SOIL ORGANIC CARBON POOLS ESTIMATION BASED ON DIGITAL MAP OF ORGANIC CARBON STOCK IN 30-CM SOIL LAYER OF RUSSIA

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ABSTRACT:

Digital map of organic carbon stock in 30-cm soil layer of Russia was created for GSOC-17 GSP FAO project. Our objective was developing and testing algorithms for soil organic carbon (SOC) mapping on the basis of information accumulated in the Information System “Soil-Geographic Database of Russia”, i.e. vectorized different-scale soil maps, analytical characteristics of reference profiles and attribute data of the regular monitoring surveys. The calculation of main SOC map have performed in the form of synthesis of two types of source data: a map of the entire territory of the Russian Federation based on the Soil Map of RSFSR (ed. V.M. Fridland, 1988) at the scale of 1:2.5 M combined with sparse and irregular grid of about 2000 soil profiles and maps of separate agricultural areas based on the large- and medium-scale soil maps and a dense grid of regular soil observations. Both maps were merged in one grid. The SOC map for litter is calculated on the base of previously published map adapted to the GSOC17 requirements. The SOC map for duff and peaty litter horizons of semi-hydromorphic soils was calculated by using the averaged expert estimations of bulk density values. The final version of the SOC map of Russia is a per pixel sum of above maps. Our calculations indicate that the total carbon stock in 30-cm soil layer of Russia is about 150 Pg, and nearly half of these stocks (45%) are concentrated in organogenic horizons.

1. INTRODUCTION

Soils play a key role in the biogeochemical cycle of carbon. Carbon reserves in soil are almost three times as much as those in vegetation and twice as much as those in the atmosphere (Batjes, 1996; Smith, 2008; Zdruli et al., 2017). Tentative estimates of the carbon stock in the 1-meter soil layer of the Earth range from 1061 to 1576 Pg, i.e. may differ by 1.5 times (Milne et al., 2007). Russia's share in the global soil carbon stock is about 20% (Kurganova et al., 2014). By increasing the quality of the estimates of total organic carbon stock and shares of various carbon pools and their dynamics, we may significantly contribute to research and prediction of climate change, prevention of desertification and development of regional and even continental level strategies for sustainable development.

The Food and Agriculture Organization of the United Nations (FAO) established the Global Soil Partnership project (GSOC17) to refine the estimates of soil carbon stock. The specific goal of the project was to develop a Global Soil Organic Carbon Map for a depth of 0-30 cm. Within the frameworks of this project a map of Russia was produced that shows the soil organic carbon stock within a 0-30-cm soil layer. It is not possible to compile a map based on the FAO Guidelines (Brus et al., 2017) for such a country as Russia, with huge area and extremely diverse natural conditions, without joint efforts of many academic and applied research organizations. All organizations, which took part in the project, are listed at the FAO web site (http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data/global-soil-organic-carbon-gsoc-map/gsocmap-contributors/en/).

There are several assessments of carbon content, stock and balance in various natural components of Northern Eurasia, some of which are available as cartographic material. The geographic analysis was as a rule conducted for large nature formations with natural borders, including basic vegetation types, zonal and intrazonal vegetation formations of each thermic belt, ecosystem types, soil types and natural and agricultural zones, and soil complexes, taking into account diversity of parent material etc. (Rodin et al., 1965; Bazilevich, 1993; Bazilevich et al., 1986; Isaev et al.,1993; Kolchugina et al., 1994; Orlov, 1994; Kudeyarov et al., 1996; Tishkov et al., 1995; Orlov et al., 1996; Rozhkov et al., 1997; Full Carbon Account…, 2000; Cherkinsky et al., without date). In addition, the results were calculated and mapped for a geographic grid of 1-by-1 degree trapezoids. Within the latter, depending on the biomes, different calculation methods were applied (Moiseev et al., 2002; Moiseev et al., 2007).

The soil carbon stock in the 0-100-cm soil layer of Russia is estimated in a number of publications using various averaging and extrapolation methods. These estimates differ by 10-30% (285–364 Gt), despite being based on almost the same original data. This is due to the fact that there are limited number reference soil profiles that have complete data sets, including bulk density values for horizons (Kudeyarov et al., 2007; Orlov et al., 1996; Rozhkov et al., 1997; Schepaschenko et al., 2013; Stolbovoi, 2002; Budiman et al., 2017, etc.).

The main goals of the study were:

- to develop and test algorithms for mapping soil organic carbon stock based on information accumulated in the *Information System «Soil-Geographical Database of Russia» (IS SGDR);* and
- to estimate proportions of basic organic carbon pools of the 0-30-cm soil layer of Russia territory.

