Carbon stock in litter of middle taiga forest ecosystems of Central Siberia

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Abstract. Litter plays an important role in the carbon cycle of forest ecosystems incorporating significant amount of carbon as a result of annual partial die-off of the biomass and releasing it during complex multistage processes of organic matter decomposition. The balance of these processes in the forests of permafrost zone significantly shifts towards the accumulation of dead organic matter. That makes the assessment of litter stock in these ecosystems particularly relevant, especially in relation to the predicted consequences of climate change in the study region. On the territory of middle taiga of Central Siberia, 14 sampling plots were established in the various landforms (slopes of different exposition, lowlands and uplands). The carbon stock in litter of the main forest types of the studied area varied from 0.47 to 4.46 kgC/m². Also, the paper considers composition of litter accumulated in these ecosystems, including the ratio between fresh litterfall, fermented and humified plant residues, and dead roots. Our results demonstrated that fermented plant residues prevailed in the litter composition in most types of studied forest ecosystems due to specificity of hydrothermal regime and quality of litterfall. The results obtained might be applied to refine the carbon budget of Siberian forests.

1. Introduction
Litter, which represents dead organic material of plant origin covering the soil surface, is an important component of forest ecosystems. Acting as a link between plants and soil, above- and belowground layers of ecosystem [1,2], it participates actively in the biological cycle, including carbon [3,4] and nitrogen [5] cycling.

According to its resistance to biodegradation, soil organic matter is divided into easily mineralizable (labile) and hardly decomposable (recalcitrant) fractions, with the last ones being firmly associated with mineral part of the soil. Forest litter belongs to pool of labile organic matter [3,6]. As a renewable resource, it changes rapidly in terms of both energy and matter, and thus is able to reflect modern processes in forest ecosystems [1,2,6].

Such sensitivity of forest litter to the environmental conditions is of particular importance in terms of detection of the current state of forest ecosystems in the Siberian permafrost zone. Permafrost zone has been actively studied, especially in recent years, both in Russia and worldwide [7-9]. Many researchers are concerned about possible consequences of permafrost degradation, including vegetation transition and significant loss of soil carbon [10,11], changes in water budget [12]. According to
calculations, up to 25% of the estimated stocks of carbon in peatlands and permafrost might be lost due to climate changes in XXI century [10]. High latitude ecosystems are expected to contribute significantly to these losses.

Boreal forests exist under extreme climate conditions and thus are characterized by low productivity during a short growing season and low rate of organic matter decomposition. As a result, they accumulate significant amount of carbon not only in phytomass (live biomass) [13,14], but also in detritus [6,15,16]. However, the expected consequences of climate change may significantly impact biogeochemical cycles in boreal forests and change the carbon balance in these ecosystems [9,10]. Thus, there is a need to identify the current carbon stocks in dead organic matter in the forest ecosystems of boreal zone.

The aim of this study was to determine carbon stock in litter in the main types of middle taiga forest ecosystems of Central Siberia (within the borders of Krasnoyarsk Krai).

2. Methods and materials

2.1. Site description

The research was conducted in the Evenkiysky District of Krasnoyarsk Krai (Siberia, Russian Federation). According to forest zoning, the territory belongs to the subzone of middle taiga. To assess the carbon stock in litter in the main types of middle taiga forest ecosystems, two key sites were selected. One site is located within the territory of ‘Tunguska’ State Nature Reserve (Vanavara settlement, 60°N 101°E; hereafter referred to as ‘Site1’); another one was established near Baykit settlement (61°N 96°E; hereafter referred to as ‘Site2’).

The annual mean temperature is -5.5 °C for Site1 and -6.2 °C for Site2, the total annual precipitation is 407 mm and 508 mm, respectively. The climate data was obtained from the nearest to the sampling site meteorological station for the common period 1932-2019 for annual mean temperature and 1966-2016 for total annual precipitation (data is available at www.meteo.ru). The soil cover of the territory is represented by Podzols, Entic Podzols, Eutric Cambisols with Cryosols in the lowlands.

