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SOIL CHEMISTRY

Forest Litters as a Link in the Carbon Cycle in Coniferous–Broadleaved Forests of the Southern Far East of Russia

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Abstract—Forest litter as a component of the carbon cycle in pine–broadleaved forests of different ages was characterized. Field studies of the forest site of the Primorskaya State Agricultural Academy in the south of the Sikhote Alin Range continued for three years. Multiple sampling of forest litter and plant litter fall and measurements of the CO_2 emission from the litter and underlying soil horizons were performed on test plots. The maximum litter pool (14.44 ± 0.86 t/ha) was found in the mature stand of *Pinus koraiensis*; the minimum litter pool (11.52 ± 0.65 t/ha), in the 80-year-old stand. The carbon stock in the litters amounted to 3.7% of the phytomass carbon. The rate of carbon turnover in the forest litters was relatively low in comparison with that in other regions: the ratio of carbon pools in the litter horizons and annual plant falloff reached 3.5. The winter season provided about 10–25% of the annual plant litter fall. The data obtained in this study describe a part of the carbon cycle and contribute to our understanding of the ecosystem function of climate regulation by valuable forest massifs in the south of the Far East of Russia. In this region, the decomposition of forest litters generates the CO_2 flux amounting up to 16% of the total CO_2 emission from the soil.

Keywords: litter, decomposition of plant residues, carbon cycle, pine stands, *Pinus koraiensis*

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INTRODUCTION

Global climate change with an increase in the average temperature of the boundary layer of the atmosphere, differently directed regional changes in precipitation, and more frequent climatic anomalies is considered a powerful factor of modification of the soil component of carbon cycle [24, 31, 37]. Every year, soils of the globe emit about 98 ± 12 Gt C into the atmosphere [24], which is an order of magnitude higher than the total anthropogenic emission (the flux of carbon from burning of fossil fuels) [30]. Generalization of experimental and field data attests to a continuous increase in the emission of carbon dioxide from the world's soils by about 0.1 Gt C/yr [24]. Simulation experiments based of different scenarios of global climate change yield different results. Some of them attest to a decrease in the soil capacity for carbon storage upon further warming of the climate [31, 37], whereas other experiments predict the opposite tendency [28, 41].

Soil respiration in forest ecosystems playing the major role in terrestrial carbon cycles is considered the sum of three CO_2 fluxes resulting from the (a) decomposition of soil organic matter, (b) decomposition of forest litter, and (c) autotrophic respiration of roots (including microbiota of the rhizosphere) [23, 32, 40]. Seasonal changes in the mean daily air temperature that are particularly pronounced in boreal forests with clear alternation of the periods of active plant growth and dormancy result in different responses of these three components of soil respiration [23, 26, 40]. A study in a broadleaved forest in Japan [23] demonstrated that the flux from decomposition of forest litter has its maximum in the early spring; the flux from root respiration, in June; and the flux from decomposition of soil organic matter by microorganisms, in August. Summer droughts in the zones of taiga and broadleaved forests inhibit the decomposition of forest litters. It was also found in this study that the considered components of soil respiration are characterized by different temperature coefficients Q_{10}: 6.0 for the decomposition of soil organic matter, 2.3 for the decomposition of forest litter, and 4.1 for root respira-

Table 1. Contribution of the decomposition of forest litters to the total soil respiration in different regions of the world

Region	Type of forest	Contribution of litter decomposition to soil respiration, %	Data source
China	*Pinus massoniana* Lamb. plantation, 20–40 yrs.	56–61	[40]
Central Japan	Larch plantations	27	[22]
Iwate Prefecture	Broadleaved temperate forest with a predominance of beech	35–39	[23]
Ohio State, USA	Oak forest	48	[26]
Southern China	*Pinus elliottii* Engelm. plantation, subtropical zone	33	[39]
Oregon, USA	Overmature *Pseudotsuga menziesii* (Mirb.) Franco plantation	19–21	[38]
Peru	Tropical mountainous forest in the Andes	37	[42]
Tennessee, USA	Broadleaved forest with a predominance of oak and maple	5–37	[25]
Hessen, Germany	35-year-old plantation of *Fagus sylvatica* L.	37	[34]
Temperate Forest zone	Review data	2–20	[35]
North America	Oak forest	23	[29]
Southern Urals, Russia	Coniferous forests	30–60	[18]
Southern Urals, Russia	Broadleaved forests	17–32	[18]

tion [23]. The contribution of forest litter to the total soil respiration is controlled by the climate of the studied area, the species composition of the stand, and the carbon content in the soil [40]. Thus, to make adequate predictions of the response of soil respiration in the forest biocenosis to some changes in the climatic parameters, we need to perform a special study with clear differentiation of the CO2 efflux into the three components described above.

