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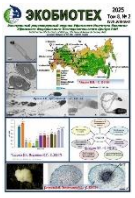

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REVIEW

CARBON POLYGONS (SUPERSITES) CHAIN IN THE RUSSIAN FEDERATION

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Abstract

Global climate change has evolved from a narrowly specialized natural science issue into one of the most pressing global economic and political problems. More than 160 countries worldwide have committed to achieve carbon neutrality by 2030-2070 in one form or another. Russia faces several challenges related to carbon offset and a low-carbon economy. Carbon polygons are the main «assistants» in determining carbon dioxide emissions and absorption not only in Russia but also worldwide. This review presents data on the development strategy, main characteristics of carbon polygons and their spreading in the Russian Federation. In addition, some main scientific results of their implementation have also been provided.

Keywords

climate changes ◆ carbon balance assessment ◆ greenhouse gases ◆ fallow land ◆ carbon farms ◆ carbon sequestration and deposition

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СЕТЬ КАРБОНОВЫХ ПОЛИГОНОВ В РОССИЙСКОЙ ФЕДЕРАЦИИ

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Аннотация

Глобальное изменение климата стало одной из самых актуальных проблем мировой экономики. Более 160 стран в той или иной степени взяли на себя обязательство по достижению углеродной нейтральности к 2030-2070 годам. Перед Россией стоит ряд задач, связанных с компенсацией выбросов углерода. Карбоновые полигоны — это своего рода «помощники» для оценки выбросов и поглощения углекислого газа не только в России, но и по всему миру. В обзоре представлены сведения о развитии стратегии, распространении и характеристиках карбоновых полигонов в России, а также приведены некоторые основные научные результаты их внедрения.

Ключевые слова

климатические изменения ◆ оценка углеродного баланса ◆ парниковые газы ◆ залежи ◆ карбоновые фермы ◆ секвестрация углерода

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INTRODUCTION

Carbon supersite is a specific area founded in order to control emissions of greenhouse gases. Moreover, carbon supersite's activity increases knowledge about the ecosystems' sequestration potential [Lal, 2023]. With these data we can adapt to global climate change and global warming (it is well-known fact that excess of carbon in the atmosphere enhances the greenhouse effect, resulting in global nonreversible climate changes on the planet, such as the melting of Arctic ice and permafrost, desertification, etc.) and lower taxes from enterprises (it must be noted that Russia is faced with a set of problems regarding carbon offsets and the carbon economy [Abakumov, 2021]. Large-scale change's monitoring allows us to observe the weather, climate, and to track and predict natural disasters. Many objects are suitable for organizing carbon supersites: virgin lands, forests, mountains, pasture, steppes, arable lands, peatland, marshland, lakes and even an ocean [Makarov, 2013].

The fundamental idea of trading emission quotas was presented in 1968 by Canadian economist J. H. Dales [Dales, 1968]. Project implementation to create a supersite complies with Action Plan on Climate Change for the period up to 2022, approved by the Government of the Russian Federation in December 2019 and the Strategy for Scientific and Technological Development of the Russian Federation, accepted in December 2016. According to the strategy, it is planned to create a group of supersites and carbon farms within their borders [Abakumov, 2022].

Carbon farms are special facilities' prototypes for the absorption of atmospheric carbon that could appear on carbon landfills. Carbon farming presents an opportunity to maintain biodiversity, economic and social co-benefits along with terrestrial carbon abatements [Sharma, 2021]. They are widespread in the USA, Australia, Finland and Sweden.

Russia holds the largest store of carbon in soils, forests and permafrost grounds. Russia's climate goal for 2030 is to reduce GHG emissions to 70% of 1990 levels, taking into account the maximum absorption capacity of forests and other ecosystems, subject to sustainable socio-economic development [Mukaeva, 2024].

The first carbon supersite in Russian Federation was founded in the Kaluga region in September 2020 assisted by global technology company Control2GO Ltd. The total potential C-sink of agricultural soils is about 3.6 Gt C with reference to the baseline of C pool under natural ecosystems in Russia [Minasny, 2017].

Below is a list of currently valid carbon Russian supersites.

