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To cite this article: O V Chernova *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **438** 012005

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Historical trends in the amount and structure of organic carbon stocks in natural and managed ecosystems in European Russia

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Abstract. Contemporary (corresponding to the modern state of ecosystems and land use) and prehistoric (for hypothetical intact natural ecosystems similar to modern virgin ecosystems) stocks of organic carbon were assessed for model regions of southern taiga, forest-steppe and steppe in European Russia. The comparison of these stocks enabled an assessment of the integral result of the multidirectional changes in land use that occurred in the studied regions over the historical period. The carbon stocks were determined using a unified cartographic basis, data on taxonomy and texture of soil units, modern land use types and the type and age structure of reconstructed and contemporary vegetation. The results obtained indicate that the modern carbon pool has reduced by 24% compared to the potential prehistoric one in the Kostroma Region and Rostov Region (southern taiga and steppe zones, respectively) and by 37% in the Kursk Region (forest-steppe zone). It was also demonstrated that the contribution of soil to the total organic carbon stock increases southwards, from southern taiga to dry steppe, from 51 to 95% during the prehistoric period and from 62 to 96% currently. The study results show that forestry and agriculture increase the contribution of soil to maintaining the region's carbon budget.

1. Introduction

Up to the present time, human activity has transformed 30-50% of Earth's natural ecosystems by various land use practices (agriculture, forestry, industrialization, urbanization, etc.) [1], which strongly affect the biogeochemical cycle of carbon [2]. The majority of organic carbon stocks of terrestrial ecosystems are accumulated within plant biomass (living and dead) and soils (including mineral horizons, forest litter and peat). The ratio of these two large pools is an important characteristic of the biological cycle that can be used to track changes in element cycling.

Assessments of the impact of land use on carbon stocks in soils and plant biomass are typically carried out for a single type of impact (farming on virgin soils, natural successions on abandoned fields, timber harvesting, tree planting, etc.) [3-6]. Global biospheric problems, such as climate change, have given rise to multiple studies focused on assessing carbon stocks of large pools (soils and vegetation) of continents and the Earth as a whole [7-9]. In most regions, land use systems changed in different directions many times over the historical period. There are a number of recently published historical reconstructions, where changes in the biochemical carbon cycle resulting from human impact have been analyzed. The accuracy of such assessments depends on the methods used as well as



the volume and reliability of the original experimental data [10-14]. Subnational (regional) assessments have their specific characteristics because of different systems of natural resource management resulting from a long history of development and implementation. Therefore, careful consideration of a specific region's natural and socioeconomic peculiarities is required.

Due to a lack of reliable data from most regions of Russia, there are only a few regional-scale studies on historical aspects of changes in carbon stocks. For example, changes in carbon cycle parameters over 150 years of land use in Siberia have been analyzed [15-17]. Long-term dynamics of soil carbon stocks under various traditional agricultural and forestry management systems in European Russia have also been assessed [18]. In our previous studies, changes in the organic carbon stocks within the regions of southern taiga and forest-steppe of European Russia over the historical period have already been estimated [19]. In the present study, similar calculations were performed for steppe regions.

The aim of this study was to determine trends of human-induced changes in the sizes and relative proportions of different organic carbon pools in southern taiga, forest-steppe and steppe regions of European Russia.

2. Materials

Administrative regions located in European Russia and characterized by different soil cover, land use types and climatic characteristics, which were chosen as “model regions” representative of different natural zones, were as follows: Kostroma Region (southern taiga), Kursk Region (forest-steppe) and Rostov Region (steppe).

Natural ecosystems of the Kostroma Region are formed under a moderately continental climate, with a mean annual air temperature from +1.5 to +3.0°C and precipitation exceeding evaporation (with the precipitation-evaporation ratio of 1.16). In the past, this southern taiga region was almost totally covered by spruce, spruce-pine and pine forests and characterized by a relatively low degree of agricultural development. Over recent decades, the proportion of farmed lands has decreased from 11.3% (in 1985) to 3.5% (in 2017). At present, 75% of the region's area are covered by forests, some of which are actively managed (table 1). The soil cover is dominated by soddy-podzolic soils (62.9% of the total area, with the exclusion of open water areas) and soddy-podzols (13.4%).

Table 1. Land use structure of the model regions (data from January 1, 2018).

Land types	Area, thou. ha	%, of area without open water
Kostroma Region		
Total area	6021.1	
without open water areas	5924.1	
Agricultural lands	994.6	16.8
including		
- arable	205.0	3.5
- hayfields and pastures	308.4	5.2
- ex-arable lands	481.2	8.1
Forest lands	4574.1	77.2
including		
- covered by forest except swamps	3986.1	67.3
- swamps	246.2	4.2
Forests not included in the category of forest lands	98.9	1.7
Peatbogs	247.8	4.2

Lands with disturbed vegetation and partly disturbed soils (urban lands, burnt areas, dead vegetation and tree harvest areas)	237.5	4.0
Land without soils (roads, dump sites, bare sands, gullies and disturbed lands)	112.9	1.9
Kursk Region		
Total area	2999.7	
without open water areas	2961.4	
Agricultural lands	2437.9	82.3
including		
- arable	1741.8	58.8
- hayfields and pastures	493.8	16.7
- perennial crops		
- ex-arable lands	202.3	6.8
Forest lands	249.3	8.4
including		
- covered by forests	234.6	7.9
Peatbogs	32.1	1.1
Forests not included in the category of forest lands	68.1	2.3
Lands with disturbed vegetation and partly disturbed soils (urban lands, burnt areas, dead vegetation and tree harvest areas)	87.1	2.9
Land without soils (roads, dump sites, bare sands, gullies and disturbed lands)	101.6	3.4
Rostov Region		
Total area	10096.7	
without open water areas	9750.6	
Agricultural lands	8513.1	87.3
including		
- arable	4887.6	50.1
- fallow crops	1019.7	10.5
- hayfields and pastures	2605.8	26.7
- perennial crops		
Forest lands	293.0	3.0
including		
- covered by forests	220.2	2.3
Bogs	54.9	0.6
Forests not included in the category of forest lands	281.9	2.9
Lands with disturbed vegetation and partly disturbed soils (urban lands, burnt areas, dead vegetation and tree harvest areas)	230.2	2.4
Land without soils (roads, dump sites, bare sands, gullies and disturbed lands)	456.8	4.7

