Litterfall carbon cycle in pine stands growing in the Central Siberian subtaiga forest-steppe zone

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Abstract. The article presents the methodology of collection and desk study of forest litterfall samples. The fractional composition of woody debris has been studied. Biomass and carbon stocks in pine stands litter have been estimated.

1 Introduction

According to the IPCC Guidelines [1], litter accumulation is important for the carbon budget in different forest types, being one of forest carbon pools. In pine forests, the main courses of organic carbon in litterfall are: woody litter (87 %) and leaf tissues [2].

Nutrient cycling by decomposing woody debris regulates the productivity and subsequent carbon sequestration in forest ecosystems [3, 4, 5, 6. 7, 8]. Nevertheless, the litter decomposition dynamics varies depending on the environment [6, 7, 9]. Tropical forests are of the highest decomposition rate [3, 4] due to high nutrient uptake rates and low storage capacity in tropical soils. Invertebrates also play a crucial role, contributing more to decomposition in the tropics than in low or high latitudes, due to more favorable and stable climatic conditions [3]. For example, the half-life of mangrove leaf litter ranges from 18 to 52 days [4], which is quite fast, hence the organic matter accumulation is insufficient for litter formation. In the northern forests, the organic matter decomposition rate is low, which contributes to organic horizon accumulation [10, 11, 12]. High soil moisture and low temperatures cause slow, season-depended organic decomposition [6, 7, 9, 13, 14].

Boreal forests cover 1/3 of the world's terrestrial forests and act as a major global carbon pool. Boreal climate slows plant litter decomposition and soil carbon mineralization, resulting in significant litterfall accumulation. For example, up to 95% of taiga forests carbon is concentrated in soil. Notably, aboveground phytomass decomposition is one of the main sources of taiga soils carbon [9].

The aim of the present research is to study the accumulation of phytomass and carbon in litter during the growing season in pine stands growing in the Central Siberian subtaiga forest-steppe zone.

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2 Materials and methods

The study was focused on litter in pine forests near Krasnoyarsk, namely in the Karaul'noe forestry of the Educational and Experimental Forestry of the Reshetnev Siberian State University of Science and Technology (Reshetnev University), Russia.

There are research papers dedicated to studying litter during different periods: semi-annual (May-October, November-April) or annual. The period from May to October (summer-autumn period) is characterized by predominantly warm weather and the formation of most of the annual litter, compared to the winter-spring period.

We placed four research plots (RP), selected by homogeneity of forest-forming species and forest site conditions to study the volume of biomass, its fractional composition and litter carbon pool. Stationary litter traps of 0,5 m x 0,5 m x 0,1 m were placed evenly on each research plot and marked with an aluminum plaque. We carried litter sampling at each research plot where the stationary litter traps were located.

The litter composition varied considerably both spatially and temporally. Among all the litter fractions branches and cones varied in the most significant range, although other fractions also varied to some extent [5].

After estimating the litter biomass, we assessed stored carbon volume. According to conducted literature review, we decided to assess litterfall carbon using the coefficients obtained by other researchers [15].

We carried out forest inventory in all research plots. Table 1 shows the results of visual and instrumental measurements conducted on the research plots.

The research plots were of referent composition, density, bonitet class, age and forest type for the study area. The stands are predominantly pure stands with an admixture of birch up to 30 %. The pine stands are either approaching maturity or mature (75–97 years old). The studied stands are of the I–II bonitet class, indicating favorable growing conditions. The density ranges from 0.5 to 1.0. The research plots were located in the most typical forest types in the study area: pine forests of forest floor dominated by sedges/herbs or herbs/moss.

The amount of incoming litterfall, its composition and decomposition rates largely determine litter formation pattern and soil morphological structure [16].

Table 1. Silvicultural and forest inventory of the studied pine stands.

FC/FU (RP)	Composition	Height, m	Age, years	Diameter, cm	Bonitet class	Forest type	Density	GS, m^3 per ha^{-1}
50/11 (RP 1)	9P1B	25.3	95	29.3	II	Herb-rich/moss	1.0	412
50/8 (RP 2)	7P3B	25.0	90	27.7	II	Sedges/herb-rich	0.8	292
38/18 (RP 3)	10P	27.0	75	23.0	I	Herb-rich/moss	0.5	219
38/25 (RP 4)	10P	29.0	97	30.0	I	Sedges/herb-rich	0.6	252

Note: FC – forest compartment; FU – forest unit; RP – research plot; P – pine; B – birch; GS – growing stock.

