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Estimation of Carbon Stock in Forest Soils of Sakhalin Region

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Abstract Forests play a significant role in the uptake of atmospheric carbon dioxide and carbon sequestration for a long time. In forests, the long-term carbon depositing mainly takes place in two pools: in tree biomass and in soil organic matter that have different sensitivity to the natural and anthropogenic disturbances. Estimation of these pool sizes and ratio is the first step to the assessment of regional forest carbon budget and prognosis of its feedback to the climate change and disturbances. In this study, we estimated carbon stock in forest soils of Sakhalin region using the information system developed to assess a spatially distributed soil organic carbon with the high resolution (1 km^2). It was found that soil organic matter of forest ecosystems in the region have accumulated about 1230.9 Mt C that is three folds higher than carbon stock in the tree biomass. Forest litter contributes not more than 10% in the northern forest ecosystems and up to 3–4% in the southern forests. Distribution of total carbon stock (live tree biomass + soil organic matter) between above- and belowground pools indicated that 80.0–82.5% of the carbon is allocated in the soil, and forest litter—the component the most vulnerable to disturbances, accounts not more than 5–6% of this stock.

Keywords: Forest ecosystems, Soil organic matter, Forest litter, Tree biomass, Carbon stock

1 Introduction

Currently, the forest biome is recognized as one of the important agents of absorption and deposition of atmospheric carbon dioxide [1]. The establishment of carbon stocks in the forests of individual regions is the first step towards assessing the regional carbon budget and is necessary to clarify the contribution of forest ecosystems to the global carbon balance [2].

Long-term carbon deposition in forest ecosystems occurs mainly in two pools: in wood biomass and in soil organic matter. The main long-term reservoir of biomass is stem wood. In this component, carbon is deposited for the entire life of the tree, and after its death, due to the slow rate of decomposition of wood, its release can stretch for tens or even hundreds of years, depending on the conditions in which the trunk falls after dieback [3]. However, this aboveground reservoir of accumulated carbon is very sensitive to various kinds of disturbances of both natural (fires, insects, adverse weather conditions) and anthropogenic (logging) origin. Unlike aboveground woody biomass, its underground part, in the form of coarse tree roots, is more resistant to disturbances, since it is located in the soil body, and the rate of its decomposition and, accordingly, the release of carbon, largely depends on the species of the tree and on the conditions in which this decomposition occurs (soil type, its texture, temperature and water load) [4].

Soil organic matter is the second important reservoir for long-term storage of carbon absorbed from the atmosphere. The turnover time of soil organic matter is estimated in tens and even hundreds of years [5], and its reserves may be comparable or even exceed the carbon reserves in wood phytomass [6]. In addition, this pool of organic carbon is less sensitive to various kinds of aboveground disturbances, compared with wood biomass. During logging, there is mainly a violation of the litter layer. The upper layer of mineral soil, rich in organic matter, is disturbed mainly on the skid trails, which make up a small percentage of the total cutting area [7]. During the passage of fires, even of high intensity, high temperatures do not penetrate deep into the soil and do not significantly affect the pool of organic matter in the mineral layers [8]. Basically, only the upper organogenic horizon is damaged—the forest floor, the turnover time of organic carbon in which is much less, compared with the stable organic matter of the mineral part of the soil. This determines the need to assess the carbon reserves in the forest floor, separately from the mineral layer of the soil, in order to be able to predict changes in the carbon budget in a changing climate and with various disturbances.

Forests are the predominant type of vegetation in the Sakhalin region, according to various authors, they occupy from 65.4 to 85.2% of the total territory [9, 10]. This determines the leading importance of forest ecosystems in the regional carbon budget. The peculiarity of the natural conditions of the Sakhalin region (the Sakhalin Island and the Kuril Islands) is determined not only by the island position of the territory and climatic factors, but also by special geological and geophysical conditions: high seismicity, the presence of active faults of the Earth's crust with increased endogenous geochemical and thermal flows, modern volcanic activity [11]. Due to these geochemical features, soil parent material are characterized by abnormally high contents of many chemical elements [11]. All these factors can affect both the productivity of forest ecosystems in the region and the accumulation of organic carbon in soils.