2. MATERIAL AND METHODS

2.1 General principles of mapping

In accordance with the FAO guidlines, the following characteristics of original data are used in calculations:

a) organic carbon content in the 0-30-cm soil layer, % (for a soil profile or polygon of soil map);
b) bulk density of horizons in natural condition, g/cm^3 (for a soil profile or polygon of soil map); and
c) stone content, % or grades (for a soil profile or polygon of soil map).

The maps were proposed to compile using $^{1}/_{120}$ angular degree grid (approximately 1x1 km); the same format was proposed to use for an error map – to assess calculation errors of the basic map (Brus et al., 2017).

The research is conducted using IS SGDR. This system permits to exchange with diverse soil data within a distributed network of soil data processing centers and to use various types of information: vector maps of different scales, analytic characteristics of soil profiles, results of regular monitoring etc. The carbon stock map is compiled by synthesizing several types of original data:

a. Soil maps of the Russian Federation compiled using the Soil Map of RSFSR at scale 1:2.5M (1988) (at present this is a soil map with the largest scale available for the whole country compiled using the unified approach and legend) combined with a sparse irregular grid consisting of about 2000 soil profiles. In our calculations 25000 soil map polygons were used; the map legend has more than 300 units. The carbon stock for each polygon of the Soil Map of RSFSR was calculated considering only the type of the main soil, associated soils were disregarded;

b. More detailed maps were compiled for several agricultural districts – two administrative regions located in European Russia – using medium and large scale soil maps and data of dense regular grid of agrochemical soil observations. For these areas, data of recent soil research (dated 2012-2016), as well as archive data (since the 1970s) were used. In total, more than 150 000 point data (dated 2012-2016) and more than 15000 map polygons were used.

The maps **a)** and **b)** are combined in one soil organic carbon layer by calculating values for the grid whose cell size was specified for each map and then by superimposing more detailed **b)** maps over the **a)** map.

c. The map of forest floor carbon stock was prepared and adapted to FAO requirements by D.G. Shchepashchenko based on an earlier publication (Schepaschenko et al., 2013);

d. The map of carbon stock in organogenic horizons of semihydromorphic soils.
The map of Russia was included in the global map GSOC17 as a sum of all aforementioned layers (**a+b+c+d**). An error map was also produced for the united layer (a+b).

2.2 Original data for calculating organic carbon stock in soils

As mentioned above, when compiling the basic map layer (**a**), soil carbon stock is estimated using information from IS SGDR. We also had information on about 2000 soil profiles, some of which lack bulk density data of horizons. In order to ensure more comprehensive use of the data accumulated in IS SGDB, additional research was conducted. As a result the bulk density of mineral soil horizons was estimated using an equation proposed by O.G. Chestnykh and D.G. Zamolodchikov (2004), which permits to predict the bulk density of soil horizons depending on humus content and horizon's depth:

$$BW = a_1 - a_2/(MID+a_3) + a_4/(HUM+a_5),$$

where BW – bulk density, g/cm^3
MID – average depth of horizon, cm
HUM – humus, %

Calculation for soil groups, which we provisionally called *Taiga*, *Meadow* and *Steppe*, were made using equation parameters listed in Table 1.

Soils	a_1	a_2	a_3	a_4	a_5
Taiga	0.252	9.110	9.939	110.999	78.805
Meadow	1.413	27.045	33.905	2.390	5.449
Steppe	1.451	13.137	20.414	0.012	-0.177

Table 1. Equation parameters

Carbon stock in peat soils (Histosols) of bogs was assessed using the ash content and bulk density of relevant peat varieties published in reviews (Table 2) (Carbon in Forest and Bog Ecosystems of Russia, 1994; Vomperskiy et al., 1994; Inisheva et al., 2012).
A separate layer of organic carbon stock in duff and peaty horizons of semihydromorphic soils was produced. The lack of empirical data described these horizons did not permit correct assessment of their variability. Therefore, this layer was not considered in the error map.

Characteristics	High-moor bogs	Transitional bogs	Low-moor bogs
Ash content, %	3.5	7.5	20
Carbon content in organic matter, %	55.5	56.0	55.3
Bulk density, g/cm^3	0.07	0.09	0.13

Table 2. Characteristics using for calculating SOC stock of Histosols

2.3 Compilation of large scale maps of carbon stock in agricultural regions

For two regions of the chernozem zone in European Russia (Rostov and Belgorod regions), where soils were historically strongly transformed by agricultural practices, maps were compiled using a regular 30 angular minute grid. This was implemented on the base of results of online assessment of humus reserves calculated on digital medium and large scale soil maps, analytic characteristics of reference soil profiles and data of regular agrochemical research.