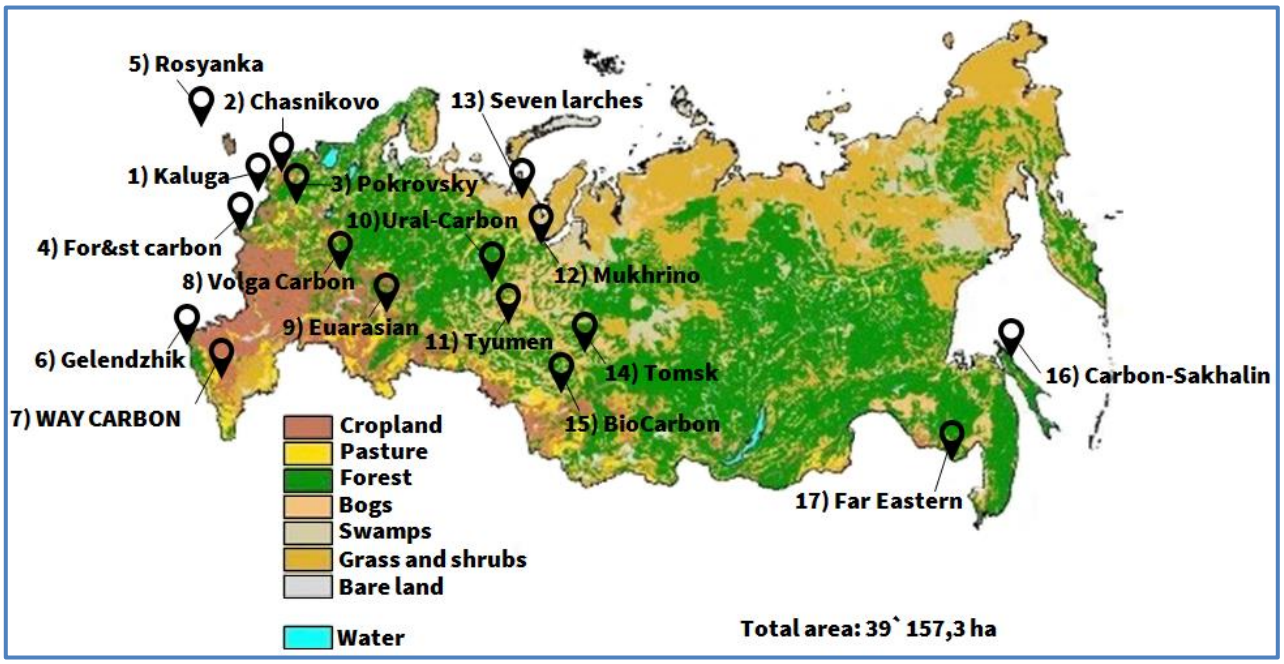

Figure 1. Land use map and locations of currently active carbon supersites in Russian Federation.
Source: https://carbon-polygons.ru/en/

Ugra (Kaluga). Test area operator: Ural Federal University. Number of plots: 1. Size: 600 ha. Industrial partner: TRANSMASHHOLDING JSC. Study site: Kaluga region, Ugra National Park, March-October 2020. The main task of organizing a carbon test site «Ugra» - development and testing of technologies for remote and ground-based emission monitoring greenhouse gases and other parameters significant for climate change in forest areas and agricultural lands. One of the initial stages of research at the Ugra supersite included inventory of soil and vegetation conditions.

The studies were carried out on soils of different land uses: present-day arable land, lay land (also known as fallow land, a territory that hasn't been cultivated for more than a year) soils with meadow vegetation, young forest areas 25–30 years old and mixed forest (75–80 years).

In the future, the development of scientific research at the Ugra Pilot Carbon Test Site will be included the following trends: 1) analysis of the effect of nitrogen- and boron-containing fertilizer compositions and thinning of the forest stand on the reserves of above-ground and underground phytomass, as well as the main components of the carbon balance in forest ecosystems; 2) assessment of the effectiveness of regenerative farming technologies in order to increase the carbon sequestration capacity of soils 3) testing technologies for remote monitoring of the carbon balance of forest areas and agricultural lands.

The main obtained results. The content of C_{org} and N in soils of all types of land use, except for arable land, decreases sharply down the profile, demonstrating the classic humus-accumulative nature of C_{org} and N distribution in the 0-50 cm soil layer. The C/N ratio in the studied soils varies widely and depends on the composition of plant litter coming to the soil surface. Microbial activity in the 0-20 cm layer of soils of the Ugra municipal enterprise decreases in the following order: fallow land under meadow vegetation > 25-30-year-old forest plantations > arable land > mixed forest [Kurganova, 2022].

Figure 2. The first Carbon Polygon in Russia using spherical tents SPHERE RT200D16 and SPHERE RT113D12, Kaluga.
Source: https://ekb.rbc.ru/ekb/05/04/2021/606aacb29a7947399e298952

Chasnikovo. Test area operator: Lomonosov MSU. Number of plots: 1. Size: 605,9 ha. Industrial partner: not appointed yet.

Chasnikovo supersite is located in the Solnechnogorsk (Moscow region) urban district on the territory of the Educational and Experimental Soil-Ecological Center of the Lomonosov Moscow State University. The territory covers the southern spurs of the slopes of the Klin-Dmitrovskaya ridge and is represented by a secondary moraine plain with coniferous-broad-leaved forests on sod-podzolic soils. Landscapes are both natural and anthropogenic. Currently, monitoring

studies of greenhouse gas flows are being carried out on its territory, carbon reserves in soils and vegetation are being assessed.

The results of the research at the Chashnikovo carbon polygon will provide the basis for the development of low-carbon strategies for nature management, forest restoration and agronomic technologies aimed at long-term deposition of atmospheric carbon in forest, floodplain and agricultural landscapes of the southern taiga of the European territory of Russia. Expected results: 1) digital maps of terrain, hydrography, land use structure, vegetation and soils for inclusion in GIS, 2) remote sensing data obtained using a quadcopter equipped with television, spectrozonal equipment and Lidar unmanned aerial vehicle [Dyachenko, 2023].

A methodology will be developed for the balanced quantitative assessment and monitoring of the carbon budget of natural and anthropogenically transformed landscapes with an analysis of the spatial and seasonal dynamics of carbon sequestration potential.

The main results. The soils of the studied biocenoses were characterized by similar C_{org} stocks in the upper 10 cm, varying from 24.2 to 26.6 t ha^{-1}, while, for the 0– to 30–cm layer, differentiation was noted. C_{org} stocks in agrosoils (72.7–75.6 t ha^{-1}) were 1.1–1.3 times higher than those in natural soils (59.4 t ha^{-1} in soils under forest and 65.0 t ha^{-1} under the meadow). At the same time, the contribution of C_{mic} to the total C_{org} content was higher in meadow soils and agrosoils under perennial grasses, which was due to the characteristics of herbaceous vegetation [Derevenets, 2024].

Figure 3. Meteorological tower in Chasnikovo supersite.
Source: https://carbon.msu.ru/carbon

Pokrovsky. Test area operator: Higher School of Economics Size: 1830 ha. Type: Anthropogenic landscape. Number of plots: 3. Industrial partner: Uralchem Group.

To implement this project, Higher School of Economics has formed a consortium of scientific and industrial partners: Shemyakin-Ovchinnikov Institute of Bioorganic Chemistry, All-Russian Williams Fodder Research Institute, Kaluga Carbon Test Site, and the United Chemical Company «Uralchem».

