Quantity Assessment of
Environmental Impact Compensation by Reforestation
Project Implemented by REHAU.

Introduction

Due to the increasing anthropogenic environmental impact, as well as the increasing relevance of climate change, one of the key problems of environmental science has become the search for a single indicator capable to measure both the negative environmental impacts output (in any form), and the results of efforts for reducing impact and compensation of the environmental damage. This indicator should have properties such as measurability, representativeness for assessing in various conditions (geographical, climatic), free conversion into indicators that quantify all anthropogenic environmental impact and measures to reduce them.

Currently the most popular and widely used indicator is the carbon balance – the sum of carbon flows between natural and artificial reservoirs in the geochemical cycle. The atmosphere is the most important carbon reservoir that has a global impact on ecosystems, natural processes and human economic activity. The carbon balance of the atmosphere in contemporary history is positive: the amount of carbon dioxide (CO_2) and methane (CH_4) in atmosphere grows, moreover, this growth is abrupt and tends to increase [1], [2]. The rapid of growth CO_2 and CH_4 concentrations is primarily due to anthropogenic emissions from the using of fossil fuel, land use change and deforestation [3], forest degradation (economic development of intact forest landscapes), logging in forests on permafrost soils, forest fires, etc. Both CO_2 and CH_4 are greenhouse gases and the anthropogenic growth of their concentration in the atmosphere is the cause of climate change, which is a threat to the stability of the environment, and humanity and its economic activities as well. Insofar as the concentration of CO_2 in the atmosphere is higher, as well as anthropogenic emissions of CO_2 are greater, CH_4 is often taken into account in carbon dioxide equivalent. In general, both CO_2 and CH_4 are converted into pure carbon.

At the same time, the scale of impacts associated with carbon emissions is enormous: carbon pollution is the strongest factor of anthropogenic impact on the environment both in absolute terms and in its consequences. The impact of carbon emissions is global and affects all ecosystems of the Earth, carbon is emitted into the atmosphere at all stages of production and consumption of products and services.

Based on this, to quantify the impact of any activity on the carbon balance, and through it on the environment, we have to calculate the carbon footprint as the amount of CO_2 and CH_4 emitted by this activity reduced to carbon equivalent. Using information about the carbon footprint of a particular activity, it is possible to implement measures to reduce or compensate it effectively. These actions will

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[1] Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Josep G. Canadell; at al., – PNAS, 2007.

[2] A 40-million-year history of atmospheric CO2. Zhang, Yi Ge; et al., – Philosophical Transactions of the Royal Society, 2013.

[3] IPCC Fourth Assessment Report, Working Group I Report «The Physical Science Basis», Section 7.3.3.1.5.

lead to a reduction or complete neutralization of the negative environmental effects of the activity through a shift in the carbon balance.

Obviously is also necessary to represent an assessment of the results of measures aimed to compensation of the environmental impact in carbon equivalent. This is clear, since carbon is the main component of living systems and has an active geochemical cycle. Carbon will dynamically transfer between reservoirs in response to the measures being implemented.

One of the effective measures of compensation of the carbon footprint is reforestation. Carbon, being a basic element of organic matter, accumulates within the biomass of an ecosystem. Among terrestrial ecosystems, forests have the highest productivity, so the carbon reservoirs of forests are also the largest on land. In the process of growth trees and other forest plants accumulate carbon in the phytomass. Carbon is withdrawn from the atmosphere at least for the lifetime of an organism, which for trees is tens and hundreds of years. However, carbon will not be fully returned to the atmosphere even after the death of the tree stand. Organic substances of the litter gradually forming during the life cycle of the forest, dead trees, and all of other organic residues will partially accumulate in the organic matter of the forest litter and soil. Up to 46% of the total carbon accumulated by the plant during its lifetime can remain in this reservoir [4]. The described process of carbon deposition is especially strong in boreal forests, where carbon can accumulate in peat soils for millennia [5].