Several calculation methods for mapping were tested: using of archive large and medium scale maps and data of analytic research of reference soil profiles; using agrochemical monitoring data and expert assessments of soil bulk density; using agrochemical monitoring data and soil bulk density calculated via pedotrasnsfer functions (PTF). The final regional maps are generated up-to-date carbon stock maps of agricultural lands superimposed on a small scale map.

2.4 Error mapping

Since the map of soil carbon stock was compiled using different approaches and methods, different approaches were employed for mapping errors. For the most of Russia territory, the relative error of carbon stock in layers beneath the forest floor is estimated for each legend unit. In this case, the error was estimated as the quotient from dividing the standard deviation by the mean, assuming the normal distribution. For some legend units, the relative error of the estimate sometimes exceeds 200%. In areas with high density of observation, a regression equation was used to calculate the bulk density. In this case, the relative error of carbon stock estimates is around 25%.

3. RESULTS AND DISCUSSION

3.1 Calculation of the bulk density of soil horizons

Some authors (Stolbovoi, 2002; Xu et al., 2015) speculated that one of the reasons why the estimates of soil carbon pools have low accuracy is the lack of the data on soil bulk density. In order to solve this problem, a number of methods were proposed to fill this gap. Quite often for this purpose researchers apply employ pedotransfer functions that permit to calculate the value of bulk density using other soil characteristics that are available. PTF are empiric and thus have a limited field of application. Everyone should be especially careful when using them under conditions significantly different from those under which they were obtained. Therefore, it is quite challenging to select PTF that would permit for the least error in determining soil bulk density for a specific region (Jalabert et al., 2010; Benites et al., 2007; Boschi et al., 2018, etc.).

The preliminary analysis of applicability of PTF proposed by various authors (Hollis et al., 2012; Manrique et al., 1991; Chestnykh et al., 2004) for calculating bulk density of soil horizons was conducted. It showed that the least error was obtained when a five-parameter nonlinear function proposed by O.G. Chestnykh and D.G. Zamolodchikov (2004) was used. The function reflects the dependence of bulk density on humus content and depth at the middle of horizon range, with equation parameters specific for various groups of soils. The authors proposed to use different equation parameters for five groups of soils. Since the method for soil grouping was not specified in the work, we used a set of soil profiles included in IS SGDB and tested the applicability of these parameters for different groups of genetically similar soils.

Our calculations showed that for soils, that were provisionally grouped as *Taiga* (Table 3), the values of bulk density calculated by the aforementioned equation with applying parameters for *Taiga* soils quite well matched the experimental values. The data were tested for 301 horizons from 61 soil profiles. The average relative error was around 15%. While for organic horizons (with organic matter content more than 15% by weight) the relative error reaches 95% (it ranges from 3.4 to 410.8%), the relative error is significantly lower in mineral horizons (8.6%) (it ranges from 0.01 to 50.1%) (Figs. 1 and 2). The test showed that the same algorithm could be also used when calculating the bulk density of mineral horizons of other soils that provisionally were included in the group of *Taiga* soils (Table 4).

Soil Map of the RSFSR legend	WRB
Iron-illuvial podzols, soddy podzols	Albic Umbric Podzols; Albic/ Dystric Retisols
Podzolic soils	Albic Retisols
Soddy-podzolic soils	Albic/ Dystric Retisols
Gley podzols, gleyed soddy-podzolic soils, peat and peat-podzolic gley soils, soddy gley soils, and mucky gley soils	Histic Gleyic Podzols; Gleyic/Stagnic Retisols; Gleysols
Light gray forest soils, gray forest soils, dark gray forest soils	Albic Luvisols; Luvisols; Luvic Phaeozems; Greyzemic Luvic Phaeozems

Table 3. Soils in group « *Taiga*» soils according to the Soil Map of the RSFSR legend and approximate analogue in the WRB

