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From carbon polygon to carbon farm: The potential and ways of developing the sequestration carbon industry in the Leningrad Region and St. Petersburg*

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Climate change is one of the most important global problems of the 21st century. The territory of Russia is located in an area of significant observed and forecasted climate change. Achieving Russia's carbon neutrality by 2060 requires the development of a national system for monitoring greenhouse gas emissions and uptake. To achieve this goal, the Ministry of Science and Higher Education launched a pilot programme to create a national network of carbon polygons. St. Petersburg State University together with Voeikov Main Geophysical Observatory created the concept of Ladoga carbon polygon focusing the study the greenhouse gas absorption (or sequestration) potential of forest ecosystems typical for Northwest Russia. The evolution of this project assumes the establishment of a forest carbon farm (nature-based solutions). Based on the assumption that the territories of forest areas that were previously part of the state agricultural lands of the Leningrad region can be used for carbon farms (afforestation, enhanced carbon uptake by changing land use), an estimate of CO_2 absorption has been made. For the total area of forest carbon farms of $677.9 \cdot 10^3$ ha, it was evaluated of 3700 ± 1900 kt CO_2/year or $(1000 \pm 520) \cdot 10^6$kg C/year. It is shown that the CO_2 absorption of such carbon farms can offset up to 20 % of the total CO_2 emission of the Leningrad Region and not more than 8 % of the total CO_2 emission for the combined region consisting of Leningrad Region and St. Petersburg. The economic effect of the operation of forest carbon farms can only be achieved in the long term. At the current price level per tonne of CO_2 (35 USD/(t CO_2)), a 1 hectare of forest carbon farm would yield an income of 9500 USD over a 75-year lifetime. This determines the economic feasibility of creating carbon farms, which is also due to the potential for the production of carbon units based on them, which will either be traded

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on carbon exchanges or be taken into account as the results of activities aimed at reducing carbon emissions.

Keywords: carbon neutrality, carbon cycle, carbon absorption, carbon balance, carbon polygon, carbon farm, carbon dioxide, greenhouse gases, representative ecosystems, climate change, climate projects, carbon sequestration industry, anthropogenic emissions, Leningrad Region, St. Petersburg.

1. Introduction

Climate change is the most important international issue of the 21st century, manifested in changes in various indicators of global warming: average surface air temperature, sea level, heating of ocean waters, changes in the extent and mass of the cryosphere, power and frequency of dangerous hydrometeorological phenomena.

Due to its geographical size and characteristics, the territory of the Russian Federation is located in an area of significant observed and forecasted climate change. At the same time, the consequences of global warming for the ecosystems and national economy may be different and have both positive and negative effects. For example, changes in the cryosphere in terms of permafrost degradation will significantly affect the safety of transport communications, capital construction facilities and structures of various purposes in the northern regions of the country. On the contrary, freeing the Arctic seas from ice cover creates favorable conditions for cargo transportation and facilitates access to the continental shelf of the Russian Federation in the Arctic Ocean[1].

The impacts of climate change are having a significant and growing impact on the socio-economic development of Russia, living conditions and human health, as well as on the state of the national economy[2]. In the territory of Russia, climate warming is about 2.5 times more intense than the global average (Kattsov, 2017). The report on climate features in the territory of the Russian Federation for 2020 (Roshydromet, 2021) prepared by the Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) states that the past year 2020 turned out to be extremely warm both in our country and on the planet as a whole. The average annual temperature anomaly, i. e. the deviation from its average values for 1961–1990, was +3.22 °C. This was more than 1 degree above the previous maximum recorded in 2007. According to long-term observations made by Roshydromet, the average rate of warming in Russia is significantly higher than the average across the globe and in the period from 1976 to 2020, reaching 0.51 °C per decade. There has been a stable tendency towards reduction of ice cover in the Arctic: since the 1980^{s}, the reduction has been 5–7 times in the area of the Northern Sea Route. In the south of European Russia, moisture availability is decreasing in summer against the background of rapidly rising average temperatures and the risk of drought is increasing (Roshydromet, 2021).

According to current scientific understanding, based on the results of simulations using three-dimensional atmospheric and oceanic general circulation models, the main cli-

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[1] Decree of the President of the Russian Federation of 17.12.2009 No. 861-rp “On the Climate Doctrine of the Russian Federation”. [online] Available at: https://docs.cntd.ru/document/902190830 [Accessed 17.03.2023]. (In Russian)

[2] National Action Plan for the first phase of adaptation to climate change for the period up to 2022. [online] Available at: http://static.government.ru/media/files/OTrFMrZsORhNIxLUsdgGHyWIAqy1154.pdf [Accessed 10.10.2022].

mate-forming factor determining the observed trends and rates of change in hydrometeorological parameters in the global ecosystem is an unprecedented increase in concentrations of thermodynamically active gases, especially CO_2, in the atmospheric air (IPCC, 2021).

Reliable predictions of changes in the Earth's climate require the formation of scenarios of changes in gas composition under various variants of anthropogenic and natural influence, including scenarios of changes in the content of carbon dioxide, methane and other greenhouse gases (GHGs). In this connection, both regular monitoring of these gases in the atmosphere and studies of their natural and anthropogenic sources and sinks are needed to build reliable models of their circulation in nature (Integrated Global..., 2021).

In November 2021, in his video message to the participants of the Climate Conference in Glasgow, the President of Russia emphasised that Russia plans to reach carbon neutrality by 2060. Achieving a carbon-neutral Russian economy requires reliable quantitative information on the sources and sinks of GHGs. This will require verified accounting not only of GHG emissions into the atmosphere, but also the value of uptake (absorption) of climatically active gases by various managed natural ecosystems in Russia, confirmed including the use of internationally recognised observational systems: local and remote; ground-based, tower-based, and obtained using various carriers — satellites, manned and unmanned aircraft. The main objective of *the carbon polygons* are being created in the frame of the pilot programme of the Russian Ministry of Science and Higher Education (Carbon Supersites, 2021) is to develop technologies and methods for the evaluation of fluxes of climatically important gases focusing on investigation of the processes of absorption and storage of GHGs in different types of natural environments and ecosystems (Abakumov and Polyakov, 2021). St. Petersburg State University in collaboration with Voeikov Main Geophysical Observatory (MGO), with the support of the Leningrad Region Government, has developed the *concept of Ladoga carbon polygon,* aimed at studying the GHG sequestration potential of the southern taiga ecosystem typical for Northwest Russia.

When conducting complex biogeochemical studies, considering St. Petersburg and Leningrad Region as separate geographical regions is not always appropriate, despite the fact that they are formally different subjects of the Russian Federation, and sometimes impossible, because the mutual influence of these regions is very large (certain processes cannot be considered in separately for both regions). The Leningrad Region, together with St. Petersburg, represents one of the most economically developed regions of Russia with a high population density. For such regions, which are the industrial engines of the Russian Federation, experiments to develop the Russian carbon-neutral strategy, are of prime importance. It should be noted that the pilot project aiming to reach carbon neutrality was launched in Sakhalin (Sakhalin Region…, 2021). In this way, St. Petersburg and the Leningrad Region can be considered as a *combined environmental and climatic polygon* for interdisciplinary research on carbon neutrality and sustainable development, including studies of sources and sinks of climatically active gases and the development of carbon farms — a new type of sequestration carbon industry.

