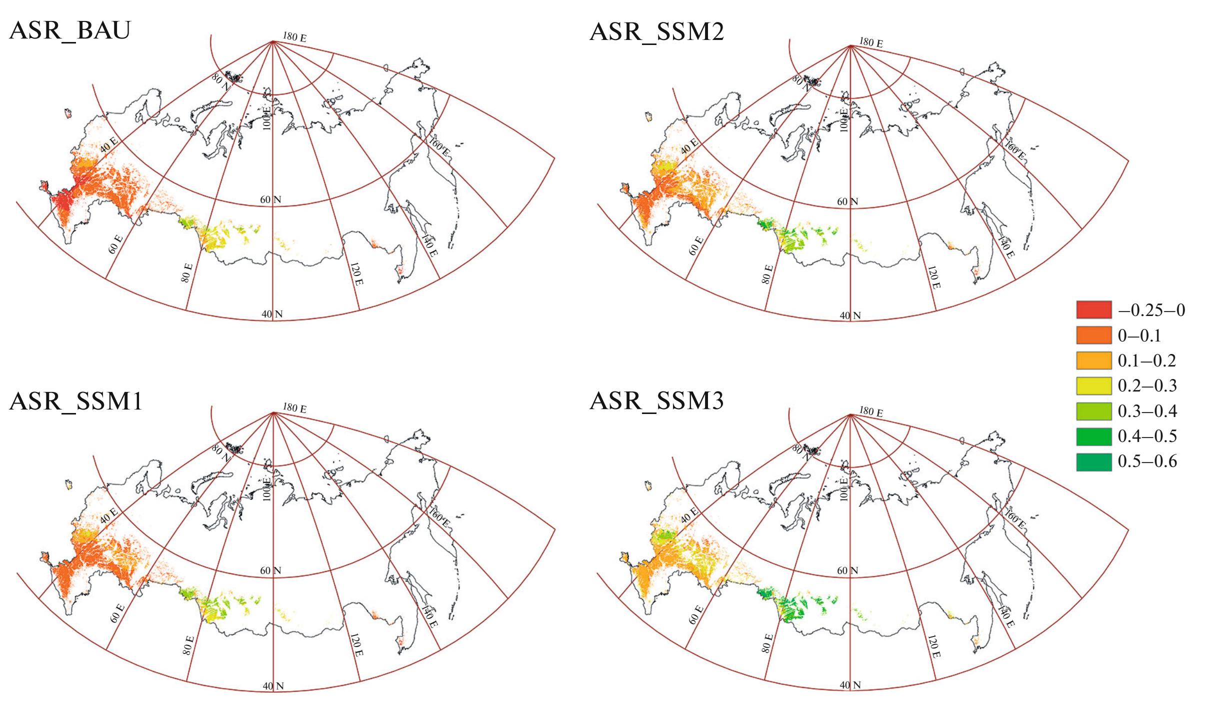

Fig. 2. Absolute soil carbon sequestration rate (ASR; t C/ha per year) under business as usual (BAU) scenario and three sustainable soil management (SSM1–SSM3) scenarios implying an increase in the organic matter input to soil by 5, 10, and 20%, respectively.

Table 2. Summary mean absolute (SASR) and relative (SRSR) soil carbon sequestration rates in the croplands of natural zones and subzones of Russia under different sustainable soil management scenarios, Kt C/ha per year

Zone or subzone	SASR				SRSR		
	BAU	SSM1	SSM2	SSM3	SSM1	SSM2	SSM3
D Subzone of gley-podzolic soils, gleyzems, and podzols of northern taiga	0.1	0.1	0.2	0.2	0.0	0.1	0.1
E Subzone of podzolic soils of middle taiga	1.5	1.9	2.2	3.0	0.4	0.8	1.5
F Zone of soddy-podzolic soils of southern taiga	271.0	401.1	488.6	664.6	132.4	217.7	393.6
K Zone of gray forest soils of deciduous forests	811.9	1160.5	1457.5	2047.6	348.8	645.6	1235.8
L Zone of podzolized, leached, and typical; chernozems and gray forest soils of forest-steppe	4165.0	5948.1	7656.8	11072.0	1784.7	3491.8	6907.0
M Zone of ordinary and southern chernozems of steppe	2940.4	4750.0	6516.6	10055.9	1811.4	3576.1	7115.4
N Zone of dark chestnut and chestnut soils of dry steppe	172.6	387.2	578.8	966.8	214.6	406.2	794.1
O Zone of burozems and podzolic burozem soils of coniferous–broad-leaved and broadleaved forests	35.4	57.7	131.7	275.8	22.7	96.2	240.4
P Zone of light chestnut and brown soils of semidesert	2.3	23.9	40.5	73.5	21.6	38.2	71.2
Mountainous areas	125.8	170.2	218.4	316.9	44.7	92.6	191.0
Total	8526.0	12900.5	17091.2	25476.3	4381.3	8565.3	16950.1