The Kursk Region located in the forest-steppe zone is characterized by a moderately continental climate with a mean annual temperature of +5.4 °C and the aridity index of 1.00. The region has been significantly modified by humans: 82% of its area is occupied by agricultural lands including 59% of arable lands (table 1). Natural vegetation was originally represented by broadleaved forests and

meadow steppes, which have been almost completely destroyed. Forests including shelterbelts occupy only 10% of the area. Soils are represented by podzolized, leached and typical chernozems (66.8%) and gray forest soils (22.7%).

The Rostov Region, the largest of the considered regions, is characterized by moderately continental climate with mild winters and hot summers, with the degree of continentality increasing from the northwest to the southeast. Rostov-on-Don city (the regional center) has a mean annual temperature of +9.9 °C. The climate is dry with the precipitation-evaporation ratio from 0.7 to 1.0. The Rostov region, where agricultural lands make up 87% of the area, is almost totally changed by human activity. Woodlands cover only 5% of the region (table 1). Soils are represented by common and southern chernozems with specific calcareous pedofeatures (66.3%), chestnut soils including slightly alkaline varieties (13.2%) and Solonetz complexes (8.8%) in the southeast.

3. Methods

An assessment of the historical trends of changes in organic carbon stocks and their structure within each region was based on comparison between actual values (corresponding to the current state of ecosystems and land use structure in the region) and potential values (reconstructed on the basis of the assumption that in the prehistoric period the entire territory of the region was occupied by ecosystems similar to modern natural ones). Differences between such values characterized the impact of the land use within the region.

Potential prehistoric and contemporary carbon stocks in phytomass and in a 0-100-cm soil layer (including forest litter and peat) were estimated using similar approaches and the unified cartographic basis. Prehistoric ecosystems within the model regions were reconstructed on the basis of the concept of potential or reconstructed vegetation, which is widely used in geobotanica and describes the condition of mature plant associations in the absence of human impact [20]. Basic data layers were taken from the Soil Map of the RSFSR (the former Russian Soviet Federative Socialist Republic), scale 1:2500000 [21] and combined with the layers of dominant vegetation from the Vegetation Map of the Soviet Union, scale 1:4000000 [22]. The resulting polygons were characterized by the predominant soil of a certain taxonomic position and textural class and the type of plant association. Polygons with similar characteristics were combined into mapping groups to compile schematic maps of reconstructed soil-vegetation cover. Overall, we separated 12 map units for the Kostroma Region (figure 1), 9 – for the Kursk Region (figure 2) and 14 – for the Rostov Region (figure 3). For each map unit, potential prehistoric organic carbon stocks were assessed in a 0-100 cm soil layer, forest litter (steppe litter) and biomass of natural vegetation.

Contemporary organic carbon pools were calculated on the basis of actual characteristics of soils and vegetation and land use types including arable lands, hayfields and pastures, recently (20-25 years ago) abandoned lands, forests (woodlands), peatbogs, urban areas and roads. The data sources, their processing algorithms and methods for calculating reconstructed and contemporary organic carbon stocks in soils and ecosystems are described in detail in our earlier publications [19, 23].

4. Results

4.1. Carbon pools of reconstructed ecosystems

In natural automorphic ecosystems of the southern taiga, organic carbon stocks in plant biomass and a 100-cm soil layer varied from 16 to 19 kg C/m² in pine and spruce forests on sandy, loamy-sandy and sandy-loamy podzols (Albic Podzols) and soddy-podzols (Umbric Podzols) and from 19 to 22 kg C/m² in spruce forests on silty-loamy, clay loamy and clayey soddy-podzolic soils (Albic Dystric Retisols) (table 2). Plants contained 60-75% of organic matter in these ecosystems. The contribution of forest litter to the soil organic carbon stock was small (10–20%) and its contribution to the overall carbon stock in ecosystems was insignificant (less than 5%). Carbon stocks in swampy forest ecosystems on Histic Gleyic Podzols, Gleyic/Stagnic Retisols and Gleysols were characterized by a greater variability (from 17–19 to 25–33 kg C/m²), with a lower contribution from phytomass (25-45%) and a higher

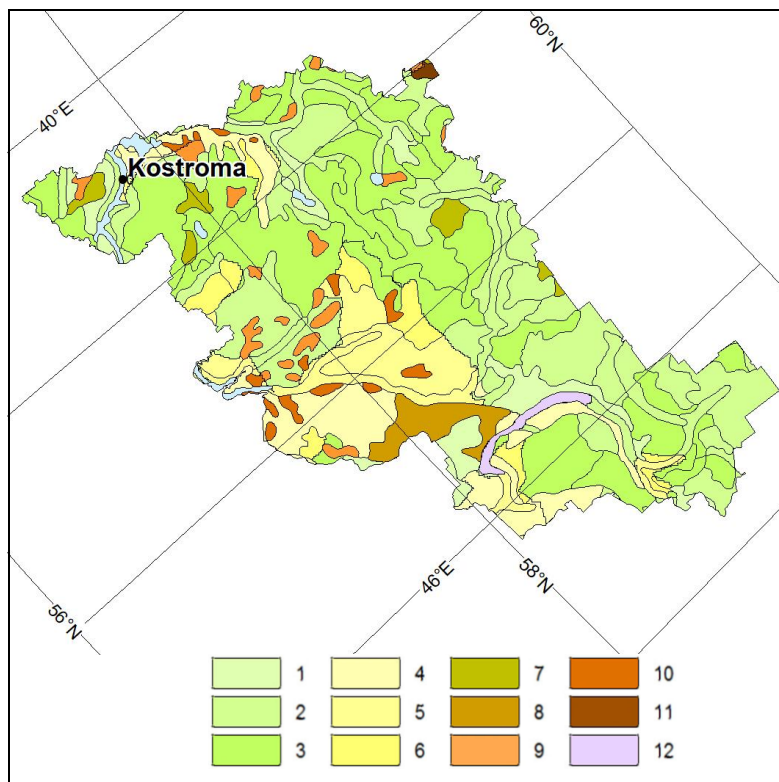


Figure 1. A schematic map of reconstructed prehistoric ecosystems in the Kostroma Region.

