Carbon stock assessment in taiga forests of Northwest Russia using the Leningrad Region as an example

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Abstract. The purpose of the study was to assess potential carbon stocks of taiga forests using a single region in Northwest Russia as an example. Using experimental data, we determined carbon stocks on the territory of the Leningrad Region. Using 53 model trees of different ages we determined the phytomass structure. The bulk of the phytomass (about 72%) is deposited in tree trunks. The green part of the crown contains about 8% of the phytomass. Branches account for 20%. The final results were obtained by forest type, taking into account the structure of forests by dominant species. The conversion of absolutely dry phytomass to carbon was carried out using a coefficient of 0.50 for woody plants and 0.45 for herbaceous plants. As of 01.01.2018, the share of conifers in the forest fund of the Leningrad Region was 58.8%. Potential carbon stocks amount to more than 408 million tons. Forest stands account for about 98% of the total carbon stocks. On average, one hectare of pine forest contains 41.76 tons of carbon, while in spruce forests this value is much higher and amounts to 112.60 tons.

1. Introduction
The topic of carbon units has been on the agenda in recent decades. The Kyoto Protocol became the starting document in the discussion on the carbon problem (Kyoto Protocol to the United Nations Framework Convention on Climate Change adopted on December 11, 1997 in Kyoto, Japan, and entered into force on February 16, 2005).

There have been several attempts to estimate carbon stocks in the forest fund of the country and in individual forest areas, and the research results have been published [1-5]. At the same time, in most cases, the existing generalized tables of the trunk volumes and timber reserves were used as the basis for calculations. There are only few publications based on experimental data [2, 4, 6-8]. This can be explained by a great difficulty of obtaining experimental data. In most cases, the materials presented in these works were based on assessments of the phytomass stocks in the lower forest canopy layers [2, 6, 7].

Forests of the Leningrad Region and other regions of Northwest Russia have been subjected to long-term and intensive economic impact [9-11]. This resulted in an increase in the share of low-value forests and an uneven age structure of forest stands [10]. First of all, this concerns pine and spruce forests which were exploited most intensively [8, 9].

The share of pine and spruce in the forest fund of the region has changed significantly over the past centuries [8-10]. The main reason for the decrease in the area of coniferous species is large-scale, "concentrated" clear fellings and the resulting change in species composition [9]. The felled primary stands (with a predominance of conifers) have been replaced by derivative stands (with a
predominance of deciduous species). Derivative forests in the taiga zone are represented by pioneer species: aspen, birch and alder [8-10].

Forest management materials, inventory of the forest fund and special studies show that the area covered by forest in any region is not constant. For example, according to M A Tsvetkova (1957), the forest cover of the Leningrad Region varied from 43 to 61% for the last two centuries [11]. The dynamics of the region's forest area, although within narrower limits, has been observed in recent decades [8-10].

2. Methods and Materials
The object of research is forest biogeocenoses of the main forest types of the Leningrad Region. The stocks of phytomass and carbon were determined on the basis of our own data and the results obtained by other authors. The total phytomass of the lower layers of forest phytocenoses was determined from our own data published earlier [8]. The conversion of phytomass to carbon was carried out using a coefficient of 0.50 for woody plants and 0.45 for herbaceous plants, mosses and lichens.

The phytomass of all forest components was determined by the gravimetric method. On the test plots, a complete inventory of trees was carried out with a distribution in thickness grades in accordance with the established requirements [8]. In three trees from the prevailing thickness grades, the height was measured to determine the volume of stem wood and to evaluate other parameters of the stand. For weighing, trees were selected from each thickness grade (the total number of model trees was 53). The trunks and crowns of the model trees were dissected into one-meter sections, and the fractional structure was studied in these sections. Simultaneously with the determination of the fresh weight, samples were taken for moisture content measurements. The samples were dried at a temperature of 105 °C to an absolutely dry state. The results were averaged by thickness grade. The average values for the thickness grades obtained were smoothed. When determining the phytomass, the density of wood was also taken into account, because wood density depends on both forest type and tree species.

3. Results and Discussion
3.1. Carbon stocks in forest stands
We determined the potential reserves of phytomass in pine and spruce forests classified by the dominant forest types. Currently, the share of conifers in forests of the Leningrad Region is less than 60% (58.8% in terms of area and 58.6% in terms of timber stock) [10]. Pine dominates in lichen, lingonberry and sphagnum forest types. In these forest types, with any pattern of species succession, pine will predominate. For the same reasons, in the oxalis and herbaceous forest types, spruce is a dominant species. The blueberry and long-moss forest types are equally suitable for pine and spruce stands, therefore the entire forest area in these forest types is divided into two parts, pine and spruce forests. This division is made in proportion to the area currently occupied by these species. Thus, when determining potential carbon stocks, we presented all forests of the Leningrad Region as pine and spruce forests (table 1).

The second condition observed in our calculations was related to the fact that all stands, regardless of the forest type, were classified as mature. It is this age stage that corresponds to the maximum reserves of phytomass; this is true not only for the stand, but also for the understorey, undergrowth, and living ground cover.

