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SOIL CHEMISTRY

Stable Carbon Isotopic Composition ($\delta^{13}C$) as a Proxy of Organic Matter Dynamics in Soils on the Western Shore of Lake Baikal

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Abstract—Assessing the main factors that control carbon dynamics in soils is an urgent problem in the context of modern climate change. The analysis of stable carbon isotope ($\delta^{13}C$) composition is one of the approaches to understanding this dynamics. The study was carried out in the landscapes of the southeastern slope and foothills of the Primorskii Range, characterized by contrasting physico-geographical conditions. Climatic parameters, spatial variations in the composition of stable carbon isotopes and their distribution in soil profiles, and soil physicochemical properties controlling carbon dynamics have been analyzed. The soil humus horizons formed in mountainous tundra and steppe landscapes manifest the highest $\delta^{13}C$ values (–24.72 and –23.97...–24.75‰); whereas the lowest (–25.61...–27.18‰) values are registered in the mountainous taiga soils. Based on the calculation of linear dependence between $\delta^{13}C$ values and the total carbon content in soil, which varies with the depth, the carbon turnover intensity was determined using the slope of linear regression. It was revealed that under the contrasting conditions of mountainous tundra and steppe landscapes, the climate (deficiency of heat and moisture) has a significant impact on the intensity of organic matter transformation, blocking the effect of edaphic (soil profile) factors. Under more favorable climatic conditions of mountainous taiga landscapes, the dynamics of organic matter in soils is controlled mainly by edaphic factors.

Keywords: carbon turnover, Primorskii Range, Cis-Olkhon Plateau

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INTRODUCTION

Study of soil organic matter (SOM) dynamics is one of the most important problem in assessing the impact of climate change on soil-forming processes, nutrient cycles, and carbon budget in landscapes [23, 51, 54]. However, assessing the ratio between the input of organic residues and their subsequent transformation under various landscape and climatic conditions still remains one of the most disputable issues [10, 38, 47, 51]. This is due to SOM origin proper, which is a heterogeneous mixture of plant and microbial biomass residues of different destruction and decomposition degree, products of decomposition and synthesis, and partially or completely stabilized humus substances [3, 23, 47, 54]. SOM stability depends on interactions between a wide range of abiotic, biotic, and physicochemical factors controlling the rate of its decomposition and stabilization [3, 23, 38, 59]. A considerable spatial variability of landscape and climatic conditions complicates this pattern significantly [38, 60].

Analysis of the stable carbon isotopic composition ($\delta^{13}C$) is one of the important methodological approaches to the study of spatiotemporal SOM variability [41, 55]. The $\delta^{13}C$ value is often considered as an integral indicator of organic matter transformation processes [39] and, thus, it has a significant potential for assessing the soil carbon dynamics [35, 50].

Since the most of organic matter enters the soil with plant residues, the $\delta^{13}C$ SOM value reflects the stable carbon isotopic composition in plant tissues and the results of subsequent isotopic fractionation in the course of their transformation [35, 40, 50, 57]. The phenomenon of SOM enrichment in ^{13}C with the depth is widely known, and it coincides with a decrease in the total carbon content in automorphic soils in different climatic zones [12, 31, 55]. In this case, the manifestation of $\delta^{13}C$ changes depends on the fractionation of carbon isotopes; and the relationship between SOM enrichment with ^{13}C and the carbon cycle intensity was confirmed by SOM mineralization measurements [42], simulation of the mass balance between carbon isotopes, and meta-analysis [31]. A linear dependence was established between the increase in $\delta^{13}C$ values on the decrease in the organic carbon content with depth (on a logarithmic scale); and the slope of linear regression (β) was proposed as an indicator of carbon turnover rate in soils [31, 42].

Being often highly spatially variable, the slope of the above-mentioned linear regression depends to a great extent on landscape and climatic conditions [36, 42, 55]; so, understanding the regional response of soils appears to be important.

The Baikal region located in the south of Eastern Siberia, is one of the planetary regions most prone to global warming [49]. Over the past century, the average annual air temperature has increased by 1.2°C there, which twice exceeds its increase on a global scale [30]. These climatic changes cannot but affect the carbon balance in regional landscapes [49].

This work is aimed at assessing the main factors that control the carbon dynamics in soils formed under various combinations of soil-formation factors. The central part of the Western Cis-Baikal region appears to be one of the most suitable areas for this purpose, as its mountainous relief provides the climate and vegetation variability at short distances resulting in the contrasting soil-formation conditions.

OBJECTS AND METHODS

The studied area is located in the junction zone between the Primorskii Range and the Cis-Olkhon Plateau (Fig. 1). The relief is mid- and low-mountainous, highly rugged. The landscape structure follows the altitudinal and zonal patterns, but it acquires specific features and significant diversity under the effect of climatic and orographic factors (the barrier, foothill and depression effects). Mountainous tundra and subtundra shrubs, dark coniferous and light coniferous mountainous taiga, subtaiga, mountain and piedmont dry steppe geosystems are found there [5, 19]. The formation of taiga-steppe landscape ecotone, i.e., a combination of typical geosystems of subtaiga light coniferous forests with lithoedaphic variants of extrazonal steppes, is the most important consequence of the barrier influence of Primorskii Range combined with landscape zonality [19].

The average long-term air temperature in January is −17.3°C, and in July +14.4°C. Most of the territory shows low atmospheric humidity. The annual atmospheric precipitation varies within 190–260 mm on the Cis-Olkhon Plateau, which is the absolute minimum for Cis-Baikal region. About two-thirds of this amount fall in summer. The precipitation rate rises to 400–500 mm in mountains. The total influx of solar radiation is high, amounting to 4400–4600 mJ/m^2. The sum of active temperatures (>10°C) decreases with distance from the Lake Baikal coast to mountainous tundra zone from 1400–1600 to 1000–1200°C [19].

The Lake Baikal water body also influences the mesoclimate in the area. Three zones of Lake Baikal impact are distinguished [7]. The zone of strong climatic impact covers a coastal band up to 2 km wide (sometimes up to 5–10 km) and 200–300 m high above the lake level with the maximum aridity and a smoothed course of air temperature. The zone of moderate impact embraces the central part of Olkhon Plateau with river valleys; it is distinguished by higher air temperatures in summer. The zone of weak impact encompasses the southeastern slope of Primorskii Range within absolute elevations of 800–1000 m a.s.l., it is characterized by increased atmospheric humidity and reduced air temperatures due to the altitude effect.

The cooling effect of water mass on the air temperature extends up to 0.5 km high from the lake level from April to July, when the water temperature is lower than the surrounding land temperature; whereas the warming effect spreads to a height of 1–2 km above the lake level from October to December [7].