Ecosystems: spruce forests on (1) Albic/Umbric Podzols, (2) sandy loamy Albic/Dystric Retisols, and (3) clay loamy Albic/Dystric Retisols; pine forests on (4) Albic/Umbric Podzols, (5) sandy loamy Albic/Dystric Retisols, and (6) clay loamy Albic/Dystric Retisols; swampy spruce forests on (7) Gleyic/Stagnic Retisols; Gleysols; swampy pine forests on (8) Histic Gleyic Podzols, Gleysols; (9) low moors with Sapric Rheic Histosols; (10) transitional moors with Sapric Rheic Histosols; (11) sphagnum bogs with Ombric Hemic Histosols; and (12) floodplain ecosystems.

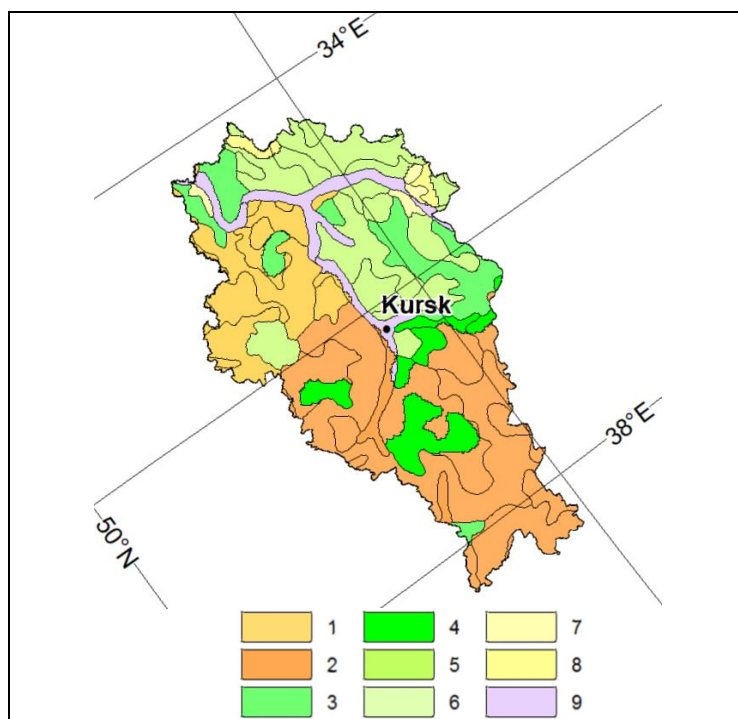


Figure 2. A schematic map of reconstructed prehistoric ecosystems in the Kursk Region.

Ecosystems: meadow steppe on (1) loamy Chernic/ Luvic Phaeozems, Luvic Greyzemic Chernozems and (2) clay loamy Luvic/ Haplic Chernozems; broad-leaved forests on (3) loamy Chernic/ Luvic Phaeozems, Luvic Greyzemic Chernozems, (4) clay loamy Luvic Greyzemic/ Haplic Chernozems, (5) loamy Phaeozems and Luvisols, and (6) sandy loamy Umbric Podzols, Luvisols; pine–broad-leaved forests on (7) loamy Albic/ Haplic Luvisols and (8) sandy loamy Luvisols, Luvic Phaeozems; (9) floodplain ecosystems.

contribution from organic horizons including forest litter and peaty-muck horizons (up to 50% of the total soil organic carbon stock). Wetland ecosystems were characterized by the maximum variability of carbon stocks (20–65 kg C/m²), which could even exceed 65 kg/m² in swampy forests on peaty lowland bog soils (Sapric Rheic Histosols). Furthermore, the majority of organic carbon was concentrated in a peat layer. The total organic carbon stock of the Kostroma Region in the prehistoric

period reached $17 \cdot 10^{10}$ kg. The structure of reconstructed prehistoric organic carbon stocks in the Kostroma Region is shown in figure 4a. More than a half of the organic carbon stock was concentrated in the phytomass of forest ecosystems, which in the prehistoric period occupied up to 90% of the area. The fraction of organic matter of automorphous soils (including forest litter) made up 33% of the total carbon stock. Ecosystems of bogs and swamps occupying less than 10% of the area accumulated about 16% of the total carbon stock. The ratio of soil to phytomass carbon stocks had values below 1 in automorphic forest ecosystems and up to 7 in waterlogged ecosystems due to differences in the thickness of soil organic horizons.