The following types of forest ecosystems are presented in the studied area: larch-, fir-, Scots pine-, Siberian pine-, birch-dominated and mixed forests. The territory is characterized by a pronounced macro- and mesorelief. It includes placores, lowlands and uplands, slopes of different exposition: north (N), south (S), west (W) north-west (NW) and north-east (NE). These landforms differ in the amount of incoming solar radiation and structure of plant communities. The main characteristics of the sampling plots (SP), including the altitude in meters above sea level (masl) are given in the table 1. Brief descriptions of plant communities presented in the study sites are listed below.

SP1. The forest stand is dominated by Pinus sylvestris L., with minor participation of Larix sibirica Ledeb. The shrub layer with a total coverage of 25% is dominated by Duschekia fruticosa (Rupr.) Pouzar and the undergrowth of Pinus sylvestris L. The herb-dwarf shrub layer with 30% coverage is multi-species and has two sublayers. It is dominated by Vaccinium vitis-idaea L., Vaccinium uliginosum L., Empetrum nigrum L. and Linnaea borealis L. Pleurozium schreberi (Willd. ex Brid.) Mitt. absolutely dominates in the moss-lichen layer with 90% coverage.

SP2. The forest stand is dominated by Larix sibirica Ledeb., with a small admixture of Pinus sylvestris L. Duschekia fruticosa (Rupr.) Pouzar prevail in the shrub layer with 50% coverage. The multi-species herb-dwarf shrub layer with 35% coverage is dominated by Vaccinium vitis-idaea L. The moss-lichen layer is discontinuous (25% coverage), both Hylocomium splendens (Hedw.) Schimp. and Pleurozium schreberi (Willd. ex Brid.) Mitt. are prevalent.

SP3. Larix sibirica Ledeb., Pinus sibirica Du Tour and Picea obovata Ledeb. co-dominate in the tree layer. The sparse shrub layer with a total coverage of 15% is dominated by Duschekia fruticosa (Rupr.) Pouzar and the undergrowth of Pinus sylvestris L. and Picea obovata Ledeb. Vaccinium vitis-idaea L. prevails in the sparse (20% coverage) and species-poor herb-dwarf shrub layer. The continuous moss-lichen layer (100% coverage) is dominated by Pleurozium schreberi (Willd. ex Brid.) Mitt. and Hylocomium splendens (Hedw.) Schimp.
| SP No. | Landform type | Altitude (m asl) | Plant community type | Tree age (years) | Crown cover (%) | Litter thickness (cm) | Carbon stock in litter (kgC/m²) |
|--------|---------------|-----------------|----------------------|-----------------|-----------------|----------------------|--------------------------------|
| 1      | Slightly inclined area, S (397) | Dwarf shrub-green moss-lichen Scots pine forest | 150-200 | 50 | 7.5±1.5 | 1.18±0.16 |
| 2      | Slightly inclined area, NW (371) | Alder herb-lingonberry larch forest | 100-150 | 55 | 15.0±2.3 | 1.99±0.21 |
| 3      | Flat land (388) | Lingonberry-herb-green moss mixed coniferous forest | 150-250 | 65 | 8.5±2.1 | 2.02±0.26 |
| 4      | Slightly inclined area, W (336) | Dwarf shrub-green moss larch forest | 100 | 60 | 5.0±1.8 | 1.51±0.28 |
| 5      | Slightly inclined area, N-NW (391) | Blueberry-green moss larch forest | 100 | 45 | 8.0±2.2 | 2.10±0.47 |
| 6      | Plateau (628) | Blackberry-green moss birch forest | 40-60 | 70 | 2.0±1.0 | 0.47±0.06 |
| 7      | First above-floodplain terrace (188) | Blueberry-green moss larch forest | 80-150 | 60 | 7.5±2.5 | 1.52±0.06 |
| 8      | Lowland (146) | Sparse larch forest | 100-150 | 25 | 13.0±2.6 | 4.46±0.53 |
| 9      | N-NW Slope, upper part (283) | Alder blueberry-green moss larch forest | 100-200 | 40 | 24.0±4.5 | 3.39±0.46 |
| 10     | S Slope, upper part (296) | Blueberry-green moss Scots pine forest | 100 | 50 | 7.0±2.1 | 0.71±0.18 |
| 11     | Plateau (712) | Blueberry-blackberry-green moss birch forest | 30-40 | 40 | 12.5±3.5 | 1.69±0.55 |
| 12     | NE Slope, middle part, stream floodplain (511) | Dwarf shrub-green moss fir forest | 150-200 | 65 | 9.0±2.6 | 1.42±0.26 |
| 13     | N Slope, middle part (483) | Blueberry-blackberry-green moss Siberian pine forest | 150-250 | 45 | 14.0±2.5 | 1.39±0.31 |
| 14     | N Slope, upper part (575) | Blackberry-horsetail birch forest | 40 | 60 | 7.0±2.5 | 2.32±0.10 |