The main goal of this paper is to present the results of multidisciplinary research that was carried out during the development of the concept of the Ladoga carbon polygon and the preparation of its financial and economic justification. The article has the following structure:

— Section 2 is devoted to financial, economic and legal issues of the creation and operation of carbon polygons and farms;

— Section 3 contains a description of the concept of the planned Ladoga carbon polygon, including data on the location of the site, information about the soils and vegetation of the polygon;

— Section 4 — an assessment of the CO_2 absorption potential for carbon farms in the Leningrad region is given;

— Section 5 — discussion of the results obtained in Section 4, including a comparative analysis of the CO_2 absorption potential and GHGs anthropogenic emissions for the Leningrad Region and St. Petersburg, as well as the evaluation of the economic effect of operating a carbon farm;

— Section 6 — summary.

2. From a carbon polygon to a carbon farm: financial, economic and legal issues in the establishment and operation of carbon polygons and farms

One of the triggers for the development of carbon polygons and carbon farms in the country as components of the sequestration carbon industry was the reform of the European climate legislation. In July 2021, the European Commission announced the European Green Deal, which sets out qualitatively new goals and guidelines for EU climate policy and the instruments implementing it, including the introduction of a cross-border carbon tax, which became a serious challenge for countries exporting carbon-intensive products to the EU, including Russia, which was at that time in the list of top ten exporting countries (Pakhomova et al., 2021).

Today, in the context of the reorientation of a number of basic hydrocarbon export flows for Russia to regions other than the European Union, the importance of the EU Green Course as a benchmarking of global climate regulation measures remains. This fully applies to such tools and mechanisms used within its framework as the exchange procedure for determining prices for carbon units and the principles of setting carbon tax rates.

Against the background of these challenges, work on the institutionalization of carbon regulation has intensified. The most important framework documents in this area are:

1. *Federal Law No. 296-FZ dated 02.07.2021 "On Limiting Greenhouse Gas Emissions"*, which established the definitions of the climate project and the carbon unit. Thus, the climate project was defined as a set of measures to reduce (prevent) greenhouse gas emissions or increase the absorption of greenhouse gases, the carbon unit — as a verified result of the implementation of the climate project, expressed in the mass of greenhouse gases equivalent to 1 ton of carbon dioxide. The adoption of related by-laws will ensure the functioning of a *voluntary carbon market*.

2. *Federal Law No. 34-FZ of 06.02.2022 "On conducting a regional experiment to Limit greenhouse gas emissions in Certain Subjects of the Russian Federation"*, according to which quotas for greenhouse gas emissions will be established for regulated organizations in certain regions (currently the Sakhalin Region), and the verified results of their implementation will be registered in the register of carbon units. Units exceeding the quota will need to be purchased on the regional market of carbon units produced by organizations that have used up their quotas incompletely. Accordingly, we are talking about a *regulated carbon market* (a rigid model of carbon regulation).

Thus, the institutional foundations have been laid for the formation of a mixed carbon regulation mechanism, the necessary condition for the functioning of which is the availability of a special infrastructure to support long-term climate projects. Important components of such infrastructure are:

a) Carbon polygons — special test sites in which a set of basic and applied researches will be carried out to monitor and evaluate fluxes of climatically active gases, and to estimate their uptake by soil and plants, including estimation in monetary terms;

b) Carbon farms (can be combined with a carbon polygon or operated separately as commercial projects) — areas of the earth's surface where carbon dioxide and other GHGs are absorbed in large quantities.

Participation in projects to create carbon polygons and farms creates competitive advantages for those organizations that will become the flagships of the development of the sequestration carbon industry. Thus, the establishment of a carbon farm can be potentially considered as a climate project, which after its verification allows the production of carbon units. Rules for verifying the results of climate project implementation were approved by the Decree of the Government of the Russian Federation No. 455 dated March 24, 2022 and entered into force from September 2022. According to the current legislation, carbon units are credited to the account of the contractor of the verified climate project in the register of carbon units of the Russian Federation. These units can be sold, and in the future, perhaps, set off to reduce the carbon footprint of products.

3. The concept of Ladoga carbon polygon

The establishment of the Ladoga carbon polygon in the Leningrad Region is a long term project of primary importance for climate and environmental security of the region, prepared by St. Petersburg State University and Voeikov Main Geophysical Observatory with the assistance of the Administration of the Leningrad Region. Ladoga carbon polygon aims to study and assess the carbon absorption potential (or carbon sequestration potential) of ecosystems in the Leningrad Region, harmonized with international regulations, with the subsequent possibility to clarify the carbon footprint of enterprises to reduce the financial burden from the introduction of a transboundary carbon tax and (or) from the obligation to implement as a regulated entity[3], other expensive climate projects.

The planned structure of the Ladoga carbon polygon includes:

— *Stationary polygon* on the territory of MGO observational site (~150.6 ha, Leningrad Region, Voeikovo) — the core of Ladoga carbon polygon equipped by a tower and a set of scientific instruments for remote and local monitoring of GHGs and their fluxes. The map of the planned location of the stationary polygon is given in Fig. 1;

— A *mobile, rapidly deployable observatory* ("mobile polygon") — to conduct mobile, complex observational campaigns to study natural and anthropogenic (including nature-like) sources and sinks of GHGs, both on and off the stationary polygon;

— The *observational stations* of MGO and SPbU for atmospheric monitoring, which are part of the WMO GAW (Global Atmosphere Watch of the World Meteorological

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[3] Federal Law No. 296-FZ of 02.07.2021 on Limitation of Greenhouse Gas Emissions. [online] Available at: http://pravo.gov.ru/proxy/ips/?docbody=&firstDoc=1&lastDoc=1&nd=602263654 [Accessed 10.10.2022].