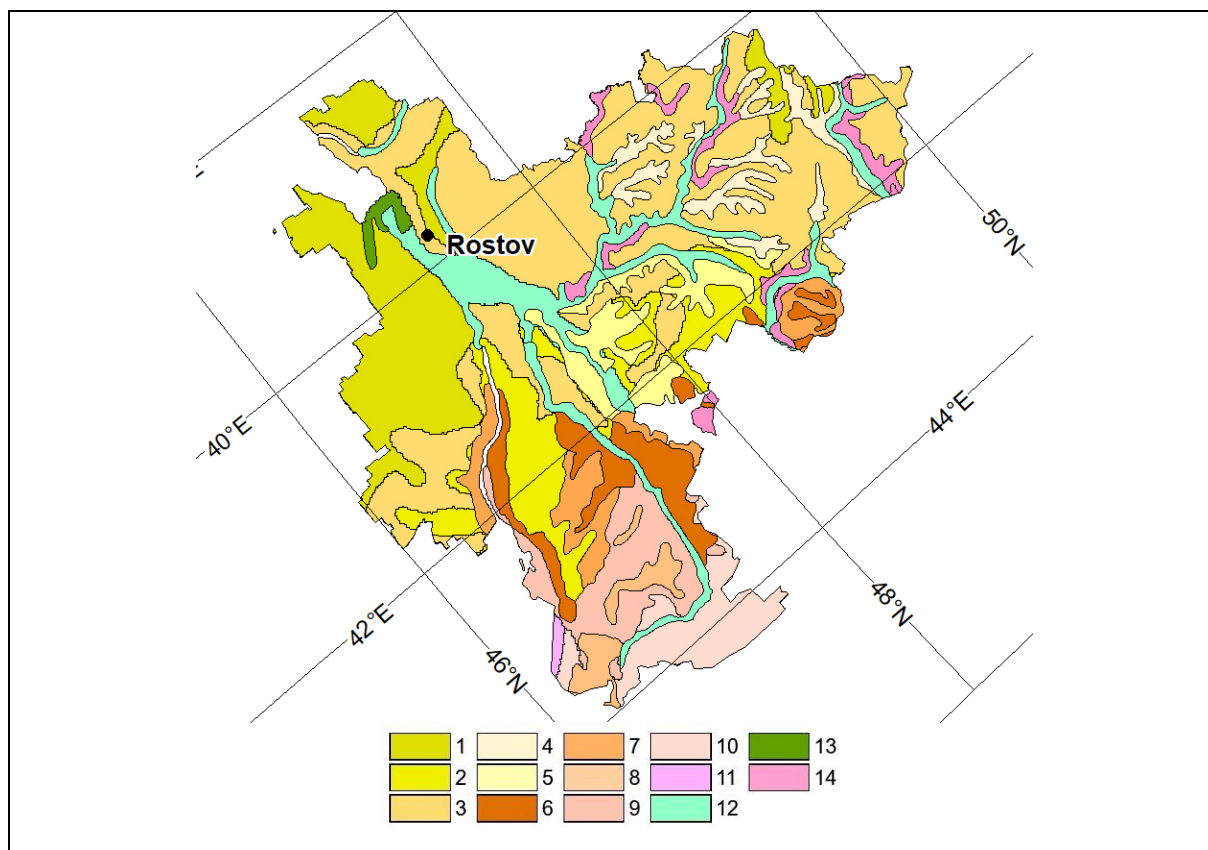


Figure 3. Schematic map of reconstructed prehistoric ecosystems in the Rostov Region.

Ecosystems: (1) meadow steppe on Haplic Chernozems; true steppe on (2) Calcic Chernozems; (3) Haplic/ Calcic Chernozems; (4) Leptic Chernozems; (5) dry steppe on Chernozems (Endosalic/Sodic); (6) on Haplic Kastanozems (Pachic); (7) on Haplic Kastanozems (Pachic/Sodic) and Mollic Solonetz; (8) on Haplic Kastanozem; (9) on Haplic Kastanozems (Endosalic/Sodic), Haplic Solonetz; (10) on soil complexes of Kastanozems (Endosalic/Sodic), Calcic/Gypsic Solonetz; (11) dry steppe with halophytic plants on Solonetz and Solonchak complexes; (12) floodplain shrub, broad-leaved forest and meadow ecosystems (13) floodplain swamp ecosystems; and (14) pine forests and psammophytic grass communities on Eutric Arenosols.

Potential carbon stocks of automorphic ecosystems in forest-steppe regions were higher than those in southern taiga. They increased from 15-18 kg C/m² in pine and mixed forests on sandy soddy-podzols and gray forest soils (Umbric Podzols; Albic Luvisols) to 31-38 kg C/m² in meadow steppes on loamy chernozems (Chernic Phaeozems, Luvic/Haplic Chernozems) and reached 40-42 kg C/m² in broad-leaved forests on chernozems (Luvic Phaeozems, Luvic Greyzemic Chernozems) (table 2). The ratio of phytomass to soil carbon pools depended mainly on the vegetation type. In broad-leaved

Table 2. Organic carbon pools in reconstructed ecosystems of the southern taiga, forest-steppe and steppe.

Vegetation	Soils (WRB, 2014)	Soil texture	Organic carbon stocks, kg C/m ²					
			soil (0–100 cm)		litter, peat		phytomass	
			min	max	min	max	min	max
Pine and spruce forests	Albic/ Umbric Podzols; Albic/ Dystric Retisols	Sandy, loamy sandy, sandy loamy	3.8	5.5	0.9	1.1	10.7	12.9
Spruce forests	Albic/ Dystric Retisols	Silty loamy, clay loamy, and clayey	5.4	7.8	0.9	1.0	11.5	12.9
Waterlogged and swampy forests	Histic Gleyic Podzols; Gleyic/ Stagnic Retisols; Gleysols	Without subdivision	14.9 ^a	23.3 ^a			6.5	8.2
Bogs	Ombric Hemic Histosols; Sapric Rheic Histosols		0.0	4.0	20.0	65.0	0.2	6.4
Pine and pine–broadleaved forests	Umbric Podzols; Albic Luvisols	Sandy, loamy sandy, sandy loamy	5.1	7.0	0.5	0.7	9.3	10.5
Broadleaved forests	Luvisols; Greyzemc/Luvisols; Phaeozems; Luvic Chernozems	Sandy/silty/clay loamy, clayey	8.0	26.2	0.4	0.5	13.0	13.7
Tall-grass steppe	Greyzemc/ Luvic Phaeozems; Luvic/Haplic Chernozems	Sandy/silty/clay loamy, clayey	30.3	36.5	0.1	0.2	0.6	1.1
Meadow steppe and meadows	Gleyic Chernozems; Fluvisols/ Phaeozems	Without subdivision	21.0	36.5	0.2	0.3	0.9	7.4
Steppe	Haplic/ Calcic Chernozems	Silty/clay loamy, clayey	15.3	28.8	0.1	0.6	0.6	1.2
Short-grass steppe	Leptic Chernozems; Haplic Kastanozems (Pachic); Chernozems (Endosalic/ Sodic)	Without subdivision	12.0	20.1	0.02	0.1	0.3	0.9
Dry steppe	Haplic Kastanozems (Endosalic/ Sodic), Haplic Solonetz	Silty/clay loamy, clayey	7.0	12.7	0.02	0.1	0.2	0.7
Pine forests and psammophytic grass vegetation	Eutric Arenosols	Sandy, loamy sandy	2.4	6.1	0.03	0.8	0.2	6.1