The extreme hydrothermal regime determines a relatively low intensity of geochemical processes in soils, which is manifested, in particular, in weakly differentiated soil profile [19]. This is true, above all, for the soils in coastal landscapes and the Primorskii Range foothills developing in arid climate and experiencing deep freezing in winter, which determine the predominantly cryoarid type of pedogenesis in Cis–Olkhon region. In mid- and low-mountainous taiga forests, as the precipitation level and incoming plant litter rise, the leading soil-forming processes change, with soil-profile differentiation by a number of mobile components being manifested. This is reflected in widespread Al–Fe-humus soils, as well as organic-accumulative soils with signs of illuvial differentiation in humus and iron [19].

To reveal the features of the isotopic carbon composition of landscape components, landscape profiles were set on the southeastern macroslope and foothills of the Primorskii Range in order to cover maximally the physiographic conditions. The Sarma profile (8 plots) of about 10 km long stretched from the Khuzhir-Nugai Bay shore (471 m a.s.l.) to the Sarminskii Golets Mt. (1652 m a.s.l.). The Chernorud profile (3 plots) extended from the elevated coastal parts of the Cis-Olkhon Plateau (915 m) to the Primorskii Ridge slopes (1160 m). To increase the share of steppe landscapes in the total sampling, additional plots were studied on the Cis-Olkhon Plateau, i.e., Krestovyi, Anga, and Sarma-1 plots.

At each plot, the characteristics of phytocenoses, lithological and geomorphological conditions were

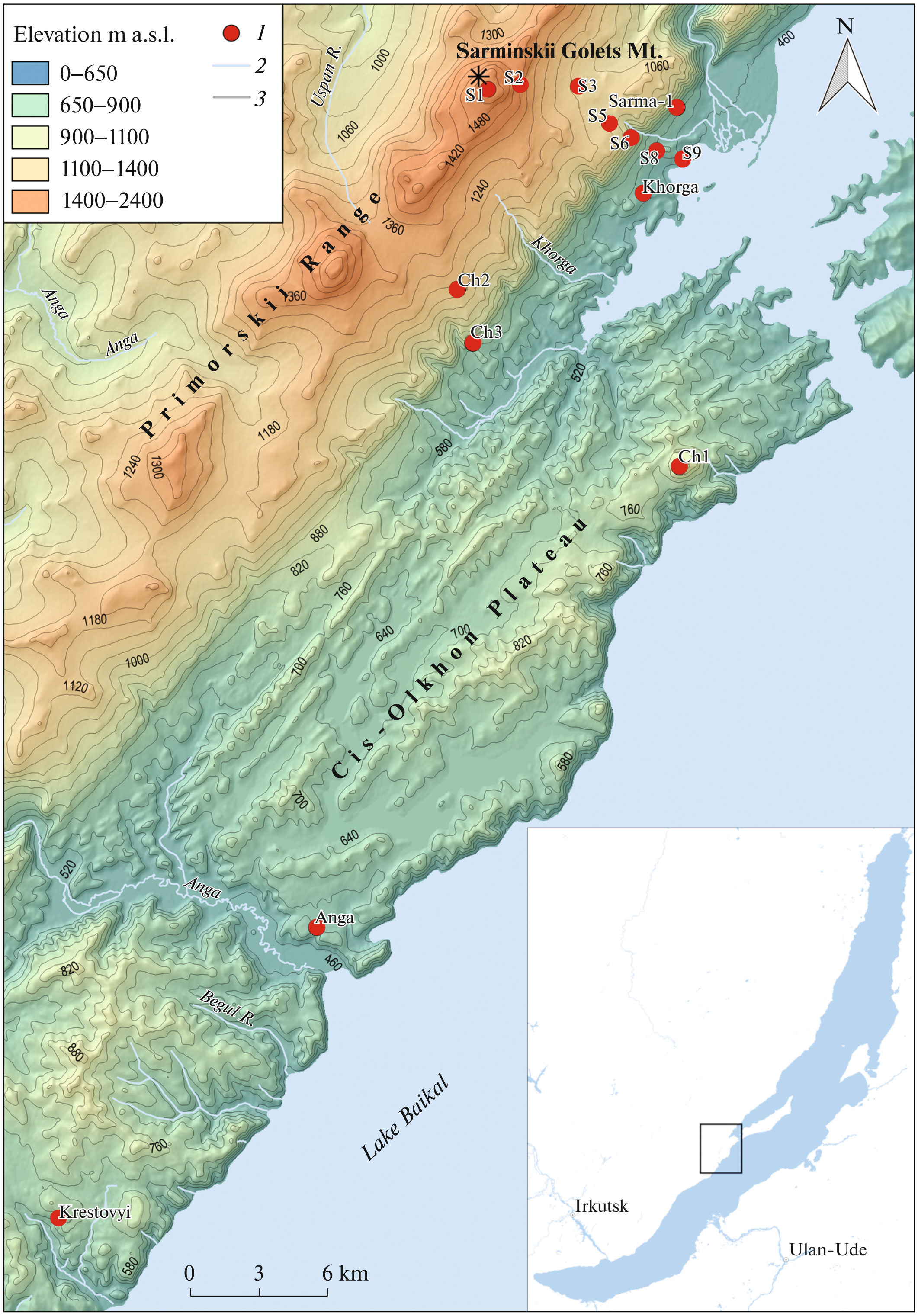

Fig. 1. Location of the study area: (*1*) the study plots; (*2*) the river network; (*3*) horizontals. The background is a SRTM digital elevation model (resolution 30 m).

recorded, and soil morphogenetic analysis was performed (Table S1). Since 2013, microclimatic observations have been launched to assess the influence of climatic factors on landscape parameters in the study area [34]. Temperature and relative air moisture at 2 m above the surface as well as the soil surface temperature were measured with Elitech RC-51H and RC-4HC automatic recorders. The temperature measurement accuracy was equal to 0.1°C and that of relative moisture, 3%. The measurements were performed at 1 h intervals. Using the methods of descriptive statistics, for each plot, we calculated the average annual and average for the growing season (May–September) values of air temperature and moisture, as well as the soil temperatures; we determined the dates of stable transition of air and soil-surface temperatures through 0 and 10°C at the beginning and in the end of the warm season as well as the duration of these seasons; and we calculated the temperature sums for the periods with temperature exceeding the given limits.

The field work was carried out in July. Having analyzed the descriptions of the vegetation species composition, we collected the aboveground parts (fresh mature leaves) of the dominant species constituting 80% of the biomass in each plot. The plant litter was sampled on the soil surface in five points (four corners and the center) of each plot. Leaf, litter, and soil samples were dried to the air-dry state. Leaves were dried additionally at 70°C for 60 h and then grinded. Samples of mineral soil horizons were sifted through a 1-mm sieve with the subsequent removal of roots. The pH values of soil suspensions were determined potentiometrically at a soil : water ratio equal to 1 : 5 and 1 : 25 in mineral and organic horizons, respectively. The organic carbon content and its isotopic composition ($\delta^{13}C$), as well as the total nitrogen content in leaves, litter, and soils were determined by dry combustion using the Vario Isotope analyzer (Elementar, Germany) combined with the Isoprime precision IRMS mass spectrometer (Elementar, UK). The measurements were carried out at the Center for Collective Use "Laboratory of Radiocarbon Dating and Electron Microscopy", Institute of Geography of the Russian Academy of Sciences. The results obtained were expressed in ‰ in respect to VPDB standard. The measurement accuracy was 0.1‰.

