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## SOIL PHYSICS

# Seasonal and Daily Dynamics of the $CO_2$ Emission from Soils of *Pinus koraiensis* Forests in the South of the Sikhote-Alin Range

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**Abstract**—The presented study shows the results of measuring soil respiration in typical burozems (Dystric Cambisols) under mixed Korean pine–broadleaved forests in the southern part of the Primorskii (Far East) region of Russia growing under conditions of monsoon climate. The measurements were performed in 2014–2016 by the chamber method with the use of a portable infrared gas analyzer. Relative and total values of the $CO_2$ efflux from the soil surface on four model plots were determined. The intensity of summer emission varied from 2.25 to 10.97 μmol/($m^2$ s), and the total $CO_2$ efflux from the soils of four plots varied from 18.84 to 25.56 mol/$m^2$. It is shown that a larger part of seasonal variability in the soil respiration is controlled by the soil temperature ($R^2 = 0.5–0.7$); the soil water content also has a significant influence on the $CO_2$ emission determining about 10% of its temporal variability. The daily dynamics of soil respiration under the old-age (200 yrs) forest have a significant relationship with the soil temperature ($R^2 = 0.51$). The pyrogenic transformation of *Pinus koraiensis* forests into low-value oak forests is accompanied by an increase in the $CO_2$ efflux from the soil.

*Keywords:* soil respiration, $CO_2$ emission, soil temperature, soil water content, *Pinus koraiensis* forests, typical burozems (Dystric Cambisols)

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## INTRODUCTION

At present, the scientific community has accumulated considerable amounts of data on various aspects of soil respiration. The flux of $CO_2$ from the soil surface—$CO_2$ emission—is considered one of the key links of the carbon cycle in the biosphere. The carbon sequestration capacity of forests can be calculated as the difference between the net primary production of photosynthesis (NPP) and the $CO_2$ efflux from the soil corrected for root respiration [6]. According to estimates from other studies, annual soil respiration in forest biomes varies from 26.83 mol/$m^2$ in boreal forests to 105.00 mol/$m^2$ in tropical rainforests (hereinafter, $CO_2$ flux values are given in the carbon (C) equivalent [10]). However, modern estimates of the carbon budget in terrestrial ecosystems of Russia and the world (global carbon sink in them is estimated at 2.1–2.5 Gt/yr [9]) indicate that the existing data need to be verified and refined [4, 5, 13–15, 20, 21, 25]. Chen et al. [21] analyzed a database on soil respiration that included 120 plots in forest ecosystems. It was shown that the soil temperature and water content together with the organic carbon content explain only 31% of the total variability in the soil respiration. One of the reasons for indefinite estimates of carbon sinks in terrestrial ecosystems of Russia is the lack of factual data on some regions; this is particularly true for the vast territory of the Far East region of Russia that comprises 36% of the total area of the country [15]. Forests of the Far East play an important climatic function, as the forest canopy retards degradation of the permafrost [18].

Temporal (daily and seasonal) and spatial variability of soil respiration can be distinguished [5, 21]. The major factors affecting temporal fluctuations in the intensity of soil respiration are the soil temperature and moisture; the degree of influence of these two factors on soil respiration varies and depends on the particular region. Thus, in the boreal forests of Russia, soil temperature is the major factor of seasonal variations in the $CO_2$ emission [5, 11], whereas in a relatively dry climate of northeastern China, the respiration of forest soils is most tightly related to the soil water content ($R^2 = 0.61$) [19]. Spatial variability is controlled by several factors, such as the organic carbon content in the topsoil, thickness of the forest litter layer, the presence of coarse woody debris, and the microbial respiratory quotient [5, 14, 25].

The presence of an autotrophic component related to root respiration in the $CO_2$ efflux from the soil surface and the influence of the structure and dynamics of forest stands on soil-forming processes allow us to consider vegetation as one of the significant factors of the spatial variability in the intensity of soil respiration [3, 7, 10, 26].

For the soils of boreal forests, an effect of sharp changes in the $CO_2$ emission intensity in relation to freezing–thawing processes is typical [16]. It can be supposed that this effect is particularly strong in the regions with temperate monsoon climate, including the Primorskii region of Russia.