SSM3. Thus, all Russian croplands can sequester 170 to 510 Mt C in the 0–30-cm layer over 20 years by 2040 depending on the land management scenario.

The computations of the mean soil organic carbon ASR predict carbon accumulation for all considered scenarios in all natural zones except for the light chestnut (Eutric Cambisols (Protocalcic)) and brown soils (Luvic Calcisols) of semidesert under the BAU scenario. In this case, a certain decrease (by 0.002 t C/year) (Figs. 2 and 3) in the soil carbon stock is predicted there, which is actually almost zero. The highest sequestration rate is observed in the subzones of gley-podzolic (Stagnic Retisols) and podzolic soils (Retisols) of the northern and middle taiga, which is most likely associated with hydromorphism, and in the zones of gray forest soils (Albic Luvisols) and podzolized, leached, and typical chernozems (Chernozems) of forest-steppe. However, the cropland areas in these two zones are different; correspondingly, the zone of podzolized, leached, and typical chernozems and gray forest soils of forest-steppe account for 49% of the 83% of total sequestration and the zone of ordinary and southern chernozems (Chernozems) of steppe, for 34%.

The following subjects of the Russian Federation have the highest potential soil organic carbon sequestration in croplands provided that the SSM practices are implemented: Altai krai, Omsk oblast, Novosibirsk oblast, and Krasnoyarsk krai. This is associated, on the one hand, with a large cropland area and, on the other hand, with a high sequestration rate, which is two–tenfold higher than the corresponding rates for the other subjects with a positive dynamics.

Low negative values of sequestration rates are observed in a number of subjects of the Russian Federation: Krasnodar krai, Republic of Crimea, Rostov oblast, Primorskii krai, Republic of Adygeya, and Kaliningrad oblast. Adoption of SSM practices is necessary because of rather large cropland areas there. This will change the trend and an increase in organic carbon input to soil even by 5% will result in carbon sequestration.

Comparing our data to the earlier studies. Our computations of the sequestration rate and potential were compared to the RothC model estimates of the changes in soil organic carbon in the croplands of European Russia to 2070 [5, 19]. The main difference of the earlier modeling consists in the calculation of carbon input. The base period of 1990–2000 for the

Table 3. Mean absolute (ASR) and relative (RSR) soil carbon sequestration rates in the croplands of the subjects of the Russian Federation under different sustainable soil management scenarios, t C/ha per year