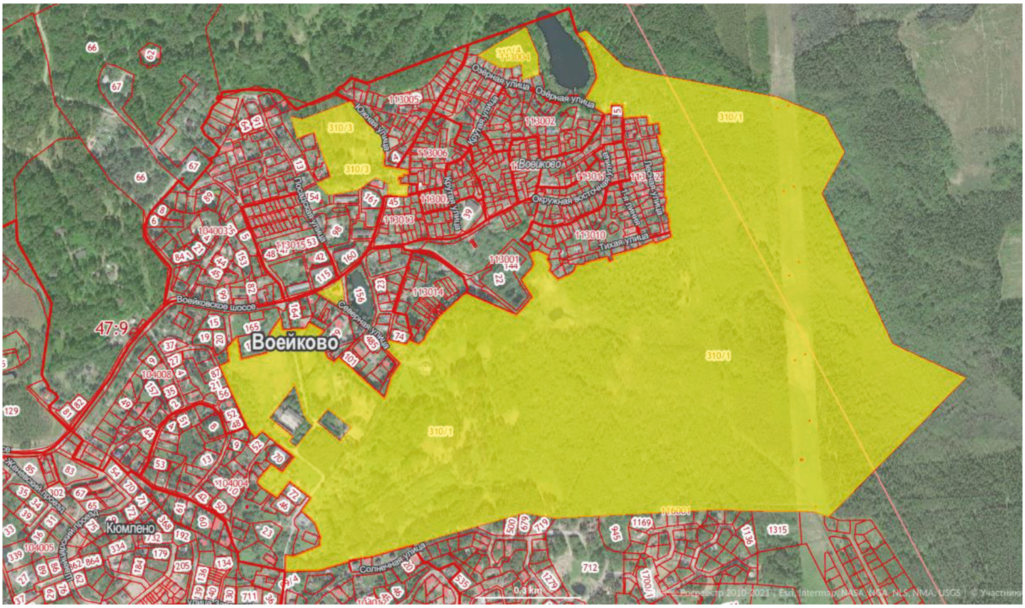


Fig. 1. The proposed location of the stationary polygon in Voeikovo (Leningrad Region) is highlighted by yellow colour (the screenshot of a map of the public cadastral resource. Available at: https://pkk.rosreestr.ru/ /search/59.9514043661247,30.72821620409625/15/@5w3ttfjvr?text=47%3A09%3A0116001%3A310&type=1&nameTab&indexTab&opened=47%3A9%3A116001%3A310 [Accessed 10.10.2022]).

Organisation, 2021) and NDACC (Network for the Detection of Atmospheric Composition Change, 2021) international networks;

— A *national centre for compatibility and calibration* to maintain the expanding network of carbon polygons and stations for the monitoring of GHGs.

The the concept of the Ladoga carbon polygon takes into account the world practices of the AmeriFlux (AmeriFlux, 2021) and ICOS (Integrated Carbon Observation System, 2021) networks for the organization of this kind of scientific infrastructure and observation stations.

The forest area where the stationary polygon is planned to be set up has long been home to the experimental site of MGO. Since the 1950s, a wide range of atmospheric and meteorological observations have been carried out there, including the launching of meteorological sondes as part of the WMO programme. Concentrations and fluxes of GHGs have been regularly monitored in the actinometric pavilion since 1996 (Zinchenko et al., 2002).

In autumn 2021, a set of preparatory research works was carried out at the MGO site:

— a detailed study of the terrain;

— description of the vegetation and ecosystem characteristics;

— soil transect and elemental analysis of soil samples.

Two main terrain types (Site 1 and 2) representative for the Leningrad Region, Northwest Russia, and Southern Finland have been preliminarily identified at the territory of stationary polygon. Information on terrain, vegetation and soils for Site 1 and 2 is given in Table 1. Photographs of the terrain types, vegetation and soil profile of both sites are shown in Figs 2a and 2b.

The organic carbon and total nitrogen stocks in the different soil horizons for the Site 1 and 2 of the polygon are shown in Figs 3 and 4. The values of carbon and nitrogen stocks in soil profiles are typical for podzol and histosol. In the case of podzol, the main carbon stock is not associated with the forest litter, but with the mineral and organo-mineral horizons. The carbon stock is slightly higher than in podzols, which is due to the presence of humus horizon, typical for alphegumus soils of the southern taiga subzone, to which most of the territory of the Leningrad Region belongs, in particular, the territory of the planned carbon polygon. The increased carbon stock in the histosol is due to additional accumulation of organic matter in the accumulative depressions of the relief. Thus, the area of the planned carbon polygon include both zonal soils of automorphic drained positions and intrazonal soils — peat soils, which are characterized by increased carbon stock in the organogenic peat horizons.

If the proposed project of Ladoga carbon polygon is successful, its further development (Phase 2) will involve the creation of a forest carbon farm (forest plantation) where intensive CO_2 absorption (sequestration) will take place. And finally (Phase 3) such a climate project potentially allows the issuing of carbon units. The spatial co-location of the carbon polygon and farm provides an opportunity to accelerate the transition from basic and applied research to commercial implementation of the results. In the second and third phases of the project, the main income from the operation of the carbon farm (a new type of carbon sequestration industry) and the financial benefits due to more accurate emissions accounting will go to the project investor.

The development of carbon farms and polygons on the scale of the Russian Federation will facilitate the development of so-called carbon farming, an environmentally friendly business model that provides economic benefits from the introduction of improved land management practices that increase carbon sequestration in biomass, organics and soils by increasing carbon sequestration and/or reducing carbon emissions into the atmosphere in accordance with environmental principles beneficial to biodiversity and nature (Sustainable Carbon Cycles, 2021). Along with the Industrial Carbon Capture and Storage Sector (CCS Sector), carbon farming is a prerequisite for the transition to sustainable carbon cycles and carbon neutrality.

Table 1. **Characteristics of terrain, vegetation and soils of Sites 1 and Site 2 on the territory of the stationary polygon (forest area of the experimental station of MGO)**

Characteristic	Site 1	Site 2
	Koltushskaya Elevation	
Terrain	Kame hill. Glacial deposits formed in the aftermath of the Valdai glaciation. The terrain is rugged, recreationally disturbed, post-anthropogenic	Kame depression of the terrain. Wetland
Vegetation	Bilberry and lingonberry pine forest with mixed herbaceous and fern plants. Undergrowth includes alder, mountain ash. Pines of high quality (1–2 grades)	Waterlogged birch forest with small amounts of pine, spruce and alder. Reed grass, green mosses, lingonberries
Soil	Podzol on kame fine-grained siltstone sandy loam	Histosol in an wetland kame depression

