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Carbon Emission from the Surface of Coarse Woody Debris in Korean Pine Forests of Southern Primorye

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Abstract—Carbon dioxide fluxes from the surface of coarse woody debris (CWD) have been measured in Korean pine forests of the southern Sikhote-Alin mountain range. The seasonal dynamics of oxidative conversion of CWD carbon have been evaluated, and average values of the CO_2 emission rate have been determined for CWD fragments of three tree species at different stages of decomposition. The degree of decomposition is an important factor of spatial variation in CO_2 emission rate, and temporal variation in this parameter is adequately described by an exponential function of both CWD temperature and air temperature (R^2 = 0.65–0.75).

Keywords: carbon cycle, Korean pine forests, carbon dioxide (CO_2) emission, coarse woody debris (CWD), decomposition stage

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The increasing interest of researchers in studies on the features of the biogeochemical carbon cycle at both local and global levels is explained by the necessity of taking scientifically valid measures to develop strategies to counteract the global increase in the temperature of the atmosphere [1–3]. Due to autotrophic CO_2 binding in the course of photosynthesis, forest ecosystems are major regulators of CO_2 exchange between the land and the atmosphere. Sustainable forest management taking into account climatic functions of forests is regarded as a promising means to prevent the growth of atmospheric CO_2 concentration [4]. However, there is no consensus in the literature with regard to the amount of the carbon sink in Russian forests: estimates made by different authors vary within a range of 0.2–0.8 Gt C per year [5–7, 8, 14].

The carbon sink in forests is estimated as the difference between net ecosystem production (*NEP*) and its loss during various disturbances (fires, felling, pest outbreaks, etc.). In turn, *NEP* is determined as $NEP = NPP - R$ [9], where *NPP* is net primary production and *R* is heterotrophic respiration, which can be divided into the flux produced by soil microorganisms (heterotrophic respiration) and the flux from decomposition of dead wood (autotrophic respiration). *NPP* can be estimated using different approaches, including remote sensing (satellite images) [10], but the determination of the emission component is impossible without direct field measurements. Insufficient knowledge of specific features in biogenic destruction of coarse woody debris (CWD) is one of the factors accounting for the aforementioned discrepancy in estimates of the carbon sink in Russian forests [6, 11]. Another factor contributing to the uncertainty of estimates at the national level is that areas included in relevant research are highly unevenly distributed over the territory of the Russian Federation, and CO_2 exchange in forest ecosystems has not yet been sufficiently studied in many regions, including the Far East [8].

The CWD pool in forests consists mainly of fallen wood remains and dead standing trees, with their ratio in Russian forests averaging 60 to 40% [6, 12]. Relatively few estimates of CO_2 fluxes from CWD decomposition have to date been obtained by direct instrumental measurements [15–20].

Oxidative conversion of CWD carbon into atmospheric CO_2 occurs in the course of mycogenic xylolysis [11, 21]. Its activity is expressed as the rate of CO_2 emission, which can be calculated per unit weight (volume) [22, 23] or per unit area of the substrate [15, 16, 19]. Mukhin et al. [24] have shown that the second variant is preferable for revealing the dependence of the emission rate on experimental parameters, since CWD fragments are anisotropic and the mycelium of decay fungi is mainly located in peripheral wood layers [24].

The proportion of CO_2 from the surface of dead wood in the total decomposition flux (*R* in the above formula) depends primarily on the CWD stock and reaches a peak in forest areas affected by windfall, large-scale tree die-off, etc. The contribution of CWD to heterotrophic respiration estimated for the ecosystem of a mixed 85-year-old forest in the Great Lakes region of North America is 1.4% [25]; the model estimate for forests of the northern temperate zone is 2%, or 30% of *NEP* [25]; for forests of northeastern China, 3% [22]; for a maple–linden–ash forest in northern Wisconsin, 13% [17]; and for a southern taiga spruce forest with a CWD stock of 84.4 m^3/ha in the Valdai Upland, 23% [15]. Our average estimate for Korean pine forests of southern Primorye (age 100–200 years, average CWD stock 46.9 m^3/ha) is 13.8% [20, 26].