Statistical calculations were performed using the MO Excel and PAST 4.03 programs [45]. In addition to above-listed microclimatic indices, we considered the pH and C/N values of humus horizons as well as the absolute elevation of the area (m, a.s.l.) as additional parameters. The verification of samples by all the analyzed parameters for compliance with the normal distribution according to the Shapiro–Wilk and Anderson–Darling criteria gave a positive result. This allowed us to use parametric methods for data processing, i.e., the paired and multiple regression analysis. To assess the carbon turnover intensity (β) in the studied soils, the linear dependences of $\delta^{13}C$ on the organic carbon content with depth were calculated (Fig. S1).

RESULTS OF THE STUDY

Climatic differentiation of the study area. Both the average annual and average for the growing season temperatures decrease inland from the Lake Baikal coast towards the upper part of the landscape profile (Fig. 2a). The average annual temperature at the soil surface exceeds the air temperature at all plots. During the growing season, the soil surface temperatures in taiga (S2, S3, S5, and Ch2) and subtaiga (S6, Ch1, and Ch3) forests become lower than the air temperatures due to the impact of the closed vegetation cover. The tree canopy and dense grass cover protect soils from frost and morning cooling in these sites in early summer and in the first autumn days; however, during the daytime, the soil surface is heated to a lesser extent there than in open sites. Therefore, the sums of positive temperatures at the soil surface are maximal on open sites in the upper part of landscape profile, i.e., mountainous tundra landscapes (S1), piedmont sparse forest areas (S8, Ch1, and Ch3), and steppe landscapes (Krestovyi and S9). The distribution of sums of temperatures >10°C reveals similar patterns (Fig. 2b).

Among the subtaiga and steppe landscapes, the S6, Ch1 and Krestovyi plots manifest the lower air temperatures. This difference is caused by the location specifics and the underlying surface properties. Absolute elevation of the terrain (810 and 915 m a.s.l., respectively) is the predominant factor controlling the microclimate formation in the aspen-larch forest (S6) located on the southeastern slope top of the ledge-escarp at the Primorskii Range as well as in the larch forest on the northwestern slope of the hill (Ch1). However, the southeastern slope aspect at S6 plot provides the stronger heating of the air throughout the year and the soil during the growing season. For the Krestovyi site, the lower temperature indices result from the peculiar air-mass circulation in the river valleys occurring within the zone of Lake Baikal influence. The Krestovaya River valley runs almost transversely to the coastline, which favors the cold air penetration from the lake in summer mainly with the southern winds. This effect was noted earlier [6]. Upwards from the water level, the periods with temperatures >0 and 10°C get shorter (Fig. 2c).

The moisture supply in the territory is assessed on the basis of the data on the relative air humidity. Its minimal values are registered in April for all plots (Fig. 3a). The maximal humidity is observed in August–September. This transition is most contrasting in bald mountains (S1) and mountainous taiga (S2, Ch2, S3, S5), with the most smoothed course of annual humidity being observed at point S9. Mountainous tundra landscapes (S1) show the highest average annual air humidity, and somewhat lower moisture is registered in mountainous taiga landscapes (S3, S5, S2, and Ch2) (Fig. 3b). The subtaiga and steppes are characterized by the minimum humidity, except for site Ch1 due to its location on the northwestern slope. A somewhat higher moistening at S9 plot is also noted as a result of Lake Baikal influence, as well as at the Krestovyi plot

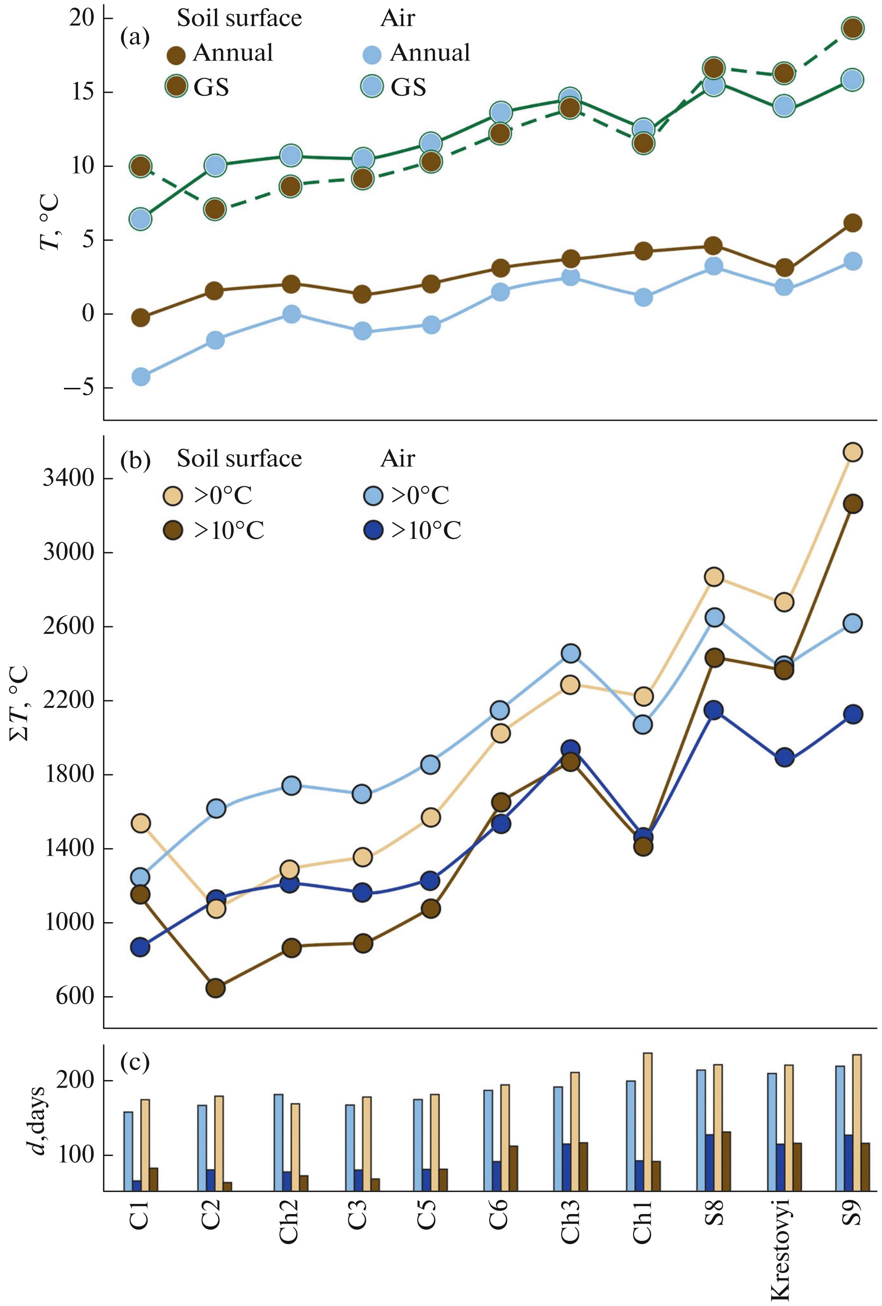

Fig. 2. Differentiation of the studied plots by the temperature conditions of the air and soil surface: (a) mean annual air temperatures and mean temperatures for the growing season; (b) sums of temperatures >0 and 10°C; (c) duration of periods with daily temperatures >0°C.

due to the peculiarities of the valley circulation in the Baikal influence zone [6].