The most comprehensive characterization of forest litters in mixed coniferous–broadleaved forests of the Sikhote Alin Range was made by Sapozhnikov et al. [16]. Chestnykh et al. [20] developed a database on litters in forests of Russia comprising more than 900 descriptions. In recent years, several works devoted to the CO_2 emission from forest litter have been published. These studies were initiated because of the need to predict and model the response of soil respiration to climate changes. Long-term monitoring studies of the respiration of forest soils in central Russia [13] attest to considerable annual variations in the intensity of emission fluxes. The classical study by Karpachevskii [10] demonstrated that the reserves of litter in natural forests may vary by seasons and have a very high spatial variability ($Cv = 40\%$). In this context, studies summarizing data obtained during several field seasons are of particular value.

Forest litter is formed under the influence of two oppositely directed process: the input of plant litter fall and its decomposition. The input of plant litter fall onto the soil surface in boreal and temperate regions is characterized by the pronounced seasonality with a distinct maximum in October, during the phenological stage of leaf fall of deciduous trees. For most of coniferous tree species, their needle fall off is extended in time; in some cases, two periods of fall off maximum are observed [6]. In the undisturbed forest stand, the mass of carbon in forest litter originating from plant litter fall is approximately equal to the mass of carbon participating in the two fluxes from the litter, i.e., the efflux of CO_2 into the atmosphere and the outflow of carbon into the deeper soil horizons, where it is fixed in the soil organic matter, or its removal from the ecosystem with water runoff. According to Vedrova [4], the major part of carbon (77–92%) is lost from the litter with the CO_2 efflux. In spruce forests of the Komi Republic, the degree of humification of plant residues is estimated at 7% [1]. Under the equilibrium conditions, the CO_2 flux related to the decomposition of forest litter can be estimated from data on the annual falloff. Published data on the portions of this flux in the total soil respiration for different regions and different forest stands are summarized in Table 1.

As seen from this table, the contribution of litter to the CO_2 emission from the surface of forest soils is highly variable: from 5% in the broadleaved forest of Kentucky to 60% in pine plantations of northeastern China and spruce forests of the southern Urals. According to the literature review (12 sources), the average value is $31.3 \pm 3.6\%$.

Forest litters of mixed coniferous–broadleaved forests of the Far East of Russia (Primorskii region) as elements of the carbon cycle remain insufficiently studied [5, 6]. Plantations of Korean pine (*Pinus koraiensis* Siebold & Zucc.) in the central and southern Sikhote Alin are unique multispecies plant communities providing important ecosystem services. In

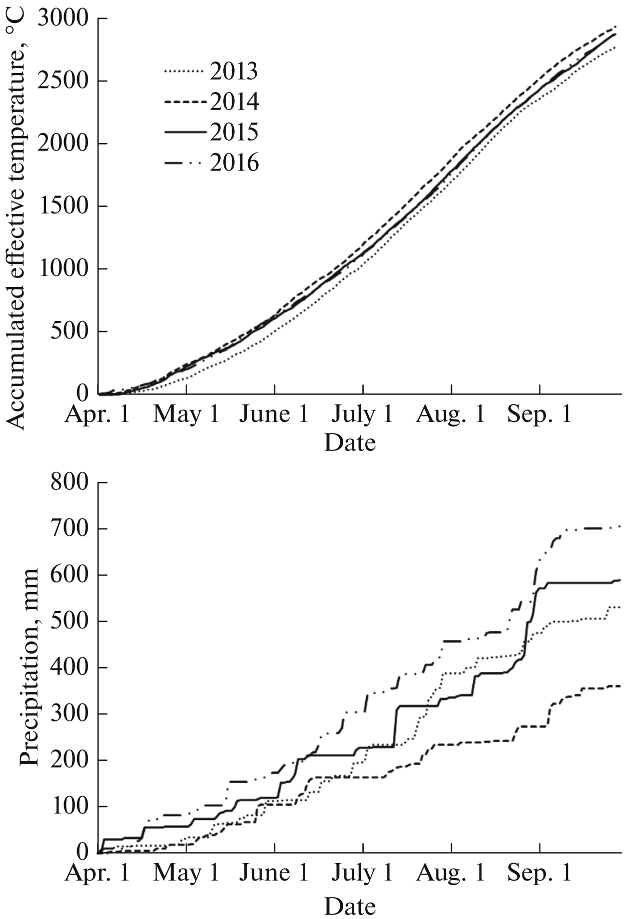

Fig. 1. Seasonal dynamics of the accumulated effective temperatures and precipitation for three studied seasons.

the past century, their area in this region has decreased from 4 to 2.5 M ha.

The aim of our study was to determine the reserves and seasonal dynamics of forest litter, annual plant litter fall, and the contribution of forest litter to the total soil respiration under Korean pine plantations of different ages in the south of Primorskii region.