Experimental sites in Moscow Region (364 ha) and Kirov Region (1440 ha) represent 27% of non-chernozem arable land. Experimental plot in Kaluga region (24 ha) covers agricultural lands

in the river interfluve; structure and types of vegetation - grassy vegetation. Like Ugra supersite this plot is also assisted by Control2GO Ltd.

5 main supersite's trends: 1) greenhouse gas monitoring, 2) searching for the best cover grasses, 3) development of agrotechnology, 4) development of biomass monitoring, and 5) sequestration validation.

It is planned to synthesize a system of equations to determine the balance's conservation of elements in soil covers, biomass and the atmosphere in a limited area.

Figure 4. Pokrovsky supersite.
Source: https://pokrovcarbon.ru/project

«FOR&ST CARBON». Test area operator: Voronezh State University of Forestry and Technologies, Voronezh Oblast. Size: 181,3 ha. Type: forests, arable lands, reclamation plantings. Number of plots: 2. Industrial partner: SIBUR (PJSC SIBUR Holding). Main tasks: organization of systemic monitoring of emissions, sequestration and carbon stocks in soils, plant biomass and mortmass of forest-steppe ecosystems, development of elements of an automated system for assessing net carbon sequestration by ecosystems of the Central forest-steppe of the Russian Plain, cultivation of economically valuable and climate-resistant forest crops using selective methods and exploring sequestration potential of different types of regional ecosystems and assessment of their balance of greenhouse gas flows.

Plots: 1) Forest fund lands on the territory of the Educational and Experimental Forestry Enterprise 158,2 ha. The territory is located on the left-bank valley-terrace region of the typical forest-steppe of the Oka-Don lowland plain and is represented mainly by forest plantations: pine plantations of natural origin, upland oak grove, mixed artificial plantations of Scots pine and silver birch. 2) Federal Nature Reserve «Kamennaya Steppe» - 23.1 ha. Situated in the Kalach ravine-gully region of the forest-steppe province of the Central Russian Upland.

The results of the systematic studies at the FOR&ST CARBON will allow to realize a huge and yet unutilized reserve for reducing the carbon footprint of the region and mitigating the local consequences of climate change [Sheshnitsan S., 2023].

During the study, comparative calculations of the current growth of the total phytomass were performed, and the carbon accumulated by the phytomass was calculated. The obtained data are presented in Table 1 [Mamonov, 2022].

Table 1. Comparative evaluation of pine-birch forest stand carbon calculated by methods № 1 (IIASA, Austria) and № 2 (ROBUL model, Russia)

Mixing scheme	Age, years	Carbon, t ha^{-1}					
		Existent forest stand*		Difference, %	Total productivity		Difference, %
		Method N 1	Method N 2		Method N 1	Method N 2	
| 5P5B	20	40,42	53,15	24,0	76,11	58,71	22,9
	30	56,15	72,30	22,3	122,44	89,28	27,1
	40	68,23	88,24	22,7	166,37	119,48	28,2
	50	78,25	90,41	13,4	209,98	140,05	33,3
	60	85,92	95,45	10,0	251,14	166,04	33,9
	70	91,52	101,54	9,9	289,72	193,73	33,1
	80	95,61	105,45	9,3	325,92	218,99	32,8
	90	99,20	108,68	8,7	362,84	244,27	32,7
Mean		–	–	15,0	–	–	30,5
| 7P3B	20	38,86	54,77	29,0	72,42	60,99	15,8
	30	54,93	76,56	28,3	117,74	95,13	19,2
	40	67,70	93,61	27,7	161,98	127,62	21,2
	50	78,10	93,12	11,1	205,91	147,81	28,2
	60	86,43	99,59	13,2	248,16	177,44	28,5
	70	92,67	105,98	12,6	288,55	208,13	27,9
	80	97,44	110,59	11,9	327,23	237,5	27,4
	90	101,44	113,78	10,8	366,06	266,24	27,3
Mean		–	–	18,1	–	–	24,4

Figure 5. Pine forest in FOR&ST CARBON supersite.
Source: https://vgltu.ru/nauka/forest-carbon/

Rosyanka. Test area operator: Immanuel Kant Baltic Federal University (BFU), Kaliningrad region. Size: 255,4 ha. Number of plots: 2. Industrial partner: «Kukushkin» IE. It became the third facility officially opened in 2021 as part of the pilot project of the Russian Ministry of Education and Science, and the first supersite with not only a land but also a sea section.

The offshore section of the test site is located on the eastern slope of the Gdansk Deep in the Baltic Sea, where a methane anomaly is observed [Bukanova, 2022]. The content of this greenhouse gas in sediments at the bottom of the deep exceeds background levels by almost 10 times.

The land section is located on the Vittgirren peat bog in the Slavsky district. The current site studies the carbon balance of the peat bog (with its flooding) to increase the sequestration of greenhouse gases from the atmosphere. The international PeatRus project «Restoration of peatlands in Russia to prevent fires and mitigate climate change» is also being implemented.

One of the sites at the Vittgirren peat bog is a carbon farm, the main purpose of which is to test secondary swamping technology to reduce greenhouse gas emissions.

The priority is to study the temporal variability of carbon flows in the marine environment, developing methods for monitoring indicators, as well as a technology for obtaining biofuel, algae biomass and marine litter.

The emission chamber method – in its manual and automated modifications – was used to measure carbon dioxide (CO2) and methane (CH4) fluxes from the peatland surface [Napreenko, 2024].

The vertical distribution of dissolved methane in water in the South-Eastern part of the Baltic Sea varied over a fairly wide range – from 0 to 1.112 μmol/L. Methane concentrations increased with depth, which is a typical distribution for the sea and is associated with the vertical stratification of the water column. The layer from the bottom to the upper boundary of the halocline is the most saturated with methane: values above 0.1 μmol/L accounted for about 5% of all measured values and occurred in the halocline and under it. Thus, the CH4 flux from bottom sediments into the water column was predominant [Ulyanova, 2024].