For correct assessment of the total annual emission of $CO_2$ from the soil surface in a given region, instrumental measurements of the emission during the entire year are necessary. Seasonal distribution of the emission fluxes is often characterized by the ratio of the fluxes in the summer period and in the entire year [7]. In the mixed broadleaved forest of central Russia, the summer emission of $CO_2$ constitutes about 41–44% of the annual emission [7]; in mixed forests of northern China, it reaches 53% of the annual emission; under the stand of *Pinus silvestris* in the northeastern China, 64% [26]. The contribution of the winter emission to the total annual emission of $CO_2$ comprises 9–11% for mixed forests of central Russia [7] and 4–7% for forest stands in the northeastern China [25, 26]. Thus, the contribution of the summer emission for forest soils of the temperate zone rises with an increase in the latitude and in the aridity of the climate.

Forests of the Primorskii region are characterized by the high level of biodiversity, while they grow under conditions of heavy anthropogenic loads. Forest ecosystems in the southern part of the Primorskii region are specified by the high level of net primary production. This is a promising region for the development of forestry on the principles of minimization of carbon loss from the ecosystems, which may become an important component of Russia's strategy to fulfill its obligations under the Paris climate agreement, which urges countries to efficient management of carbon fluxes and carbon pools in forests [23]. Russian Federation with its vast forest areas plays the key role in the global transition to the economy with minimum carbon emissions [20, 24]. However, the specificity of carbon cycle in ecosystems of the Primorskii region and the climate change mitigation potential of forest vegetation in this region remain insufficiently studied.

The aim of our study was to measure $CO_2$ fluxes from the soil surface under *Pinus koraiensis* forests in the southern part of the Sikhote-Alin Range and to determine daily and seasonal dynamics of these fluxes under the impact of the soil temperature and moisture factors.

## OBJECTS AND METHODS

Field measurements were performed at the forest site of the Primorskaya State Agricultural Academy (PSAA) in the southern part of the Sikhote-Alin Range (Primorskii region of Russia). In the scheme of zoning of the Far East of Russia according to forest-growing conditions, this site in the area of the Ussuriisk forest division is found at the junction of the Amur–Ussuri, Southern Sikhote-Alin, and Khasan–Khanka forest regions. This site, as well as the entire Primorskii region, is characterized by the monsoon type of climate forming under the impact of the Pacific Ocean in summer and cold air masses from the Mongolian–Tibetan Plateau and from Yakutia in winter. The mean annual air temperature is 4.2° (according to records in 2011–2014); the mean annual precipitation is 620–890 mm, and the mean annual air humidity is 75–80% [12].

Forest taxation materials of 2010 were used for selection of four key plots characterized by the predominance of Korean pine (*Pinus koraiensis*) and differing in its age characteristics. According to the classification developed by Kudinov, the selected stands belonged to the groups of mixed grassy–shrub maple–hornbeam and maple pine forests [8]. They were found in the Barsukovka River basin (43°38′48.4″ N, 132°15′41.2″ E) on the southwestern spurs of the Przhevalsky Ridge. The absolute height varied within 160–220 m a.s.l. The soils of the selected plots were classified as typical burozems (brown forest soils, Dystric Cambisols) [17]. The mean ages of the studied stands comprised 50, 80, 130, and 200 yrs (Table 1).