OBJECTS AND METHODS

Field studies were performed on permanent test plots representing a chronological sequence of the succession of Korean pine–broadleaved forest with the ages from 50 to 200 years. The test plots were found in the forest area belonging to the Primorskaya State Agricultural Academy in the southern part of the Primorskii region. In the scheme of the division of the Far East according to forest-growing conditions, this area is found at the junction of the Amur–Ussuri, Southern Sikhote Alin, and Khasan–Khanka provinces. According to the modern floristic zoning, it is found at the boundary between cold and slightly cold zones and the mountainous belt [33]. It is characterized by the monsoon type of climate typical of the entire Primorskii region. The mean annual temperature is 4.2°C, the mean annual precipitation ranges from 620 to 890 mm, and the mean annual relative air humidity is 75–80%. Data on the dynamics of climatic characteristics are necessary to identify possible reasons for changes in the litter stock and plant litter fall. Figure 1 displays the graphs of the sum of efficient temperatures (calculated for the period of mean daily temperatures above 0°C) and precipitation from April 1 to September 30 for three years of observations at the Timiryazevskaya weather station located 35 km to the northeast of the studied plots. For the considered years, the differences in the accumulated sums of efficient air temperatures were relatively small (no higher than 100°C for the given date), whereas the differences in precipitation were considerable. Thus, precipitation in the spring–summer period of 2016 was two times higher than that in the same period of 2014.

The studied forest stands are developed on typical brown forest soils (burozems, Dystric Cambisols) [17]. Average ages of the stands on the four plots comprised 50, 80, 130, and 200 years (Table 2).

The stand on the first test plot was characterized by post-fire succession. Therefore, pioneer tree species constitute 60% of the stand and are represented by birch (*Betula platyphylla* Sukaczev) and aspen (*Populus tremula* L.). All the studied plots represent the stages of restoration succession of the Korean pine. At the age of 80 years (plot 2), the stand contains typical broadleaved species. According to the classification of forest litters by Sapozhnikov with coauthors [16], the litters in the studied stands are characterized by two subhorizons. The A01 subhorizon is a brown-colored compact weakly decomposed needle and leaf falloff; it is easily separated from the underlying AO2–O3 sub-

Table 2. Taxation characteristics of forest plantations on test plots (TPs)

No. of TP	Age, yrs.	Species composition	N, ind./ha	d_{av}, cm	G, m^2/ha	M, m^3/ha
1	50	4K5A1B + M, O, F, E	1096	19.4	37.5	353.1
2	80	5K1F1O1L1M1A + E, As, H	752	22.3	37.9	342.6
3	130	5K2O1L1M1A + F, E, H	944	20.0	43.4	360.1
4	200	5K3F1L1M + B, O, H	856	23.1	61.5	642.5

Tree species are designated as follows: K—Korean pine, F—needle fir, O—Mongolian oak, A—Manchurian ash, L—Amur lime, M—mono maple, As—common aspen, E—mountain elm, and B—Japanese white birch. Taxation characteristics: N—stand density, d_{av}—average diameter, G—absolute stand density, and M—stem wood storage.

horizon consisting of decomposed falloff with layered structure and densely penetrated by fungal mycelium. Coprolites can be seen in its lower part. This subhorizon cannot be easily separated from the underlying humus (A1) horizon. Such a morphology corresponds to the falloff–raw-humus type of forest litters.

The sampling of forest litter was performed with the use of a squared frame (25 × 25 cm) in three replicates on each plot during spring–summer–fall (from April to November) seasons of 2014, 2015, and 2016 with a frequency of one sampling per 7–15 days. The frames were placed in the most typical places on the soil surface at a distance of no less than 1 m from tree trunks and fallen trees; the places with evident disturbance of the litter by animals, loci with bare soil surface, and microlows were excluded from the sampling. The small number of replicates (3) was compensated for by the high sampling frequency. The thickness of the litter was measured in three points for each sample. The samples were placed into hermetic bags. In laboratory, we determined the dry mass of the samples and their volumetric water content; the litter storage was calculated in tons of dry matter per 1 ha. To sample falloff, special falloff traps of 0.8 m in diameter were used. On plots 3 and 4 (130 and 200 years), seven falloff traps were installed. In 2016, plant falloff was taken from them three times in the fall (on October 2, 16, and 23) with the latter sampling after the end of falloff season for deciduous trees. Additional sampling was performed on April 15, 2017 to determine falloff from the trees in the winter. On plot 3, the winter falloff was only partly estimated, because some of the traps were destroyed by vandals. Winter falloff for this plot was calculated using data on its portion in the annual falloff obtained for the plot under the 200-year-old stand. Thus, this is an expert estimate rather than the experimental value. The collected samples were dried in a drying chamber at 101°C to determine their mass in the absolutely dry state. The weighing of the samples was performed after they reached the constant weight. To calculate the mass of carbon from data on the dry mass of litter and falloff, the coefficient of 0.37 recommended by the Intergovernmental Panel on Climate Change [20] was used.