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3 Results

We summarized and presented in tabular and graphical forms the desk research results. Table 2 shows the litter structure by fractions and research plots.

Table 2. Absolute dry weight of the pine forests litter fractions, g per m^{-2} .

Fraction (hygroscopic coefficient)	Forest compartment/forest unit (research plot)			
	50/11 (RP 1)	50/8 (RP 2)	38/18 (RP 3)	38/25 (RP 4)
Leaves (0.91)	1.22±0.25	17.32±4,12	17.48±4.01	8.42±2.58
Pine needles (0.91)	185.65±36.09	112.81±20.00	165.79±36.20	115.49±23.97
Grass (0.92)	0.94±0.17	2.26±0.32	2.76±0.45	2.45±0.45
Pine seeds (0.89)	0.71±0.14	0.68±0.15	0.19±0.04	0.13±0.03
Tree bark (0.89)	34.25±3.98	19.59±2.58	27.31±3.59	20.88±2.40
Other (unidentified biomass) (0.89)	28.46±4.35	35.54±4.70	20.00±2.68	23.30±3.37
Total for active fraction	**251.23±37.51**	**188.20±23.07**	**233.53±42.48**	**170.67±24.45**
Branches (0.88)	61.70±16.90	30.93±5.42	23.30±4.95	11.10±2.63
Cones (0.61)	28.34±2.56	60.93±7.78	14.60±2.18	19.98±3.30
Total for inactive fraction	**90.03±17.84**	**91.86±9.19**	**37.90±6.42**	**31.08±2.96**
Total litter	341.27±54.90	280.06±24.95	271.43±44.00	201.75±24.59

Note: the statistics obtained at a confidence level of 0.954.

Of all the fractions, regardless of the research plot, pine needles had the highest proportion (40.3–61.1 %), followed by cones (5.4–21.8 %), tree bark (7.0–10.4 %), branches (5.5–18.1 %) and other unidentified residues (7.4–12.7 %). The proportion of seeds and grass did not exceed 1.0 %. Notably, the proportion of green biomass (leaves, grass, needles) was around or exceeded 50 % in pine forests on different research plots. This indirectly indicates the sustainability of pine forests, as the green biomass is similar in mass of woody and non-woody parts (bark, branches, cones, seeds).

Overall, the proportion of the active fraction was 67.2–86.0 % in all research plots. The inactive fraction took 14.0–32.8 %.

The differences in the studied pine stands litter fractions are due to different reasons. The considerable volume of leaves is both due to the presence of individual birch trees in the stand (RP 2), and to a nearby birch-dominated stands (RP 3). The amount of needles depends on both the density of the pine forests (RP 1) and the presence of old trees with a spreading crown (RP 3). Mass of grass depends the ground cover type, i.e. herbaceous plants projective cover. The proportion of seeds depends on the density and stocking of the pine forests (the higher the density, the greater the number of seeds), which is evidenced on RP 1 and RP 2. The volume of bark is determined by the same factors as the amount of needles. The mass of unidentified residues, branches and cones depends on the density and stocking of the stand (the greater the density, the greater the mass of unidentified biomass, branches and cones).

We analyzed the temporal dynamics of carbon accumulation in the litter for the study period. The evaluation was carried out during most of the growing season, namely from early May to early November. In 2022, the growing season started on April 14.

During the study period, we collected litter samplings and assessed carbon stock there. Each sampling was analyzed in relation to the time of accumulation. Litterfall accumulation depends on a number of factors, including climate, dominant species phenology and growing season stage.

Here we present a cumulative data, i.e. the values for all study periods are summed up. Table 3 shows periods of carbon growth and its dynamics in active litter fraction.

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Table 3. Stages of the active fraction carbon accumulation.