So, forests are capable of both long-term, but temporary accumulation of carbon from the atmosphere, and its deposition for a longer period, which allows simultaneously reduce the intensity of anthropogenic environmental impact and contribute to its reduction. Therefore, reforestation and conservation of forest landscapes, prevention of deforestation are effective measures to compensate the carbon emission and other anthropogenic impacts in carbon equivalent. At the same time, the huge diversity of forest ecosystems and landscapes, causes heterogeneity of carbon accumulation in various reservoirs of forest ecosystems due to different external conditions. Temperature, precipitation, physical and chemical composition of the soil affect both the growth rate of forests and their biological productivity, as well as carbon accumulation by forest litter and soil. In turn, the breed structure and density of plantings, reforestation technology determine the amount of carbon deposited in phytomass. The variety of combinations of these factors determines the need for an information and analytical assessment of the carbon budget of each forest on the local level. Summary for a project aimed to compensation of the environmental impact through reforestation, it is important to assess the amount of carbon storage in each particular tree stand.

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[4] Global Forest Resources Assessment – FAO, 2010

[5] Soil organic carbon pools in the northern circumpolar permafrost region. Tarnocai et al., – Global Biogeochemical Cycles, 23(2),2009.

Methodology for assessment of carbon accumulation as a result of reforestation activities

For a quantitative assessment of the compensation effect the Methodology for Information and Analytical Assessment of Forest Stands Carbon Budget at a Local Level [6] is used. The Methodology was developed by the Center for Ecology and Productivity of Forests for the Russian Academy of Sciences.

According to the Methodology, carbon absorption is assessed in 4 carbon reservoirs (pools): living phytomass, dead timber, litter and soil in accordance to recommendations of the Intergovernmental Panel on Climate Change (IPCC) [7].

For litter and soil pools the IPCC methodology for assessment of carbon change in these pools when transfer from one management regime to another is applied [7]. According to this approach volume of the litter reservoir is zero before a reforestation project and its stable level is achieved in 20 years [8].

Assessment is made for a single stand, the following data is considered: area (in hectares), species composition, age (in years). For each tree species the following data in needed: average height (in meters), average diameter (in centimeter), timber volume (m^3/ha). For not closed forest stands (with average height below 1.3 m) information on stand density (pc/ha) is used instead. Information on soil type and time elapsed since soil treatment stopped (years).

Assessment of carbon accumulation in phytomass and dead timber pools are based of a difference of volumes occurring due to dying of trees in the stand. Calculations are based on data on volumes of stands obtained through repetitive inventories. Due to field inventory is delayed at all areas because of small age of stands and other reasons listed below, we use data on volumes dynamics from regional growth progress tables. These tables consider local features of stands growth and development and reforestation techniques. This approach is allowed by the Methodology of Carbon Accumulation Forecast and consistent with the key objective of the report. When no regional growth progress tables available, it is possible to use generalized growth progress tables for forest stands. For stands older then the starting point of tables linear interpolation is used. However, in the youngest ages the dependence could be unlinear interpolation is used based on height, diameter and density of stands.

Calculation algorithm to assess carbon absorption by regenerated forest stands includes the following steps:

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[6] Zamolodchikov, D.G., V.I. Grabovsky, G.I. Kraev. Informational and Analytical Assessment of Carbon Budget of Forest Stands at a Local Level. Version 1.1. Moscow: Center for Forest Ecology and Productivity of the Russian Academy of Sciences, 2019. http://old.cepl.rssi.ru/local.htm

[7] Good Practice Guidelines for LULUCF. IPCC Program on National Greenhouse Gas Inventories. IPCC, 2003.

[8] Chestnykh, O.V., V.A Lyzhin, A. V. Koksharova. Carbon Stocks in Litter in Forests of Russia // Forestry. 2007. # 6. 114-121 pp.