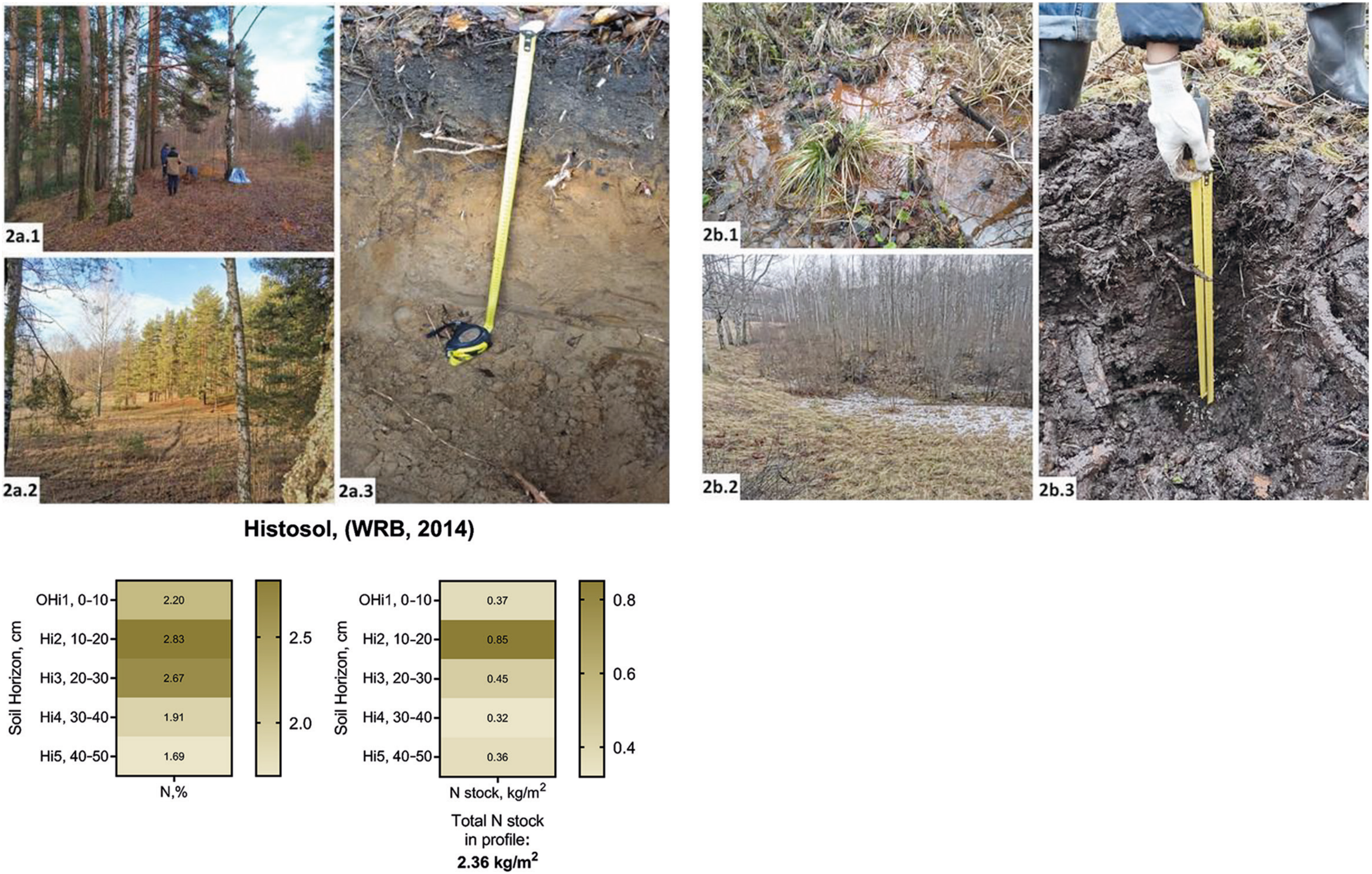


Fig. 2. Terrain, vegetation (2a.1 and 2a.2) and soil profile (2a.3) of Site 1, and terrain, vegetation (2b.1 and 2b.2) and soil profile (2b.3) of Site 2 of the Ladoga carbon polygon

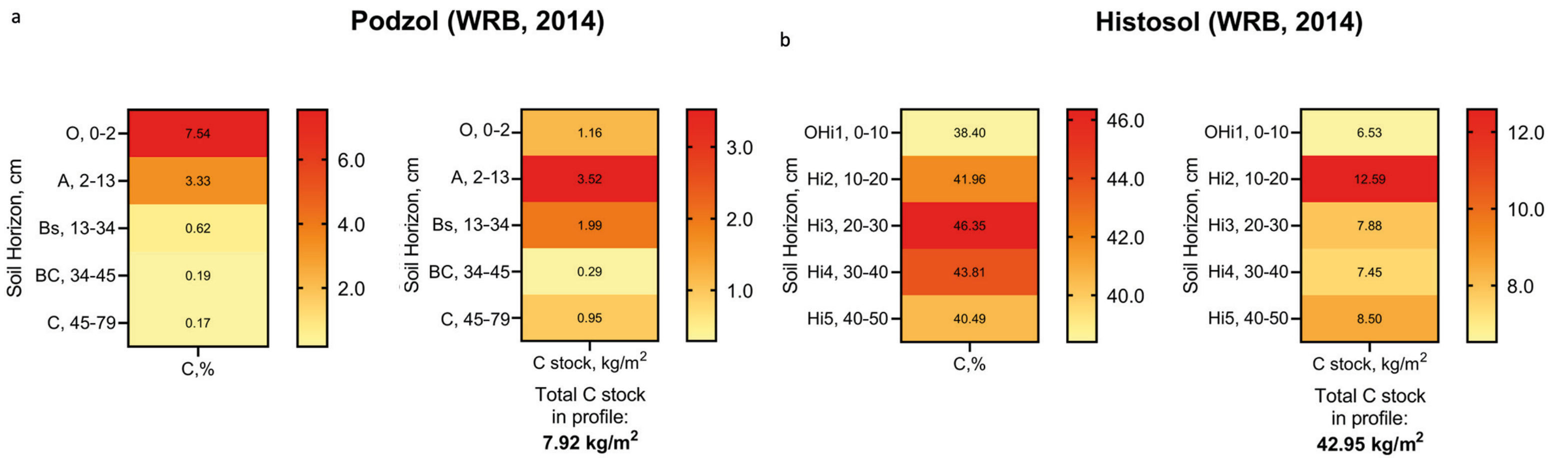


Fig. 3. Profile distribution of organic carbon stocks and total stock in the soil profile: a — podzol; b — histosol

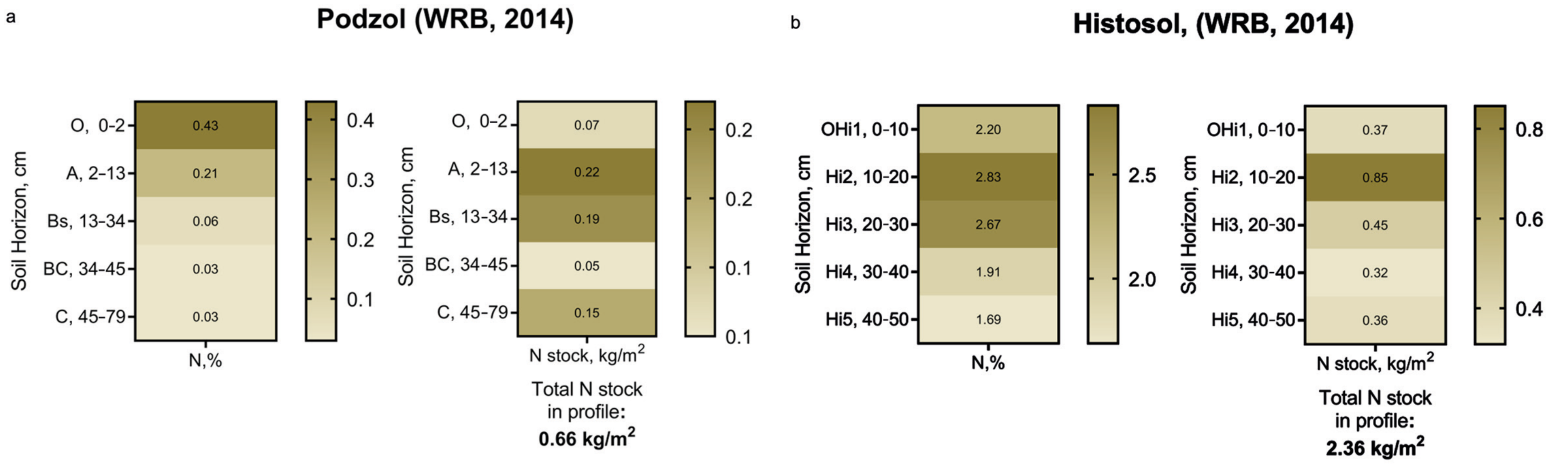


Fig. 4. Profile distribution of total nitrogen stocks in the soil profile: a — podzol; b — histosol