The purpose of this study was to assess the carbon reserves in the live biomass and soil of forest ecosystems of the Sakhalin region and to identify the features of the formation of these carbon reservoirs in island conditions.

2 The Object and Methods of Research

Sakhalin Island is located near the eastern coast of the Asian continent. It is elongated in the meridional (142°20' E) direction by 948 km: its northern tip of the island reaches 54°25' N., the southern—45°54' N. Most of its territory is medium–high mountains, elongated in the meridional direction [12].

The Kuril Islands, also part of the Sakhalin Region, are the peaks of two parallel underwater ridges: the Greater and Lesser Kuril Ridge. The length of the Greater Kuril Ridge is 1200 km. It consists of more than 30 islands, which are active or extinct volcanoes. The Lesser Kuril Ridge stretches for 105 km and includes 6 islands. There are no young volcanoes on the islands of the Lesser Kuril Ridge. The relief of the islands is flat, sometimes hilly. Land areas rise above the ocean by 20–40 m [12].

The climate of Sakhalin and the Kuril Islands is monsoon. Winter is cold, but wetter and less severe than on the mainland. Summer is cool and rainy [12]. Due to the considerable length from north to south, the complex mountainous terrain and the different temperature regime of the seas, various climatic conditions are created on Sakhalin and the Kuril Islands. The average annual air temperature ranges from − 1.5 °C in the north to + 2.2 °C in the south. The absolute minimum is − 26 °C in the southeast, − 49 °C in the northwest, − 53 °C in the interior of Sakhalin Island. The absolute maximum ranges from + 26 °C in the area of Cape Patience to + 37 °C in the Tymovskaya Valley [13, 14]. The physical and geographical features of the territory determine the uneven distribution of precipitation. Their annual amount increases from 500–600 mm in the north to 800–1200 mm in the south [12].

Winter lasts from November to March. Due to the large amount of snow and deep groundwater level, the soil freezes to a relatively shallow depth: 140–160 cm in the north and in the middle part of the island and up to 40–70 cm in the south. There are areas of permafrost on the North Sakhalin Plain [12].

The structure of the vegetation cover of Sakhalin Island is caused by landscape-zonal differentiation of vegetation. On the territory of the island there are four vegetation subzones, the boundaries between which run in a north-westerly direction and correspond to the isolines of temperatures and humidity [15]: The northern plains of Sakhalin are covered with larch forests (*Larix cajanderi* Mayr) [16], taiga forests with a predominance of Yezo spruce (*Picea ajanensis* Fisch) are common in the central mountainous areas, ex Carrière), the territory south of the isthmus of the Belt is occupied by stands with a predominance of Sakhalin fir (*Abies sachalinensis* (F. Schmidt) Mast.), and the southwestern tip of the island is dark coniferous forests with an admixture of broad-leaved species [10]. In the mountains on the island there is a vertical belt: spruce-fir lichen-green moss forests with shrubs grow in the lower belt, above 500–700 m above sea level. They are replaced in the Eastern Sakhalin Mountains by Erman's birch forests with shrubs, and in the Western Sakhalin Mountains by Erman's birch forests with bamboo. The peaks of the foothills are covered with Siberian dwarf pine (*Pinus pumila* (Pall.) Regel) [10].

On the northern islands of the Kuril Ridge, forest vegetation is absent or is extremely fragmentary in the form of groups and sparse woodlands of willow (*Salix udensis* Trautv. et Mey.) in river valleys or in the lower part of mountain slopes [17]. In the Southern Kuriles, dark coniferous, Erman's birch, hard deciduous forests are widespread, soft deciduous forests are found. Larch forests are present in the Iturup island. Well-drained territories are occupied by mixed grass meadows. Marsh vegetation grows on the lowland-shores of lakes, watercourses, sea terraces. Mountain tundra vegetation appears at altitudes of more than 600 m and forms a sparse vegetation stone belt [18].