Measurements of soil respiration were performed by the chamber method. In 2014, the emission was measured 13 times (from April 27 to November 3); in 2015, 17 times (from May 2 to October 17); and in 2016, 7 times (from May 8 to October 2). On each of the plots, 8 plastic cylinders (chambers) of 110 mm in diameter and 250 mm in height were inserted into the soil along 15- to 20-m-long transects. Before measurements, the cylinders were hermetically closed with lids equipped with air hoses. The change in the $CO_2$ concentration in the closed chamber was measured with a portable gas analyzer assembled at the Biological Faculty of Lomonosov Moscow State University on the basis of an infrared sensor AZ 7722 (AZ Instrument Corp.) and an E 134-11-120 pump (Hargraves Thechnologies Corp.). The time of exposure (with hermetically sealed lid) was about 4 min.; during the first minute, the uniformity of changes in the $CO_2$ concentration in the entire system (chamber, air hoses, and gas analyzer) was achieved. Then, the records were taken for the time series: 0, 1, 2, and 3 min. If the changes in the $CO_2$ concentration (over 1 min.) during this measurement series were close to one another, the measurement was determined as valid. Simultaneously, air temperature was measured above the ground and the soil temperature at the depth of 10 cm with a Checktemp-1 thermometer (Hanna Instruments). Data on the rate of changes in the $CO_2$ concentration, volume of the measuring system, base area of the chamber, and air temperature were used to calculate the $CO_2$

**Table 1.** Forest taxation characteristics of test plots

| Age, yrs | Composition | N, trees/ha | $D_{av}$, cm | $G$, m$^2$/ha | $M$, m$^3$/ha |
|---|---|---|---|---|---|
| 50 | 4Kp5As1B + M, O, F, E | 1096 | 19.4 | 37.5 | 353.1 |
| 80 | 5Kp1F1O1L1M1As + E, A, H | 752 | 22.3 | 37.9 | 342.6 |
| 130 | 5Kp2O1L1M1As + F, E, H | 944 | 20 | 43.4 | 360.1 |
| 200 | 5Kp3F1L1M + B, O, A | 856 | 23.1 | 61.5 | 642.5 |

The following designations are applied: Kp—Korean pine (*Pinus koraiensis* Siebold & Zucc.), F—fir (*Abies holophylla* Maxim.); O—oak (*Quercus mongolica* Fisch. ex Ledeb.), A—ash (*Fraxinus mandshurica* Rupr.), L—lime (*Tilia amurensis* Rupr.), M—maple (*Acer mono* Maxim.), As—aspen (*Populus tremula* L.), E—elm (*Ulmus japonica* (Rehder), Sarg.), B—birch (*Betula platyphylla* Sukaczev), H—hornbeam (*Carpinus Cordata* Blume); N is the stand density, $D_{av}$ is the mean quared diameter of the trees, $G$ is the basal area of the stand, and $M$ is the stock of stem wood.

emission per unit area using the Mendeleev–Clapeyron equation [4, 5]. Simultaneously with the measurements of $CO_2$ concentration and soil temperature, three soil samples from the upper horizon were taken from each of the plots to determine the volumetric soil water content. On May 22, 2015, the measurements were performed during the entire day (once in three hours, i.e., 8 measurements per day). The significance of differences in the obtained data was tested using Student's pair correlation criterion; the validity of the models was tested using Fisher's *F*-criterion.

From October 1, 2015 to September 31 2016, the soil temperature at the depth of 10 cm and the air temperature above the ground surface on the plots were measured once in 4 h with the help of temperature loggers DS1921G-F5 with an accuracy of 0.5°C.

The statistical treatment of the data was performed using Microsoft Excel, R-Studio, and Matlab software packages.

## RESULTS AND DISCUSSION

Data on soil and air temperatures obtained with the help of temperature loggers were treated to obtain mean monthly values shown with the bar charts in Fig. 1.

The mean monthly soil temperatures under Korean pine forests in the southern part of Primorskii region are close to those under forests of northeastern China [25]. Hence, though the difference in precipitation between these two regions is considerable (450 and 700 mm, respectively), the soil temperature regimes in them do not differ much. The mean monthly air temperature in 2016 varied from −16.4°C in January to 20.7°C in August. The period with the soil temperatures above zero ($t_s \geq 0$°C) averaged for the studied plots comprised 260 days, and the period with air temperatures $t_a \geq 0$°C comprised 230 days.

The temporal (seasonal) variability of specific fluxes of $CO_2$ on the studied plots is characterized by the coefficient of variation $Cv$ = 40–43%. In the particular chambers, seasonal variation in the intensity of the $CO_2$ emission reached 46–74%. Average values of emission intensity calculated for separate years of measurements (Fig. 2) are characterized by the much lower variation (19%) specified by certain differences in temperature regimes of measurement seasons. Relatively low values of the average emission intensity in 2015 and 2016 can be explained by the long-term activity of typhoons in the south of the Primorskii region in these years, so that the end of summer seasons was cold and moist.