Variations in the physicochemical properties of soils. The soil and litter acidity becomes less pronounced with a decreasing absolute height of the area. The most acidic soil reaction (pH 3.9) is typical for the humus soil horizons in the mountainous tundra and subtundra zones (S1 and S2) (Fig. 4). The humus and organic horizons of the mountainous taiga soils manifest higher pH values varying from 4.1 (Ch2) to 4.9 (S3). The humus horizons of the subtaiga soils at the foothills of the Primorskii Range and the Cis-Olkhon Plateau (S6, S8, Ch1, Ch3, and Khorga sites) are characterized by close to neutral pH. For steppe soils (S9, Anga, and Krestovyi sites), weakly alkaline pH values are noted.

In all the studied soils, acidity decreases down the soil profile. However, the litter analysis shows devia-

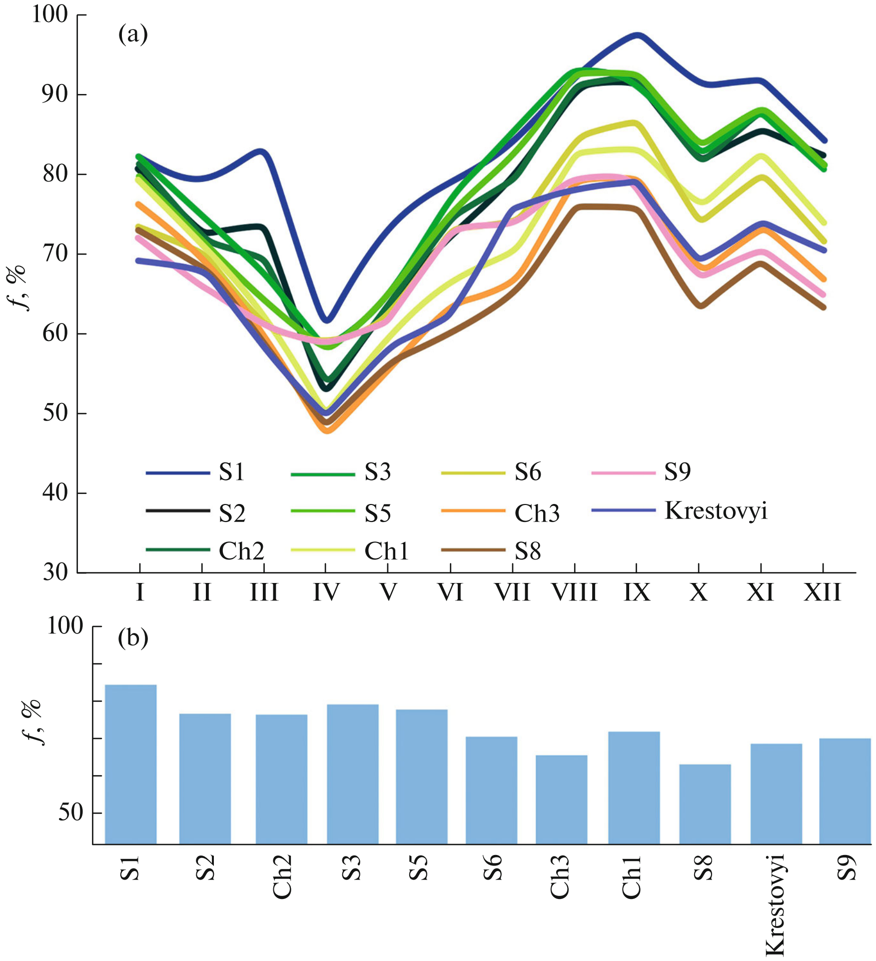

Fig. 3. Annual variation of air moisture in the studied plots (a) and mean annual values of air moisture (b).

tions from this regularity. For example, the litter acidity grows from OL to OH horizons on plots S2, S3, and Ch2; whereas an opposite trend is registered at lower elevations a.s.l. (S5, S6, Ch1, Ch3).

Total organic carbon, total nitrogen, and C/N. A decrease in the organic carbon content down through the soil profile takes place (Table S1). It is most abrupt upon the transition from organic to mineral horizons. The buried humus horizons contain more organic carbon (S3, S8, Ch1). As a rule, the carbon content decreases more gradually in the mineral soil horizons in the upper part of the landscape profile due to the organic matter mobility and its illuviation into the underlying horizons. There is a trend to decreasing organic carbon content from the upper to lower absolute heights, which is somewhat better pronounced in the surface mineral horizons than in organic ones (Fig. 4).

Nitrogen is distributed in a somewhat different way. As a rule, the falloff (OL) contains less N as compared to the litter (OF, OH). In the mineral horizons, the total nitrogen content decreases gradually down the soil profile. Along the landscape profile, the variation in the nitrogen content within the surface organic and humus horizons does not manifest any pronounced patterns, often changing significantly from one section to another.

The C/N ratio in humus and organic horizons tends to become less variable down the landscape profile. The most significant fluctuations are noted for the soils in its middle part, less pronounced variations are typical for the soils in the Primorskii Range foothills (Ch3–Ch9). In individual soil profiles, C/N value is usually the highest in fresh falloff. This ratio increases again in the surface mineral horizons. In the rest of the profile, the C/N values decrease.