Heterogeneity of the natural conditions of Sakhalin Island, age diversity and lithological diversity of sediments forming its surface determine the distribution and representation of various types of soils on the island [19]. Under the coniferous forests in the southern part of the island, mountain brown soils are formed. Podzolic soils are widespread under low-density larch forests on the North Sakhalin Plain, which are formed on loose, chemically and mineralogically poor, well-drained rocks. On high sea terraces under dark coniferous forests, sod-humus soils are formed, which frame the southern part of the island, along the sea coast. Meadow soils are formed on high river terraces, and low surfaces are occupied by various types of gley and swampy soils. Peat soils are formed at various geomorphological levels: depressions on watersheds and gentle mountain slopes, on river and sea terraces [19–21]. A characteristic feature of all the soils of the island is their acidic nature, the pH of all soils is on average 4.5–5.0 [14, 21].

Calculations of carbon reserves in the soils of the region were carried out using a specially developed information system that allows to estimate spatially distributed reserves of organic carbon in soils with high resolution (1 km²). The automated information system for calculating the reserves of organic carbon in soils was created on the basis of: Soil Map of the Russian Federation (scale 1:2.5 million) and data base of typical soil profiles to it [22]; a database of in-situ measurements of organic carbon content in Russian soils (to account for zonal, regional features and register the influence of vegetation type and land use); maps of prevailing vegetation types and land use [23] with a spatial resolution of 1 km², maps of natural zones of the Russian Federation [24] (for adjustments of carbon stocks depending on zonal conditions), and the Administrative Map of Russia [24] (for regional adjustments of carbon stocks). A detailed description of the calculation methodology is presented in the work of Schepaschenko et al. [25].

To assess the carbon reserves in the live biomass of woody vegetation in the Sakhalin Region, data on the stocks of stem wood from two accounting systems were used: the State Forest Register (SFR) and the state forest inventory (SFI), combined with remote sensing data [26].

To convert the wood stock (m^3) into carbon reserves in living biomass, the following conversion coefficients were used: the stock in carbon of living biomass of trees, including roots—0.35035; the stock in carbon of aboveground living biomass of trees—0.27923; the stock in aboveground living biomass—0.56131; the biomass of roots to aboveground phytomass—0.288. The carbon content in wood biomass was assumed equal to 50%, for foliage (needles) the carbon content was assumed to be equal to 45% [27].

3 Results and Discussion

Carbon reserves in the soil of forest ecosystems of the research region were calculated separately for the forest litter layer and for the 1 meter layer of mineral soil (Fig. 1).

In the forest ecosystems of the Sakhalin region, the total carbon reserves in the forest litter are estimated at 72.7 Mt. In the mineral part of the soil profile—1158.2 Mt C. In general, about 1230.9 Mt C were deposited in the forest soils of the region. Of these, 878.1 Mt C were deposited under coniferous forests of the region, and 352.8 Mt C were deposited under deciduous forests (Table 1).