1. Carbon stock in k tree species phytomass is calculated by the following formula:

$$CPh_k = 0.5\ M_k\ D_k\ BEF_k\ (1+R_k)$$

where:

CPh_k – carbon stock in k tree species phytomass, t C/ha,

M_k – timber volume of k tree species, m^3/ha;

D_k – conversion coefficient from timber volume of k tree species into trunk phytomass, $t \times m^{-3}$;

BEF_k – phytomass expansion factor, specific for k tree species;

R_k – ratio of underground phytomass to above ground phytomass specific for k tree species;

0.5 – coefficient of calculation from organic biomass into carbon.

2. Forest stand phytomass carbon volume is calculated by the formula:

$$CPhS = \Sigma\ (P_k\ CPh_k)/10$$

where:

CPhS – forest stand phytomass carbon volume, t C/ha;

P_k – share of k tree species in the species composition of the stand, from 1 to 10;

CPh_k – k tree species phytomass carbon volume, t C/ha.

3. Forest stand phytomass pool carbon budget is calculated by the formula:

$$BCPhS_i = CPhS_i - CphS_{i-1}$$

where:

$BCPhS_i$ – forest stand phytomass pool carbon budget for a year i, $\frac{t\ C/ha}{year}$

$CPhS_i$ – forest stand phytomass pool carbon volume for a year i, t C/ha;

$CphS_{i-1}$ – forest stand phytomass pool carbon volume for the previous year i-1, t C/ha.

For the first year of a stand existence its previous carbon accumulation is considered to be a zero.

4. Carbon volume in dead wood of k tree species in a year i is determined by a formula:

$$CD_{ki} = CPh_{ki}\ KD_{ki}$$

where:

CD_{ki} – k tree species dead wood carbon volume in a year i, t C/ha;

CPh_{ki} – k tree species phytomass volume in a year i, t C/ha;

KD_{ki} – conversion coefficient for dead wood carbon volume calculation from phytomass carbon volume.

5. Dead wood carbon volume in a forest stand in a year I is determined by a formula:

$$CDS_i = \Sigma\ (P_k\ CD_{ki})/10$$

where:

CDS_i – dead wood volume of a stand in a year i, t C/ha;

P_k – share of the k tree species in the species composition of the stand, from 1 to 10;

CD_{ki} – dead wood carbon volume of k tree species in a year i, t C/ha.

6. Forest stand dead wood carbon pool balance is determined by the formula:

$$BCDS_i = CDS_i - CDS_{i-1}$$

where:

$BCDS_i$ – forest stand dead wood carbon pool balance for a year i, $\frac{t\ C/ha}{year}$;

CDS_i – forest stand dead wood carbon volume in a year i, t C/ha;

CDS_{i-1} – forest stand dead wood carbon volume in the previous year i-1, t C/ha.

For the first year of a stand existence its previous carbon accumulation is considered to be a zero.

7. Carbon budget for a litter pool is calculated for the first 20 years since stand establishment only. For the subsequent years carbon absorption by a litter pool is considered zero. Litter pool carbon budget in any of the 20 subsequent years can be calculated:

$$BLS = \Sigma\ (P_к\ BL_k/10)$$

where:

BLS – forest stand litter pool carbon budget, $\frac{t\ C/ha}{year}$;

P_k – share of k tree species in the stand, from 1 to 10;

BL_k – k tree species litter carbon absorption, $\frac{t\ C/ha}{year}$.

8. Soil pool carbon budget is determined by the formula:

$$BS_i = a_j\ e^{-bj(i+t)}$$

where:

BS_i – carbon absorption by soil in the stand age i, $\frac{t\ C/ha}{year}$;

t – time elapsed from the moment when soil treatment (ploughing) was stopped and till a forest stand was established, years.

a_j – parameter a of a j soil type carbon absorption calculation;

b_j – parameter b of a j soil type carbon absorption calculation.