4. Carbon farms in the context of nature-based solutions projects

Carbon farms in the Russian Federation can be classified as nature-based solutions projects if, in the context of domestic legislation, they meet the basic criteria of the climate project specified in the Order of the Ministry of Economic Development of the Russian Federation No. 248 dated May 11, 2022. One of the most important criteria in this regard is "additionality", meaning that "the results of the project are the reduction (prevention) of greenhouse gas emissions and (or) an increase in their absorption (calculated in absolute and (or) specific units) relative to the projected result of quantifying greenhouse gas emissions or removals in the absence of a project during the project implementation period …" (Order of the Ministry of Economic Development of the Russian Federation No. 248 dated May 11, 2022). Thus, the "additionality" of the project is the presence of a difference between the reduction/absorption of greenhouse gases in the usual scenario (the so-called baseline) in comparison with the scenario of the implementation of the climate project. Carbon units are calculated as the difference between the baseline and the project scenario. Note that the effect of nature-based solutions projects from the point of view of additionality may be negative, and in this case it will be impossible to implement and monetize such a project (Business Solutions…, 2022), therefore, before implementing a climate project, it is important to assess its economic effect.

Currently, Russia is actively developing a regulatory and methodological framework for the implementation of nature-based solutions projects. Thus, the most promising areas for the development of forest projects are as follows (Business Solutions…, 2022):

1. Protection of ecosystems:
- projects on voluntary conservation of forests;
- forest fire projects to reduce the burning of forests.

2. Sustainable ecosystem management:
- projects on sustainable intensification of forest management.

3. Ecosystem restoration:
- reforestation;
- afforestation;
- watering of wetlands.

Each of these types of projects has its own specifics, as well as strengths and weaknesses (Fedorov, 2022). Currently, it is planned, for example, that projects on afforestation and increasing the productivity of plantings can be implemented on agricultural land (Fedorov, 2022).

Let's focus on a specific type of forest projects — afforestation on unused agricultural land. Here, as an example, we can mention a potential project to enhance carbon uptake by changing land use, which was developed by the operator of a carbon polygon in the Kaluga Region (Ugra National Park). It is expected that the increase in CO_2 uptake is ~1.44 thousand tons of CO_2/year from an area of ~145.3 hectares. In the baseline scenario (baseline), the land is returned to agricultural use, trees and shrubs are removed. The project scenario involves the prevention of logging (timber cutting), forestry management.

According to the VERRA international classification, such an approach can be attributed to the VM0015 Methodology for Avoided Unplanned Deforestation (v1.1), which consists in measures to protect forests from unplanned logging, protect forests on overgrown agricultural lands, and prevent the return of land to agricultural circulation. At the same time, the project should include only territories classified as "forest" at least 10 years before the start date of the project. The project may include forested wetlands, but not peat forests.

5. Assessment of the CO_2 absorbtion potential for forest carbon farms in the Leningrad Region

Considering the ability of the Leningrad Region to organise forest carbon farms (nature-based solutions projects) on agricultural lands, we will evaluate the CO_2 absorption potential (AP_{CO_2}) for this category of land. We will assume that the forest areas that previously (until 2021) were part of agricultural lands can be used to create carbon farms — managed ecosystems, while afforestation projects (strengthening carbon uptake by changing land use, described in paragraph 4) will be carried out on these territories.

According to the "Report on the condition and use of land in the Leningrad region in 2020" (Federal Service…, 2021), agricultural land accounts for 20.28 % of the total land fund of the Leningrad Region. In the Leningrad Region the total area of agricultural land (as of January 1, 2021) was $S_{agr} = 1701.3 \cdot 10^3$ ha.

As stated in Report 2021, "the largest part of agricultural land, amounting to $1246.7 \cdot 10^3$ ha (73.27 % — this value will be used further in equation (2) as $\cdot\, k_3 = 0.7327$), is in state ownership".

The agricultural lands are subdivided into several types of areas which are indicated in Table 2. Table 2 corresponds to Table 1.3 from Report 2021. Peculiarity of the agricultural lands in the Leningrad Region is that forest areas (see the seventh row of Table 2) prevail in that category — $848,6 \cdot 10^3$ ha (49.88 %), while agricultural areas are of $616 \cdot 10^3$ ha

Table 2. **Summary on distribution of agricultural land of the Leningrad Region by areas of different types**

N	Name of area	Square (10^3 ha)	Percentage of agricultural land (%)
1	Agricultural area, including	616	36.2
1.2	cropland	359	21.1
1.3	perennial plants	36.4	2.1
1.4	hayfields	119.6	7.0
1.5	pastures	101	5.9
2	*Forest areas*	*848.6*	*49.9*
3	*Forest plantations that are not part of the forest fund*	*76.4*	*4.5*
4	Under the roads	23.5	1.4
5	Buildings	11.1	0.7
6	Underwater	36.1	2.1
7	Marshes	59.9	3.5
8	Disturbed lands	2.3	0.1
9	Other	27.4	1.6
Total		**1701.3**	**100**

(36.21 %). It should be noted that forest plantations (see the eighth row of Table 2) which are not part of the forest fund provide an additional 4.5 % of the total area of agricultural lands, which together with forest areas constitutes 54.38 % (this value will be used further in equation (1) as $\cdot k_2 = 0.5438$). It should be noted that here we are not talking about forest lands belonging to the forest fund, namely, forest areas that were part of agricultural lands until 2021.

Forests on the territory of the Lenigrad Region are represented, with the exception of the north of the Karelian Isthmus and the northern part of the Lodeynopolsky District, by southern taiga boreal forests (Nitsenko, 1959; Sennikov, 2005). Most of the forest ecosystems are secondary — post logging, post pyrogenic, post agroforests of coniferous or mixed type, depending on the stage of post-anthropogenic succession. Most likely, there are unaffected forest areas only in the Veps forest on the border with the Vologda Region. Even the forests of Nizhnesvirsky Nature Reserve are secondary. The secondary nature of forests is a typical feature of the forests of the boreal belt of the European territory of Russia. Therefore, the territory of planned Ladoga carbon polygon is a typical site for both a carbon polygon and a carbon farm.