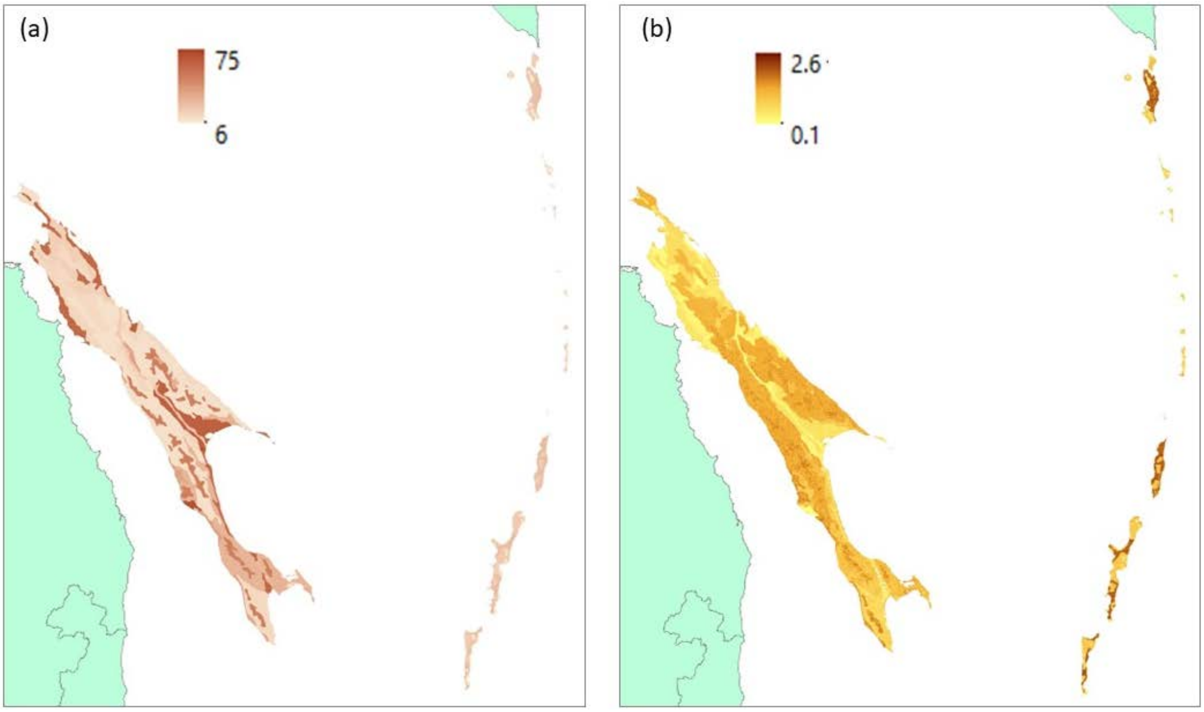

Fig. 1 Carbon reserves in soils (a) and litter (b) on the territory of the Sakhalin region, kg/m² C

Table 1 Carbon reserves in the soil of forest ecosystems of the Sakhalin region

Subzone	Litter, Mt C		Soil 1 m, Mt C		Total, Mt C
	Coniferous	Deciduous	Coniferous	Deciduous	
Tundra	0.19	0.04	1.68	0.44	2.35
Forest tundra and northern taiga	0.03	0.02	0.36	0.20	0.61
Middle taiga	47.47	15.37	599.17	272.06	934.07
Southern taiga	7.12	2.47	222.09	62.16	293.85
					1230.88

An assessment of the spatial distribution of carbon stocks in the litter and soil shows that the largest specific carbon stocks in the litter are characteristic of the tundra zone, which accounts for no more than 0.2% of the territory occupied by forests. The smallest reserves are observed in the North taiga zone, which occupies only 0.1% of the territory. The average carbon reserves in the litter of middle taiga forests are slightly higher than in the southern taiga. The mineral part of the soil is characterized by an almost twofold increase in carbon reserves in the soil profile when moving from north to south (Fig. 2). This distribution of carbon reserves is a reflection of the spread of certain types of soils across the territory: the spread of organic matter-rich sod-humus soils at the southern tip of the island. Sakhalin, and poor podzolic soils under the northern taiga larch trees in the north.

The contribution of litter to the total carbon reserves in the soil system decreases from 10% in northern ecosystems to 3–4% in southern taiga forests (Fig. 3).