Depending on the structure of tree stand and causes of tree transition into the CWD pool, differences also arise in the structure of dead wood fragments and their volume distribution by decomposition stages (classes). Therefore, to correctly estimate CO_2 emission from CWD, it is necessary to take into account the degree of its decomposition. There are relatively few studies on carbon fluxes from the CWD surface in which differentiation of dead wood fragments by the degree of decomposition is considered [15, 18, 22, 25]. Several authors have revealed a significant positive correlation between the degree of CDW decomposition (including its conversion into soil organic matter at final stages) and the rate of CO_2 emission [19, 20, 22]. However, the majority of publications are based on data concerning only one tree species.

The temporal variability of oxidative conversion of CWD carbon is almost completely dependent on fluctuations of substrate temperature and moisture content. The degree of influence from each factor is closely correlated with climate aridity. For boreal forests, temperature is usually the main predictor (R^2 = 0.6–0.8) [11]. Very high coefficients of determination (up to R^2 = 0.95) have been obtained in laboratory experiments [18]. The spatial variability of the CO_2 emission rate from CWD depends on tree species, wood density, diameter of a given fragment, and category of CWD (dead fallen or dead standing wood) [27].

Factors responsible for the absence of correct global estimates of CWD contribution to the decomposition component of the forest carbon cycle are as follows: (1) poor knowledge about the processes of wood decomposition by basidiomycetes; (2) the absence of regional and global models of CO_2 fluxes from the CWD surface; (3) strong spatial variability depending primarily on the species of wood and degree of its decomposition [28]; (4) differences in methodological approaches to obtaining empirical data; (5) the lack of data on CWD-related carbon stocks and fluxes in the same sites; (6) uncertainty resulting from seasonal differences in CWD contribution to the total carbon flux; and (7) technical complexity of field instrumental measurements of the CO_2 emission from the surface of CWD fragments.

The purpose of this study was to measure the CO_2 emission rate from CWD by instrumental methods in Korean pine–broadleaf forests of the Ussuri forestry (the southern Sikhote-Alin) in order to reveal specific features of its spatial and temporal variability. The tasks to be accomplished were as follows: to choose appropriate CWD fragments and classify them by decomposition stages; install measuring chambers; perform seasonal measurements of the CO_2 emission rate and, simultaneously, of wood temperature and moisture; and analyze the resulting data set distinguishing between driving factors of temporal variability (air temperature, wood temperature and humidity) and spatial variability (wood species and decomposition stage).

MATERIAL AND METHODS

The study site was located in the forest plot used in perpetuity by the Primorye State Agricultural Academy (PSAA) in the territory of the Ussuri forestry [29]. The plot has a total area of 28 830.7 ha and is characterized by diverse site conditions, large areas covered by conifer–broadleaf forests, and a dense network of streams; elevations range from 100 to 500 m a.s.l. Annual average air temperature is 2.5°C; annual average precipitation, 620–890 mm; relative air humidity, 75–80%. Forests with dominance of Mongolian oak (*Quercus mongolica* Fisch. ex Ledeb.) prevail in the plot, occupying 36.4% of the total forested area; the proportion of conifer forests is 38.2%, with 23.7% accounted for by Korean pine forests [29]. The patchwork pattern of forest vegetation in the plot is typical of southern Primorye. With respect to age structure, middle-aged and maturing forests are prevalent. Tree stand density in the majority of forests is high (0.6–0.8). On the whole, forests have medium productivity, with stands of quality class 4 being dominant.

Field studies were performed in forest inventory compartments of the Korean pine (*Pinus koraiensis* Siebold & Zucc.)–Manchurian fir (*Abies holophylla* Maxim.) formation. Korean pine forests were chosen for the study in view of their important ecosystem functions in the region [30] and the vast area they occupy (in Primorye, 2.1 × 10^6 ha). These forests in the southern Far East have mixed composition and a complex pattern [31].