Subject of the Russian Federation	S, km^2	ASR				RSR		
		BAU	SSM1	SSM2	SSM3	SSM1	SSM2	SSM3
Altai krai	85310	0.235	0.281	0.327	0.422	0.0442	0.0907	0.1876
Amur oblast	8351	0.044	0.054	0.106	0.204	0.0091	0.0616	0.1593
Arkhangelsk oblast	89	0.060	0.061	0.072	0.095	0.0057	0.0134	0.0385
Astrakhan oblast	1501	−0.011	0.043	0.078	0.147	0.0553	0.0900	0.1589
Belgorod oblast	21375	0.011	0.052	0.089	0.163	0.0391	0.0775	0.1528
Bryansk oblast	9958	0.056	0.095	0.119	0.166	0.0389	0.0630	0.1072
Vladimir oblast	3912	0.043	0.065	0.083	0.119	0.0211	0.0403	0.0762
Volgograd oblast	46112	0.015	0.051	0.085	0.151	0.0353	0.0675	0.1337
Vologda oblast	1228	0.075	0.064	0.077	0.100	0.0035	0.0057	0.0253
Voronezh oblast	42433	−0.004	0.036	0.076	0.158	0.0413	0.0818	0.1647
Jewish autonomous oblast	1000	0.052	0.059	0.101	0.192	0.0135	0.0552	0.1436
Zabaikal'skii krai	788	0.100	0.249	0.276	0.342	0.1381	0.1682	0.2406
Ivanovo oblast	1513	0.031	0.052	0.068	0.099	0.0205	0.0372	0.0677
Ingushetia	1137	0.044	0.071	0.113	0.200	0.0262	0.0695	0.1565
Irkutsk oblast	8838	0.224	0.243	0.280	0.342	0.0194	0.0553	0.1185
Kabardino-Balkarian Republic	4800	0.039	0.072	0.120	0.204	0.0345	0.0789	0.1619
Kaliningrad oblast	2716	−0.023	0.126	0.147	0.195	0.1495	0.1706	0.2180
Kaluga oblast	3504	0.074	0.104	0.124	0.161	0.0293	0.0490	0.0862
Karachay-Cherkess Republic	2548	0.027	0.067	0.118	0.214	0.0417	0.0942	0.1942
Kemerovo oblast	14467	0.289	0.340	0.393	0.499	0.0466	0.1006	0.2086
Kirov oblast	10126	0.037	0.050	0.064	0.094	0.0129	0.0272	0.0571
Kostroma oblast	1171	0.029	0.048	0.062	0.089	0.0194	0.0335	0.0608
Krasnodar krai	44670	−0.025	0.028	0.071	0.156	0.0499	0.0925	0.1758
Krasnoyarsk krai	28250	0.277	0.302	0.350	0.445	0.0334	0.0787	0.1717
Kurgan oblast	8507	0.032	0.084	0.130	0.221	0.0502	0.0967	0.1868
Kursk oblast	25005	0.083	0.129	0.176	0.270	0.0450	0.0952	0.1897
Leningrad oblast	1165	0.029	0.069	0.082	0.118	0.0402	0.0532	0.0888
Lipetsk oblast	20811	0.067	0.119	0.169	0.269	0.0510	0.1016	0.2022
Moscow oblast	6213	0.082	0.100	0.118	0.153	0.0223	0.0410	0.0760
Nizhny Novgorod oblast	16776	0.066	0.092	0.119	0.174	0.0242	0.0514	0.1065
Novgorod oblast	768	0.066	0.072	0.086	0.113	0.0054	0.0176	0.0440
Novosibirsk oblast	42976	0.282	0.334	0.386	0.489	0.0493	0.1001	0.2022
Omsk oblast	39191	0.299	0.355	0.411	0.524	0.0530	0.1086	0.2219
Orenburg oblast	65225	0.033	0.059	0.095	0.169	0.0333	0.0724	0.1492
Orel oblast	21246	0.116	0.161	0.206	0.304	0.0463	0.0972	0.1998
Penza oblast	21750	0.030	0.077	0.120	0.211	0.0471	0.0898	0.1810
Perm krai	4689	0.053	0.081	0.097	0.125	0.0275	0.0444	0.0742
Primorskii krai	5266	−0.024	-0.004	0.040	0.134	0.0217	0.0623	0.1536
Pskov oblast	1242	0.078	0.080	0.097	0.133	0.0381	0.0468	0.0812
Republic of Adygea	2287	−0.037	0.023	0.083	0.206	0.0603	0.1208	0.2442
Altai Republic	155	0.228	0.272	0.321	0.422	0.0467	0.0900	0.1940

Table 3. (Contd.)