FC/FU (RP)	Accumulation stage	Stage length, days	Date	Litter carbon stock, t C per ha^{-1}	Litter carbon sequestration rate, t C ha^{-1} per day
50/11 (RP 1)	moderate	101	05.05.2022 – 13.08.2022	0.0 – 0.4158	0.00412
	intensive	81	14.08.2022 – 03.11.2022	0.4158–1.1808	0.00944
50/8 (RP 2)	moderate	101	05.05.2022 – 13.08.2022	0.0 – 0.3414	0.00338
	intensive	81	14.08.2022 – 03.11.2022	0.3414 – 0.8845	0.00670
38/18 (RP 3)	moderate	82	24.05.2022 – 13.08.2022	0.0 – 0.3028	0.00369
	intensive	79	14.08.2022 – 01.11.2022	0.3028–1.0976	0.01006
38/25 (RP 4)	moderate	81	25.05.2022 – 13.08.2022	0.0 – 0.2806	0.00346
	intensive	79	14.08.2022 – 01.11.2022	0.2806 – 0.8022	0.00660

We observed the maximum carbon accumulation in the active litter fraction on RP 1 and RP 3, and the minimum ones on RP 2 and RP 4. The stages are clearly defined and typical of all the research plots.

It is quite difficult to reveal patterns when studying the inactive fraction, since branches and cones are of high variability (that is why we divided the litterfall into two fractions in the first place). One can distinguish an intensive accumulation at the beginning of the study period, which can be caused by wind gusts. During the rest of the study period, the accumulation is rather low and uniform, except for RP 1. Table 4 shows carbon accumulation dynamics in the inactive litter fraction.

Table 4. Stages of the inactive fraction carbon accumulation.

FC/FU (RP)	Accumulation stage	Stage length, days	Date	Litter carbon stock, t C per ha^{-1}	Litter carbon sequestration rate, t C ha^{-1} per day
50/11 (RP 1)	moderate	101	05.05.2022 – 13.08.2022	0.0 – 0.1317	0.00131
	intensive	81	14.08.2022 – 03.11.2022	0.1317 – 0.4232	0.00360
50/8 (RP 2)	intensive	84	05.05.2022 – 27.07.2022	0.0 – 0.3199	0.00381
	moderate	98	28.06.2022 – 03.11.2022	0.3199–0.4317	0.00114

38/18 (RP 3)	moderate	160	24.05.2022 – 01.11.2022	0.0 – 0.1781	0.00111
38/25 (RP 4)	moderate	161	25.05.2022 – 01.11.2022	0.0 – 0.1461	0.00091

Pine stands with maximum tree density (maximum density and tree size) are of the highest carbon sequestration. Total litter carbon stock by the end of the growing season ranged from 0.8 to 1.6 tonnes of carbon per ha^{-1} (Figure 1).

4 Discussion

Karpachevsky divided coarse woody debris according to their ability to decompose into two fractions: active and inactive [5]. The active fraction includes leaves (needles), bud scales, inflorescences, pollen and seeds. The inactive fraction includes branches, cones, bark and lichens. In the studied forest communities, the active litter fraction took 77.86 % and the inactive litter fraction took 22.14 %. Pine needles predominated in the total litter mass in all the research plots (from 40 % to 61 %). The proportion of leaves, grass and seeds were minimal due to forest composition, litter traps design, high recreational load, zoogenic effects and low seed weight (Table 2).

Carbon stock in the studied forest stands depends on density, share of birch in the stand composition and the distance to birch-dominated stands. Differences in total carbon stocks values at the end of the growing season between the research plots ranged from 0.8 to 1.2 tonnes of carbon per ha^{-1}. We distinguished two stages in the active fraction accumulation: moderate (81–101 days from the beginning of the growing season) and intensive (79–81 days). Carbon accumulation rate in the active fraction per day varied from 0.00346 to 0.01006 tonnes of carbon per ha^{-1} at different stages (Table 3).

When analyzing the carbon in the inactive litter fraction, one can observe a significant accumulation on RP 1 and RP 2. The highest carbon accumulation rate is related to the amount of each fraction`s component: branches on RP 1 and cones on RP 2. RP 1 and RP 2 were of the maximum accumulation of inactive fraction carbon, while RP 3 and RP 4 were of the minimum inactive fraction carbon accumulation values. Differences in total carbon stocks values at the end of the growing season between the research plots ranged from 0.42 to 0.43 tonnes of carbon per ha^{-1} on RP 1 and RP 2 and from 0.15 to 0.18 tonnes of carbon per ha^{-1} on RP 3 and RP 4.