Measurements of the CO_2 emission from the soil surface (soil respiration) were performed by the chamber method. In 2014, they were performed 13 times in the period from April 27 to November 3; in 2015, 17 times in the period from May 2 to October 17; in 2016, 7 times in the period from May 8 to October 2. On each plot, eight plastic cylinders (chambers) of 110 mm in diameter and 250 mm in height were installed into the soil along 15- to 20-m-long transects. Before measurements, they were hermetically closed by lids equipped with air ducts. Changes in the CO_2 concentration in the closed chambers were determined with the help of a portable gas analyzer with an infrared sensor AZ 7722 (AZ Instrument Corp.) and a pump E 134-11-120 (Hargraves Technologies Corp.). The time of exposure was about 4 min; the first minute was necessary to ensure the even distribution of CO_2 concentrations in the entire measuring system (chamber, air ducts, and gas analyzer). Then, the CO_2 concentration was measured four times (0, 1, 2, and 3 min). The convergence of measured concentrations during this time was a criterion for the correctness of the measurements. Simultaneously, we measured the temperature of the aboveground air and the soil (at the depth of 10 cm) using a Checktemp 1 thermometer (Hanna Instruments). Data on the rate of changes in the CO_2 concentration in the chamber, the volume of the measuring system, the base area, and the temperature were used to calculate the CO_2 emission per unit area according to the Mendeleev–Clapeyron equation [9].

The statistical treatment of the results was performed using Microsoft Excel and R-studio software. To determine reliability of the differences between the means, Student's *t*-test was used after the preliminary verification of the equality of variances according to Fisher's criterion.

RESULTS AND DISCUSSION

Figure 2 presents data on variation in the forest litter storage under the 200-year-old stand of Korean pine during three seasons. The intraseasonal changes of the litter storage take place under the impact of its continuous decomposition by microorganisms and supply with new falloff. The most active loss of litter takes place in the second half of summer, when mean daily air temperatures reach their maximum. For xylotrophic basidiomycetes—the main destroyers of dead organic material in forest ecosystems—temperature is the major limiting factor [14]. The mass leaf falloff in October together with falloff of twigs, branches, and bark compensates for the decomposition of forest litter, so that the maximum litter storage is observed from November to March. Our data do not allow us to estimate the loss of litter owing to its decomposition in winter. According to other studies [21], it may reach about 10%.

The dependence of the forest litter storage on the age of tree stands was proved to be similar for the studied seasons (Fig. 3); interannual changes in the litter storage on all the plots also had close patterns. According to the earlier published data, the average litter storage in the pine–broadleaved forests of the Primorskii region is about 20 t/ha [15] (Verkhnechuguevskii experimental station of the Far East Branch of the Russian Academy of Sciences in the central Sikhote Alin); the average value for Korean pine stands is 14 t/ha according to Zolotarev (cited from [19]).

In 2015, the storage of forest litter on all the plots was lower in comparison with that in 2014. In the 130-year-old and 200-year-old stands, this decrease was estimated at about 3 t/ha of dry matter, or 17–18%

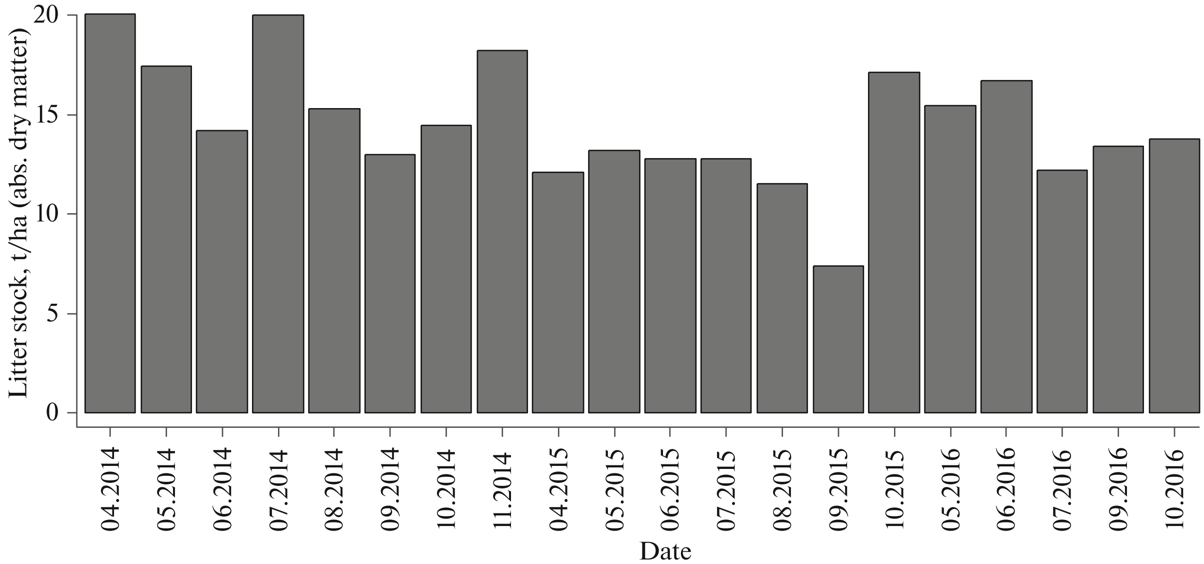

Fig. 2. Seasonal dynamics of the litter stock in the 200-year-old Korean pine stand.