^aTotal organic carbon stocks in litter and mineral layers of soil.

forests on gray forest soils (Luvisols) carbon stocks were almost evenly distributed between soil and phytomass. In broad-leaved forests on chernozems (Chernic Luvic Phaeozems, Luvic Greyzemic Chernozems), the soil pool was twice as large as the phytomass pool. In intact meadow steppes ecosystems on chernozems (Haplic/Vermic Chernozems, Gleyic Chernozems), the soil pool exceeded the phytomass pool by 50 times and more. Thus, within the territory of the Kursk Region in the prehistoric period soils contained about 83% of the total prehistoric carbon stocks. In forest ecosystems, which in prehistoric times covered nearly 40% of the region, phytomass pool comprised slightly more than 15%, while the soil pool contained nearly 23% of the total organic carbon stock. Soils of virgin steppes contained more than 60% of the total carbon stock (figure 4b). The intact ecosystems of the region as a whole contained $103 \cdot 10^{10}$ kg of organic carbon.

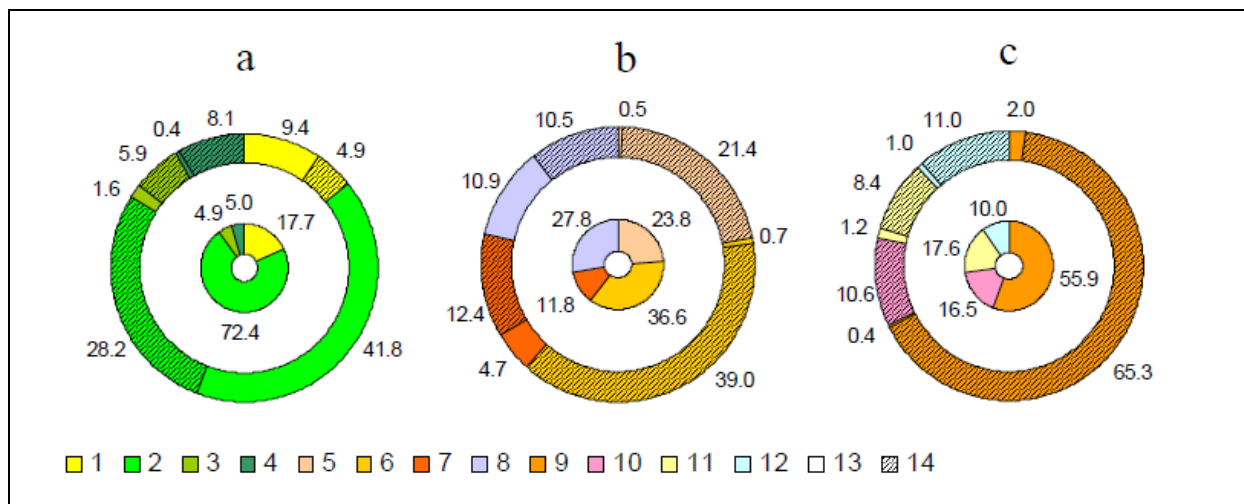


Figure 4. Proportions (%) between the areas and reconstructed prehistoric carbon stocks in some regions of European Russia.

The areas are shown inside diagrams, and the carbon stocks are shown outside diagrams. Regions: (a) southern taiga (Kostroma Region), (b) forest-steppe (Kursk Region), and (c) steppe (Rostov Region). Ecosystems: (1) pine forests on Albic/ Umbric Podzols; (2) pine and spruce forests on Albic/ Dystric Retisols; (3) swampy forests on semihydromorphic soils; (4) bogs; (5) meadow steppe on loamy Chernic/ Luvic Phaeozems; (6) meadow steppe on clay Luvic/ Haplic Chernozems; (7) linden–oak forests on Luvic Phaeozems, Luvic Greyzemic Chernozems; (8) pine–broad-leaved forests on Luvisols, Luvic Phaeozems; (9) true steppe on Haplic/Calcic Chernozems; (10) true steppe on Calcic/Leptic Chernozems; (11) dry steppe on Haplic/Luvic Kastanozems and Haplic Solonetz; (12) floodplain ecosystems (reeds, shrubs and secondary broad-leaved forests); (13) phytomass carbon, (14) soil carbon.

Virgin ecosystems of true steppe on chernozems (Haplic/Calcic Chernozems) had carbon stocks of $16\text{--}30 \text{ kg C/m}^2$. Dry steppe on chestnut (Haplic Kastanozems and Luvic Kastanozems) and slightly alkaline chestnut soils (Haplic Solonetz) had lower organic carbon stocks of $8\text{--}14 \text{ kg C/m}^2$. The lowest organic carbon stocks in the region were found in ecosystems of psammophytic steppes and dry pine forests on sandy soils (Eutric Arenosols) (table 2). All typical ecosystems of the region were characterized by an absolute predominance of the soil pool in the total carbon stock. The phytomass pool increased only in ecosystems of riparian forests and dry pine forests. According to our calculations, natural terrestrial ecosystems of the Rostov Region could accumulate about $198 \cdot 10^{10}$ kg of organic carbon, 95% of which was concentrated in soils (figure 4c).