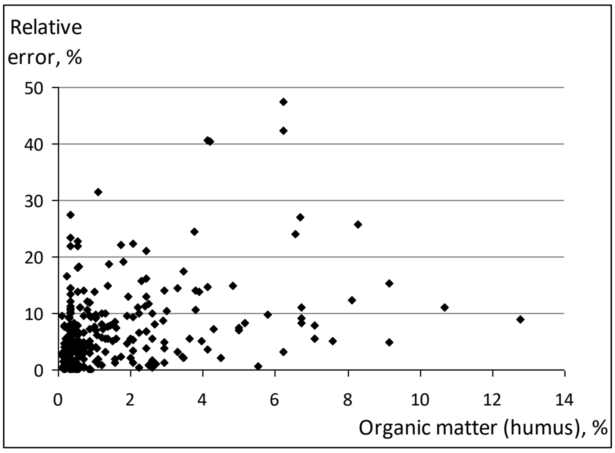

Figure 1. Relative errors of mineral horizons soil bulk density obtained using «podzolic soils » equation parameters

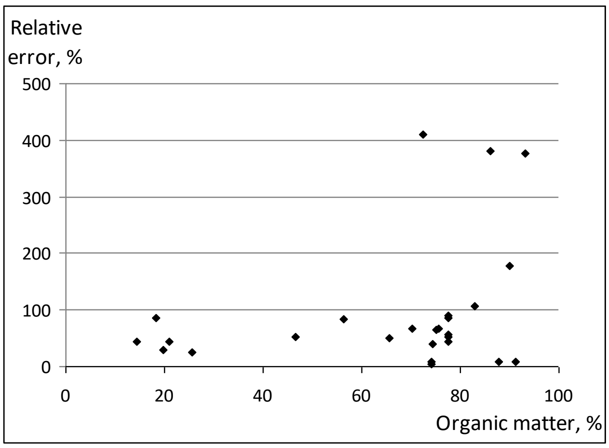

Figure 2. Relative errors of organogenic horizons soil bulk density obtained using «podzolic soils» equation parameters

Since it is generally unknown, whether a data set used to develop the equation overlaps with the SGDB set, which we used to test the applicability of PTF, or not, the latter was also tested on a data set that is known to be independent. This set consists of soddy-podzolic, mainly slightly gleyic and gleyic soils and of mineral horizons of several peat soils (Histosols), whose organogenic horizons were not present in the set. The humus content in all considered horizons was less than 6.8%. In total 125 horizons from 31 soil profiles were analyzed. The average relative error for determining the bulk density of these soils was 7.5%.

Soils	Average relative errors, %			N
	Horizons			
	All	Organogenic	Mineral	
Equation parameters «*Taiga*» soils				
Retisols, Luvisols	15.0	94.7	8.6	301
Podzols	24.5	80.7	10.5	55
Cambisols	23.2	113.4	12.3	37
Entic Podzols	87.8	315.2	13.2	77
Equation parameters «*Steppe*» soils				
Chernozems, Kastanozems	9.2			427
Equation parameters «*Meadow*» soils				
Phaeozems, Fluvisols	23.8		14.7	102

Table 4. Average relative errors of soil bulk density obtained using different equation parameters

The similar algorithm was applied to a big group of humus-rich soils, that included all variants of Chernozems and Kastanozems. Relative errors for all data set (450 horizons) vary from 0.02 to 54.4%, with the average relative error is 9.2% (Table 4). The applicability of the equation and coefficients was also tested for soils of this group using the independent data set – 307 horizons of 111 soil profiles of Rostov region soils, including different chernozems, meadow chernozems, meadow soils and alluvial soils. The average relative error is 7.6%.

Somewhat worse results were obtained for a group, which unites meadow floodplain soils (Phaeozems and Fluvisols) (Table 4). Therefore, it was shown that for mineral horizons of soils provisionally united in the group of *Taiga* and *Meadow* soils, as well as for all horizons of *Steppe* soils, calculation of the bulk density of horizons by the indicated formula using equation parameters specific for the given soil group produces satisfactory results.

3.2 Map compilation

When compiling a SOC map based on Soil Map of RSFSR (1988), the organic carbon stock in mineral horizons of soils considered above was calculated using the bulk density of horizons obtained by the analyzed equation (in case of the absence of direct measurements). For other mineral soils, bulk density was obtained using statistically averaged rare empirical data or expert estimates. Carbon stock in peat soils (*Histosols*) of bogs was estimated using ash content, bulk density and carbon richness of relevant peat (Table 2). Then organic carbon stock was calculated to a depth of 30 cm for each soil profile and then these stocks were averaged for each legend unit.

In soil complexes, the carbon stock was calculated proportionally to the number of soil units included in the complex. For complexes that included two soil units, the share of the former was taken as 60%, while the latter, as 40%. In three-unit complexes, the share of components was assumed equal to 34, 33 and 33%, respectively. When considering soil complexes with the presence of frost cracks, the share of crack was taken as 25% based on the size of polygons and cracks as cited in different sources (Boch, 1974; Karavaeva, 1969).