of the litter storage. Karpachevskii [10] reported on an even higher interannual variability of litter storage in coniferous forests of the Russian Plain. This may be explained by differences in weather conditions of the considered seasons. Thus, precipitation in 2014 was low, and the plants developed under relatively dry conditions, which became the reason for the high falloff of Korean pine and fir species and for a sharp decrease in the intensity of litter decomposition. It can also be supposed that the decrease in the forest litter storage in 2015 was related to a smaller falloff, because needles of previous years were subjected to the intense falloff in 2014. An increase in the forest litter storage in 2016 was a consequence of more active falloff (in comparison with that in 2015), on the one hand, and the strong typhoon in August–September 2016, when it rained for two weeks, which slowed down the decomposition of litter, on the other hand. The coefficients of variation in the litter storage for different plots during the studied years were 7.7–10.1%; within the particular plots, they were from 5.5 to 8.4%.

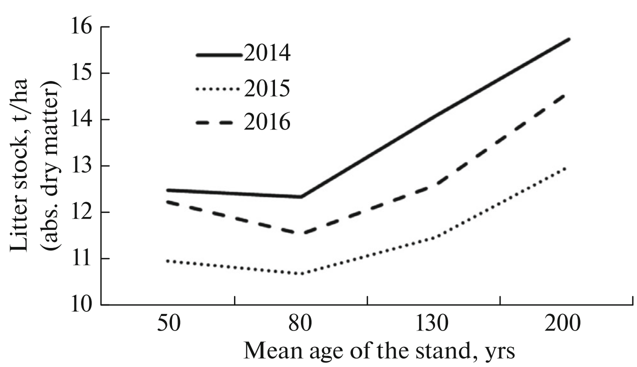

Fig. 3. Relationships between the average litter stock and the age of Korean pine stands for the studied seasons 2014–2016.

The differences in the forest litter storage for most of the plots were statistically significant ($p < 0.05$) (Table 3). The comparison of the plots was based on the entire sets of data obtained during the three seasons.

Data on the litter storage were used to calculate the pools of carbon in the litter horizons. For the 50-year-old stand, the carbon pool of litter comprised 4.25 ± 0.13 t C/ha; for the 80-year-old stand, 4.21 ± 0.11 t C/ha; for the 130-year-old stand, 4.59 ± 0.16 t C/ha; and for the 200-year-old stand, 5.25 ± 0.19 t C/ha. The pools of carbon in the aboveground phytomass of the stands on the studied test plots were estimated earlier [8]. The carbon storage in the litter on the four studied plots was estimated at 3.7, 3.8, 3.7, and 3.7% of the carbon storage in the aboveground phytomass. For the southern part of the Primorskii region, a positive correlation between these two pools of carbon in Korean pine stands is observed: with an increase in the carbon pool of the aboveground phytomass, the carbon pool of litter also increases, so that the ratio between these two pools remains virtually stable.

On the plots under 130-year-old and 200-year-old stands, plant falloff was sampled in the period from September 1, 2016 to April 20, 2017. The falloff value for the spring and summer seasons was taken equal at 15% of the annual falloff according to the earlier estimate by Sapozhnikov et al. [16] (Fig. 4).

A larger part of the annual litter fall enters the litter in the autumn (64%); the litter fall in the winter and spring seasons reaches 21% of the annual litter fall and

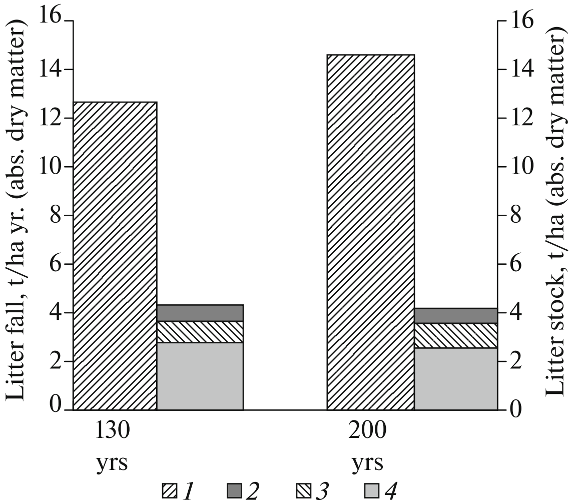

Fig. 4. Relationships between (*1*) litter stock and annual litter fall ((*2*) spring and summer, (*3*) fall, and (*4*) winter) in Korean pine stands.

is mainly represented by the needle falloff of Korean pine and fir.