Table 1. Main characteristics of the sampling plots (SP).
SP4. The forest stand is dominated by *Larix sibirica* Ledeb., with an admixture of *Pinus sylvestris* L. The sparse (15% coverage) shrub layer is dominated by the undergrowth of *Pinus sylvestris* L. The herb-dwarf shrub layer is multi-species, with a total coverage of 40% and two sublayers. It is dominated by *Empetrum nigrum* L. The moss-lichen layer is well-developed (70% coverage) and dominated by *Pleurozium schreberi* (Willd. ex Brid.) Mitt. and *Cladonia stygia* (Fr.) Ruoss.

SP5. The forest stand is dominated by *Larix sibirica* Ledeb., with an admixture of *Betula pendula* Roth. The shrub layer formed by the undergrowth and willows is extremely sparse. The herb-dwarf shrub layer is species-poor and dense, with a total coverage of 45%. It is dominated by *Vaccinium uliginosum* L. The coverage of the moss-lichen layer is 70%, the moss species *Pleurozium schreberi* (Willd. ex Brid.) Mitt. and *Hylocomium splendens* (Hedw.) Schwimp. are prevalent.

SP6. *Betula pendula* Roth dominates in the tree layer. The shrub layer formed by undergrowth of conifers and hardwoods is sparse. *Vaccinium myrtillus* L. and *V. uliginosum* L. prevail in the herb-dwarf shrub layer with a total coverage of 35% and two sublayers. The moss-lichen layer is discontinuous and dominated by *Pleurozium schreberi* (Willd. ex Brid.) Mitt. and lichens of genus *Cladonia* P. Browne.

SP7. Two-storey forest stand is dominated by *Larix sibirica* Ledeb. and *Picea obovata* Ledeb. The undergrowth of *Picea obovata* Ledeb. prevails in the shrub layer with 10% coverage. The sparse (25% coverage) and species-poor herb-dwarf shrub layer is dominated by *Vaccinium uliginosum* L. and *V. vitis-idaea* L. and has two sublayers. The continuous moss-lichen layer (95% coverage) is dominated by *Pleurozium schreberi* (Willd. ex Brid.) Mitt., *Hylocomium splendens* (Hedw.) Schwimp. and co-dominated by *Dicranum polysetum* Sw.

SP8. The forest stand is sparse and dominated by *Larix sibirica* Ledeb. The undergrowth of *Picea obovata* Ledeb. and, more rarely, *Pinus sibirica* Du Tour prevails in the sparse shrub layer with 25% coverage. The herb-dwarf shrub layer with a total coverage of 30% is multi-species and has two sublayers. *Chamaedaphne caliculata* (L.) Moench and *Vaccinium uliginosum* L. are prevalent in this layer. The continuous moss-lichen layer (95% coverage) is dominated by *Aulacomnium palustre* (Hedw.) Schwagr. and *Sphagnum warnstorffii* Russow.

SP9. The forest stand is dominated by *Larix sibirica* Ledeb., with an admixture of *Picea obovata* Ledeb. and *Pinus sibirica* Du Tour. The shrub layer is dense (40% coverage) and dominated by *Duschekia fruticosa* (Rupr.) Pouzar. The herb-dwarf shrub layer with 30% coverage has two sublayers, with the prevalence of *Vaccinium uliginosum* L. and *Ledum palustre* L. The continuous moss-lichen layer (95% coverage) is dominated by *Hylocomium splendens* (Hedw.) Schwimp. and co-dominated by *Aulacomnium palustre* (Hedw.) Schwagr. and *Pleurozium schreberi* (Willd. ex Brid.) Mitt.