Oblast in natural condition may accumulate about $198 \cdot 10^{10}$ kg of organic carbon, 95% of which is concentrated in soils (figure 4c).

4.2. *The size and structure of carbon stocks in modern ecosystems*

At the present time, most of the Kostroma Region (southern taiga) is used for forestry purposes. Forests cover more than 70% of the area. More than half of these are secondary deciduous forests (dominated by birch), while the rest are almost equally shared between pine and spruce forests. Mature and overmature forests (with the age greater than 80-120 years) occupy less than 15% of the region's area, while young forests including forests on abandoned fields represent 30% of the area covered with forests. Agricultural lands occupy 16.5% of the region's area, with arable lands making up 3.5%, hayfields and pastures - 5%, and abandoned (ex-arable) lands - 8% (table 1). Modern carbon stocks in a 0-100 cm soil layer of agricultural and forestry lands differ insignificantly (from 4.5 kg C/m² in sandy and loamy sandy soddy-podzols (Umbric Podzols) to 8.5 kg C/m² in loamy soddy-podzolic soils (Dystric Retisols) (table 3). The phytomass carbon pool of forestry lands is 10 times as large as that of agricultural lands. Therefore, differences in contemporary carbon stocks in automorphic ecosystems of southern taiga depend on the type, age and species composition of vegetation. Nowadays, the region's total organic carbon stock is estimated at $89 \cdot 10^{10}$ kg. The soil pool makes up 60% of the region's total carbon stock, with carbon of organic horizons of waterlogged soils including peat making up one-fourth of this amount. The phytomass contributes only 40% to the region's total carbon stock, with mature and overmature forests making up 27% of the carbon pool of the plant biomass. Phytomass of agricultural and post-agricultural lands contributes less than 1% to the total carbon stock, although they occupy over 16% of the region's area (figure 5a).

The modern Kursk Region, like many other forest-steppe regions, has been transformed by human activity: natural vegetation has been significantly damaged and more than a half of the area has been cultivated, with hayfields and pastures occupying 15% and abandoned fields – about 7% of the region's area. Farming has now resumed on some arable lands that were abandoned during the period of 1990-2012. Forests and shelterbelts cover near 10% of the area (table 1). The carbon stocks of arable lands range from 10-16 kg C/m² on gray forest soils (Luvisols, Luvic Phaeozems) to 16-31 kg C/m² on chernozems (Luvic Chernozems, Haplic Chernozems) (table 3). In hayfields, pastures and abandoned fields, the carbon stocks are by 1-4 kg C/m² higher than those in similar arable soils. Intact ecosystems of the Central Chernozem Biosphere Reserve are characterized by the maximum carbon stock (greater than 40–50 kg C/m²). The total modern carbon stock of the Kursk Region is estimated at $64 \cdot 10^{10}$ kg, with the soil pool making up 94% of this value. Agricultural lands that prevail in the area contain the largest part of carbon stock. Nearly 6% of total carbon stock is accumulated in phytomass, with slightly more than half (3.5%) being in biomass of woody vegetation (figure 5b).

In the modern Rostov Region, most of the area is used for agriculture. Natural vegetation of true steppe that in the past covered most of the region has now almost disappeared. Its remnants can be seen only on slopes and bottoms of some ravines. Forest covers only 2.3% of the region's area, while forest shelterbelts cover slightly more, i.e., 2.9% (table 1). More than 60% of the area is farmed. In the southern part of the region, natural ecosystems of dry steppe are strongly degraded due to grazing. In this region, almost all chernozems (Haplic/Calcic Chernozems) are cultivated. Such soils of agroecosystems accumulate 15-22 kg C/m² of organic carbon. Carbon stocks are somewhat lower in shallow chernozems (Leptic Chernozems) and chestnut soils (Haplic Kastanozem) of agroecosystems (table 2). Dry steppes on weakly alkaline and saline chestnut soils and alkaline soils (Kastanozems (Endosalic/Sodic, Calcic/Mollic Solonetz), which are used as hayfields and pastures, accumulate 5-10 kg C/m², with the share of phytomass being 9-14%. The highest organic carbon stocks are accumulated in the least disturbed ecosystems on chernozems (Haplic/Calcic Chernozems) within protected areas: it reaches 25 kg C/m² in grassland ecosystems and 32 kg C/m² in broad-leaved forests, with the phytomass shares being 5% and 25%, respectively. The minimum organic carbon stocks (if technogenic areas and badlands are disregarded) can be found in sandy and loamy sandy soils (Eutric Arenosols) with psammophytic grassy vegetation or young pine stands planted for rehabilitation of eroded sandy areas (2-4 kg C/m²) (table 2). We estimate the modern organic carbon stock in the region at $151 \cdot 10^{10}$ kg, with 96% contained in the soil carbon pool and mainly (88% of the total pool)

Table 3. Organic carbon pools in modern ecosystems of the southern taiga, forest-steppe and steppe.