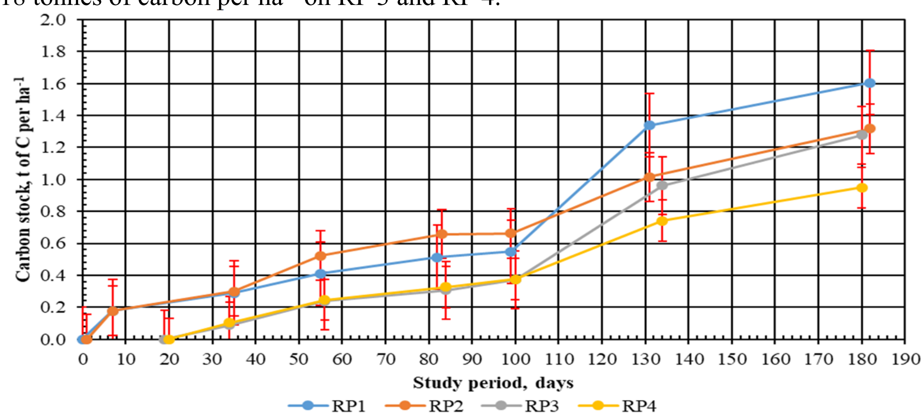

Fig. 1. Temporal dynamics of carbon input in the total litter.

Figure 1 shows total litterfall carbon input dynamics. The trend line reflection litter carbon sequestration is smooth (Figure 1). Bounces in the accumulation curve on RP 3 are explained by inclusion of the inactive fraction results. That is why we did not indicate separate stages. In general, the accumulation was moderate until August 13. Then the accumulation increased due to the active fraction input (needles). We distinguished two inactive fraction accumulation stages on RP 1 and RP 2 (moderate and intensive accumulation) and one stage on RP 3 and RP 4 (moderate accumulation). The active fraction carbon accumulation rate per day varied from 0.00091 to 0.00381 tonnes of carbon per ha^{-1}.

5 Conclusion

The present research let us make a number of statements revealing the dynamics of phytomass and litter carbon in pine stands growing in the Central Siberian subtaiga forest-steppe zone:

- the studied forest stands are predominantly pure with an admixture of birch up to 30 %. The pine stands are either approaching maturity or mature (75–97 years old). The studied stands are of the I–II bonitet class, indicating favorable environmental conditions. The stands density ranges from 0.5 to 1.0;
- both forest inventory characteristics and stands composition contribute to the difference in litterfall fractions in the pine stands;
- pine needles took the highest proportion among all litterfall fractions, followed by cones, tree bark, branches and other unidentified biomass. The share of seeds and grass did not exceed 1 %;
- the proportion of green biomass (leaves, grass, needles) was about 50 % or exceeded this level. The fact that green biomass is of the same mass as woody and non-woody debris (bark, branches, cones, seeds) indirectly indicates the sustainability of pine forests;
- on all the research plots the active litter fraction took 67–86 % and the inactive litter fraction took 14–33 %;
- the active litter fraction carbon stock depends on the stands density, share of birch in the stand composition and the distance to birch-dominated stands. Differences in total carbon stocks values at the end of the growing season between the research plots ranged from 0.8 to 1.2 tonnes of carbon per ha^{-1};
- it is advisable to distinguish two stages in the active fraction accumulation: moderate and intensive. Carbon sequestration rate in the active litter fraction per day varied from 0.00346 to 0.01006 tonnes of carbon per ha^{-1} at different stages;
- one can distinguish two inactive fraction accumulation stages on RP 1 and RP 2 (moderate and intensive accumulation) and one stage on RP 3 and RP 4 (moderate accumulation). The inactive fraction carbon accumulation rate per day varied from 0.00091 to 0.00381 tonnes of carbon per ha^{-1} at different stages.

We can state that carbon accumulation in pine stands litter undergoes certain stages. These stages can be distinguished by unevenness in litter accumulation rates, which is more intense for the active litter fraction. Litter plays an important role in mineralization, carbon emissions, and cycling in forest ecosystems.

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