SP10. *Pinus sylvestris* L. dominates both in the forest stand and in the shrub layer (the coverage of the latter is about 20%). The herb-dwarf shrub layer is discontinuous (30% coverage) and species-poor, with the prevalence of *Vaccinium uliginosum* L. and *V. myrtillus* L. The continuous moss layer is dominated by *Pleurozium schreberi* (Willd. ex Brid.) Mitt. and co-dominated by *Aulacomnium palustre* (Hedw.) Schwagr.

SP11. The mixed forest stand is dominated by *Betula pendula* Roth, with a significant admixture of *Abies sibirica* Ledeb. The shrub layer is sparse (10% coverage) and formed mostly by the undergrowth of *Abies sibirica* Ledeb. The coverage of the herb-dwarf shrub layer is 40%, with the prevalence of *Vaccinium myrtillus* L. and *V. uliginosum* L. The moss layer is well-developed, dominated by *Pleurozium schreberi* (Willd. ex Brid.) Mitt. and co-dominated by *Polytrichum commune* Hedw.

SP12. *Abies sibirica* Ledeb. and *Pinus sibirica* Du Tour form the first storey of the forest stand; the second one is dominated by *Betula pendula* Roth. In the dense shrub layer with 50% coverage the undergrowth of *Abies sibirica* Ledeb. prevails. The herb-dwarf shrub layer (30% coverage) is implicitly dominated by *Vaccinium uliginosum* L. with small boreal herbs on the background. The well-developed moss-lichen layer with 65% coverage is dominated by *Pleurozium schreberi* (Willd. ex Brid.) Mitt., *Hylocomium splendens* (Hedw.) Schwimp. and *Dicranum polysetum* Sw.

SP13. The forest stand is dominated by *Pinus sibirica* Du Tour, with a significant admixture of *Picea obovata* Ledeb. In the shrub layer with 20% coverage the undergrowth of *Abies sibirica* Ledeb. prevails.
The dense herb-dwarf shrub layer (50% coverage) has two sublayers, with the prevalence of Vaccinium myrtillus L. and V. uliginosum L. The moss-lichen layer with 85% coverage is dominated by Pleurozium schreberi (Willd. ex Brid.) Mitt.

SP14. The forest stand is dominated by Betula pendula Roth. In the shrub layer with 60% coverage the undergrowth of Abies sibirica Ledeb. and Picea obovata Ledeb. prevails. The herb-dwarf shrub layer is species-poor and sparse, with a total coverage of 25%. It is dominated by Vaccinium myrtillus L. The moss-lichen layer is discontinuous (30% coverage), with the prevalence of Hylocomium splendens (Hedw.) Schimp. and Pleurozium schreberi (Willd. ex Brid.) Mitt.

2.2. Sampling design and litter stock calculation

The size of the sampling plot was 25×25 m. In total, 14 SP were established in the various landforms. On each plot, samples of forest litter were collected in 5 replicates using metal round frame with a 20-cm diameter. Forest litter was extracted entirely, up to the mineral soil horizon. All the litter samples were air-dried at room temperature in the laboratory. After that, every sample was divided into several fractions using the series of sieves with mesh sizes from 10 to 1 mm [6]. In our research, the following fractions of forest litter had been identified: 1. the litterfall residues that retained the morphological structure such as branches, leaves, needles etc (the AOL fraction, fresh litterfall); 2. the plant residues at various stages of decomposition retained on the 1.0 mm sieve-mesh after the removal of roots and AOL fraction components (the AOF fraction, fermented plant residues); 3. the plant residues with no morphological structure that passed through the 1.0 mm sieve-mesh (the AOH fraction, humified plant residues); 4. the dead roots, including roots of herbs, shrubs and trees.

The air-dried samples were then dried in an oven at 60 °C for 24 hours and weighted. The data obtained were converted into the mass per unit area (kg/m²). All the values in the following sections of the paper are given in absolute dry weight.

Carbon content was determined using an Elementar Analyser (Vario Isotope Cube, Elementar Analysis Systems GmbH, Germany), for each fraction of forest litter separately. Carbon stock in forest litter (kgC/m²) was calculated by multiplying the litter mass per unit area by its carbon content. The statistical analysis was performed in MS Excel. The significance of differences was determined using ‘t-Test: Two-Sample Assuming Unequal Variances’ from the Data Analysis ToolPak. In our calculations, detected differences were deemed significant if p<0.05. Mean values in the text are given together with values (±) of standard error.