Subject of the Russian Federation	S, km^2	ASR				RSR		
		BAU	SSM1	SSM2	SSM3	SSM1	SSM2	SSM3
Republic of Bashkortostan	37198	0.057	0.100	0.133	0.211	0.0420	0.0808	0.1625
Republic of Buryatia	202	0.197	0.252	0.288	0.353	0.0519	0.0890	0.1579
Republic of Dagestan	1099	0.028	0.073	0.118	0.204	0.0475	0.0918	0.1772
Republic of Kalmykia	4312	−0.010	0.032	0.061	0.115	0.0395	0.0659	0.1222
Republic of Karelia	99	0.064	0.095	0.110	0.145	0.0308	0.0457	0.0814
Komi Republic	12	0.046	0.053	0.065	0.094	0.0071	0.0194	0.0488
Mari-El Republic	4771	0.043	0.056	0.072	0.104	0.0131	0.0295	0.0615
Republic of Mordovia	12305	0.050	0.093	0.127	0.197	0.0419	0.0750	0.1456
Republic of North Ossetia–Alania	2667	0.037	0.061	0.103	0.195	0.0261	0.0689	0.1520
Republic of Tatarstan	44208	0.072	0.104	0.131	0.186	0.0333	0.0600	0.1145
Republic of Tyva	7	0.132	0.164	0.192	0.260	0.0316	0.0601	0.1285
Republic of Khakassia	1064	0.270	0.260	0.306	0.403	0.0243	0.0443	0.1331
Rostov oblast	75229	−0.007	0.031	0.062	0.127	0.0368	0.0682	0.1327
Ryazan oblast	16674	0.079	0.119	0.157	0.235	0.0460	0.0930	0.1777
Samara oblast	35909	0.052	0.090	0.131	0.211	0.0375	0.0789	0.1592
Saratov oblast	60872	0.028	0.062	0.094	0.168	0.0343	0.0691	0.1373
Sakhalin oblast	18	0.087	0.097	0.148	0.241	0.0096	0.0612	0.1538
Sverdlovsk oblast	7019	0.041	0.082	0.115	0.181	0.0364	0.0622	0.1154
Smolensk oblast	3544	0.071	0.084	0.100	0.134	0.0131	0.0280	0.0614
Stavropol krai	47420	0.012	0.049	0.085	0.162	0.0368	0.0737	0.1501
Tambov oblast	26702	0.011	0.054	0.089	0.168	0.0452	0.0839	0.1642
Tver oblast	3185	0.104	0.102	0.116	0.144	0.0088	0.0145	0.0422
Tomsk oblast	3344	0.166	0.196	0.218	0.272	0.0308	0.0520	0.1076
Tula oblast	15753	0.143	0.198	0.252	0.359	0.0494	0.1035	0.2149
Tyumen oblast	8571	0.038	0.076	0.104	0.153	0.0379	0.0615	0.1119
Udmurt Republic	10023	0.052	0.079	0.097	0.134	0.0266	0.0449	0.0817
Ulyanovsk oblast	14896	0.069	0.114	0.160	0.250	0.0468	0.0924	0.1819
Khabarovsk krai	295	0.061	0.080	0.123	0.209	0.0268	0.0583	0.1485
Chelyabinsk oblast	18666	0.027	0.072	0.110	0.194	0.0447	0.0824	0.1660
Chechen Republic	1651	0.034	0.069	0.111	0.198	0.0327	0.0746	0.1605
Chuvash Republic	8702	0.061	0.081	0.102	0.148	0.0193	0.0412	0.0871
Yaroslavl oblast	2603	0.042	0.054	0.069	0.098	0.0146	0.0282	0.0557
Republic of Crimea	11833	−0.026	0.018	0.059	0.142	0.0463	0.0999	0.1887

Median was taken as the estimate of the mean; S, cropland area.

BAU scenario was used. The carbon input to soil was calculated according to the mean values of the yield over this period in the subjects of the Russian Federation with the crop rotation planned based on the cropland structure of the corresponding region and the areas under cereals and row crops. The adaptation scenarios were computed according to the regional economic model. One of the scenarios provided a constant soil organic carbon stock or its growth. The carbon input was calculated from the crop yields assessed using the Climate–Soil–Yield dynamic model taking into account the effect of climate change and optimization of mineral nutrition.