Let us estimate the AP_{CO_2} of total forest areas within state-owned agricultural land, using equation

$$AP_{\mathrm{CO}_2} = k_1 \cdot S_{carb\_farm} \cdot F_{\mathrm{CO}_2}, \tag{1}$$

where k_1 [dimensionless] is the relative part of land in $S_{\mathrm{carb\_farm}}$ directly occupied by carbon farms (assume $k_1 = 1$ at this stage, i. e. total area of $S_{\mathrm{carb\_farm}}$ is occupied by a farm); $S_{\mathrm{carb\_farm}}$ [m^2] is the total forest area within state-owned agricultural land (all these areas could be potentially occupied for the establishment of carbon farms). For the calculation of $S_{\mathrm{carb\_farm}}$ we used equation (2); F_{CO_2} [kg $\mathrm{CO}_2/(m^2$ yr)] is the average flux of CO_2 for the managed forest ecosystem. For the calculation of F_{CO_2} we used equation (3).

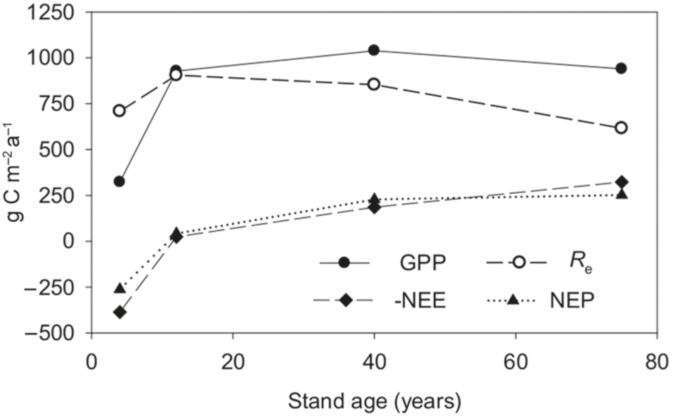
$$S_{carb\_farm} = S_{agr} \cdot k_2 \cdot k_3, \tag{2}$$

where S_{agr} [m^2] is the total area of agricultural land in the region; k_2 [dimensionless] is the proportion of agricultural land that is total forest area i. e. forest areas and forest plantations not included in the forest fund (see seventh and eighth rows of Table 2); k_3 [dimensionless] is the share of agricultural land owned by the state.

For an approximate calculation of the average CO_2 flux (F_{CO_2}) for managed forest ecosystems in the Leningrad Region, the results of carbon flux studies for Scots pine plantations of various ages (Kolari, 2010), obtained for the territory of Southern Finland bordering the Leningrad Region (geographically and climatically close regions), were used. Fig. 5 borrowed from (Kolari, 2010), shows the following values depending on the stand age in the range from 4 to 75 years:

$NEE(t)$ [g $C/(m^2 yr)$] is the net ecosystem exchange;
$GPP(t)$ [g $C/(m^2 yr)$] is the photosynthesis or gross primary productivity;
$R_e(t)$ [g $C/(m^2 yr)$] is respiration;
$NEP(t)$ [g $C/(m^2 yr)$] is the net ecosystem productivity.

The first three values are derived from eddy covariance measurements and are related by the following relationship: $NEE(t) = GPP(t) - R_e(t)$.



Annual net ecosystem exchange (NEE, negative sign for convenience), photosynthesis (GPP) and respiration (R_e) from eddy covariance in four different aged Scots pine stands (paper I). Net ecosystem productivity (NEP) is based on biomass inventories and modelled decomposition of cutting residue, positive values indicate carbon uptake by the stand, negative loss of carbon from the stand to the atmosphere.

Fig. 5. Values of NEE(t), GPP(t), Re (t), and NEP(t) for Scots pine plantations of various ages, obtained for the territory of Southern Finland bordering the Leningrad Region. Borrowed from: (Kolari, 2010)

We assume that the minimal lifetime of a forest plantation is of 70–80 years: when this age is reached, the stand can be cut down followed by a new plantation. Thus the average F_{CO_2} value for the forest ecosystem can be calculated as the integral of the *NEE* value over the period of available data (Kolari, 2010) from 4 (t_1) to 75 (t_2) years, normalized to the length of this period $T = 75 - 4 = 71$ years.

Since the plots in Fig. 5 show the carbon (C) fluxes, a multiplier equal to the ratio of the molecular weights of carbon dioxide $m_{\mathrm{CO}_2} = 44.01$ g/mol and carbon $m_{\mathrm{C}} = 12$ g/mol must be entered in equation to calculate F_{CO_2}.

$$\overline{F}_{\mathrm{CO}} = \frac{m_{\mathrm{CO}}}{m_{\mathrm{C}}}\frac{1}{T}\int_{t}^{t} NEE(t)dt, \tag{3}$$

where F_{CO_2} [kg $\mathrm{CO}_2/(m^2$ yr)] is the average flux of CO_2 for the forest ecosystem; m_{CO_2} [g/mol] is the molecular mass of CO_2; m_{C} [g/mol] is the molecular mass of *C; NEE* [kg *C*/(m^2 yr)] is the net ecosystem exchange; *t* [yr] is time, the integration variable; t_1, t_2 [yr] are integration limits; *T* [yr] is the duration of the integration period ($T = t_2 - t_1$), i. e. the lifetime of the managed ecosystem.

In order to perform the numerical integration, the plot in Fig. 5 (Kolari, 2010) has been digitised. We calculated F_{CO_2} for the idealised assumption that forest stands of different ages forming the forest carbon farm have equal areas, i. e. have the same weights in equation (3) (in practice this is usually not always the case). Hence, an approximate estimate of the average value of CO_2 flux for managed forest ecosystem (forest carbon farm) in the Leningrad Region is $F_{\mathrm{CO}_2} \approx 0.55$ kg $\mathrm{CO}_2/(m^2$ year), a positive sign of the value F_{CO_2} indicates that ecosystem absorbs CO_2. Thus, an upper bound for the CO_2 absorption potential $AP_{\mathrm{CO}_2} = 1701.3 \cdot 10^7 \cdot 0.7327 \cdot 0.5438 \cdot 0.55 = 373 \cdot 10^7$ kg CO_2/*yr* or ~3730 kt CO_2/*yr*

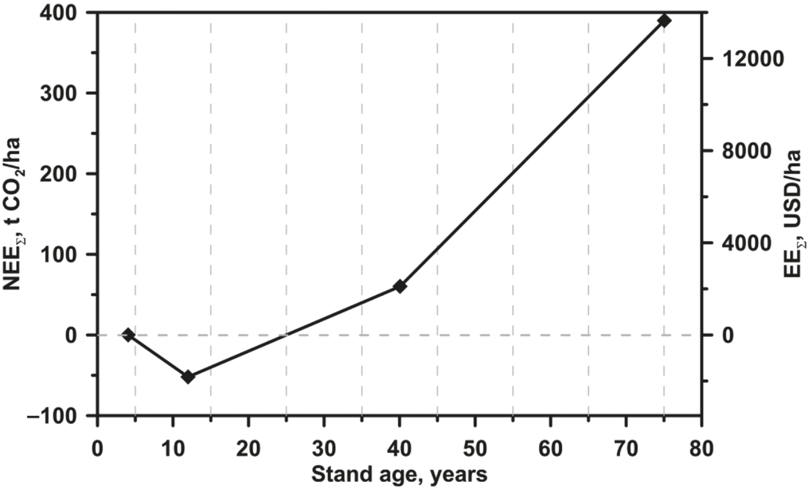


Fig. 6. Dependencies of the cumulative (integral) net ecosystem exchange $NEE_{\Sigma}(t)$ and its monetary equivalent $EE(t)$ on the stand age

for the hypothetical forest carbon farm with area of $S_{\text{carb\_farm}} = 677.9 \cdot 10^3$ ha (~8.1 % of the total area of Leningrad Region).