The ratio between the pools of litter and annual litter fall is characterized by the litter stock-to-litter fall coefficient; for the studied plots, it reached 3.5. This is a relatively small value for the forests of Russia. Thus, according to Bobkova with coauthors [2], this coefficient in the mature spruce forests of the Komi Republic reaches 27. With respect to the world forests, the obtained value of the litter stock-to-litter fall coefficient attests to the slow decomposition of litter (the coefficient is >1) [27]. According to Sapozhnikov et al. [16], this coefficient for Korean pine stands in the Primorskii region varies from 3 to 5. The annual influx from litter fall on the plots with 130-year-old and 200-year-old stands amounted to 4.28 ± 0.18 and 4.13 ± 0.29 t/ha, respectively. Earlier, we tried to estimate annual litter fall on the basis of allometric equations linking the phytomass of the leaves to the breast-height diameter of the trees $d_{1.3}$ [6]. For this purpose, we used the data obtained by Kasatkin et al. [11, 12] in the stands of the forest site of the Primorskaya Agricultural Academy. The estimates obtained by this method for the 130-year-old and 200-year-old stands were 4.23 and 3.64 t/ha, i.e., they differed from the experimental values by 1 and 12%, respectively, which attests to the adequacy of the allometric calculations. We plan to confirm this statement via long-term year-round observations over the litter fall on all the test plots.

Table 3. Significance of differences between the mean stocks of forest litter on test plots with different ages of forest stands (*t*-test)

Stand age, yrs.	Stand age, yrs.		
	80	130	200
50	0.8188	0.10280	0.00006
80		0.04854	0.00012
130			0.01095

Measurements of the soil respiration by the chamber method [7] were performed simultaneously with the litter sampling in the same areas. The results of these measurements in 2016 were used to calculate annual carbon efflux from the soils of the studied stands. For the 130-year-old and 200-year-old stands, they comprised 69.08 and 93.75 mole C/m^2, respectively. To determine the contribution of litter to the total soil respiration, we supposed that the influx and efflux of substances for the litter horizon are balanced, because an increase in the litter storage with the transition of the forest stands to overmature state was weakly pronounced and comprised 0.02–0.03 t/ha in the interval from 130 to 200 years. The annual flow of carbon from the litter to the soil organic matter was taken equal to 10% of the influx of substances from the annual falloff according to [3, 4]. The remaining part of the annual litter fall (90%) was recalculated into the carbon equivalent mass using the coefficient of 0.37 [20]. As a result, we obtained that the fluxes of carbon from the forest litter in the 130-year-old and 200-year-old stands comprised 11.83 and 11.42 mol/(m^2 year), or 16 and 12% of the total soil respiration, respectively.

CONCLUSIONS

Korean pine forests in the southern Sikhote Alin Range are characterized by a considerably smaller contribution of forest litters to the carbon efflux from the soil surface in comparison with that in forests of other regions. This difference may be related both to the difference in methodological approaches for the assessment of fluxes from litter decomposition (with application of destructive and nondestructive methods) and to the specificity of the Korean pine–broadleaved forests as the object of our study in the south of the Far East. The botanical specificity of this region consists of the development of the elements of the Okhotsk (northern) and Manchurian (southern) flora under conditions of the monsoon climate, which is reflected in the structure of the phytomass of forest stands and its impact on the organic matter turnover and pedogenic processes.