9. Forest stand carbon budget for all pools for a year i is calculated by the formula:

$$BC_i = BCPhS_i + BDS_i + BLS + BS_i$$

where:

BC_i – forest stand carbon budget for all pools for a year i, $\frac{t\ C/ha}{year}$;

$BCPhS_i$ – forest stand phytomass pool carbon budget for a year i, $\frac{t\ C/ha}{year}$;

$BCDS_i$ – forest stand dead wood carbon pool budget for a year i, $\frac{t\ C/ha}{year}$;

BLS – forest stand litter carbon pool budget, $\frac{t\ C/ha}{year}$;

BS_i – soil carbon absorption for a year i, $\frac{t\ C/ha}{year}$.

10. Carbon absorption calculation for the whole reforested area is accomplished by the formula:

$$BCT_i = S\ BC_i$$

where:

BCT_i – carbon budget for all pools for the whole forest stand are for a year i, t C/year;

S – forest stand area, ha;

BC_i – forest stand carbon budget for all pools for a year i, $\frac{t\ C/ha}{year}$.

11. Carbon absorption conversion into CO_2 equivalent is accomplished by the formula:

$$BCO_2 = \frac{BCT_i \times 44}{12}$$

where:

BCO_2 – phytomass carbon absorption converted into carbon dioxide, t CO_2

BCT_i – carbon budget for all pools for the whole forest stand area for the year i, t C/year;

44 – CO_2 molar weight, g/mol;

12 – C molar weight, g/mol.

This methodology is a basis for a computer program [[9]], designed for automatic calculation when all necessary data is provided. This computer program is used for automatic data processing hereinafter.

Carbon accumulation forecast for reforested areas established in the framework of environment footprint compensation measures

In accordance to the methodology described, the results of reforestation accomplished under the Agreement # 2/AMO of 17.08.2021 in the fall of 2021 are assessed below. The output of the assessment is a forecast for carbon absorption in forest stands phytomass converted into CO_2 volume from the moment when these stands have been established till the age of 7. This time period is chosen because in the most cases after 7 years a forest stand could be considered to be a full-fledged forest (for Siberian pine this period is longer but for this report the uniform approach to the forecast was taken for the sake of data consistency).

In this report carbon absorption forecast will be provided for phytomass of the established forest stands only, because in the early years of stands development

[9] http://old.cepl.rssi.ru/carbondoc/local/loc2.xls

volumes of dead wood could be neglected, and also litter and soil pools cannot be assessed with an acceptable accuracy since it can be based only on theoretical approaches to carbon absorption by various soil types but local factors are not taken into consideration.

In the frame of the project 30.4 hectares were reforested in 2 regions of Russia in 2 forest regions, 104 500 trees of 2 species were planted. See details in the Table 1.

#	Region of Russia	Forest management unit	Local division of the forest management unit	Forest region	Quarter	Location	Area, hectares	Species	Number of trees
1	Republic of Altay	Turochanskoe	Iogachskoe	Altay-Sayan Mountain Taiga	41	6	18.5	Siberian pine	57350
2	Republic of Altay	Turochanskoe	Iogachskoe	Altay-Sayan Mountain Taiga	11	19	6.5	Siberian pine	20150
3	Moscow region	Orekhovo-Zuevskoe	Likinskoe	Conifer-Broadleaved (mixed) forests of European Russia	47	2;5;6;12;13;21	5.4	Scots pine	27000
Всего:							30.4		104 500

Table 1. Data on reforestation areas, locations, tree species and number of planted trees

Scots pine reforestation in the Moscow region

Data on volume dynamics of pine stands in the Moscow region is obtained from the growth progress tables of dense (normal) pine stands [[10]]. Total area of reforestation is 5.4 hectares, density 5.0 thousand pc / hectares on grey forest soils, II forest bonity, the age of transfer to forest - 7 years.

Carbon accumulation in phytomass at 7 years will be 186.8 tons of CO_2 equivalent. Forecast of carbon accumulation on phytomass is provided in a Diagram 1 and Table 2.