Composition of stable carbon isotopes. The δ^{13}C values range within –25.5...–32.5‰ in leaves and needles of higher vascular plants, and within –23.03...–24.6‰ in lichens. The values of δ^{13}C are heavier by 0.1–2.8‰ in the falloff as compared to the dominant vegetation; with the minimum difference in values being observed

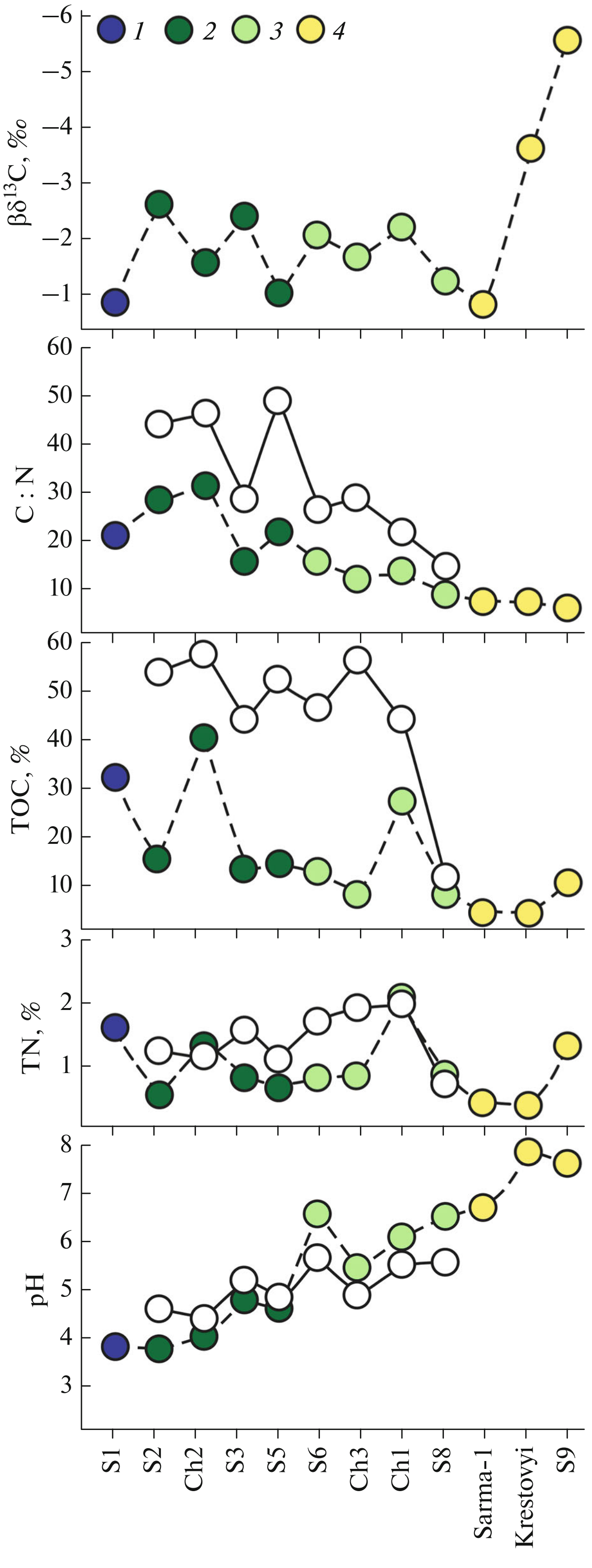

Fig. 4. Some chemical properties of soils in the studied plots and the slope of linear regression (β). Landscapes: (*1*) mountainous tundra; (*2*) taiga; (*3*) subtaiga; (*4*) steppe. Solid circles show the values or humus horizons and white circles, for litter.

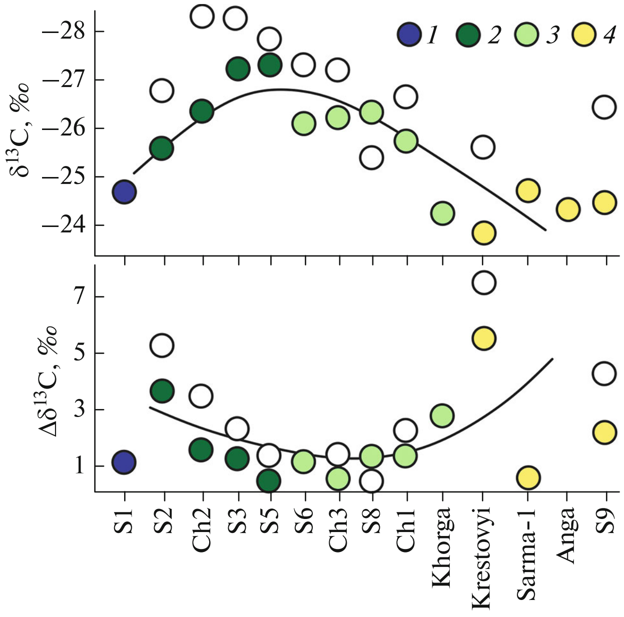

Fig. 5. Variations in the isotopic composition of carbon in the soils of the studied plots. Landscapes: (*1*) mountainous tundra; (*2*) taiga; (*3*) subtaiga; (*4*) steppe. Solid circles show the values for humus horizons and white circles, for litter.

in the steppe larch forest (S8), and the maximum, in the mountainous taiga zone (S2, S3). The organic matter δ^{13}C varies from –25.4 to –28.3‰ in the falloff. In all mountainous taiga soils, the carbon isotopic composition becomes heavier by 0.75–1.8‰ upon the transition from the litter to the humus horizon, with the maximum values at points S2 and S6.

The δ^{13}C values of organic matter in the soil humus horizons vary from –24 to –27.2‰. The highest δ^{13}C is registered in the soils that are formed in bald mountainous tundra and steppe landscapes (Fig. 5). In the central part of the profile, in mountainous taiga landscapes, the δ^{13}C values are the highest. Regardless of the soil-forming conditions and type of pedogenesis, the soils manifest an increase in δ^{13}C values down through the profile.

DISCUSSION

δ^{13}C in vegetation. The obtained values of δ^{13}C in organic matter of the soil humus horizons prove that the plant biomass is coming mainly with the C3 type of photosynthesis, which is consistent as a whole with the climatic conditions in the study area [13]. However, steppe fragments on the Olkhon Plateau belong to the Mongolian-Chinese florogenetic type [4], and according to [17, 26], some species with CAM type (*Aizopsis aizoon* (L.) Grulich, *Orostachys malacophylla* (Pall.) Fisch., *O. Spinose* (L.) C.A. Mey, [52]) and C4 type of photosynthesis (*Atriplex sibirica* L., *Kochia prostrate* (L.) Schrad., *Spodiopogon sibiricus* Trin.,