Figure 6. Mobile laboratory in Rosyanka supersite.
Source: https://minobrnauki.gov.ru/press-center/news/nauka-i-obrazovanie/39151/

Gelendzhik. Test area operator: P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Krasnodar Krai. Size: 26 ha. Type: forests, basin. Number of plots: 3. Industrial partner: EuroChem Group AG.

The 12-kilometer-long offshore section of the test site is located around the Golubaya Bay on the outer side of the water area. The land section includes two areas: one is occupied by pines and oaks, the other by shrub vegetation. This supersite is an oceanographic innovation and has no analogues in the Black Sea.

Autonomous measuring systems have been installed at the testing area. They include bottom stations with acoustic Doppler current velocity profilers (ADCP), automatic Aqualog probe profilers, and thermocouples at moored buoy stations. This equipment provides regular acquisition of hydrophysical, hydrochemical, and bio-optical data with high spatial and temporal resolution.

Along with automatic measurements in the test site's waters, regular ship observations (including hydrochemical and biological) are carried out and satellite information in the optical and IR spectral ranges is being analyzed. The obtained data are used to calibrate satellite measurements, analyze the characteristics of variability of key parameters of the aquatic environment, study water exchange processes in the shelf-deepwater basin system, ocean-atmosphere interaction processes, and others.

Results: the maximum content of biolabile Dissolved Organic Matter (DOM) (with a fluorescence maximum of 340 nm) is typical for coastal stations in Gelendzhik Bay; in particular, in the area of the Gelendzhik harbor. The content of fluorescent DOM there was about three times higher than outside the bay [Drozdova, 2023].

Figure 7. Gelendzhik bay.
Source: https://gelendzhik-magic.ru/dostoprimechatelnosti/gelendzhikskaya-buhta/

WAY CARBON. Operators: Kadyrov Chechen State University and Grozny State Oil Technical University named after Academician M.D. Millionshchikov. Size: 1785 ha. Number of plots: 14. Industrial partner: JSC «Grozneftegaz», JSC «Chechenneftekhimprom», LLC «Teplostroyproekt-S», JSC «Chechengazprom», LLC «Uspekh», LLC «KIRUS», Infometeos LLC, LLC «Research and Production Co «Gardens of Chechnya», JSC «Agrovin-Sultan», LLC «Greenhouse Complex YugAgroHolding». The site is fitted with stationary measuring and meteorological equipment (Picarro G2508 soil cameras, Eddy covariance station for measuring greenhouse gas flows, MesoPRO weather station [Tsugaev, 2023], «INFOMETEOS» agrometeorological station). The carbon polygon is a geographically distributed research platform designed to solve two main tasks: developing a model for calculating the carbon balance of the area, taking into account the absorption and emission of the local ecosystem, and developing a method for using aerospace data to track greenhouse gases emitted and retained within specific biogeocenoses [Rustam, 2022].

At the supersite's carbon farm, special woody plants with high sequestration potential were planted, including trees' varieties of the Broussonetia (paper tree) family - mulberry, ficus, fig, as well as willow, linden, poplar and ash, which will allow solving both scientific and socio-ecological problems in the region.

Results. The amount of phytomass in low-mountain landscapes is almost twice the amount of phytomass on the plain. The transition into mortmass varies. The conservation area leads to more intense accumulation of ground mortmass, restoration of undergrowth, and a more complex vertical structure. However, this does not guarantee the deposition of carbon in the soils; most of it goes into the atmosphere [Gunya, 2023].

Figure 8. Autonomous agrometeorological station «INFOMETEOS» in WAY CARBON supersite.
Source: https://minobrnauki.gov.ru/press-center/news/novosti-ministerstva/37984/

Volga Carbon. Test area operator: Kazan Federal University, Republic of Tatarstan. Size: 60 ha. Number of plots: 3. Industrial partner: Tatneftekhiminvest-holding JSC. The test site is located on sod-podzolic soils in the southern taiga subzone. The objects of the study included soils [Zorina, 2024], rivers, forests and reservoirs. The vegetation of the test site is typical for the Prikazan region and represents various successional stages of indigenous coniferous-broad-leaved sub taiga and nemoral broad-leaved forests. The main part of the phytocenoses is hairy-sedge linden forests (70%), including various variations in the abundance of other species, including Finnish spruce, Scots pine, English oak, silver birch, trembling aspen. About 15% of the test site's territory is occupied by nemoral-grass birch forests with linden. Remote Sensing Monitoring actively used on the site to estimate vegetation biomass [Usmanov, 2023].

Two sites are intended for monitoring terrestrial ecosystems: 1) The «Observatory» site is located in the Zelenodolsk region, in a phytocenosis that is widespread in the territory of the European part of Russia, namely, a broad-leaved forest experiencing anthropogenic pressure of medium intensity and having a long history of development. 2) The «Bolshie Kabany» site is located in the Laishevsky district, in the forest-steppe zone of the Russian Federation, is a

watershed plain of the Volga and Kama rivers. Gray forest soils of this area occupy 21% of the total area of agricultural land. They are characterized by a periodically flushing type of water regime, have an acidic or slightly acidic reaction of the salt solution, a small amount of humus, poor water resistance of the structure, after rain they become swamped and form a crust.

Results. The overall reserves of total carbon in the 0-100 cm layer was 48.05±13.86 t/ha, the stock of microbial carbon was 4.89±1.13 g/ha. Despite the low concentrations of total and organic carbon in the A_2, B_1, B_2 horizons, the contribution of these horizons to the total reserve was 22-40% and 51-58%, respectively, which is due to the rather large thickness of these horizons (44-60 cm) [Alexsandrova, 2023].