Vegetation	Soils (WRB, 2014)	Soil texture	Organic carbon stocks, kg C/m ²					
			soil (0–100 cm)		litter, peat		phytomass	
			min	max	min	max	min	max
Arable, hayfields, and pastures	Anthrosols (Luvic/Dystric)	Southern taiga Loamy sandy, sandy/silty/clay loamy	4.4	8.4	0.0	0.1	0.2	0.8
			4.9	7.6	0.1	0.6	0.7	4.5
			4.2	7.8	0.9	1.1	10.7	13.9
			0.3	7.5	0.0	0.1	0.0	0.5
			8.9	15.0	0.0	0.0	0.3	0.5
Ex-arable land and young forests	Albic Umbric Podzols; Albic/ Dystric Retisols	Sandy, loamy sandy, sandy/silty/clay loamy	16.7	30.5	0.0	0.1	0.4	0.5
			7.0	45.7	0.4	0.5	5.8	13.7
			1.0	19.4	0.0	0.1	0.0	0.9
Mature forests	Albic Umbric Podzols; Albic/ Dystric Retisols	Sandy, loamy sandy, sandy/silty/clay loamy	15.0	21.0	0.0	0.0	0.4	0.5
			4.0	9.0	0.0	0.1	0.1	0.7
			2.0	18.0	0.5	0.6	0.5	8.2
Roads, construction sites, disturbed land and other land	Eutric Arenosols; Haplic/ Calcic/ Leptic Chernozems	Steppe Loamy, clayey	1.0	14.7	0.0	0.1	0.0	0.7
			1.0	19.4	0.0	0.1	0.0	0.9
			1.0	19.4	0.0	0.1	0.0	0.9
Arable	Anthrosols (Luvic/Dystric)	Forest-steppe Sandy/silty/clay loamy	8.9	15.0	0.0	0.0	0.3	0.5
			16.7	30.5	0.0	0.1	0.4	0.5
			7.0	45.7	0.4	0.5	5.8	13.7
Pine, pine–broadleaved and broadleaved forests	Umbric Podzols; Luvisols; Chernic/ Luvic Phaeozems; Luvic/Greyzemnic/ Haplic Chernozems	Sandy, loamy sandy, sandy/silty/clay loamy	1.0	19.4	0.0	0.1	0.0	0.9
			1.0	19.4	0.0	0.1	0.0	0.9
			1.0	19.4	0.0	0.1	0.0	0.9
Roads, construction sites, disturbed land and other land	Anthrosols (Eutric/ Calcic)	Steppe Loamy, clayey	15.0	21.0	0.0	0.0	0.4	0.5
			4.0	9.0	0.0	0.1	0.1	0.7
			2.0	18.0	0.5	0.6	0.5	8.2
Hayfields and pastures	Haplic/ Luvic Kastanozems (Anthric)	Silty/clay loamy, clayey	1.0	14.7	0.0	0.1	0.0	0.7
			1.0	14.7	0.0	0.1	0.0	0.7
			1.0	14.7	0.0	0.1	0.0	0.7
Pine and broadleaved forests	Eutric Arenosols; Haplic/ Calcic/ Leptic Chernozems	Sandy, loamy sandy, sandy/silty/clay loamy	1.0	14.7	0.0	0.1	0.0	0.7
			1.0	14.7	0.0	0.1	0.0	0.7
			1.0	14.7	0.0	0.1	0.0	0.7
Roads, construction sites, disturbed land and other land	Eutric Arenosols; Haplic/ Calcic/ Leptic Chernozems	Sandy, loamy sandy, sandy/silty/clay loamy	1.0	14.7	0.0	0.1	0.0	0.7
			1.0	14.7	0.0	0.1	0.0	0.7
			1.0	14.7	0.0	0.1	0.0	0.7

accumulated in soils of agricultural lands. The contribution of phytomass to the total region's carbon pool is negligible (figure 5c).

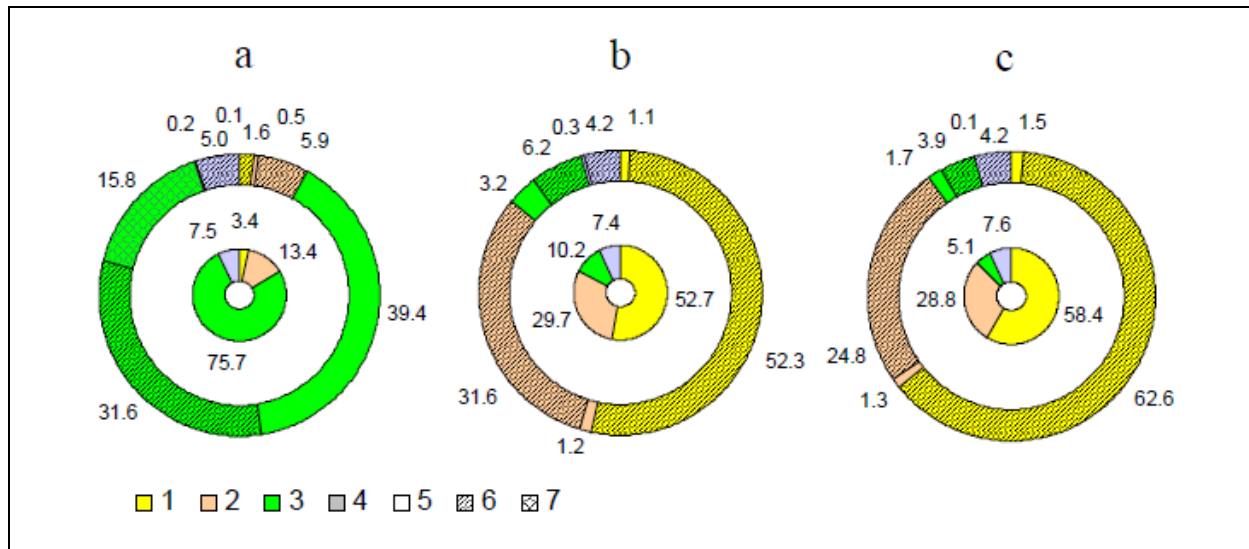


Figure 5. Proportions (%) of areas and carbon stocks under different land use in the model regions. The areas are shown inside diagrams, and the carbon stocks are shown outside diagrams. Regions: (a) southern taiga (Kostroma Region), (b) forest-steppe (Kursk Region), (c) steppe (Rostov Region). Land use: (1) croplands; (2) hayfields, pastures and permanent fallow; (3) forests and shelterbelts; (4) other land use; (5) phytomass carbon; (6) soil carbon of mineral horizons; (7) soil carbon of organic horizons.