In the analysis of the spatial variability in the CO2 emission intensity from the soil surface, data sequences with averaged values for separate dates of measurements were compared for the studied plots

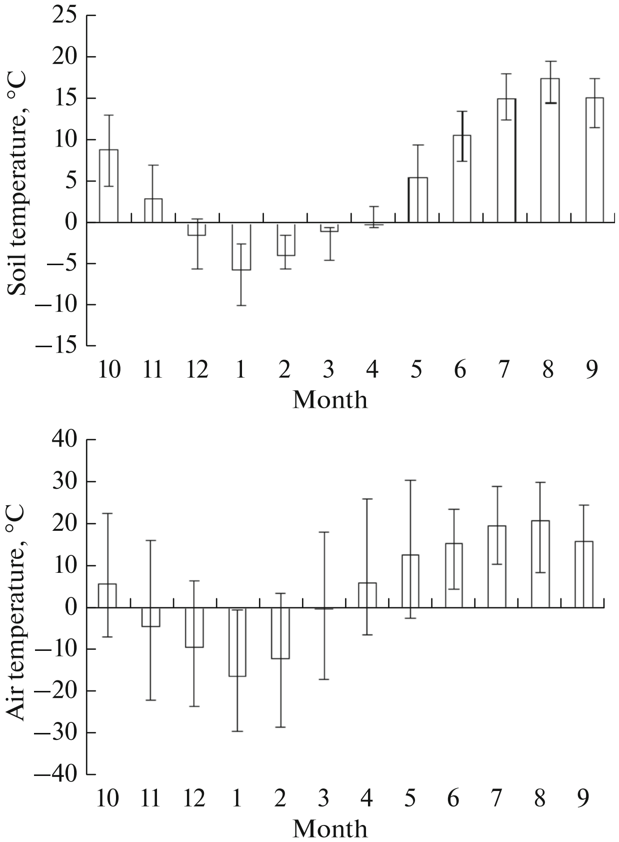

**Fig. 1.** Mean monthly soil and air temperatures in the 200-year-old pine stand according to data from temperature loggers (ranges of variation are indicated by the bars).

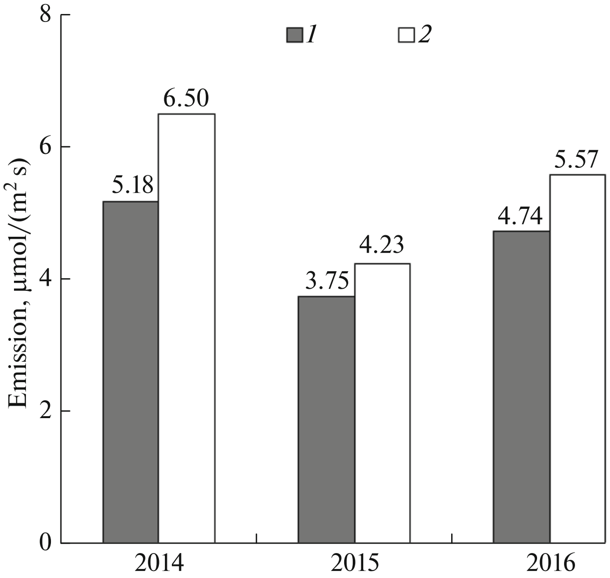

**Fig. 2.** Soil respiration values averaged for the (*1*) entire measurement period and (*2*) summer period. Data extrapolation was made according to trapezoidal rule.

using Student's *t*-test. The differences between the plots under Korean pine stands with the age of 50 and 130 yrs, 50 and 200 yrs, 80 and 130 yrs, 80 and 200 yrs, and 130 and 200 yrs proved to be significant at $p < 0.001$; the difference between the plots under the 50- and 80-year-old stands were significant at $p < 0.05$. Thus, we can conclude that the character of forest vegetation largely controls the efflux of $CO_2$ from the forest soils. Though our data do not allow us to identify the most significant characteristic of forest stands affecting soil respiration, we can suppose that the mean age of the stand is the key predictor.