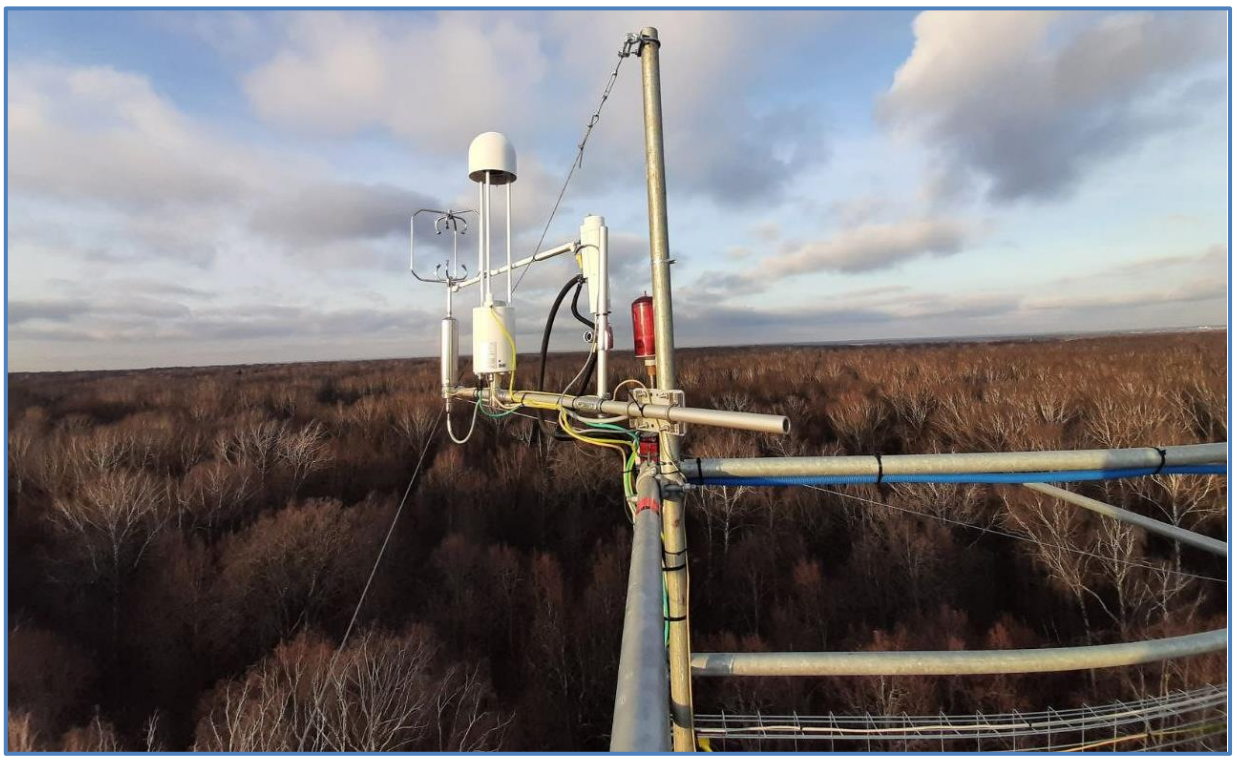

Figure 9. Eddy covariance system in forest area of Volga Carbon supersite.
Source: https://kpfu.ru/ecology/karbon-povolzhe/novosti/nachaty-nepreryvnye-nabljudeniya-na-lesnom-455922.html

Eurasian. Test area operator: Ufa State Petroleum Technological University (USPTU), Republic of Bashkortostan (RB). Size: 11599,5 ha. Types: fallow lands, marshlands, forests, feather grass steppe. Number of plots: 7. Industrial partner: «Bashkir soda company» JSC, «Gasprom neftekhim Salavat» Ltd.

The main goal of creating a carbon polygon in the RB is the method's practice and assess the volumes of greenhouse gas emissions by ecosystems, studying the possibility of carbon sequestration, and finding optimal solutions for decarbonization of the region and basic industries.

Test area № 1. «Feather grass steppe» – 10,0 ha. The site is located in the forest-steppe zone. Feather grass-steppe plants prevail. In the past fifteen years, the site had been periodically used as a haying; then regular usage terminated. It is one of the most typical areas of the slightly disturbed steppes in the Cis-Urals, which makes it a reference object for assessing the role of these plants in greenhouse gas emissions.

Figure 10. Feather grass steppe in Davlekanovo region, RB.
Source: Author's own photo

Test area № 2. «Berkazan-Kamysh» – 700,0 ha. The peat massif is located on the territory of the Asly-Kul natural park in the steppe zone of the Republic of Bashkortostan and is partially drained for peat extraction and mainly for agricultural use. This tract, one of the largest swamps in the region, had a range of negative consequences after drainage. At the site of peat extraction, secondary swamping occurred due to a decrease in hypsometric marks, and numerous fires occurred in the over-dried areas of peat-swamp soils. The soil cover of the Berkazan-Kamysh tract is represented by organogenic and mineral soils, but in terms of type, 40 years after drainage, it has changed slightly [Shirokikh, 2024].

Figure 11. «Berkazan-Kamysh» bog in Davlekanovo region, RB.
Source: Author's own photo

Test area № 3. Educational scientific center, tillage - 95,5 ha. Agricultural land intended for tillage is located on the territory of the educational and scientific center of the Bashkir State Agrarian University. The landscape represents upland-plain characterized by minor erosional risks. The area is mainly covered with agricultural field crops [Belan, 2023].

Test area № 4. Educational research center, forest - 109,0 ha. Has the same location as the test area № 3. The purpose of the plot is defensive forest. The plot category is a green zone of forests that perform the functions of protecting natural and objects.