4.3. Change in organic carbon pools in the model regions of European Russia

Assuming that size and ratio of basic carbon pools reflect the resilience of biological cycle, we assessed the natural and anthropogenic characteristics of the considered regions. Technogenically modified and urbanized areas as well as disturbed sites (roads, dumps, etc.) occupy relatively small areas of 5.9, 6.3 and 7.1% in Kostroma, Kursk and Rostov regions, respectively. Therefore, the difference between potential prehistoric and contemporary carbon stocks is influenced by a cumulative effect of various land use types under specific natural conditions. Mean weighted carbon stocks in the phytomass and 0-100 cm soil layer were used as regional characteristics. The calculations showed that the mean weighted carbon stocks, potential prehistoric and contemporary, in the Kursk Region located in forest-steppe were much higher than those in the regions of Kostroma (southern taiga) and Rostov (steppe), i.e., potential prehistoric stocks were 43% and 41% higher and contemporary stocks were 44% and 42% higher, respectively. The contemporary carbon stocks as compared to their potential prehistoric stocks were 24% lower in both Kostroma and Rostov Regions and about 37% lower in the Kursk Region (figure 6). In the southern taiga (Kostroma Region), the loss of carbon was almost fully (98%) associated with the reduction of phytomass, which resulted from intensive forest cutting. Insignificant losses of soil carbon stocks (including forest litter and peat) can be explained by the poor development of agriculture in the region. In the forest-steppe (Kursk Region), the high proportion (59%) of arable lands and almost complete removal of woody vegetation resulted in reduced carbon pools of both phytomass and soils (by 82% and 19%, respectively). Within the subzones of true and dry steppes (Rostov Region), 93% loss of total carbon stocks was associated with soils. This was explained by the fact that both potential prehistoric and contemporary soil organic carbon stocks were much greater than those of plant biomass in the region dominated by grasslands.

The results have demonstrated that the contribution of soils to total organic carbon stocks of prehistoric ecosystems increased from the north to the south, i.e., from 51% in southern taiga to 95%

in dry steppe. More intensive land use practices, both forestry and agriculture, were associated with increasing importance of soils in the maintenance of carbon stocks due to a greater resilience of the soil pool. This conclusion is supported by some other studies [10].

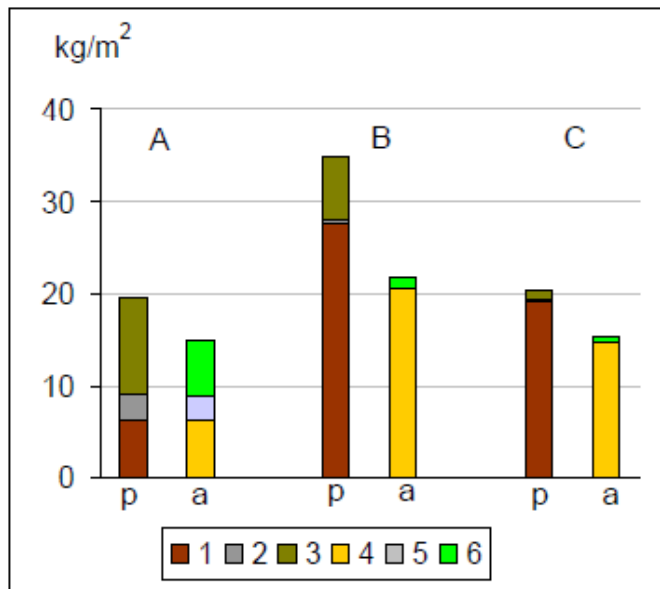


Figure 6. Mean weighted potential (p) and actual (a) organic carbon pools in the regions of (A) Kostroma, (B) Kursk and (C) Rostov: (1, 4) mineral soil horizons, (2, 5) organic horizons (litter, peat, steppe mat), (3, 6) phytomass.

Widespread farming in forest-steppe and steppe regions resulted in a noticeable decrease in organic carbon content in soil. Unfortunately, it is quite difficult to assess what percentages of carbon stocks were lost from arable soils due to humus mineralization, erosion and deflation. According to Titlyanova et al. [15, 17, 24], Western Siberian soils being in agricultural use for 50 years have lost from 1.0 kg/m² (chestnut soils) to 10.2 kg/m² (meadow and chernozem-meadow soils), i.e., 10–40% of their organic carbon stocks. The weighted average values obtained in the present study were 2-3 times as high as the estimated rate of humus loss from arable chernozems as a result of accelerated mineralization and decreased input of organic matter [25-27]. We assume that carbon losses from soils in steppe and forest-steppe resulting from erosion and deflation are equal or above the rate of organic matter mineralization during long-term farming. The Kursk Region (forest-steppe) with a longer, but less intensive agricultural use than the Rostov Region (steppe) is characterized by higher relative (27 and 24%) and absolute (7.2 and 4.5 kg/m²) losses of soil carbon.

5. Conclusions

The comparison of reconstructed (potential prehistoric) and contemporary (actual) organic carbon stocks in three regions (southern taiga, forest-steppe and steppe) of European Russia allowed for the assessment of the impacts of environment and land use type and duration on the structure of regional carbon pools on a historic scale. It has been demonstrated that the contribution of soil pool to the total organic carbon stock in ecosystems increases from southern taiga to dry steppe. The contemporary carbon pool of the 100-cm soil layer exceeds the phytomass carbon pool in all the regions studied, particularly in the forest-steppe and steppe regions, where it is exceeded by many times. Thus, more intensive land use, both forestry and agriculture, increases the contribution soil cover to maintaining the regional carbon balance.

Acknowledgments

The authors thank the anonymous reviewer for his helpful suggestions. Financial support from the Ministry of Science and Higher Education of the Russian Federation project (Grant No. RFMEFI60719X0298) is acknowledged.

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