For each of the four plots, a regression model linking soil respiration with the soil temperature (Table 2) was built. As a rule, such regression models are based on exponential curves [3, 5, 26].

For the particular plots, seasonal variation in the intensity of the $CO_2$ emission from the soil surface can mainly be explained (by 50–70%) by changes in the temperature of the upper soil layer. The number of measurements of the soil water content was insufficient to develop multiple regression equations for each of the plots. Therefore, we built a two-factor mode for the entire set of obtained data. In this model, daily $CO_2$ emission from the soil surface is a dependent variable, and the soil temperature at the depth of 10 cm ($t$) and volumetric soil water content ($W$) of the upper soil layer are independent variables (Fig. 3).

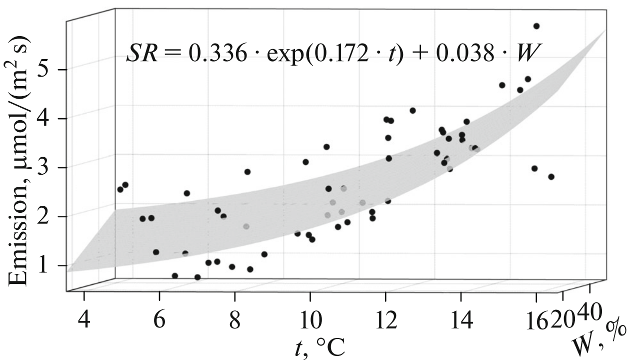

**Fig. 3.** Dependence of soil respiration on the soil temperature and water content. The plotted surface reflects the relationship of the emission ($SR$) with the soil temperature at the depth of 10 cm ($t$) and the soil volumetric water content ($W$); $R^2 = 0.62$, $p < 0.001$.

For the mixed coniferous–broadleaved forests of the southern Sikhote-Alin, the major limiting factor of seasonal dynamics of the soil respiration is the soil temperature. However, the soil water content is also a significant factor of the temporal variability of the emission. It controls about 10% of the total variability of the emission because of a generally sufficient soil water supply and high relative humidity of the air during the summer period.

Data on the soil temperature obtained with the help of temperature loggers were used to calculate total efflux of $CO_2$ for the summer period and for the frost-free period (the period when the soil temperature at the depth of 10 cm is 0°C and higher) (Fig. 4).

As noted earlier, the frost-free period in the interval from October 1, 2015 to September 30, 2016 lasted about 260 days. Secondary data suggest that the total efflux of $CO_2$ in the period with subzero temperatures was no higher than 10% of the annual efflux, as was found for forest ecosystems of the northeastern China [25, 26]. The summer efflux averaged for the plots

**Table 2.** One-factor regression dependence of soil respiration on the soil temperature under Korean pine stands of different ages ($SR$ is the soil respiration, µmol/(m² s), and $t$ is the soil temperature at the depth of 10 cm, °C)

| Plot | Regression equation | $R^2$ | $p$ |
|---|---|---|---|
| 50 yrs | $SR = 9.23 \times 10^{-8}e^{0.096t}$ | 0.64 | <0.001 |
| 80 yrs | $SR = 1.13 \times 10^{-7}e^{0.075t}$ | 0.51 | <0.001 |
| 130 yrs | $SR = 9.78 \times 10^{-8}e^{0.093t}$ | 0.69 | <0.001 |
| 200 yrs | $SR = 1.23 \times 10^{-7}e^{0.091t}$ | 0.53 | <0.001 |