As described in (Kolari, 2010), the change in sign of the $NEE(t)$ flux for the considered forest carbon farm occurs around 12 years: from this age, the pine forests of Southern Finland become a sink for atmospheric CO_2. When considering the value of cumulative (integral) net ecosystem exchange $NEE_{\Sigma}(t)$ (see equation (4)) as a function of time (Fig. 6), we obtain that pine forest ecosystem reaches carbon neutrality only by the age of 25 years, i. e. carbon emission during the first 12 years of the ecosystem life offsets only by the age of 25.

$$NEE_{\Sigma}(t) = \frac{m_{\text{CO}_2}}{m_{\text{C}}} \int_{t_1}^{t} NEE(t)dt, \tag{4}$$

where $NEE_{\Sigma}(t)$ [kg CO_2/m^2] is the cumulative (integral) net ecosystem exchange; m_{CO_2} [g/mol] is the molecular mass of CO_2; m_{C} [g/mol] is the molecular mass of C; NEE [kg $C/(m^2$ yr)] is the net ecosystem exchange; t [yr] is time, the integration variable; t_1 [yr] is the lower limit of integration.

6. Discussion

For the forests of the Leningrad region, if we use the information of the Leningrad Region Administration (2019), we get that F_{CO_2} lies in the range from 0.6 kg $CO_2/(m^2$ yr) to 3.4 kg $CO_2/(m^2$ yr). Other independent published estimates of F_{CO_2} also have considerable uncertainties, up to ~50 % (Kolari, 2010; Stephens et al., 2007). In papers (Stephens et al., 2007; Magnani et al., 2007) long-term average of CO_2 absorption by European forests is estimated to be 70 g $C/(m^2$ yr) (in CO_2 units 0.26 kg $CO_2/(m^2$ yr)) and 90 g $C/(m^2$ yr) (in CO_2 units 0.33 kg $CO_2/(m^2$ yr^2)), respectively. Thus, with an estimate of error (uncertainty), the value of $AP_{\text{CO}_2} = (3700 \pm 1900)$ kt CO_2/yr.

The economic effect of operating a carbon farm can be demonstrated as a plot of the $EE(t)$ which is a monetary equivalent of $NEE_\Sigma(t)$. For this purpose, we use available data on the price of carbon units according to the Decree of the Government of the Russian Federation No. 518 of 30.03.2022 resolution "On the procedure for determining the fee for the provision of services by the operator for operations in the register of carbon units" at a minimum level of 2000 rubles per carbon unit or 35 USD. It should be noted that, by 2050, Bloomberg forecasts prices from 50 USD to 120 USD per ton depending on the scenario (Beloglazova, 2022). We will evaluate the economic feasibility at the minimum threshold level, so we believe that the average price of a ton of CO_2 in Russia is about 2000 rubles or 35 USD. For convenience, let us estimate the economic effect for the area of 1 hectare of the forest carbon farm, i. e. $EE(t)$ will have the dimension [USD/ha]. The dependencies of $NEE_\Sigma(t)$ and $EE(t)$ on the age of the forest stand are shown in Fig. 6. Thus, while maintaining the current price level per ton of CO_2, for its 75-year cycle of existence, a 1-hectare plantation will approximately bring income due only to the deposition of CO_2 from the atmosphere (not including the cost of wood) at the level of ~560 thousand rubles or 9.5 thousand USD, taking into account investment and operating costs in the amount of ~262 thousand rubles for planting and maintaining 1 ha of plantation (Morkovina et al., 2021).

Comparison of absorption potential with CO_2 emission data for Leningrad Region and St. Petersburg. "Strategy for socio-economic development of the Russian Federation with low greenhouse gas emissions until 2050" (hereinafter "Strategy 2050")[4] aims to ensure a reduction of GHG emissions by 2030 to 70 % relative to 1990 levels, taking into account the maximum absorption capacity of forests and other ecosystems and subject to sustainable and balanced socio-economic development of the Russian Federation. It should be noted that Russia has already achieved this target in 2020 (TASS, 2020), which is also confirmed by information on total GHG emissions in Russia, presented in the international database EDGAR (Crippa et al., 2021).

Strategy 2050[5] assumes that, by 2050, net GHG emissions would be reduced by 60 % of 2019 levels and 80 % of 1990 levels. Further implementation of this scenario would allow Russia to achieve carbon neutrality by 2060[6]. Comparison of our AP_{CO_2} values with integral CO_2 emissions for Leningrad Region and St. Petersburg allows us to estimate the possible contribution of forest carbon farms to achieving carbon neutrality of the region. The region can be understood here both as the Leningrad Region separately (without St. Petersburg) and as a union of the Leningrad Region and St. Petersburg.

Table 3 gives information on the CO_2 emissions for the Leningrad Region and St. Petersburg obtained from official information sources (Administration of the Leningrad Region, 2019; Government of St. Petersburg, 2018), evaluated by the authors of current study (Ionov et al., 2021; Makarova et al., 2021), and calculated using information from the EDGAR database (Crippa et al., 2021) on CO_2 emissions per capita in Russia. CO_2 emissions per capita in Russia for 1990, 2015, 2019 and 2020 were: 16.23, 12.05, 12.36 and 11.64 $t\ CO_2$ /cap, respectively (Emissions Database for Global Atmospheric Re-

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[4] Strategy of socio-economic development of the Russian Federation with low greenhouse gas emissions until 2050. Order No. 3052-r dated October 29, 2021. [online] Available at: http://static.government.ru/media/files/ADKkCzpfWOeyABhtIpyzWfHaiUa33220.pdf [Accessed 10.10.2022].

[5] Ibid.

[6] The Government has approved the Strategy for Socio-Economic Development of Russia with Low Greenhouse Gas Emissions until 2050. [online] Available at: http://government.ru/news/43708/ [Accessed 10.10.2022].

search, 2021). Using official data for the same years on the population of the Leningrad Region (1.67, 1.78, 1.85 and 1.88 million people) and St. Petersburg (5.00, 5.19, 5.38 and 5.40 million people), we obtain the corresponding estimates of CO_2 emissions given in the fourth row of Table 3. Note that unofficial estimates of St. Petersburg's population (Kiber, 2021) based on big data technology are higher than the official ones by about 1.6 million people (2020). In this case the value of integrated CO_2 emission for St. Petersburg increases to ~81400 kt CO_2/yr.