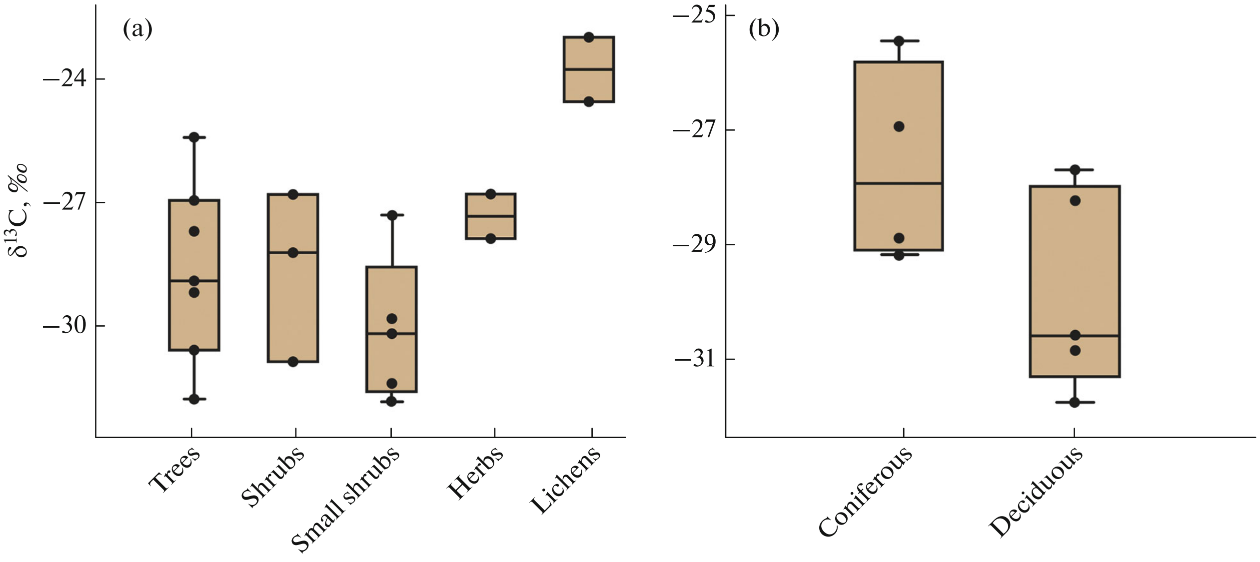

Fig. 6. Ranges of $\delta^{13}C$ values in different life forms of higher vascular plants and lichens (a). Ranges of $\delta^{13}C$ values for coniferous and deciduous tree species (b). Dots show the actual values, the line inside the box is the mean, and the box edges designate quartiles.

Cleistogenes kitagawae Honda, *C. squarrosa* (Trin.) Keng [2]) are met in these associations. The analysis of geobotanical descriptions revealed a single *Orostachys spinose* at plot S8 and *Kochia prostrata* with a projective cover of 1% at the Krestovyi site. Nevertheless, chernozem formed at the Krestovyi site is specified by the highest $\delta^{13}C$ values (–23.97‰) as compared to all other soils.

Comparison of $\delta^{13}C$ values for different life forms of plants (Fig. 6a) showed their greatest scattering in trees. In shrubs and dwarf shrubs, the spread of values is smaller, but the former are heavier on average by the carbon isotopic composition. Differences in the $\delta^{13}C$ values of herbaceous plants amounted to 1.1‰. With the highest $\delta^{13}C$ values, lichens that dominated in the ground cover of the mountainous tundra (S1) were regarded in a separate group.

Higher $\delta^{13}C$ in lichens as compared to vascular plants in the study area is associated with the peculiarities of carbon fractionation in this group of organisms. The $\delta^{13}C$ values in the organic matter of lichens are controlled to a great extent by the algae photobiont photosynthesis specifics [8, 46]. Under optimal conditions for lichen, ^{13}C discrimination is observed; when conditions get worse, enrichment in this isotope occurs both due to inhibition of photosynthesis and due to more intense respiration [9]. There are data about a negative correlation between the $\delta^{13}C$ value of lichens and the relative air humidity, as well as about its positive correlation with precipitation. Growing average annual precipitation by 260 mm leads to an increase in $\delta^{13}C$ by 1‰ due to worse CO_2 diffusion in water-saturated thalli [8].

The studied *Flavocetraria nivalis* (L.) Kärnefeltet A. Thell and *Cladonia rangiferina* (L.) F.H. Wigg. belong to the group of two-biont chlorolichens [28], with $\delta^{13}C$ value varying substantially (from –35 to –17‰) in them [9]. The obtained $\delta^{13}C$ values (–23.03...–24.587‰) point to unfavorable conditions for the growth of lichens in the mountainous tundra; this agrees with the data obtained for *Flavocetraria nivalis* in the Western Yamal tundra (–24.3...–24.4‰) [18]. Additionally, differences in the composition of stable carbon isotopes were analyzed between coniferous and deciduous trees and large shrubs (Fig. 6b). Conifers show in general higher $\delta^{13}C$ values than deciduous woods, which is consistent with the literature data. For example, for *Pinus sylvestris*, average values of $\delta^{13}C$ are reported equal to –27.46 ± 1.13‰, *Larix sibirica* –28 ± 1.51‰, *Populus tremula* –29.21...–32.58‰, and *Betula pendula* –29.96...–30.55‰ [16, 20, 39]. This differences are explained by more efficient water use by coniferous species as compared to deciduous species. In the complex communities of mountainous taiga (S2–S5), the carbon isotope composition becomes lighter with a tier change from conifers (in the first tier) to shrubs. In this case, the effect of the forest canopy is manifested, which is related to the changing photosynthesis under shading conditions [27].

$\delta^{13}C$ in the litter. Despite the tendency for the carbon isotopic composition to become heavier in the falloff and litter with depth, deviations from this regularity are observed at several plots (S2, S8, Ch1, and Ch3). This is pronounced in the heavier composition of the upper falloff horizons as compared to the litter. Such deviations can be explained by the selective preservation of hardly mineralizable components of plant tissues upon litter decomposition [59]. Lignin appears to be one of the most stable components, as it shows the lowest δ^{13}C values as compared to those in the total plant tissue, cellulose, starch, and sugars [35]. The residual accumulation of lignin can lead to depletion of the lower litter horizons in^{13}C. This interpretation well agrees with the fact that the described phenomenon is observed at the sites with mainly coniferous litter, the richest in lignin (as compared to small-leaved and herbaceous litter) [3]. However, this pattern is not universal, being pronounced only at the forest boundaries in ecotones. Point S2 is located at the upper border of the forest; whereas Ch3, S8, and Ch1, in steppe subtaiga light coniferous landscapes.

Despite a relatively short term of their formation, litters are polygenetic bodies sensitive to local spatial variability of soil-formation factors [25]. Disturbed ecological balance between the litter and other landscape components due to recurrent expansion and contraction of the taiga area could be one of the factors that caused the observed differences in the carbon isotopic composition in the upper part of the soil organoprofile.

Obviously, this dynamics should have been manifested most vividly on the considered plots. For example, the upper forest boundary varies within 1300–1450 m in the study area due to climate changes [11, 19]. The analysis of satellite images for the years of 1985–2019 testifies to vertical motions of the forest boundary by 10–13 m in the plot S2 (1420 m a.s.l.). The cryogenic-slope processes [1], as well as the pyrogenic factor [5], have an additional effect on landscape dynamics there.