Test area № 5. «Mishkino» - 10000 ha. According to botanical and geographical zoning, the territory of the Mishkino site belongs to the zone of broad-leaved forests. One of the predominant types of vegetation is former arable lands (hay harvest, cultivated area) overgrown with forests, which are at different stages of successional restoration, promising for the foundation of carbon farms. The soil cover is represented by the most common type in this zone, gray forest soils, and subtypes of proper gray and dark gray forest soils. The largest part of the area is taken by derelict agricultural lands, overgrown primarily with silver birch, less frequently with Scots pine and goat willow. Aspen forests, spruce forests and pine cultures, are less frequent. On steep slopes, there are meadow-steppe communities that are not extensively distributed.

Results. The main carbon sequestration on fallow lands overgrowing by forest occurs in the growing tree stand and soil. The average carbon content in the trunk wood is 48.4%, and those in leaves and branches are 49.2% and 49.7%, respectively. The carbon content in the above-ground parts of the herbs varied from 39.2 to 43.3% of dry organic matter with an average content of 42.0%. This value was lower than the carbon content in the above-ground biomass of birch and did not depend on the stage of succession or soil type. The carbon content in the combined root biomass of trees and herbs varied from 34.6 to 44.8% and it increased together with the formation of the tree stand and the increase in the proportion of woody species in the root biomass during succession [Fedorov, 2023].

Figure 12. Fallow lands in Mishkino region, RB.
Source: Author’s own photo

Test area № 6. Resort «Yangan-Tau» – 675 ha. Just like the test area № 5 this site includes derelict arable lands overgrown with forests and has the similar destination.

Test area № 7. «Soluni» – 10 ha. This area represented as erosional-accumulative terrace of the Ufa River valley. The choice of this site is due to the ecosystem’s diversity and the fact that a research center Soluni is located on its territory. This center is also intended for cultural, health, tourism and sports purposes.

Ural-Karbon. Test area operator: Ural Federal University, Sverdlovsk region. Size: 606 ha. Type: taiga forests. Number of plots: 2. Industrial partner: Sinara Group, Pipe Metallurgical Company PJSC. In accordance with current regulatory documents, the carbon polygon of the Ural

State Technical University is part of the Middle Ural taiga forest region. Consists of two sites («Kourovka» and «Severka»). The forest vegetation of the site is represented by three predominant species: pine, spruce and birch. The main objective of the research: 1) Analyzing the taxation indicators of plantations growing within the boundaries of the carbon research site of the Ural State Technical University «Ural-carbon». 2) Quantitative assessment of greenhouse gas emissions and sequestration in natural and transformed landscapes of the Sverdlovsk region by combining the results of ground-based and remote sensing methods to understand the spatial and temporal variability of carbon sequestration and the dynamics of climate-active gas flows. 3) Technology development for assimilating heterogeneous data (satellite and ground-based; inventory, remote and direct measurements) into a common model of sources and sinks in the region and Russian Federation.

The Sverdlovsk Region Carbon Test Site consists of two main sections:

-Kourovskaya Astronomical Observatory of Ural Federal University;

-Ural Educational and Experimental Forestry Enterprise of the Ural State Forest Engineering University;

Both sections of the carbon supersite, with an area of 300 hectares, are represented by relatively modified taiga forests.

The overall strategic multi-year goal until 2030-2035 is to develop a regionally verified methodology that considers expected climate change, determine the volume of carbon sequestration by terrestrial ecosystems, and develop optimal basic technologies for monitoring carbon sequestration and deposition. Allometric equations for estimating tree phytomass were used to quantify the amount of carbon sequestration by trees of the main forest-forming tree species [Fomin, 2024]. Results. The average carbon stock was 70.06 t/ha with an average wood stock of 194.2 m^3/ha. The total carbon stock deposited by forest stands in the studied area currently amounts to 37.88 thousand tons, the average carbon stock in the pool of wood biomass is 70.06 t/ha [Rogachev, 2022].

Figure 13. Astronomical equipment – the Master-II Ural telescope at the Kourovskaya Observatory.

Source: https://ural-carbon.urfu.ru/fileadmin/_processed_/f/8/csm_7_75e9e31f57.jpg

Tyumen. Test area operator: University of Tyumen, Tyumen Oblast. Size: 10 670 ha. Type: mixed forests, lakes, rivers. Number of plots: 1. Industrial partner: SIBUR (PJSC SIBUR Holding). Based on the Tyumen State University biological station on Lake Kuchak (Nizhnetavdinsky District). The Tyumen supersite covers the most typical types of ecosystems for the region: various types of forests, lakes, swamps, and agrocenoses. The equipment installed at the landfill allows for monitoring greenhouse gas emissions over an area of more than 10.6 thousand hectares. Study area: wildlife sanctuary Guzeneyevo. The area has a medium degree of anthropogenic disturbance and is represented by mixed forest, meadow-marsh ecosystems and basins. The research will also be carried out on Lake Kuchak. The area of the water surface is 342 ha, the depth is up to 5 m, the bottom is muddy, carbon in water is predominantly inorganic (hydrocarbonate) [Aleshina, 2024], the shore is composed of loams.

Carbon in water of the lake is mainly inorganic (TIC) in the form of hydro carbonates. The average content of total carbon for the entire period was 45.09±0.57 mg/l, inorganic carbon - 31.13±0.53, organic carbon - 13.96±0.43 mg/l

The results will be used in the implementation of projects on reforestation, development of the agro-industrial complex, as well as in the creation of carbon farms.