When compiling medium- and large-scale maps of agricultural regions (Rostov and Belgorod regions), several approaches were tested that used various volumes of original information and different calculation algorithms. At the first stage, the mapping was made using a traditional expert approach based on vector medium- and large-scale maps, characteristics of reference soil profiles and generalized information about humus stock from reports of soil surveys conducted by agricultural organizations. It was assumed that several specific soil profiles were representative for a relevant mapping unit within the study area. Maps compiled using a regular 30'-grid reflect the results of online estimation of humus stock based on dense grid of humus content data collected during agrochemical monitoring and then statistically averaged, expert's or calculated (using different methods) values of soil bulk density without considering cartographic material. Different variants of mapping were tested: with averaging data over all years of observation, with neighbors averaging using variable radius, with calculation based on PTF. Analytic soil data of reference soil profiles were used for verification of obtained maps.

Thus, based on all dataset of available information, both archive and recent, up-to-date maps of soil carbon stock on agricultural lands of Rostov and Belgorod regions were compiled. These maps were superimposed on a general small-scale map.

3.3 Ratio between carbon pools

All vector and raster map layers presented in ArcGIS v.10.1 project are accessible by link: https://drive.google.com/open?id=1QilNuRzjiHjZLCrxRBv9FeJnqJ3N46Z-

The final basic map layer of Russia shows the organic carbon stock in the 0-30-cm layer of mineral horizons of all soils and of peat sols of bogs (Histosols). The total stock of organic carbon in this layer is estimated as 115 Gt, including 84 Gt in mineral horizons and 31 Gt in the 0-30-cm peat layer (Table 5).

Soil organic carbon	Pg	%	
		Total	Organogenic horizons
Total	151	100	
Mineral horizons	84	56	
Organogenic horizons, including	67	44	
Histosols	31	20	46
Duff and peaty litter horizons of semi-hydromorphic soils	21	14	31
Litter	15	10	22

Table 5. Organic carbon pools structure in 30-cm soil layer of Russia

Carbon stock in forest litter of Russia ranges from 0 to 36 t/ha. The maximum values are found for old-growth coniferous forest, often in poorly drained soils. The total organic carbon stock in forest litter of Russia is estimated as 15 Gt (Table 5).

The situation is more complicated with estimates of the carbon stock in duff and peaty horizons of semihydromorphic soils. The data in available publications are quite variable: the organic matter content may reach 90%, while the bulk density may vary from 0.4 to 1.1 g/cm^3. Therefore, a separate layer of the carbon stock in duff and peaty horizons of semihydromorphic soils was developed using statistically averaged data and expert data of carbon stock, without any calculations based on organic carbon content and bulk density of horizons. It is likely that carbon stock estimates in the layer are characterized by maximum uncertainty among all considered pools. According to our calculations, the total carbon stock in duff and peaty horizons of semihydromorphic soils of Russia is about 21.0 Gt (Table 5).

The final map of soil organic carbon stock represents a sum of all described layers. According to this map, the organic carbon stock in the 0-30-cm soil layer of soils of Russia varies from 0 to 330 t/ha, the overall organic carbon stock is about 150 Gt.

4. CONCLUSIONS

While compiling a map of organic carbon stock in the 0-30-cm soil layer of the Russian Federation, algorithms were developed permitting to use data from multiple sources, having different spatial scale and spatially and attributively sparse but which mutually complement each other with varying reliability.

The availability of big data sets (dense grid of observations) permitted to calculate statistically significant coefficients of pedotransfer functions as well as to estimate spatially the calculation error. Technical solutions on organization of calculation based on distributed (in the internet) network of data centers will enable online calculation, including timely update of the results in case of obtaining new information or refining of the existing one.

According to our estimates, the overall organic carbon stock in the 0-30-cm layer of soils of Russia is about 150 Gt. Almost half of this stock is within organogenic horizons (44%). Therefore, 44% of overall soil organic carbon is represented by organic substances, which are unfixed or poorly fixed to soils mineral components. The most decomposable pool – forest litter – could make up to 10% of the overall carbon pool, i.e. being just slightly less of a quarter of the carbon pool of organogenic horizons (Table 5). About 20% of the total soil carbon stock (almost half of the pool of organogenic horizons) concentrates in the 0-30-cm peat layer, while about 14% (31% of carbon stock in organogenic horizons), in peaty and duff horizons of semihydromorphic soils. So, most deal of carbon stock of organogenic horizons is concentrates in wetland soils.

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