Measurements of the CO_2 emission were made during the field seasons of 2015 and 2016. Stages of decomposition were distinguished as described [15]: (1) thin branches are preserved, no rot; (2) the bark is preserved, thin branches are lost, the trunk may by covered by mosses and lichens; (3) the bark is preserved as fragments, only first- and second-order branches remain on the trunk, heart rot is possible; (4) the bark is almost completely lost, first-order branches shorter than trunk diameter; (5) the initial shape and structural integrity are lost. For statistical analysis, the number of stages was reduced to three (by pooling the data on stages 1 and 2 and on stages 4 and 5) in order to improve statistical significance of the results, as was done in some other studies [18, 22].

Three CWD fragments at each stage of decomposition were selected for measuring CO_2 emission. Three species were included in the study: the Korean (cedar) pine (*Pinus koraiensis* Siebold & Zucc.), Mongolian oak (*Quercus mongolica* Fisch. ex Ledeb.), and Japanese elm (*Ulmus japonica* (Rehder), Sarg.). Measurements were made as described [32]. A cylindrical plastic collar 100 mm in diameter and 250 mm in height was installed in the circular groove cut in the CWD fragment with a core drill and hermetically closed with a lid to which air hoses were fitted. Changes in the CO_2 concentration in this chamber were recorded with a portable gas analyzer assembled at the Faculty of Biology, Moscow State University, on the basis of AZ7722 CO2 detector (AZ Instrument, Taiwan) and E 134-11-120 pump (Hargraves Technology, United States). Simultaneous measurements of near-ground air temperature near the chamber (T_a) and wood temperature at depths of 2, 5, and 10 cm (T_2, T_5, T_{10}) were made with a Checktemp1 digital thermometer (Hanna Instruments, Germany). CWD moisture was measured using a Hydromette HT 85 T instrument (Gann, Germany) with 4.5-cm-long electrodes. The rate of CO_2 emission per unit area was calculated based on the recorded rate of change in CO_2 concentration and known values of the measuring system volume, chamber base area, and air temperature.

The results of field measurements were processed statistically using MS Excel and R software [33]. The significance of differences in the average values of CO_2 fluxed from CWD between stages of its decomposition was estimated by Student's *t*-test. The dependence of emission rate on different factors (decomposition stage, temperature, moisture) was evaluated by multiple regression analysis. Emission values were expressed as logarithms, which made it possible to use linear regression methods. Models taking into account CWD moisture were constructed based on complete data sets grouped only with regard to tree species. The significance of predictors was assessed using *F*-test.

RESULTS AND DISCUSSION

Figure 1 shows the seasonal dynamics of the CO_2 emission rate from Korean pine CWD. Its pattern in 2015 and 2016 was similar: the highest rate (3.8–4.0 g C/m^2/day) was recorded in the warmest period—late June to early August—and the lowest (1.9 g C/m^2/day), in October and April. The data on seasonal average emission rates from CWD of different tree species is presented in Fig. 2.

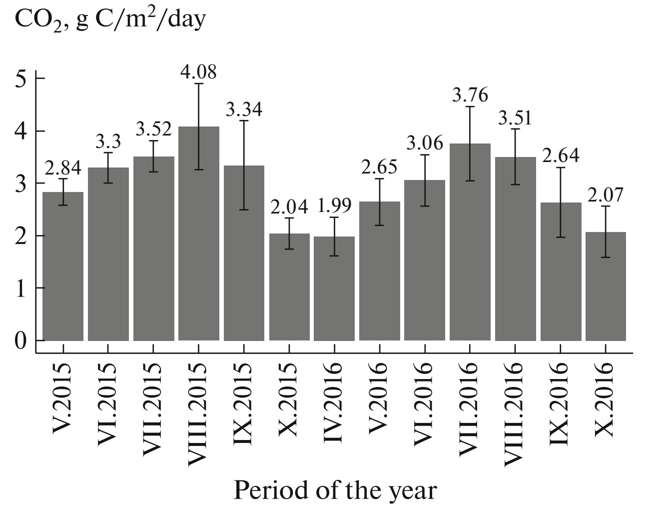

Fig. 1. Seasonal dynamics of CO_2 emission rate from Korean pine CWD of all decomposition stages, arithmetic means with standard errors. Roman numerals refer to months.