3. Results and discussion

3.1. Litter stock in different types of forest ecosystems

Litter stock in the larch forests of the studied area varied from 4.05±0.25 to 8.86±1.28 kg/m². The statistical test showed that the differences between Site1 (‘Tunguska’ State Nature Reserve) and Site2 (Baykit settlement) were not statistically significant. The only exception was the sparse larch forest (SP8), where litter stock equaled to 10.89±1.05 kg/m².

The fir forest (SP 12) and the Siberian pine forest (SP13) demonstrated similar litter stock (3.57±0.65 and 3.59±0.80 kg/m², respectively). For the Scots pine forests (SP1 and SP10) the value was within 1.80±0.41 – 3.21±0.41 kg/m², no statistically significant differences were determined for this type of forest between Site1 and Site2. Litter stock in the birch forests (SP6, SP11 and SP14) ranged from 1.29±0.17 to 6.34±0.34 kg/m², in the mixed coniferous forest (SP3) it equaled to 5.44±0.71 kg/m².

The mean carbon content (C) amounted to 44.4±1.9% for the AOL fraction, 35.2±4.0% and 28.8±1.6% for the AOF and AOH fractions, respectively. Calculated carbon stock in litter was: 1.51±0.28-4.46±0.53 kgC/m² in larch forests, 0.71±0.18-1.18±0.16 kgC/m² in Scots pine forests, 1.39±0.31 kgC/m² in Siberian pine forest, 1.42±0.26 kgC/m² in fir forest, 0.47±0.06-2.32±0.10 kgC/m² in birch forests and 2.02±0.26 kgC/m² in mixed coniferous forest (table 1).
3.2. Composition of forest litter

In the composition of forest litter, the ratio of four main fractions had been identified: the litterfall residues that retained the morphological structure (AOL), fermented plant residues (AOF) and humified plant residues (AOH) fractions, and dead roots (figure 1).

The AOL fraction made up about 26.6±3.1% of the litter stock. The highest contribution of this fraction to the total litter stock was observed on SP8 (45.3±1.4%) and SP12 (50.8±0.8%). These plots were differ from others statistically significantly in terms of the AOL contribution. Other sampling plots demonstrated lower percentage of litterfall residues (10.1-36.4%). The main contribution to the AOL on the Site1 belong to branches (40.6±4.7%), followed by moss residues (18.9±4.0%) and cones (11.9±2.1%). On the Site2, the percentage of moss residues was higher (60.5±6.3%), while percentage of branches was lower (13.8±2.7%). Thus, the contribution of total tree litterfall (the sum contribution of needles, leaves, cones and branches) to the forest litter was significantly higher on the Site1 than on the Site2 (70.9±4.3% versus 21.2±4.6%, respectively).

![Figure 1. Composition of the forest litter: AOL – litterfall residues that retained the morphological structure, AOF – fermented plant residues, AOH – humified plant residues (1-14 – numbers of the sampling plots).](image)

The average contribution of fermented plant residues to the total litter stock was 60.3±3.1%. SP8 and SP12 were characterized by the lowest contribution of the AOF (in contrast to the AOL described above) 45.8±3.0 and 42.8±0.9%, respectively. On the other studied sampling plots, the contribution of AOF exceeded 50% and in the blueberry-green moss larch forest (SP5) it reached 80.1±1.9%.

The humified plant residues (the AOH fraction) and dead roots contributed the least to the total litter stock in the studied forest ecosystems (the average percentage of these fractions was 8.0±1.2% and 5.1±0.9%, respectively).

3.3. Effects of topographic characteristics on carbon stock in litter

The carbon stock in litter of the forest ecosystems studied is determined not only by composition of plant communities, but also by the topography. Different landforms receive unequal amounts of solar radiation and precipitation, which contributes to the formation of microclimatic gradients. Consequently, the rates of litter input and organic matter decomposition differ between landforms [3,17,18].