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REFERENCES

1. K. S. Bobkova, A. V. Mashika, and A. V. Smagin, *Dynamics of Organic Carbon Content in Middle-Taiga Spruce Forests on Automorphic Soils* (Nauka, St. Petersburg, 2014) [in Russian].
2. K. S. Bobkova and A. F. Osipov, "Carbon cycle in the phytocenosis–soil system of the blueberry–sphagnum pine forests of middle taiga in the Komi Republic," Lesovedenie, No. 2, 11–18 (2012).
3. E. F. Vedrova, "Organic matter decomposition in forest litters," Eurasian Soil Sci. **30** (2), 181–188 (1997).
4. E. F. Vedrova, "Transformation of plant remains in 25-year-old cultures of main forest-forming tree species of Siberia," Lesovedenie, No. 4, 13–21 (1995).
5. D. G. Zamolodchikov and A. V. Ivanov, "Carbon pools and fluxes in forests of the Ussuri forestry according to evaluation by the ROBUL system," Agrar. Vestn. Primor'ya, No. 1, 12–15 (2016).
6. A. V. Ivanov, "The reserves of forest litter in the cedar–broadleaved forests of the southern Sikhote-Alin," Sib. Lesn. Zh., No. 5, 87–95 (2015).
7. A. V. Ivanov, D. G. Zamolodchikov, and V. A. Tataurov, "Respiration of forest soils in coniferous–broadleaved forests of the southern part of Primorskii region," in *Proceedings of All-Russian Conference with International Participation "Sustainable Management of Forests in Siberia and the Far East"* (Khabarovsk, 2014), pp. 427–430.
8. A. V. Ivanov and A. S. Kasatkin, "Dynamics of aboveground phytomass in chronological recovery succession of cedar–broadleaved forest," *All-Russia Conference "Boreal Forests: Status, Dynamics, and Ecosystem Services," Abstracts of Papers* (Karelian Scientific Center, Russian Academy of Sciences, Petrozavodsk, 2017), pp. 118–119.
9. D. V. Karelin, D. I. Lyuri, S. V. Goryachkin, V. N. Lunin, and A. V. Kudikov, "Changes in the carbon dioxide emission from soils in the course of postagrogenic succession in the chernozems forest-steppe," Eurasian Soil Sci. **48**, 1229–1241 (2015). doi 10.1134/S1064229315110095
10. L. O. Karpachevskii, *Forests and Forest Soils* (Lesnaya Prom-st, Moscow, 1981) [in Russian].
11. A. S. Kasatkin, A. S. Zhanabaeva, A. V. Ivanov, D. V. Paukov, and R. Yu. Akimov, "Aboveground phytomass of trees in forests of southern Sikhote-Alin, Part 3," Eko-Potentsial, No. 1 (13), 32–36 (2016).
12. A. S. Kasatkin, A. S. Zhanabaeva, D. V. Paukov, R. Yu. Akimov, and V. A. Tataurov, "Aboveground phytomass of trees in forests of southern Sikhote-Alin, Part 2," Eko-Potentsial, No. 4 (12), 28–31 (2015).
13. I. N. Kurganova, V. O. Lopes de Gerenyu, T. N. Myakshina, D. V. Sapronov, I. Yu. Savin, and E. V. Shorohova, "Carbon balance in forest ecosystems of southern part of Moscow region under a rising aridity of climate," Contemp. Probl. Ecol. **10**, 748–760 (2017).
14. V. A. Mukhin, P. Yu. Voronin, A. V. Sukhareva, and Vl. V. Kuznetsov, "Wood decomposition by fungi in the boreal-humid forest zone under the conditions of climate warming," Dokl. Biol. Sci. **431**, 110–112 (2010).
15. *Good Practice Guidance for Land Use, Land-Use Change and Forestry IPCC/IGES*, Ed. by J. Penman, M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe, and F. Wagner (Intergovernmental Panel on Climate Change, Hayama, 2003).
16. A. P. Sapozhnikov, G. A. Selivanova, T. M. Il'ina, et al., *Pedogenesis and Biological Cycle of Substances in Mountain Forests of Southern Sikhote-Alin* (Far Eastern Scientific Research Institute of Forestry, Khabarovsk, 1993) [in Russian].
17. V. A. Semal', "Properties of soils in southern Skhote-Alin using the example of the Ussuri Reserve," Eurasian Soil Sci. **43** (3), 278–286 (2010).
18. I. A. Smorkalov and E. L. Vorobeichik, "Stability of the CO_2 emission from the forest litter affected by industrial pollution," Lesovedenie, No. 1, 34–43 (2016).
19. K. P. Solov'ev, *Cedar-Broadleaved Forests and Their Economics* (Khabarovsk. Knizhn. Izd., Khabarovsk, 1958) [in Russian].
20. O. V. Chestnykh, V. A. Lyzhin, and A. V. Koksharova, "Carbon pools in the forest litters of Russia," Lesovedenie, No. 6, 114–121 (2007).
21. D. Čiuldienė, J. Aleinikovienė, M. Muraškienė, V. Marozas, and K. Armolaitis, "Release and retention patterns of organic compounds and nutrients after the cold period in foliar litterfall of pure European larch, common beech and red oak plantations in Lithuania," Eurasian Soil Sci. **50**, 49–56 (2017). doi 10.1134/S1064229316110028
22. M. Ataka, Y. Kominami, M. Jomura, K. Yoshimura, and C. Uematsu, "CO_2 efflux from leaf litter focused on spatial and temporal heterogeneity of moisture," J. For. Res. **19** (2), 295–300 (2014). doi 10.1007/s10310-013-0422-1
23. M. Atarashi-Andoh, J. Korashi, S. Ishizuka, and K. Hirai, "Seasonal patterns and control factors of CO_2 effluxes from surface litter, soil organic carbon, and root-derived carbon estimated using radiocarbon signatures," Agric. For. Meteorol. **152**, 149–158 (2012). doi 10.1016/j.agrformet.2011.09.015
24. B. Bond-Lamberty and A. Thomson, "Temperature-associated increases in the global soil respiration record," Nature **464**, 579–582 (2010). doi 10.1038/nature08930
25. L. M. Cisneros-Dozal, S. E. Trumbore, and P. J. Hanson, "Effect of moisture on leaf litter decomposition and its contribution to soil respiration in a temperate forest," J. Geophys. Res.: Biogeosci. **112** (10), G01013 (2007).
26. J. L. DeForest, J. Chen, and S. G. McNulty, "Leaf litter is an important mediator of soil respiration in an oak-dominated forest," Int. J. Biometeorol. **53** (2), 127–134 (2009). doi 10.1007/s00484-008-0195-y
27. *Field Measurements for Forest Carbon Monitoring*, Ed. by C. M. Hoover (Apringer-Verlag, New York, 2008).
28. P. Gottschalk, J. U. Smith, M. Wattenbach, J. Bellarby, E. Stehfest, N. Arnell, et al., "How will organic carbon stocks in mineral soils evolve under future climate? Global projections using RothC for a range of climate

change scenarios," Biogeosciences **9**, 3151–3171 (2012). doi 10.5194/bg-9-3151-2012