Table 3. **Integral CO_2 emissions for the Leningrad Region and St. Petersburg; estimates of CO_2 absorption by forest ecosystems in the Leningrad Region**

Source of information	**Integral CO_2 emission, kt/yr**		**CO_2 absorption, kt/yr**
	Leningrad region	**St. Petersburg**	**Leningrad Region (forest ecosystems)**
Official reports on the environmental situation (Administration of the Leningrad Region, 2019; Government of Saint Petersburg, 2018)	19 327.5 (2018) 16 941.5 (2015)	29 571 (2015)	3000–16 000 (source category 5A "Forest lands", area 4719.0· 10^3 ha)
Independent literature data (Ionov et al., 2021; Makarova et al., 2021)	–	68 400 (2020) 75 800 (2019)	–
EDGAR database (Crippa et al., 2021)	21 900 (2020) 22 900 (2019) 21 400 (2015) 27 100 (1990)	62 900 (2020) 66 500 (2019) 62 500 (2015) 81 200 (1990)	–
The present work	–	–	3700 ± 1900 (forest carbon farms, area 677.9 · 10^3 ha)

For St. Petersburg a significant variation of the given estimates of integral CO_2 emissions is noteworthy. For the Leningrad region the official data on integral CO_2 emissions are close to the estimates obtained using the EDGAR database.

Thus, based on the information in Table 3, it can be concluded, that the AP_{CO_2} of forest carbon farms, which can be organized in the Leningrad Region on the territory of forest areas that were previously part of state agricultural lands, can offset of 20% of the integral CO_2 emissions of the Leningrad Region and up to 8 % of the integral CO_2 emissions of St. Petersburg and Leningrad Region together.

As stated in the report "On the Environmental Situation in the Leningrad Region in 2019" (Administration of the Leningrad Region, 2019): "In the Land Use sector, the carbon dioxide balance is estimated as the sum of emissions and sinks for source category 5A "Forest lands". For the entire inventory period, this sector is a sink of CO_2 with total annual removals ranging from 3000 Gg to 16000 Gg in different years. CO_2 sequestration in the sector offsets, on average, up to 50 per cent of GHG emissions over the period". We assume that this estimation of CO_2 sink refers to 4719.0 · 10^3 ha of lands of forest fund.

Note that the estimate of $AP_{CO_2} = (3700 \pm 1900)$ kt CO_2/yr obtained in this paper for hypothetical forest carbon farm having area $S_{carb\_farm} = 677.9 \cdot 10^3$ ha is comparable to the lower limit of the range of total annual CO_2 absorption 3000–16000 kt · CO_2/yr for lands of forest fund (area $4719.0 \cdot 10^3$ ha) (Administration of the Leningrad Region, 2019).

7. Summary

An estimate of CO_2 absorption potential $AP_{CO_2} = (3700 \pm 1900)$ kt CO_2/yr has been derived for the hypothetical forest carbon farms located in the Leiningrad Region and having total area of $S_{carb\_farm} = 677.9 \cdot 10^3$ ha. This value of AP_{CO_2} is obtained on the assumption that 100 % of forest areas (forest areas and forest plantations not included in the forest fund), which were part of the state agricultural lands of the Leningrad Region until 2021, are used through afforestation (increased carbon uptake by changing land use) for the organization of carbon farms — a new sequestration carbon enterprises. At the same time, we emphasise that the legal, financial and economic issues related to the possibility of using agricultural lands for climate projects for the organisation of forest carbon farms are currently under development in Russia.

When organising carbon polygons and farms in the Leningrad region, involving new forest plantations, it must be taken into account that the economic effect can only be achieved in the long term. This is due to the fact that the compensation of carbon emissions observed on average during the first 12 years of life of the forest ecosystem (Scots pine) occurs only by the age of 25 years. While maintaining the current price level per ton of CO_2 (2000 rubles/t CO_2 or 35 USD/t CO_2) for a 75-year cycle of existence, the 1 ha of forest plantation will bring income due only to the deposition of CO_2 from the atmosphere at the level of ~ 560 thousand rubles or 9500 USD (including investment and operating costs). To achieve a faster effect, it is possible to consider the use of fast-growing tree species. However, it should be taken into account that coniferous forests have a higher carbon-absorbing capacity in the long term. At the same time, an increase in the price of carbon units is very likely.

It is shown that the CO_2 absorption of forest carbon farms, which can be organized in the Leningrad Region on the territory of former forest areas as part of state agricultural lands (~8.1 % of the entire territory of the Leningrad Region), can offset of 20 % of the integral CO_2 emissions of the Leningrad Region and up to 8 % of the integral CO_2 emissions of St. Petersburg and Leningrad Region together.

One of the promising area for related research is the assessment of damage caused by air pollution of St. Petersburg and the Leningrad Region, which, similarly to European studies, can be carried out as part of the development of carbon polygon project.

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От карбонового полигона к карбоновой ферме: потенциал и пути развития секвестрационной углеродной индустрии на территории Ленинградской области и Санкт-Петербурга*

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Изменение климата — важнейшая международная проблема XXI в. Территория Российской Федерации находится в области значительных наблюдаемых и прогнозируемых изменений климата. Для достижения Россией углеродной нейтральности к 2060 году необходима национальная система мониторинга эмиссии и поглощения парниковых газов. С этой целью МНВО запустило программу создания сети карбоновых полигонов. СПбГУ и ФГБУ «ГГО» разработали проект карбонового полигона «Ладога», нацеленный на исследование потенциала поглощения парниковых газов лесными экосистемами Северо-Запада России. Развитие проекта предусматривает создание карбоновой фермы на территории Ленинградской области. Исходя из предположения, что территории лесных площадей, находившиеся ранее в составе государственных земель сельхозназначения Ленинградской области, могут быть задействованы под карбоновые фермы (климатические проекты по лесоразведению,

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усилению поглощения углерода путем изменения землепользования), была сделана оценка поглощения CO_2. Для общей площади карбоновых ферм ~677.9 тыс. га она составила 3700 ± 1900 кт CO_2/год или (1000 ± 520) ·10^6кг C/год. Потенциал поглощения CO_2 таких карбоновых ферм может составлять до ~20 % от интегральной эмиссии CO_2 Ленинградской области и не более 8 % от интегральной эмиссии CO_2 для объединенного региона, состоящего из Ленинградской области и Санкт-Петербурга. Экономический эффект от функционирования карбоновых ферм может быть достигнут только в долгосрочной перспективе. При сохранении текущего уровня цен за тонну CO_2 (35 долл./т CO_2) за 75-летний цикл существования участок леса площадью 1 га принесет доход, обусловленный депонированием CO_2 из атмосферы, на уровне ~9.5 тыс. долл. Этим определяется экономическая целесообразность создания карбоновых ферм, которая также обусловлена потенциальной возможностью выпуска на их базе углеродных единиц, которые будут либо обращаться на углеродных биржах, либо приниматься к зачету в качестве результатов деятельности, направленной на сокращение углеродных выбросов.

Ключевые слова: углеродная нейтральность, углеродный цикл, углеродное поглощение, углеродный баланс, углеродный полигон, углеродная ферма, углекислый газ, парниковые газы, репрезентативные экосистемы, изменение климата, климатические проекты, углеродсвязывающая промышленность, антропогенные выбросы, Ленинградская область, Санкт-Петербург.

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