In the Primorskii Range foothills (S8, Ch1, Ch3), the soils were formed upon changing taiga and steppe landscapes as a result of climate dynamics [19]. The analysis of peat bog deposits in various landscape zones of the Olkhon region [15] attests to a pronounced response of the taiga and steppe geosystems to climatic changes in the Olkhon region in late Holocene. In particular, in the interval of 900–350 years ago, a trend is assumed for replacing cedar forests with pine and larch forests, and for expanding the steppe xerophytic cenoses. In response to climate humidification 350–250 years ago, the area of cedar forests with fir tree expanded. Later, in the interval 250–130 years ago, the humid phase was replaced by the arid phase, which resulted in the new expansion of steppe landscapes and increasing participation of light coniferous and small-leaved-light coniferous forests in the mountainous taiga [15]. Sharp short-term climate fluctuations in this period were also recorded in clearly pronounced stratification of subaerial deposits in the Olkhon region [14].

Changes in δ^{13}C and β coefficient along the soil profiles. Discrimination of carbon isotopes in plant tissues and, as a result, in the produced soil organic matter may be controlled by many environmental factors. Air temperature and atmospheric precipitation are the main of them [33, 53, 58]. Their leading role is provided by the temperature effect on enzymatic activity and photosynthesis intensity and the humidity influence on stomatal conductance [39, 58]. These effects are manifested on a global scale [33, 53]. However, on a regional scale, their manifestations differ. For climatic transects on the plains, the linear dependences are often traced between the intensity of carbon isotope fractionation by plants and temperature and humidity [56, 62]; whereas, for transects in mountainous conditions, a polynomial dependence is most often observed [16, 40, 58, 61].

Changes in the carbon isotopic composition with absolute heights are also non-linear in the study area (the second-order polynomial dependence $r^2 = 0.62$, significance level $p = 0.005$). The highest values of δ^{13}C are registered in the soils that are formed in the mountainous tundra and steppe landscapes. At the same time, in terms of climate, these parts of the altitudinal profile are opposite. Plots S1 and S2 occur under the most humid and cold conditions, whereas steppe plots are the warmest and driest. It is logical to assume that the similar δ^{13}C values in the upper and lower parts of the studied profile originate from different reasons. In the lower part of the landscape profile, δ^{13}C is controlled by plants growing under moisture deficit; in the upper part, this value is controlled by low temperatures and, consequently, by the formation of plant communities adapted to such conditions. Both factors can lead to less discrimination of carbon isotopes, promoting a rise in δ^{13}C [58].

In the mountainous taiga landscapes, the carbon isotope composition is the lightest, which must result from the more favorable combination of moisture and temperature. A trend towards increasing ^{13}C discrimination with growing altitude and humidity is observed there, which is typical for many regions [13, 16, 33, 61].

The paired regression analysis revealed the average statistically significant correlation of δ^{13}C values in the upper humus soil horizon with the soil surface temperature indices, i.e., the average temperature for the growing season, the sum of positive temperatures, and the sum of temperatures >10°C (Table 1). No significant relationships were found with other microclimatic parameters. The multiple regression analysis also did not give results, which points to a complex system of factors affecting the fractionation of carbon isotopes, including, probably, those related to the dynamics of landscape and climatic conditions. Therefore, the available data set does not allow us to describe adequately all variations in δ^{13}C values.

Temperature and humidity are known to exert a significant impact not only on the photosynthetic effects of C3 plants, but also on the microbiota activity [3, 24, 29, 51, 60]. Rising temperature under favorable moisture conditions has a positive effect on soil microbiota functioning, it intensifies the organic matter mineralization and enhances the fractionation of carbon isotopes [44]. As a result of the predominant use of ^{12}C and the residual accumulation of ^{13}C, the composition of stable isotopes becomes heavier in soil organic matter [31].

This dependence is traced not only on a spatial scale but also in changes in the composition of stable carbon isotopes in soil profiles [31, 41, 43, 57]. An increase in $\delta^{13}C$ values with depth is typical for the soils in the study area regardless of the soil-forming conditions. Also a general trend is traced towards intensifying the organic matter mineralization (the growth of absolute β value) upon the transition from taiga soils to steppe soils, which, according to the results of pair correlation analysis, is related to the varying soil temperature. However, these parameters are responsible just for 34–41% of β variation. The expression of β is diverse in soil profiles of different landscape zones, which may point to a various intensity of soil organic matter mineralization and carbon cycle as affected by different set of factors [31, 42, 43].

The study area may be conventionally divided into three sections according to the conditions of organic matter mineralization and determining landscape and climate conditions. The organic matter dynamics in soils of the upper part of the altitudinal profile is limited by low temperatures. This is true for the mountainous tundra zone (S1) and to soils that develop in sub-tundra landscapes (S2). At the highest parameters of air humidity, the soils and litter show the elevated $\delta^{13}C$ values there. However, along with high values of $\delta^{13}C$ in the soil profile, the point S1 manifests a weakly pronounced gradient $\Delta\delta^{13}C$ and one of the gentlest sloping of the linear regression; whereas, in the point S2, both β and $\Delta\delta^{13}C$ values grow significantly, which may point to only partial effect of the temperature factor on the organic matter mineralization. Microclimatic monitoring data support this assumption. A dense multi-layer vegetation cover is developed on the S2 soil surface; it protects this soil from frost and cooling, which is particularly pronounced in early summer and in the first days of the fall.

Soils and vegetation of the subtundra (S2) and the upper part of taiga zone (S2, Ch2, S3, and S5) are formed upon the sufficient moisture, which is proved by the lowest $\delta^{13}C$ values in the humus horizons and litter for the entire altitudinal profile. Despite this fact, the values of the $\Delta\delta^{13}C$ isotope gradient decrease gradually in this altitudinal segment, which also agrees with the decreasing coefficient β. The latter varies widely. Its minimal values are registered in points Ch2 and S5, and the maximal, in points S2 and S3.

Comparison of these changes with the C/N ratio in the litter and humus horizons of soils at these points showed that the values of β coefficient decrease with higher C/N values.

The C/N ratio indicates the rate of organic matter decomposition depending on its biochemical composition [44, 60]. Many experiments have revealed the slowing down mineralization of organic residues with growing C/N [24, 37]. Low values of this index usually correlate with high intensity of soil organic matter mineralization, since nitrogen availability for heterotrophic microorganisms increases [21, 37]. Taking β as an indicator of the carbon turnover intensity in soil, we may assume that it slows down in the soils with the organic matter depleted in nitrogen (high C/N values).

Table 1. The pair correlation results, Pearson coefficients

Factor	$\delta^{13}C$			β-coefficient		
	r	r^2	p	r	r^2	p
pH	0.80	0.64	0.001	–0.54	0.29	0.07
Ts_m	0.48	0.23	0.16	–0.59	0.35	0.05
Ts_{gsm}	0.64	0.41	0.05	–0.58	0.34	0.06
$\sum Ts > 0°C$	0.64	0.40	0.05	–0.61	0.38	0.04
$\sum Ts > 10°C$	0.66	0.43	0.04	–0.64	0.41	0.03

Values pH and $\delta^{13}C$ for humus horizons, Ts_m is the mean annual soil surface temperature, Ts_{gsm} is the mean surface soil temperature during the growing season.