The maximum accumulation rate of soil organic carbon in the earlier work amounted up to 0.2 t/ha per year, to the greatest degree for the northwestern region of the Nonchernozem zone. This is considerably lower as compared with that estimated under the BAU sce-

Table 4. Summary mean absolute (SASR) and relative (SRSR) soil carbon sequestration rates in the croplands of the subjects of the Russian Federation under different sustainable soil management scenarios, Kt C/ha per year

Subject of the Russian Federation	SASR				SRSR		
	BAU	SSM1	SSM2	SSM3	SSM1	SSM2	SSM3
Altai krai	1915.8	2287.7	2663.2	3441.4	372.0	747.4	1525.6
Amur oblast	40.7	50.6	97.3	185.7	10.1	56.7	145.0
Arkhangelsk oblast	0.6	0.6	0.7	1.0	0.1	0.2	0.5
Astrakhan oblast	−1.6	6.7	12.1	22.8	8.3	13.7	24.4
Belgorod oblast	32.9	116.9	197.1	355.1	84.0	164.2	322.1
Bryansk oblast	53.7	92.6	114.3	158.0	38.9	60.6	104.3
Vladimir oblast	18.5	26.8	34.2	48.4	8.3	15.7	29.9
Volgograd oblast	69.3	233.7	384.1	689.2	164.4	314.8	619.9
Vologda oblast	9.6	8.6	10.2	13.2	0.2	0.7	3.6
Voronezh oblast	−2.1	172.3	331.2	654.3	174.4	333.3	656.4
Jewish autonomous oblast	4.6	5.8	10.2	19.6	1.3	5.6	15.0
Zabaikal'skii krai	8.4	19.4	21.8	27.3	11.1	13.4	18.9
Ivanovo oblast	5.1	8.3	10.7	15.6	3.2	5.7	10.5
Ingushetia	5.1	7.8	12.7	22.5	2.7	7.6	17.3
Irkutsk oblast	197.5	215.0	248.1	305.8	18.4	50.6	108.3
Kabardino-Balkarian Republic	14.6	34.2	57.0	101.9	19.7	42.4	87.3
Kaliningrad oblast	−5.7	36.1	42.5	56.6	41.9	48.3	62.3
Kaluga oblast	27.3	37.1	44.2	58.2	9.8	16.8	30.9
Karachay-Cherkess Republic	5.1	18.4	31.1	55.2	13.3	26.0	50.1
Kemerovo oblast	389.7	451.2	522.5	661.0	61.6	132.8	271.3
Kirov oblast	40.7	54.8	70.2	102.2	14.0	29.5	61.5
Kostroma oblast	3.4	5.9	7.5	10.9	2.4	4.1	7.5
Krasnodar krai	−104.3	122.3	331.5	735.6	226.6	435.8	840.0
Krasnoyarsk krai	760.7	852.0	991.0	1261.7	92.7	230.3	500.9
Kurgan oblast	33.3	73.8	108.5	177.8	40.5	75.1	144.5
Kursk oblast	206.6	317.5	431.0	649.3	110.9	224.4	442.7
Leningrad oblast	4.4	8.8	10.5	15.0	4.3	6.1	10.6
Lipetsk oblast	129.1	230.6	322.5	506.5	101.5	193.4	377.4
Moscow oblast	49.7	63.8	78.4	107.2	14.2	28.8	57.5
Nizhny Novgorod oblast	109.0	155.6	201.9	293.6	46.6	92.9	184.6
Novgorod oblast	5.3	5.6	6.6	8.7	0.4	1.3	3.4
Novosibirsk oblast	1057.1	1243.8	1435.6	1818.0	187.0	378.6	761.0
Omsk oblast	1095.5	1296.1	1498.4	1896.9	200.8	402.9	801.4
Orenburg oblast	216.4	437.3	672.3	1140.7	220.9	455.8	924.3
Orel oblast	246.0	345.6	436.3	616.2	99.6	190.3	370.2
Penza oblast	67.1	169.9	259.6	446.7	102.8	192.5	379.7
Perm krai	26.7	39.2	47.4	62.2	12.5	20.8	35.6
Primorskii krai	−11.9	-0.6	22.0	67.9	11.3	34.0	79.9
Pskov oblast	8.4	11.6	14.5	21.0	3.4	6.1	12.6
Republic of Adygea	−8.0	4.4	18.9	46.0	12.5	26.9	54.1
Altai Republic	3.3	4.1	4.8	6.3	0.7	1.4	2.9
Republic of Bashkortostan	205.8	365.8	504.6	787.9	160.1	298.8	582.1
Republic of Buryatia	3.9	5.0	5.7	7.1	1.0	1.8	3.2

Table 4. (Contd.)