29. P. J. Hanson, E. G. O'Neill, M. L. S. Chambers, J. S. Riggs, J. D. Joslin, and M. H. Wolfe, "Soil respiration and litter decomposition," in *North America Temperate Deciduous Forest Responses to Changing Precipitation Regimes* (Springer-Verlag, New York, 2003), pp. 163–189. doi 10.1007/978-1-4613-0021-2_10
30. R. B. Jackson, J. G. Canadell, C. Le Quéré, R. M. Andrew, J. I. Korsbakken, G. P. Peters, and N. Nakicenovic, "Reaching peak emissions," Nat. Clim. Change **6**, 7–10 (2016). doi doi 10.1038/NCLIMATE2892
31. C. Jones, C. McConnell, K. Coleman, P. Cox, P. Falloon, D. Jenkinson, et al., "Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil," Global Change Biol. **11**, 154–166 (2005). doi 10.1111/j.1365-2486.2004.00885.x
32. D. B. Metcalfe, P. Meir, E. O. C. Aragao, Y. Malhi, A. C. L. da Costa, A. Braga, P. H. L. Concalves, J. de Athaydes, S. S. de Almeida, and M. Williams, "Factors controlling spatio-temporal variation in carbon dioxide efflux from surface litter, roots, and soil organic matter at four rain forest sites in the eastern Amazon," J. Geophys. Res. **112**, 1–9 (2007). doi 10.1029/2007JG000443
33. Y. Nakamura and P. V. Krestov, "Coniferous forests of the temperate zone of Asia," in *Ecosystems of the World*, Vol. 6: *Coniferous Forests* (Elsevier, Amsterdam, 2005), pp. 163–220.
34. J. Ngao, D. Epron, C. Brechet, and A. Granier, "Estimating the contribution of leaf litter decomposition to soil CO_2 efflux in a beech forest using ^{13}C-depleted litter," Global Change Biol. **11** (10), 1768–1776 (2004). doi 10.1111/j.1365-2486.2004.01014.x
35. N. C. Prévost-Bouré, K. Soudani, C. Damesin, D. Berveillera, J.-C. Latac, and E. Dufrêne, "Increase in aboveground fresh litter quantity over-stimulate soil respiration in a temperate deciduous forest," Appl. Soil Ecol. **46** (1), 26–34 (2010). doi 10.1016/j.apsoil.2010.06.004
36. J. W. Raich and W. H. Schlesinger, "The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate," Tellus B **44** (2), 81–99 (1992). doi 10.1034/j.1600-0889.1992.t01-1-00001.x
37. P. Smith, "Soils and climate change," Curr. Opin. Environ. Sustainability **4** (5), 539–544 (2012). doi 10.1016/j.cosust.2012.06.005
38. E. W. Sulzman, J. B. Brant, R. D. Bowden, and K. Lajtha, "Contribution of aboveground litter, belowground litter, and rhizosphere respiration to total soil CO_2 efflux in an old growth coniferous forest," Biogeochemistry **73**, 231–256 (2005). doi 10.1007/s10533-004-7314-6
39. Y. Wang, H. Wang, Z. Ma, X. Wen, Q. Li, Y. Liu, X. Sun, and G. Yu, "Contribution of aboveground litter decomposition to soil respiration in a subtropical coniferous plantation in Southern China," Asia-Pac. J. Atmos. Sci. **45** (2), 137–147 (2009).
40. W. Xiao, X. Ge, L. Zeng, et al., "Rates of litter decomposition and soil respiration in relation to soil temperature and water in different-aged *Pinus massoniana* forests in the three gorges reservoir area, China," PLoS One **9** (7), e101890 (2014).
41. A. Y. Yurova, E. M. Volodin, G. I. Agren, O. G. Chertov, and A. S. Komarov, "Effects of variations in simulated changes in soil carbon contents and dynamics on future climate projections," Global Change Biol. **16**, 823–835 (2010). doi 10.1111/j.1365-2486.2009.01992.x
42. M. Zimmermann, P. Meir, M. Bird, Y. Malhi, and A. Cahuana, "Litter contribution to diurnal and annual soil respiration in a tropical montane cloud forest," Soil Biol. Biochem. **41** (6), 1338–1340 (2009). doi 10.1016/j.soilbio.2009.02.023

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