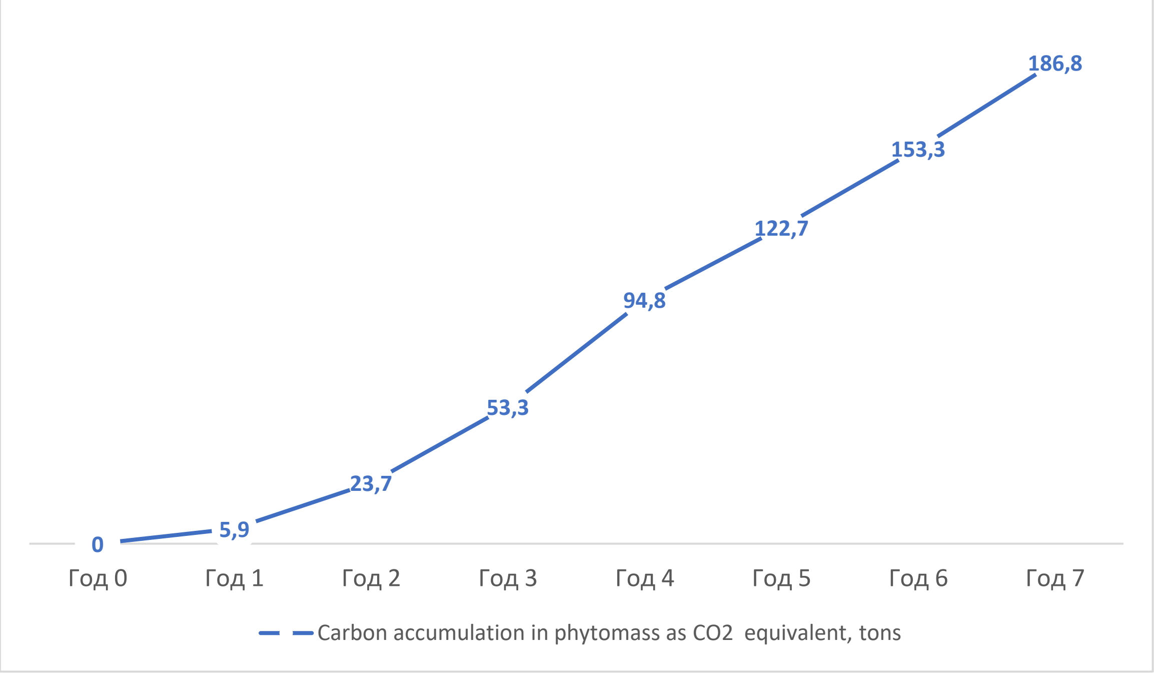

Diagram 1. Phytomass carbon accumulation forecast in pine stands in the Moscow region for years from 1 to 7.

Year	C accumulation in phytomass, t	CO_2 equivalent, t
0	0	0.0
1	1.61	5.9
2	6.46	23.7
3	14.54	53.3
4	25.86	94.8
5	33.46	122.7
6	41.82	153.3
7	50.94	186.8

Table 2. Carbon accumulation forecast in phytomass of pine stands in the Moscow region from year 1 to 7.

[10] Zagreev, V.V. Forest Stands Geographical Regularities of Growth and Productivity. Moscow: Forest Industry, 1978.

Siberian pine reforestation in the Republic of Altay

Data on volume dynamics of Siberian pine stands in the Republic of Altay is obtained from the growth progress tables of dense (normal) Siberian pine stands [[11]]. Total area of reforestation is 25.0 hectares, density 3.1 thousand pc / hectares on grey forest soils, II forest bonity, the age of transfer to forest - 10 years.

Carbon accumulation in phytomass at 7 years will be 299.2 tons of CO_2 equivalent. Forecast of carbon accumulation on phytomass is provided in a Diagram 2 and Table 3.