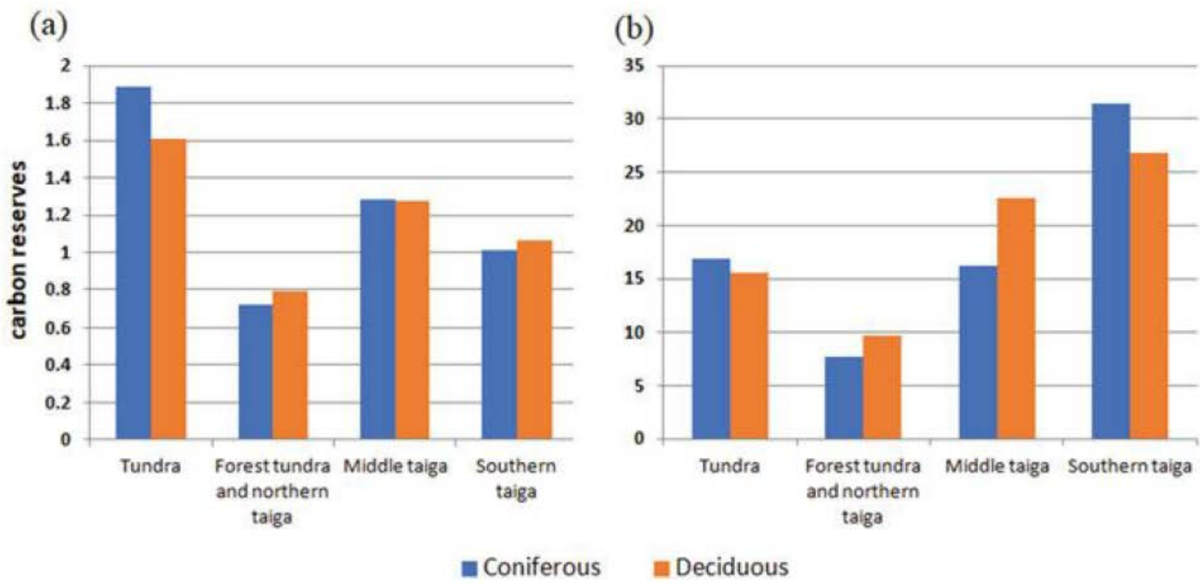

Fig. 2 Specific carbon reserves (kg/m²) in the litter (a) and in the soil (1 m) (b) of coniferous and deciduous forests of the Sakhalin region

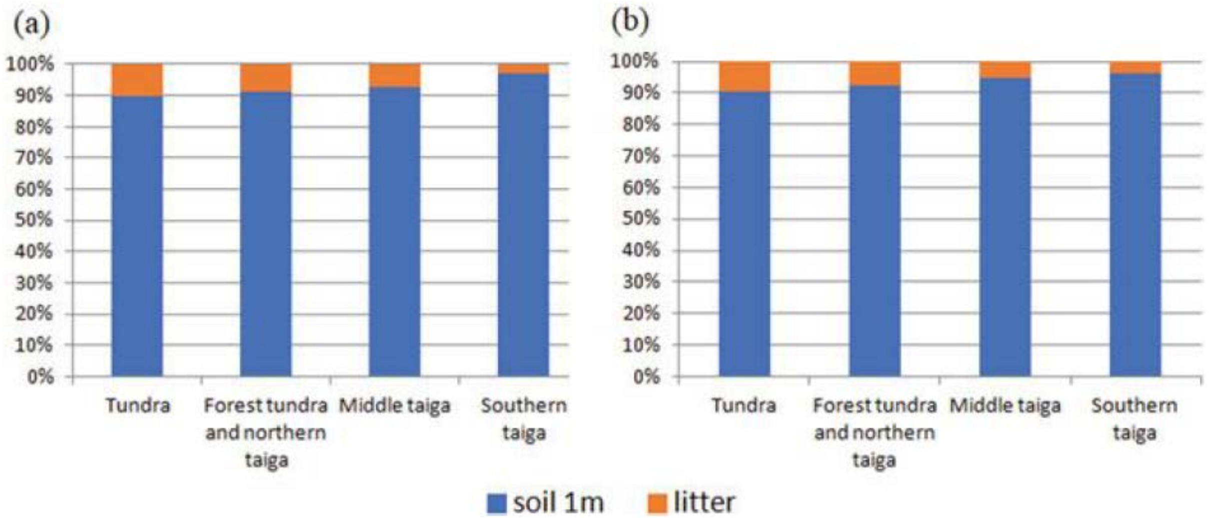

Fig. 3 The contribution of litter to the total carbon reserves in the soils of coniferous (a) and deciduous (b) forests of the Sakhalin region

According to our estimates, the specific carbon stock in the soils of the region is 8–18 kg/m² in the northern forests, up to 17–24 kg/m² C in the middle taiga and 28–32 kg/m² C in the southern taiga forests. These values are within the range of variation of carbon reserves in the soils of Sakhalin Island. According to field studies, for peat soils and gleyzems of the northeastern part of the island (middle taiga zone), carbon reserves range from 16.6 to 112.4 kg C/m² [28], for podzols of North Taiga larch forests—from 3.9 to 8.6 kg C/m² [29], for alluvial soils under floodplain larches—6.5–12.0 kg C/m² [30].

In order to assess the contribution of soil to the total carbon reserves in the forest ecosystems of the region, it was necessary to calculate the carbon reserves in the live biomass of woody vegetation. The total area covered by forest vegetation in the Sakhalin region is 6117 thousand hectares. The total stock of stem wood in these forests is estimated at 1168 million m3 according to SFI and remote data [26]. The area of managed forests of the Sakhalin region is 5608 thousand hectares, and their stock is 1071 million m3 according to the SFI or 637 million m3 according to the SFR, which is the main repository of forest information, and is used for national reporting to the IPCC (UNFCCC) [26]. The reason for the almost twofold difference in the stocks of wood given by these two accounting systems may be that the prescription of forest management materials used for SFR for most of the country's forests exceeds 20 years, and there is no acceptable system for updating data [31, 32]. Therefore, in further calculations, we used SFI estimates combined with remote data to estimate wood biomass reserves.