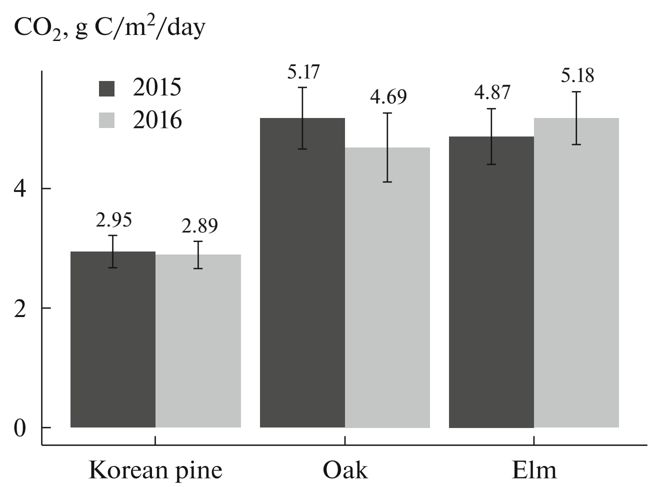

Fig. 2. Average CO_2 emission rates from CWD of different tree species over two seasons.

On average, hardwood species—oak and elm—are decomposed at a twice higher rate than Korean pine (4.93 and 5.03 vs. 2.92 g C/m^2/day), which is in agreement with data of other authors [27]. This is explained by differences in anatomical structure and chemical composition, particularly in the C/N ratio, which in hardwood species is close to 25–30, i.e., is optimal for wood-decay basidiomycetes [9, 11, 34]. In the study on CWD decomposition in forests of northeastern China (400 km southwest of the PSAA forest plot), the rate of CO_2 flux from decaying wood surface was estimated at 2.64 g C/m^2/day for Korean pine and 6.23 g C/m^2/day for Mongolian oak, which is close to our measurements.