Subject of the Russian Federation	SASR				SRSR		
	BAU	SSM1	SSM2	SSM3	SSM1	SSM2	SSM3
Republic of Dagestan	2.8	7.7	12.5	21.7	4.9	9.7	18.9
Republic of Kalmykia	−4.0	13.5	25.8	51.4	17.5	29.8	55.4
Republic of Karelia	0.7	1.0	1.2	1.5	0.3	0.5	0.9
Komi Republic	0.1	0.1	0.1	0.1	0.0	0.0	0.1
Mari El Republic	21.1	27.4	35.1	50.6	6.4	14.0	29.5
Republic of Mordovia	61.2	110.4	148.4	227.6	49.2	87.2	166.4
Republic of North Ossetia–Alania	7.9	14.7	26.8	50.3	7.0	18.9	42.4
Republic of Tatarstan	314.4	475.8	621.4	905.6	161.4	307.0	591.2
Republic of Tuva	0.1	0.1	0.1	0.2	0.0	0.0	0.1
Republic of Khakassia	26.4	27.2	31.8	40.8	1.3	5.3	14.4
Rostov oblast	−40.7	234.9	466.6	941.0	275.5	507.3	981.7
Ryazan oblast	135.2	206.3	275.0	410.7	71.2	139.8	275.6
Samara oblast	187.2	325.0	462.0	730.4	137.8	274.8	543.2
Saratov oblast	164.5	375.3	577.7	984.0	210.8	413.2	819.5
Sakhalin oblast	0.2	0.2	0.3	0.4	0.0	0.1	0.3
Sverdlovsk oblast	35.6	61.7	81.6	121.2	26.0	45.9	85.6
Smolensk oblast	28.6	33.0	39.5	52.6	4.6	10.9	24.0
Stavropol krai	59.8	232.7	407.2	757.3	172.9	347.4	697.5
Tambov oblast	34.5	148.0	240.0	431.9	113.5	205.5	397.4
Tver oblast	31.4	32.1	36.6	45.2	1.3	5.1	13.8
Tomsk oblast	57.9	64.8	73.7	92.3	7.1	15.9	34.4
Tula oblast	219.6	298.8	375.8	527.0	79.2	156.1	307.4
Tyumen oblast	36.4	68.2	92.4	140.8	31.8	56.1	104.5
Udmurt Republic	57.1	82.0	101.8	141.0	24.9	44.7	83.9
Ulyanovsk oblast	99.6	164.0	226.0	349.0	64.4	126.4	249.4
Khabarovsk krai	2.0	2.2	3.6	6.4	0.5	1.5	4.3
Chelyabinsk oblast	49.4	129.5	200.0	350.8	80.1	150.6	301.4
Chechen Republic	5.2	11.0	18.0	31.9	5.8	12.8	26.7
Chuvash Republic	56.2	78.5	100.8	145.5	22.2	44.5	89.2
Yaroslavl oblast	13.3	17.0	21.4	29.6	3.8	8.1	16.3
Republic of Crimea	−67.9	24.4	75.2	175.3	92.3	143.1	243.1

nario and agrees with the predictions for the SSM3 scenario. Nonetheless, a loss in organic carbon under the BAU scenario is predicted either for chernozem zone, or for the light chestnut and brown semidesert soils zone. Similar to this study, it was possible either to maintain the initial carbon stock, or to provide its small increase for many areas despite a potential increase in yields under future climate of even in the case of BAU scenario implementation.

RSR, i.e., relative sequestration, in the case of implementation of the SSM scenarios as compared with BAU one is also comparable to the computed carbon accumulation by 0.8–7.0 t/ha to 2070, reported in the earlier study in the case of adaptation scenario as compared with BAU. As is evident from Fig. 3, RSR for most contours does not exceed 0.05 t C/ha per year under the SSM1 scenario, which can be undetectable in actual crop rotations because of the year-to-year variation in the soil organic carbon content with changes in cultivated crops and the corresponding changes in carbon input.