Estimates have shown that in the forests of the Sakhalin region, the total reserves of aboveground wood biomass amount to 665.6 Mt, which is equivalent to 317.7 Mt of carbon. An additional 91.5 Mt C has been accumulated in the underground biomass of woody vegetation. In total, 409.2 Mt C were deposited in the living wood biomass of the region. Coniferous species account for almost 75% of the total biomass reserves in the region, 16% are hardwood deciduous and 3% are softwood deciduous [9]. Accordingly, about 306.6 Mt of carbon is concentrated in the biomass of coniferous forests, while 102.6 Mt of carbon is deposited in deciduous stands.

The total carbon reserves of biomass obtained in our studies are 1.5 times higher than those given in the work of Utkin and co-authors [9], who estimated the carbon pool in the biomass of forests of the Far Eastern Federal District according to SFR records. The estimates of carbon reserves in the soil given by these authors, on the contrary, are slightly higher than those obtained by us (1718.6 Mt C).

The average specific stock of aboveground biomass in the forests of the Sakhalin region is 191 m3/ha, which is equivalent to 66.9 tC/ha. In total, with the underground biomass of woody vegetation, the specific carbon stock of biomass in the forests of the region is 86.2 tC/ha.

The contribution of soil organic matter to the total carbon reserves ranges from 74% under coniferous forests to 77% under deciduous forests.

In order to assess the ratio of carbon reserves in the above and belowground, it is necessary to add the belowground part of the biomass of woody vegetation to the organic matter of the soil, since it, as well as the organic matter of the soil, is protected from the direct impact of disturbing factors by the thickness of mineral soil. The distribution of organic matter reserves (living wood biomass + soil) between the above and belowground spheres shows that, in general, 80–82.5% of total carbon reserves are concentrated in the soil system, while the share of forest litter—the most vulnerable to violations of the soil profile horizon, accounts for no more than 5–6% of these reserves. For coniferous and deciduous ecosystems, no significant differences were found in the ratio of above and belowground components of total carbon reserves.

In recent decades, the forest ecosystems of Sakhalin Island have been subjected to active forest management and a significant spread of forest fires [10]. Most of the forests of the Sakhalin region are characterized by a moderate and high level of fire danger [33]. Since the most of carbon reserves are allocated belowground, the soil can prevent the rapid loss of carbon by the forest ecosystems of the region as a result of the passage of fires.

A comparison of the data obtained with the forest territories of the continental regions of Siberia and the Far East, located at the same latitudes as the Sakhalin Region, shows that the average specific carbon reserves in the soils of the forest territories of the Sakhalin Region (20.98 kgC/m²) are slightly higher compared to the inland regions (Zabaikalsky Krai, Republic of Buryatia, Republic of Tyva, Republic of Khakassia, Republic of Altai)—10.6–17.9 kgC/m² and Khabarovsk Krai (17.1 kgC/m²). Comparable specific reserves of carbon in the soil are characteristic only for the Amur Region and the Altai Territory (19.9–21.4 kgC/m²). At the same time, the contribution of soil to the total carbon reserves of forest ecosystems in all these regions is comparable and amounts to 62.1 to 82.7%, since most of them are characterized by lower carbon reserves in wood phytomass.

4 Conclusions

About 1230.9 Mt C were deposited in the organic matter of forest soils of the Sakhalin region. This is 3 times more than the carbon reserves accumulated in the woody biomass of the forests of the region. The distribution of carbon reserves between living wood biomass and soil does not differ significantly from that characteristic of the continental forests of Siberia and the Far East of the same latitudes. Higher total specific carbon stocks in the forest ecosystems of the Sakhalin region are formed both due to higher carbon stocks in the soil and due to higher productivity of stands, since the average specific stock of wood in these forests is 20–30% higher than in continental areas with a monsoon climate and in some regions with a sharply continental climate.

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