In general, our estimates of litter stock in different types of forest ecosystems are similar to results reported by other researchers for this area [19].
The highest carbon stock in forest litter in our study was observed in the sparse larch forest (SP8) growing in the waterlogged lowland (4.46±0.53 kgC/m²). The difference between SP8 and the rest of the sampling plots in terms of carbon stock in litter was statistically significant. The observed phenomenon can primarily be linked to the microclimatic conditions of the sampling plot, namely a lower amount of incoming solar radiation and a higher humidity. These factors decrease the rate of litter decomposition. Moreover, these conditions favor the growth of moss-lichen cover (the percentage of moss residues on SP8 was the highest among the sampling plots). The presence of decay resistant [1] mosses of the genus *Sphagnum* L. in the living ground cover and, consequently, in litter also contributes to the relatively low rate of dead organic matter decomposition.

The carbon stock in litter was also relatively high in the alder blueberry-green moss larch forest (SP9) growing on the upper part of the north-facing slope (3.39±0.46 kgC/m²). It is followed by blackberry-horsetail birch forest (SP14) located on the similar landform (2.32±0.10 kgC/m²). Higher litter stock on north-facing slopes (compared to south-facing ones) have been noted by other researchers [3,17,20].

In the blackberry-green moss birch forest growing on the plateau (SP6), the carbon stock in forest litter was statistically the lowest among the studied ecosystems (0.47±0.06 kgC/m²). Also the stock was relatively low in the blueberry-blackberry-green moss Scots pine forest (SP10) growing on the upper part of south-facing slope (0.71±0.18 kgC/m²). These observations can be explained by a higher amount of solar radiation reaching the landforms and a better drainage of the territory. The additional factor for SP6 is forest stand composition. Some studies show [21-23] that the rate of litter decomposition in deciduous forests is higher than in coniferous ones. In comparison to SP6, blueberry-blackberry-green moss birch forest (SP11), that also grows on the plateau, had higher carbon stock in the forest litter (1.69±0.55 kgC/m²). This result is caused by the fir (*Abies sibirica* Ledeb.) admixture in the forest stand, which leads to lower rate of litterfall decomposition.

The differences between the rest of the sampling plots in terms of the carbon stock in forest litter were not statistically significant (the values lie within 1.18±0.16-2.10±0.47 kgC/m²).

3.4. **Interrelations between topography and composition of forest litter**

One of the most important characteristics of litter, apart from the organic matter stock, is its composition. The presence and ratio of the AOL-, AOF- and AOH fractions reflect both the intensity of dead organic matter input and the relative rate of decomposition of litter components. The higher is the rate of decomposition of a certain litter component, the less will be its percentage in the composition of litter [6].

In the ecosystems studied, the main contribution to the composition of forest litter was made by fermented plant residues (the AOF fraction). Only the sparse larch forest (SP8) growing in the waterlogged lowland and the dwarf shrub-green moss fir forest (SP12) on the slope of north-eastern exposition were inconsistent with the general pattern (the percentages of AOF fraction were 45.7±0.6% and 42.8±0.9%, respectively). This is attributable to the relatively high ratios of the AOL fraction on these sampling plots.

The contribution of the AOL fraction to the total litter stock in the area studied may reach 50.8±0.8%, with an average of 26.6±3.1%. It is composed of litterfall residues, slightly affected by decomposition, namely branches, cones, needles, leaves, fragments of bark, moss residues, lichens, etc. An increase in percentage of this fraction in the total litter stock, on the one hand, can be associated with an increase of fresh plant material input, and, on the other hand, with a decrease of litter decomposition rate. The significant percentage of the AOL fraction in the larch forest (SP8) and in the fir forest (SP12) is most likely due to the low decomposition rate of litter related to plot-specific microclimatic conditions. An additional reason may be the presence of decomposition-resistant components in the litter (moss residues account for 80-82% of the total stock of AOL fraction).

4. **Conclusion**

Carbon stock in the litter in forest ecosystems of middle taiga in Central Siberia is determined not only by forest type, but also by topography. Our assessments demonstrated that the highest carbon stock in litter (4.46 kgC/m²) is observed in the sparse larch forest growing in the waterlogged lowland, while the
blackberry-green moss birch forest growing on the plateau is characterized by the lowest one (0.47 kgC/m²). The decisive agent explaining these differences is plot-specific hydrothermal regime. The fraction of fermented plant residues prevailed in litter composition in most of the studied ecosystems. The results obtained might be applied to refine the carbon budget of the Siberian forests.

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