Another cause of the discrepancies of our current results and earlier modeling is the nonequilibrium of

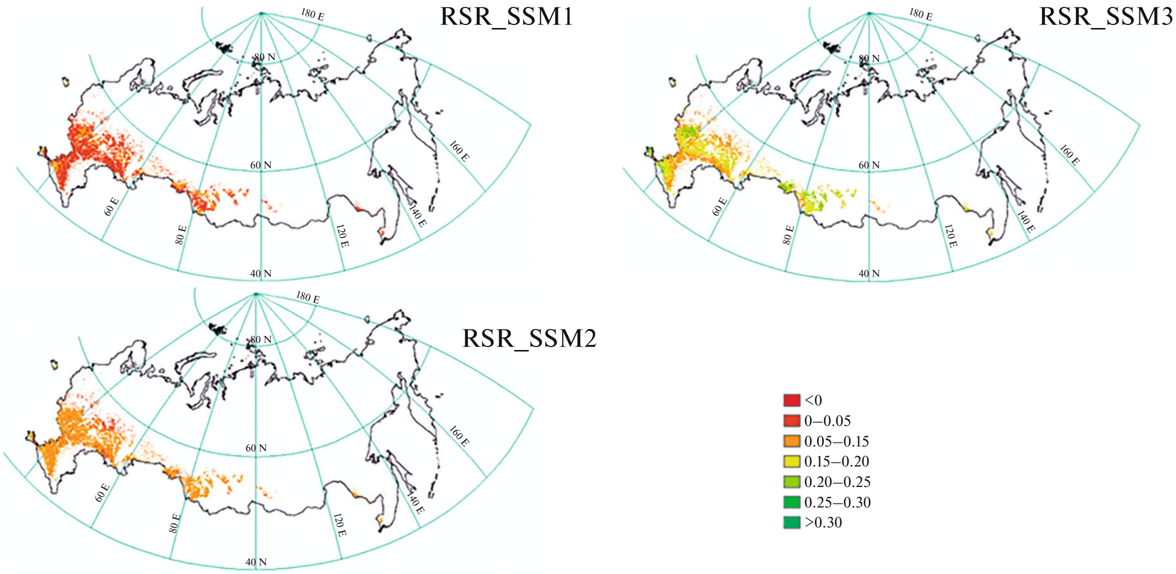

Fig. 3. Relative soil carbon sequestration rate (RSR) under three sustainable soil management (SSM1–SSM3) scenarios implying an increase in the organic matter input to soil by 5, 10, and 20%, respectively.

organic carbon stock over 20 years. The earlier computations demonstrated that the equilibrium could well be unattainable even after a 70-year modeling period [5]. This is associated with that the carbon sequestration is effectively provided only in some areas even within the same region, whereas the losses in the neighboring areas merely decrease.

CONCLUSIONS

The agriculture in Russia has a high potential for decreasing the greenhouse gas emissions on national and global levels. According to the FAO data, Russian soils contain almost 20% of the global soil organic carbon stock (133 Gt C in the top 30 cm versus 680 Gt in the world). The current soil organic carbon ASR and RSR in arable soils in all natural soil ecological zones and subzones (except for one) and on a national scale are weakly positive. The calculations for implementation of the agricultural practices which increase carbon input to soils demonstrate that the maximum soil carbon sequestration potential of arable soils in Russia is 25.5 Mt/year. Russia is the fifth in the list according to this value after Brazil, China, United States, and India.

It is reasonable to regard our maps of organic carbon sequestration potential as estimation maps until the repeated measurements with the more accurate input data on climate, soil, and vegetation cover, which is a global priority in the soil carbon change monitoring. Taking into account the limitations, our results, and the applied methods are useful as the initial steps in assessing the soil carbon sequestration potential on a regional scale and determining the practices for mitigating climate change along with estimating the carbon fluxes from arable soils for reconciling with greenhouse gas inventory. This approach is reproducible and improvable with the new initial and detailed country- and region-specific data as well as the model parameters for better prediction accuracy of soil carbon content and a decrease in the prediction uncertainty. Only preliminary data have been obtained so far. The computations of sequestration potential of Russian soils are in progress to refine it and assess the uncertainties under all the four scenarios.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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