Figure 14. Tyumen State University biological station on Lake Kuchak in Nizhnetavdinsky District.
Source: https://ria.ru/20210830/tyumen-1747791092.html

Mukhrino. Test area operator: Yugra State University. Size: 1573,4 ha. Number of plots: 1. Type: bogs, forests, lakes. Industrial partner: «Gaspromneft-Khantos» Ltd., «Salym Petroleum Developmen N.B.», JSC Samotlorneftegaz. This testing ground is a part of the West Siberian meridional megatransect of the West Siberian Scientific and Educational Center, which will cover the territory from the forest-steppe to the Arctic tundra. Soil types: podzols and podzolic soils. A weak drainage role of rivers is observed, which indicates waterlogging and swampiness of the territory [Kupriianova, 2022]. As a result of the polygon's activities, a unique array of data on the dynamics of greenhouse gas flows, trends in their changes will be obtained, an assessment of

carbon absorption by forest and wetland ecosystems will be carried out, and the main microclimatic factors influencing the dynamics of carbon balance elements will be identified. In addition, the polygon is planned to be used as a base for practical training of students from Yugra State University and partner universities.

The obtained patterns of spatiotemporal dynamics of methane in different periods (including the cold season) will help to achieve new approaches to landscape snow survey for assessing gas exchange in the cold period of the year and to compare the results with data from traditional chamber-static measurements.

Results. Fluxes of carbon dioxide, methane and water from the bog surface show significant temporal variability. After removing peak values, the standard deviation calculated for the entire time interval decreased by 31% for the CO2 flux and by 44% for the CH4 flux. The daily cycle of methane emissions is evident only in the warm season. The content of water vapor, unlike the content of CO2 and CH4, does not have a clear diurnal variation in all seasons. Significant carbon absorption in the wetland ecosystem was recorded from May to August in 2022. [Dyukarev, 2023].

Figure 15. 131,23 -foot-tall (40 meters) observation tower in Mukhrino supersite.
Source: https://www.ugrasu.ru/news/carbon-polygons/na-evraziyskom-kongresse-2023-prezentovali-karbonovyy-poligon-mukhrino/

Seven larches. Test area operator: Arctic Research Center of the Yamalo-Nenets Autonomous Okrug. Size: 2395 ha. Number of plots: 1. Industrial partner: Government of the Yamalo-Nenets Autonomous Okrug. It is the only carbon polygon beyond the Arctic Circle [Nizamutdinov , 2024]

The carbon supersite «Seven Larches» is in the vicinity of the town of Labytnangi and the village of Obskoy, on the left bank of the Ob River, and is the only such facility in the Arctic, in the forest-tundra zone which dominated by foothill terrain. The polygon was created to inventory the reserves and flows of carbon in tundra ecosystems and is characterized by minimal anthropogenic load. Currently, a permafrost temperature monitoring system was installed at the site, which allows obtaining data on the soil temperature in the studied areas in the depth range from 0 to15 meters and deeper. Temperature observations of permafrost soils are a necessary condition for all field

experiments. Main difficulties in the development of supersite: hard logistics, severe climate and long distances from settlements with developed infrastructure.

Using a nearly 200-meter tower, which is rarity, especially for the Arctic, it is possible to monitor the movement of greenhouse gases within 800 km. In addition to the tower and equipment, the site also has two operating bodies: a laboratory and a meteorological station.

Results. It has been established that the snow cover thickness in the city averagely 1.5 times less than in the background areas and the carbon polygon, which is due to mechanical and thermal factors of redistribution of snow masses. The melted snow waters of the background areas, the carbon polygon and urban areas are slightly acidic and do not differ significantly in pH value [Chicherin, 2024].

Figure 16. 649,606-foot-tall (198 meters) observation tower in «Seven larches» carbon supersite.
Source: https://goarctic.ru/kultura/monitoring-merzloty-v-yanao-gidrologicheskaya-karta-salekharda-i-karbonovyy-poligon-sem-listvennits-/

Tomsk. Test area operator: Tomsk State University, Tomsk Oblast. Size: 450 ha. Type: forests, floodplain territories, wetlands. Number of plots: 4. Industrial partner: Engineering Chemical-Technological Center, Tomsk.

Carbon measurement supersite in Tomsk region is part of a large-scale strategic project, «Global Changes of the Earth: Climate, Ecology, Quality of Life» implemented with the support of the «Priority 2030» program. 15 universities are participating in the project, and its goal is to study the transformation of the environment during global warming. The project is aimed at developing the existing system of ground-based measurements of flows of climate-active gases based on pulsation and chamber measurements.

The Tomsk testing ground represents three ecosystems and consists of several research stations. The first plot is the southern taiga, mixed forest landscapes on the right bank of the Ob River. Despite its vast area, estimates of carbon emissions from the Ob River floodplain are largely absent. Here are located the «Fonovaya» observatory and the «Kireyevsk» stationary station, the area of which is 30 hectares and two hectares respectively. The second ecosystem is bog. The Plotnikovo and Vasyuganye stations operate here, monitoring areas of over 650 hectares. The third plot is the floodplain landscapes, which are supervised by the Kaibasovo station.

These sites have equipment to account the total runoff and emissions of climate-active gases. The research centers will also receive a carbon and nitrogen analyzer, which is necessary to determine organic carbon in the water.

The highest carbon emissions from the middle Ob River floodplain lakes occurred during late June and July, and largely exceeded the emissions from the main stem. Among possible driving factors of CO2 concentration and emissions from floodplain water surfaces, we invoke dissolved organic carbon and water temperature, whereas the pH and oxygen concentration anti-correlated with both CO2 concentrations and emissions. For the full open-water period, the floodplain accounted for 65% of the net river C emission [Krickov, 2021].

Figure 17. Kaibasovo station.
Source: https://www.riatomsk.ru/article/20230424/tgu-karbonovij-poligon/

Biocarbon. Test area operator: Novosibirsk National Research University (NSU). Industrial partner: Novaya Shkola Ltd, Gasprom Marketing and Trading, Biocarbon. Size: 1008 ha. Type: foothill sub taiga. Number of plots: 2.