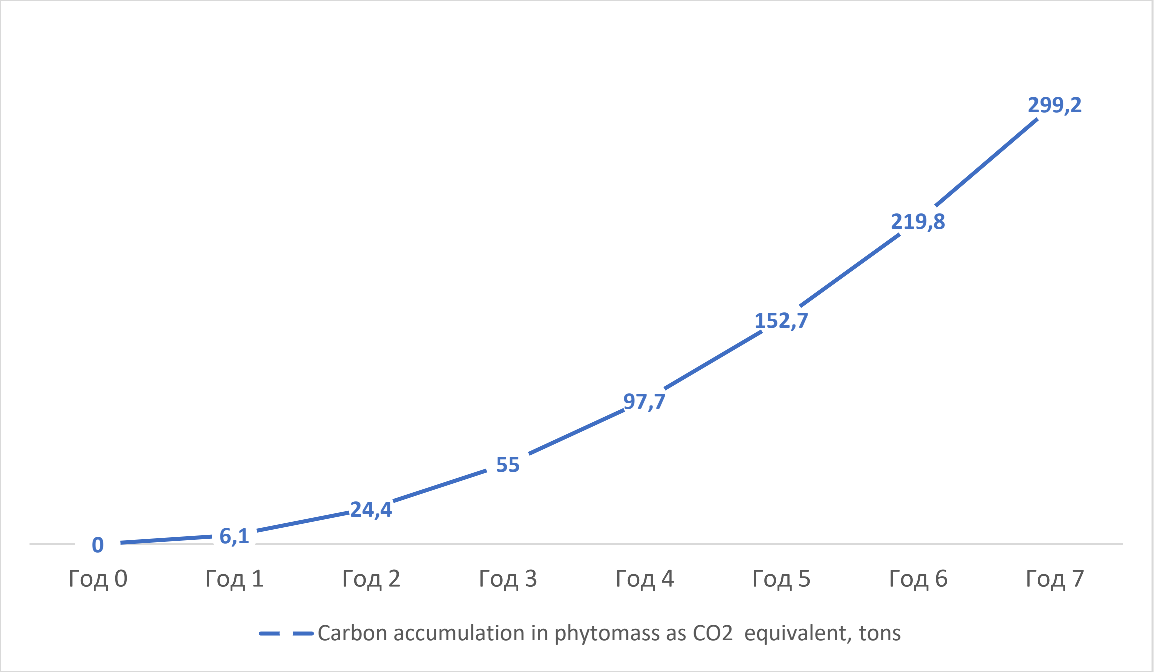

Diagram 2. Phytomass carbon accumulation forecast in Siberian pine stands for years from 1 to 7.

Year	C accumulation in phytomass, t	CO_2 equivalent, t
0	0	0.0
1	1.66	6.1
2	6.66	24.4
3	14.98	55.0
4	26.64	97.7
5	41.63	152.7
6	59.95	219.8
7	81.60	299.2

Table 3. Carbon accumulation forecast in phytomass of Siberian pine stands from year 1 to 7.

11 Shvidenko, A.Z., D.G. Schepaschenko, S. Nilsson, Yu.I. Buluy. Tables and Models of Growth and Productivity of Forests of Major Forest Forming Species of Northern Eurasia (standand reference materials). 2-nd edition. Moscow: Federal Forest Service, 2008. 886 pp.

Generalized forecast

Total accumulated carbon volume in phytomass in all reforested areas by the year 7 is 486 tons of CO_2 equivalent. Total reforested area is 30.4 hectares, average stand density is 3.42 thousand pc / hectare. Please see the forecast of carbon accumulation in phytomass in the Diagram 3 and Table 4.