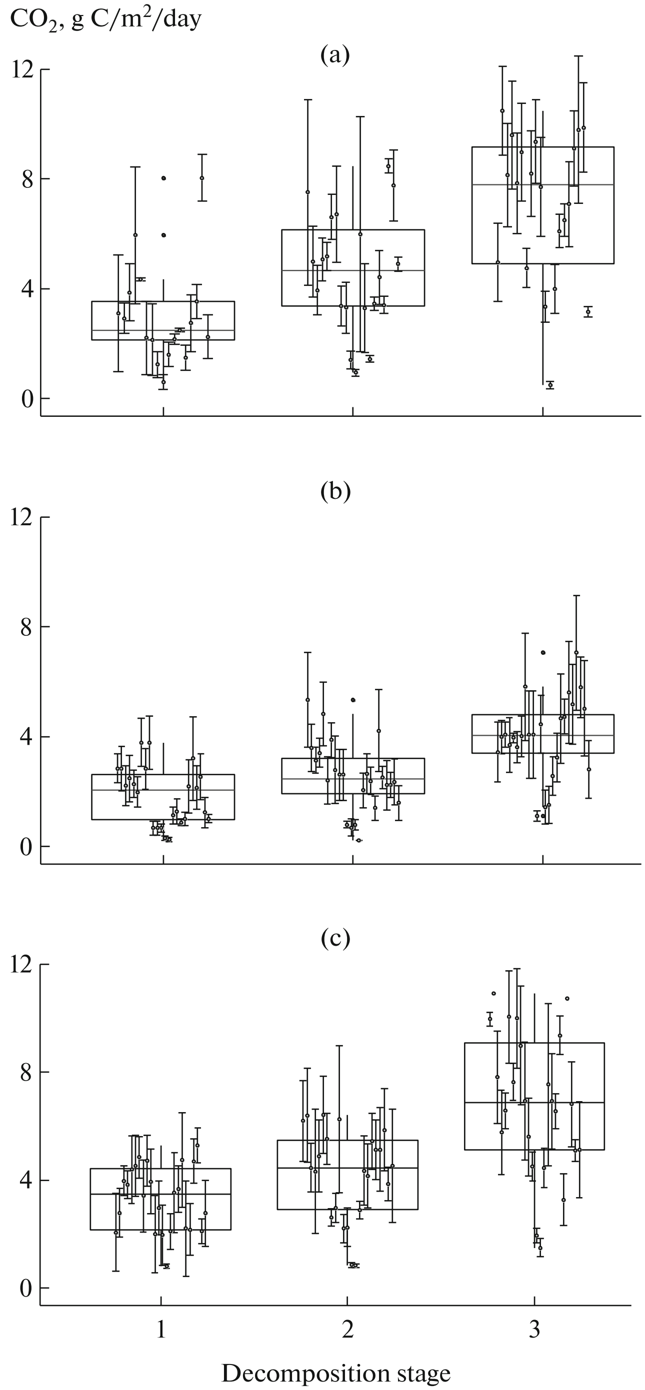

Fig. 3. Differences in CO_2 emission rates from CWD of (a) oak, (b) elm, and (a) Korean pine at three decomposition stages.

Comparisons of CO_2 emission from CWD of the same species at different stages of its decomposition have shown that its rate increases in the course of wood decay in all three species (stage 3 > stage 2 > stage 1), with differences between each pair of stages being statistically significant (Student's pairwise *t*-test, $p < 0.01$) (Fig. 3). This trend is explained by an increase in the biological diversity and biomass of decay fungi colonizing the wood substrate during its passage from the first to the last stage. As found in a study on the composition of xylotrophic fungi on aspen [35], recently fallen wood is colonized by only one fungal species during the first 1–3 years and by as many as 14 species after 15 years. The hyphae of basidiomycetes extending from the wood surface penetrate into the litter and soil and utilize available nitrogen to accelerate the process of wood decomposition, with consequent change in the C/N ratio.

CWD of Korean pine and probably of other conifers emits very small amounts of CO_2, because oleoresin in recently fallen trees inhibits the activity of xylotrophs during the first 2–3 years. Thus, the degree of decomposition of wood fragments is an important factor of spatial variability in oxidative carbon conversion in CWD of both conifer and hardwood species.

The influence of temperature and moisture content on CO_2 emission rate was initially evaluated for the total data set on a certain tree species. Coefficients of determination (characterizing contribution to the total variance of emission) obtained for oak were as follows: for CWD temperature (T_{10}), $R^2 = 0.45$ ($p < 0.001$); for CWD moisture, $R^2 = 0.13$ ($p < 0.05$). After differentiation by decomposition stages, the correlation of emission with temperature increased to $R^2 = 0.71$ ($p < 0.001$), while the influence of moisture proved to lack statistical significance ($p > 0.05$). The leading role of temperature for mycogenic decomposition of fallen wood have also been noted by other authors [21]. Therefore, further analysis was performed only for the factor of temperature, with differentiation by decomposition stages.

After grouping the data by species and decomposition stages, exponential regression models were calculated (Fig. 4).