Stands with a predominance of pine and spruce occupy a total of 58.8% of the current forest area [10]. Derived or secondary forests account for over 30%. This ratio varies significantly by forest type. Thus, in the oxalis forest type deciduous species and spruce predominate, and in the sphagnum type, pine predominate. The potential productivity of forests of the Leningrad Region is increasing and will increase due to spruce. In the conditions of the taiga zone, spruce forests are primary phytocenoses and a zonal vegetation type. Spruce gradually displaces other forest-forming species and occupies these territories.
Table 1. Distribution of the forested area of the forest fund of the Leningrad region by forest type, thousand ha.

| Forest type, series of forest types | Pine forests | Spruce forests | Total |
|-----------------------------------|--------------|----------------|-------|
| Lichen pine forests               | 31.9         |                | 31.9  |
| Lingonberry pine forests          | 282.3        |                | 282.3 |
| Oxalis spruce forests             |              | 860.0          | 860.0 |
| Blueberry pine and spruce forests | 834.8        | 1305.7         | 2140.5|
| Long-moss pine and spruce forests | 193.3        | 166.9          | 360.2 |
| Herbaceous spruce trees           |              | 469.0          | 469.0 |
| Sphagnum pine forests             | 409.8        |                | 409.8 |
| **Total**                         | **4553.7**   |                |       |

We calculated the potential productivity of forest phytocenoses in the Leningrad Region using empirical data on forest types. We used our data [8] and materials of other authors [2, 3, 5]. When assessing potential carbon stocks in the forest stands of the Leningrad Region, data on the productivity of pine forests [1, 2, 4, 6, 10] and spruce forests [1, 4, 6, 10] were also taken into account. The obtained data were averaged by forest type. The averages were multiplied by the area of the corresponding forest type. The calculation results are presented in table 2.

Table 2. Potential stocks of phytomass in forest stands of the Leningrad region, thousand tons.

| Forest type                  | Pine forests | Spruce forests | Total    |
|------------------------------|--------------|----------------|----------|
| Herbaceous                   |              | 58474.0        | 58474.0  |
| Sphagnum                     | 37888.9      |                | 37888.9  |
| Long-moss                    | 33403.5      | 29032.0        | 62435.5  |
| Blueberry                    | 17867.5      | 273925.0       | 291792.5 |
| Oxalis                       |              | 279208.8       | 279208.8 |
| Lingonberry                  | 71849.8      |                | 71849.8  |
| Lichen                       | 41.6         |                | 41.6     |
| **Total phytomass**          | 161051.3     | 640639.8       | 801691.1 |
| **Total carbon**             | 80525.65     | 320319.90      | 400845.55|
| **Carbon reserves per 1 ha, ton** | 41.76        | 112.60         | -        |

Our calculations show that the potential reserves of phytomass that can be accumulated by a stand are almost twice as large as the current ones [8]. This suggests that forest communities of the Leningrad Region have a significant capacity. With sustainable forestry practices, region's forests can store much more carbon than at present.

3.2. Carbon stocks in the forest undergrowth

Potential carbon stocks in the undergrowth were estimated based on experimental data and published materials. Forest inventory records the composition, numbers, height and age of undergrowth. Only viable undergrowth is taken into account and only if conifers predominate in the species composition. Non-viable and dry undergrowth are ignored. According to our data, the proportion of non-viable and dry undergrowth in terms of numbers is, depending on the characteristics of forest stands, from 5 to 45%.

In our calculations, we made the following assumptions: in all forest types, under the canopy of all forest-forming species, the height structure of undergrowth and its numbers are taken in the proportions that are typical for mature stands. We calculated the potential carbon stocks accumulated in the undergrowth using the following procedure:

- the area of mature forests in which the undergrowth was studied was multiplied by the average number of undergrowth per hectare;
• the total undergrowth numbers were multiplied by the weight of one plant (small, 8.87 g; average, 549 g; large, 1912 g; the average value, taking into account the number of undergrowth by height groups, is 823 g of dry matter);
• the coefficient for converting phytomass to carbon was 0.50.

All data were summarized and average values were calculated for each forest type. As in the case with the determination of the phytomass of forest stands, the average values were smoothed and the obtained values were used to determine the total phytomass of the undergrowth.

The amount of carbon accumulated by undergrowth primarily depends on its abundance and average height. The maximum number of undergrowth under the canopy of mature stands, according to our data, reaches 25 thousand / ha. The height of undergrowth varies widely: from 0.1 m to 4.0 m. On average, undergrowth contains 0.958 tons of carbon per 1 ha (table 3). In general, region's forests deposit 4.57 million tons of carbon in the undergrowth, which is about 1.8% of the carbon reserves of the stands.