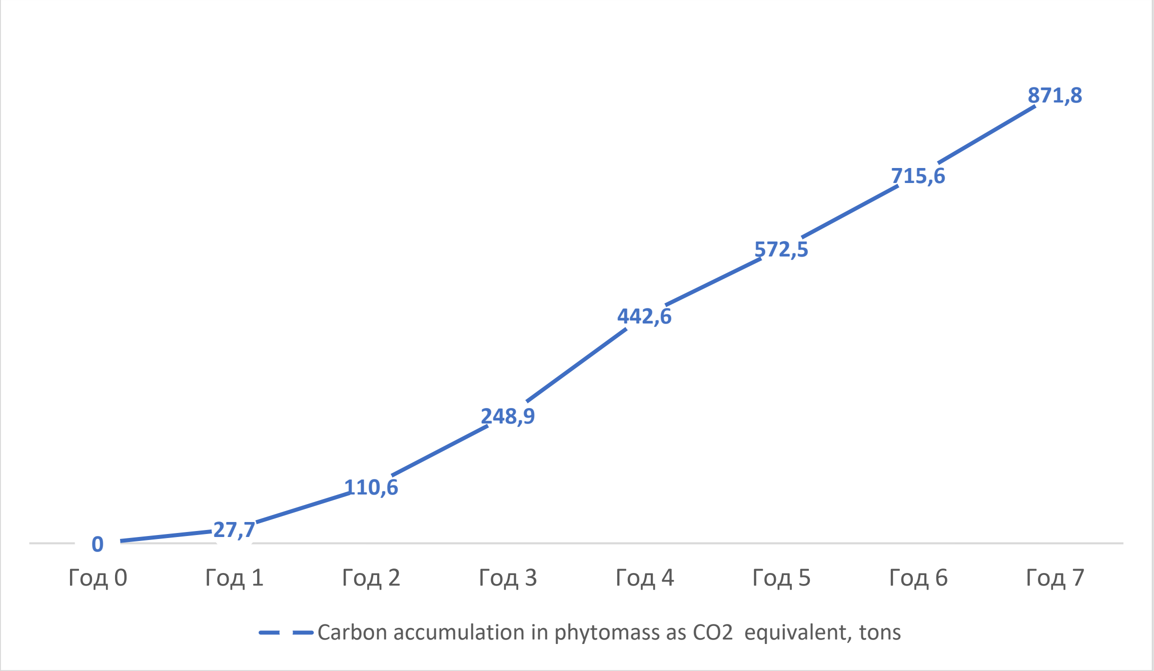

Diagram 3. Carbon accumulation forecast in phytomass for all established stands from year 1 to 7.

Year	C accumulation in phytomass, t	CO_2 equivalent, t
0	0	0.0
1	3.28	27.7
2	13.12	110.6
3	29.53	248.9
4	52.50	442.6
5	75.09	572.5
6	101.77	715.6
7	132.55	871.8

Table 4. Total accumulated carbon volume in phytomass in all reforested areas from year 1 to 7.

In average, volume of CO_2 accumulated in 1 hectare of stands till 7 years is 28.7 tons.

Forecast limitations

Despite the solid and tested methodology was used to develop this forecast, there are several limitations related to the specifics of the methodology and the project:

1. Accuracy of the forecast version of the methodology correlates with correct choice of growth progress tables for retrospective analysis of biomass accumulation in the first years of stand existence. It is a challenge to ensure precise consistency of reference data with real stand development under specific characteristics of a reforestation area even when regional tables are applied. Some scientific discussions are going on relevance of growth progress tables in general – reference data has been collected 40-60 years ago and are not adapted to contemporary climate conditions.
2. For high precision measurement of absorbed carbon in forest stand phytomass it would be necessary to measure diameters of stems, high of trees and count trees on model areas at each of reforestation sites. But even this could be not enough – in the first year trees are too small to be measured with high precision by 'traditional' means: biomass of trees younger than 5 years can be measured precisely if they are removed and weighted.

At the same time the forecast approach can be used in accordance with this methodology and it is based at the wide-scale growth progress tables data which is widely used in forest management practice. It is proposed to consider carbon accumulation by forest litter and soil at reforested sites as a bonus, as well as a number of other positive side effects of the project, such as preservation of habitats, water regime regulation, input into clean water and air, comfort environment which hardly can be assessed and appreciated by carbon accumulation.