Additional relationships are also found upon comparing pH and C/N values ($r = -0.84$, $r^2 = 0.7$, $p = 0.0001$) in this part of vertical profile. At low pH, higher C/N values are registered, soils and litter with low acidity are characterized by lower C/N values and higher β values. Proceeding from this dependence and taking into account the fact that high acidity reduces significantly the microbial activity and the intensity of organic matter decomposition [48], it is logical to assume that pH is one of the important parameters that control the use of carbon and nitrogen by microorganisms in the studied soils and affect the intensity of organic matter mineralization in taiga soils of the Primorskii Range.

Such observations suggest that, in this part of the altitudinal profile, the carbon turnover in soils is mainly controlled by the qualitative composition of the litter, as well as by the soil properties affecting the intensity of litter decomposition. The dependence of the carbon isotopic composition on the litter quality can be well explained by a more favorable combination of temperature and humidity conditions in this profile part than in the lower and upper areas. In the areas with unfavorable climatic conditions, decomposition of plant residues is limited mainly by environmental factors, while under favorable hydrothermal conditions, it is limited by the organic matter quality [37]. In the mountainous taiga soils of the Primorskii Range, the principal restrictions for microbiological activity are probably associated with nitrogen availability. This interpretation fits the fact that temperate forests show a closed nitrogen cycle with low loss of nitrogen due to a high competition for this important resource for plant and microbiota nutrition, which is also typical for Siberian forest soils [21]. In this part of the altitudinal profile, the soil organic matter is formed upon the input of predominantly coniferous falloff rich in lignocellulosic compounds that require high activation energy for decomposition [32, 54]; this makes the organic matter mineralization intensity still more dependent on the litter quality.

Despite the most favorable combination of temperature and moisture in this part of the profile, thermal resources are still limited here. From the standpoint of the currently widely discussed CQT hypothesis [38], we may assume that the mountainous taiga landscapes in the Baikal region, which are formed under limited thermal resources at elevations of about 1400–800 m a.s.l., will experience the most pronounced changes in the carbon balance during the predicted climate warming.

The lower part of the landscape profile also differs in β values. Among the steppe soils, the linear regression sloping (i.e., the largest absolute value of β coefficient) is most pronounced in point S9 located 30 m far from Lake Baikal, and in plot Krestovyi in the valley, with its mouth going to the lake. The lowest β-coefficient among all the studied soils was revealed at the Sarma-1 point. Although these soils are formed in steppes, and the composition of stable carbon isotopes in humus horizons in the Cis-Olkhon region is similar to that in other steppe soils of the Baikal region [13], significant differences in the β coefficient, in our opinion, attest to soil differentiation by carbon turnover intensity. These differences are most likely to be associated with heterogeneous hydrothermal regime in the steppe soils of the Cis-Olkhon region. With a generally low moistening of the territory, the soils that form in the immediate vicinity of Lake Baikal are subject to significantly lower drying of the profile due to the cooling effect of water masses of Lake Baikal in summer and the valley circulation specifics (the case of plot Krestovyi). Microclimatic monitoring data confirm this assumption.

The steeper (as compared to other subtaiga soils) sloping of the linear regression at point Ch1 is most likely related to the northwestern aspect and the plot elevation a.s.l., which results in an increased air humidity.

The described changes in the β-coefficient expression in the subtaiga and steppe soils are not accompanied by significant fluctuations in C/N and pH. In combination with a decrease in $\delta^{13}C$ values in the humus horizons of soils and litter, these changes in the β-coefficient may testify to an insignificant role of edaphic factors, their influence being overlapped by the influence of moistening conditions on the carbon turnover intensity.

This interpretation is in good agreement with the idea that soil drying decreases the rate of SOM mineralization due to mitigation of microbial activity [29]. At the same time, comparison of the radial growth of larches and pines in this area with the atmospheric moisture [22] proves that not only steppe, but also subtaiga landscapes are limited in moisture. This issue is still more interesting, taking into account that from the standpoint of SOM mineralization intensity, most temperate forests do not suffer from moisture deficit [32]. Therefore, this case elucidates a regional specifics in functioning of subtaiga landscapes formed under the conditions of the barrier effect of mountains surrounding Lake Baikal.

CONCLUSIONS

The study area shows a contrasting landscape pattern and a significant variability of climatic parameters, which affect the composition of stable isotopes in vegetation and soil organic matter. The analysis of variations in $\delta^{13}C$ values in soil humus horizons has proved that the heaviest carbon isotopic composition is typical for the soils of mountainous tundra and steppe landscapes (–24.72 and –23.97...–24.75‰, respectively); and the lightest, for the taiga soils (–25.61...–27.18‰). The data obtained on the carbon isotopic composition in vegetation and litter provide an important evidence on the factors limiting plant productivity in various landscapes. A comprehensive analysis of vertical and horizontal variations in the composition of stable carbon isotopes, as well as a number of chemical properties controlling its dynamics in soils, permitted us to reveal differences in the intensity of organic carbon turnover in soils on the western coast of Lake Baikal.

Despite the generally linear changes in climatic indices from the upper to lower hypsometric levels (an increase in temperature and duration of the growing season, a decrease in moisture), variations in isotope characteristics are more complicated.

With the revealed average positive relationship between β and temperature parameters of soils, the subtaiga and steppe soils, which are characterized by the highest heat supply, show one of the lowest β values due to low moisture content. Among other phenomena, this is evidenced by the fact that the steppe soils, formed under conditions of high moisture and lower desiccation of soil profile in summer in the immediate vicinity of Lake Baikal are specified by an elevated intensity of carbon turnover.

In the soils of the upper part of the landscape profile, which are characterized by the highest moisture supply, the least intense carbon turnover is observed. This is caused by heat deficiency and is confirmed by the heavier isotope composition of vegetation and SOM in high mountains.

Insignificant changes in climatic parameters in mountain-taiga landscapes do not result in substantial β variations. The latter variations correlate more closely with sharp changes in the physicochemical soil properties that control the rate of organic matter decomposition/stabilization.

Thus, in contrasting conditions of the upper and lower profile parts, the climate affects significantly the intensity of organic matter transformation and blocks the effect of soil factors. Under more favorable climatic conditions of mountainous taiga landscapes, the dynamics of organic matter in soils is controlled mainly by soil factors.

Despite the most favorable combination of temperature and moisture in the mountainous taiga landscapes surrounding Lake Baikal at heights of about 800–1400 m a.s.l., thermal resources are limited there. These are landscapes, where the possible intensification of carbon turnover upon the predicted climate warming may cause the most pronounced changes in the carbon budget. Taking into account their significant contribution to the carbon budget in the Baikal region, further research is needed for better understanding of this problem.

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CONFLICT OF INTERESTS

The authors declare no conflict of interests.

SUPPLEMENTARY INFORMATION

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Table S1. The main characteristics of the studied sites.

Fig. S1. Coefficients of linear regression sloping (β) for the studied soils.

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