Table 3. Potential carbon stocks in the undergrowth.

| Indicators                               | Values            |
|-----------------------------------------|-------------------|
| Area of mature forests with undergrowth, ha | 735521            |
| Average number of undergrowth per ha, pcs. | 2231              |
| Average weight of one plant, g          | 823               |
| Phytomass of undergrowth per 1 ha, ton   | 1.836             |
| Total phytomass of undergrowth, ton      | 1350499.7         |
| Carbon stocks in undergrowth, ton        | 675249.8          |
| Carbon stocks per 1 ha, ton              | 0.918             |

Calculations show that, on average, 1 ha of undergrowth contains 1.836 t of organic matter and accumulates 0.918 t of carbon. Consequently, all the forests of the region contain more than 675 thousand tons of carbon in this forest component.

3.3. Carbon stocks in the understory

By analogy with undergrowth, here we used the same calculation option. To determine the potential reserves of carbon stored in the understory, we took into account the distribution of areas by the understory density under the canopy of mature stands. For each density category, the area was multiplied by the average abundance, and the calculated values were added. The resulting total was multiplied by the average weight of one plant in an absolutely dry state (at a height of up to 1 m, 33.8 g; from 1.1 to 2 m, 670 g, above 2 m, 1780 g; the average value, taking into account the number of understory plants by group heights is 726 g). The total stock of phytomass was converted into carbon through a coefficient of 0.50. The results of calculations are presented in table 4.

Table 4. Carbon stocks in the understory.

| Indicators                              | Values            |
|-----------------------------------------|-------------------|
| Area of mature forests with understory, ha | 958252            |
| Average amount of understory per 1 ha, pcs. | 1247              |
| Average weight of one plant, g          | 726               |
| Phytomass reserves in the understory, ton / ha | 0.905             |
| Total phytomass of the understory, ton   | 867526.6          |
| Carbon stocks in understory, ton         | 433763.3          |
| Carbon reserves per 1 ha, ton            | 0.452             |

The quantitative characteristics of the understory are less variable than those of the undergrowth. The most variable characteristic of the understory is its composition; it depends on the forest type and other characteristics of the stand. Unlike undergrowth, this forest component accumulates noticeably less phytomass. It was found that, on average, 0.905 tons of organic matter accumulates in the
understorey per hectare and contains 0.452 tons of carbon. Thus, the total carbon reserves in the understorey are about 434 thousand tons.

3.4. Carbon stocks in the living ground cover

The phytomass of the living ground cover was determined on the basis of our experimental data and the data of other researchers. These data have been grouped by dominant species, and the averages have been calculated. For pine forests, this value was 3.74 ton / ha, and for spruce forests, 2.31 ton / ha. Taking into account the distribution of all forests into pine forests and spruce forests, we get: in pine forests 7211.1 thousand tons, and in spruce forests 6570.6 thousand tons.

In total, 13781.7 thousand tons of phytomass, or 6201.7 thousand tons of carbon, have been accumulated in the living ground cover. The potential reserves of carbon in the phytomass of the living ground cover have been determined. The coefficient for converting phytomass to carbon is 0.45. Compared to trees, the living ground cover deposits about 2.4% of the total phytomass of the forest ecosystem.

The living ground cover is represented by annual and perennial herbaceous plants, shrubs, mosses and lichens. Under the canopy of taiga forests, the proportion of mosses and lichens is always high. Depending on the forest type, the ratio of mosses and herbaceous plants changes dramatically. For example, in the sphagnum and moss forest types, the share of herbaceous plants in the living ground cover is less than 5%, and in the herbaceous forest type, on the contrary, the share of herbaceous plants reaches 95%. In some forest types with the maximum crown density, the complete absence of a living ground cover is possible. Such a picture is often found in spruce forests of high density, when the illumination under the canopy is insufficient for the growth and development of vegetation of the lower layers.

3.5. Total carbon stocks

The current carbon reserves in the forest stands of the Leningrad Region amount to 257 million tons, and their distribution by dominant species is uneven [8]. More than 90% of these reserves are accounted for by the three main forest-forming species: pine, spruce and birch. Potential carbon reserves may be over 408 million tons (table 5).

Table 5. Potential carbon reserves in forests of the Leningrad Region, thousand tons.

| Ecosystem component    | Potential reserves |
|------------------------|--------------------|
| Tree stand             | 400845.55          |
| Undergrowth            | 675.25             |
| Understorey            | 433.76             |
| Living ground cover    | 6201.70            |
| **Total**              | **408156.26**      |

4. Conclusion

The potential reserves of phytomass is an abstract value determined analytically, based on the highest productivity of a phytocenosis under the given forest conditions. The result of these calculations will depend on many factors, both natural and anthropogenic. Natural phenomena and natural disasters cause the replacement of primary species by pioneer ones, and a large-scale economic impact (primarily felling) lead to a significant reduction in the area of mature and overmature coniferous forests. As a rule, the area of productive forest stands is decreasing. Intensive removal of mature coniferous forests in the 1930–1950s has led to a widespread distribution of deciduous species. The productivity of forest phytocenoses depends not only on the growing conditions, but also on the forest-forming species present. In the conditions of the Leningrad Region, spruce forms the most productive communities. Compared to the current stocks (257 million tons), the potential carbon stocks may amount to 408.2 million tons. More than 95% of carbon stocks are deposited in growing stands.
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