Description of the plots. 1) Sites of forest and climate research of the Central Botanical Garden of the Siberian Branch of the Russian Academy of Sciences - 848 ha. This site represents a fragment of the landscape of zonal grassy birch forests of Western Siberia on drained elevated plains, characterized by diverse vegetation, in accordance with the dissected relief. 2) Natural pine forest area (Experimental Pirogovsky forest) - 160 ha.

The area is represented by a typical landscape of Priob pine forests on an ancient dune relief.

As a result of the project, new methodological approaches to assessing the effectiveness of climate projects in Siberia will be developed.

Based on the detailed study of the characteristics of the sectoral structure of the economy of the Novosibirsk region, it is planned to obtain a quantitative assessment of the carbon intensity of the economy of the regions of Russia, compare it with the world level, and also check for interregional convergence.

This makes it possible to identify key sources of greenhouse gas emissions and to zone the region’s territory according to the level of economic activity and industrial potential. It is also planned to develop methodological recommendations for the development of climate projects in Siberia, considering the experience of the Novosibirsk region.

Figure 18. Central Siberian Botanical Garden.
Source: https://topgid.net/7259-centralnyj-sibirskij-botanicheskij-sad-so-ran.html

Carbon-Sakhalin. Test area operator: Sakhalin State University, Sakhalin Oblast. Size: 4004 ha. Number of plots: 3. Industrial partner: Sakhalin Energy Investment Company Ltd. Research target: sea and seashore.

Following a tendency of many economies to shift towards carbon neutrality, there came the necessity for certain regions to be assessed in terms of their greenhouse gas emissions from the ocean. The carbon testing supersite on Sakhalin was founded in 2021 to study the absorption capacity of Sakhalin's natural ecosystems. This will lead to the forest's cover increase, water purification and a decrease in the number of garbage dumps. Employees of the Sakhalin Climate Center, which is a structural division of the Sakhalin State University, are taking part in the work at the site. According to the experts, the main differences between the Sakhalin carbon test site and similar projects in other regions, is that Sakhalin and the Kuril Islands form a unique area due to the marine theme in the northern part of the Pacific Ocean. The site covers the marine ecosystem of Aniva Bay (Sea of Okhotsk).

Figure 19. Aniva Bay's shore.
Source: https://sakh.online/news/18/2023-05-17/karbonovye-poligony-razvivayut-na-sahaline-368043?ysclid=m6ulj0wsg6998723391

The region has several climate zones, ranging from broadleaf forests in the south to tundra in the north. Studying climate change, including at various sites at the Sakhalin carbon test site, will differentiate it from other sites in the country, which are mostly in the same climate zone. Sakhalin is the only region where a hydrogen cluster program is being developed.

Results. The annual cycle of dissolved oxygen (especially in surface layers) is negatively related to the water temperature and, basically, so are their mirror reflections. The main maximum is observed in spring (>9.3 mg/L or >114% at the 10 m depth) after ice melting in the bay, and the main minimum (<5.6 mg/L or <97% on the surface) in the beginning of September. A more detailed analysis in the upper 30 m layer reveals a local minimum in mid-July and a local maximum in the first half of August [Pishchalnik, 2024].

Far Eastern supersite. Test area operator: Far Eastern Federal University, Primorsky Krai. Size: 304,23 ha. Number of plots: 5. Industrial partner: LLC Avis Innofarm-dv, non-profit partnership for the development of renewable energy «Eurosolar Russia». Includes 5 sites, the project participants are the Federal State Budgetary Scientific Institution Pacific Oceanological Institute named after V.I. Ilychev of the Far Eastern Branch of the Russian Academy of Sciences and the Federal State Budgetary Scientific Institution «National Scientific Center of Marine Biology named after A.V. Zhirmunsky» of the Far Eastern Branch of the Russian Academy of Sciences. The sites involve marine aquatorium and coastal terraces (like Ajax Bay in the Sea of Japan). The main project is «Assessment of the sequestration potential of coastal marine ecosystems». Main objectives of the scientific research: development, testing and implementation of carbon sequestration technologies by coastal marine ecosystems and adaptation of existing advanced sequestration technologies to the conditions of the Far East, including assessment of the sequestration capacity of coastal ecosystems, monitoring of carbon cycles, carbon reserves estimating [Kostyk, 2025], monitoring of the environmental situation and the formation of new scientific teams in the field of carbon topics with international reputation.

Figure 20. Ajax Bay.
Source: https://fishing-vl.ru/place/buhta-ajax/

Contemporary projects have a very broad development prospects. A research team from Murmansk Arctic University is preparing a new methodology for monitoring, assessing and forecasting greenhouse gas emissions from ships navigating in Arctic waters. This methodology will be used for real-time forecasting and minimization of negative impacts on Arctic ecosystems considering the growth of transport activity in the region. The approach is based on the data analysis from automatic identification system (AIS). The project is promising for integration with carbon supersites initiatives and the national carbon monitoring system.

CONCLUSION

Russia counts more than 18 polygons with total area of 39`157 ha. Each of them complies with the recommendations of the Ministry of Science and Higher Education of the Russian Federation for carbon testing sites.

It has been established that the operating landfills are representative of more than 25% of the territory of Russia. The potential role of Russian bioresources in CO_2 absorption is that the country can become a global donor of this process thanks to its extensive forest areas.

The conducted results have shown that the content of total and microbial carbon generally reduces with increasing depth. Accumulation of soil organic carbon depends largely on vegetation cover. Grazing and plowing have a negative impact on the condition of the soil and its structural and aggregate composition, reducing fine particles that have the best potential for carbon storage. The reduction in carbon dioxide fluxes in seawater resulted in a decrease in the content of dissolved carbon dioxide and bicarbonate ions, while the concentration of carbonate ions has increased.

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