The dependences of CO_2 emission from CWD on its temperature measured 2, 5, and 10 cm below its surface are statistically significant ($p < 0.01$, $R^2 = 0.69$–0.75), with no difference in the strength of influence between T_2, T_5, and T_{10}. Air temperature is also a good predictor of seasonal fluctuations of emission ($R^2 = 0.64$–0.72 depending on tree species and decomposition stage, $p < 0.05$). The Van't Hoff temperature quotient (Q_{10}) for the CO_2 emission rate from CWD of Korean pine, elm, and oak averaged 2.41, 1.89, and 2.28, respectively. This quotient for Korean pine CWD in northeastern China in 2004 was 2.74 [22]. Therefore, oxidative conversion of CWD carbon in forests of the southwestern Russian Far East responds to rise in temperature less rapidly than in more southerly regions.

Thus, experiments with three tree species—Korean pine, Mongolian oak, and Japanese elm—have shown that CWD decomposition is an important factor determining the spatial variability of specific CO_2

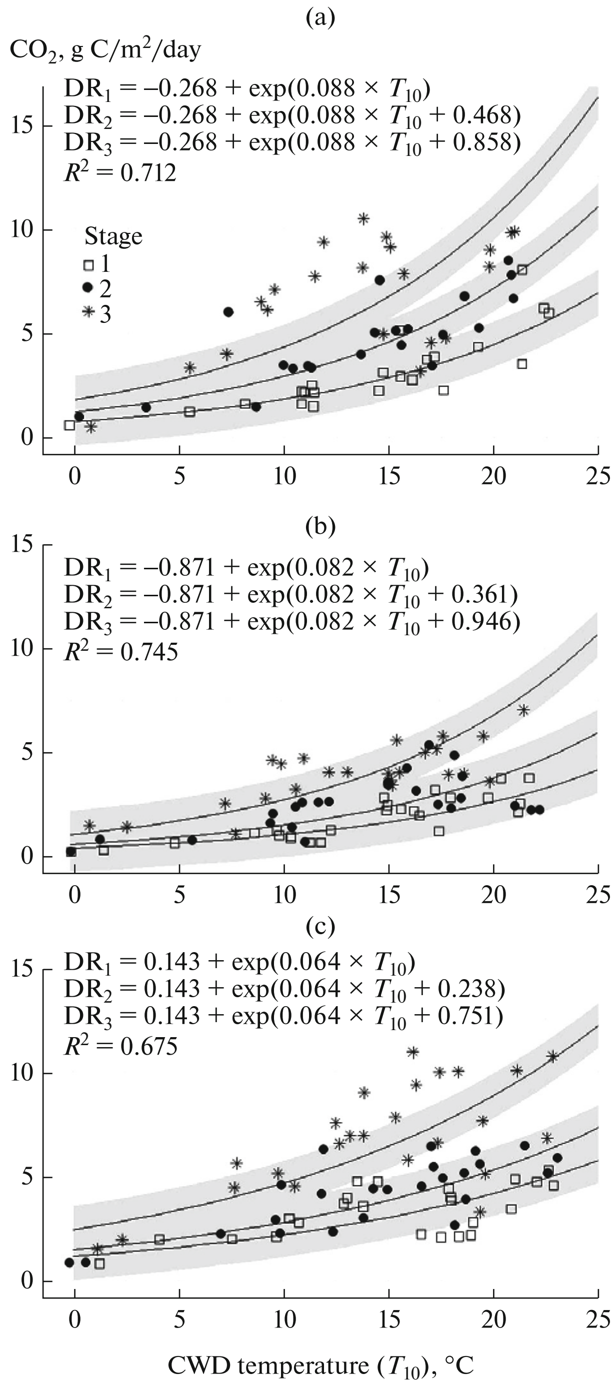

Fig. 4. Regression models of CO_2 emission rate (DR) as a function of temperature (T_{10}) for CWD of (a) Korean pine, (b) oak, and (c) elm at three decomposition stages (for all equations, $p < 0.001$).

fluxes from its surface. Among factors accounting for temporal (intraseasonal) dynamics of the rate of these fluxes, the key role is played by temperature. Air temperature (T_a) and CWD temperature are similar and show a statistically significant correlation with CO_2 emission rate ($R^2 = 0.65–0.75$) when CWD is differentiated by stages of wood decomposition.

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