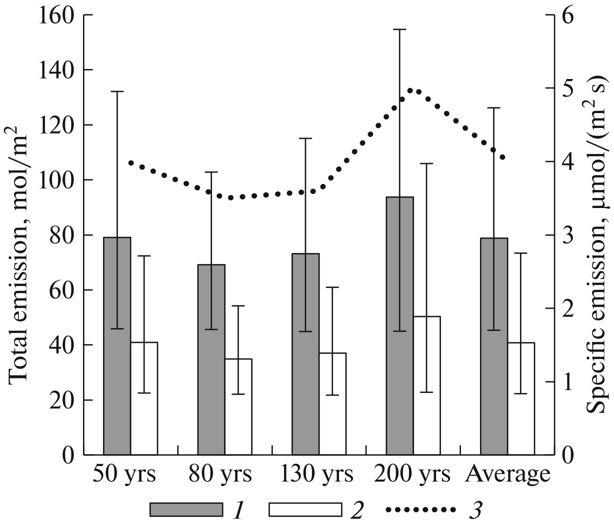

**Fig. 4.** Variation in the total (according to models) and mean daily (according to the results of measurements) effluxes of C–$CO_2$ from the soils under Korean pine stands of different ages: (*1*) entire year, (*2*) summer period, and (*3*) mean daily emission during the period of measurements.

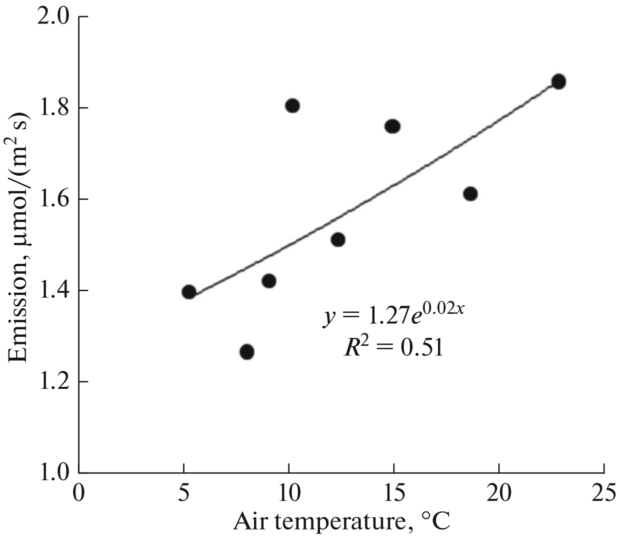

**Fig. 5.** Soil respiration intensity under the 200-year-old Korean pine stand versus air temperature during measurements on May 22, 2015.

comprised 40.75 mol/m$^2$, or 51.8% of the efflux during the frost-free period. The average value of the $CO_2$ emission from the frost-free period (78.75 mol/(m$^2$ yr)) was 46% higher than the estimate by Raich and Schlesinger for broadleaved forests [22]. Maximum values of emission intensity and total emission were obtained for the plot under the old-age (200 yrs) stand of Korean pine. The minimum total emission was measured on the plot under the 80-year-old stand, and the maximum total emission was measured under the 200-year-old stand. The difference between them (for the frostless period) comprised 24.68 mol/m$^2$, or 36%. If the age of the stand really controls the spatial heterogeneity of soil respiration, than higher emission values under the 50-year-old stand in comparison with the 80-year-old stand may be explained by the fact that the litter and soil properties under the 50-year-old stand still retain some characteristics typical of the litter and soil under the previous old-age stand (the 50-year-old stand appeared after the forest fire). The earlier performed estimates of forest litter pools on the considered plots [1] make it possible to hypothesize that the pool of forest litter is directly proportional to the intensity of $CO_2$ emission from the soil and can be considered one of the factors of the spatial variability in soil respiration. Such a relationship proved to be statistically significant for spruce stands of the Valdai Upland [5].

The average value of specific emission for all the plots during the three measurement seasons comprised 5.64 ± 1.23 μmol/(m$^2$ s). It is interesting that the average specific summer emission from the soils under the secondary oak stands of the forest site of the PSAA was somewhat higher and reached 7.04 ± 0.38 μmol/(m$^2$ s) [2]. These oak stands are the results of the pyrogenic degradation of Korean pine stands, one of the negative consequences of which is the increase in the $CO_2$ efflux from the soils.

The daily dynamics of the $CO_2$ emission from the soil was determined ion May 22, 2015 on the plot under the 200-year-old stand. May in the southern part of the Primorskii region is characterized by considerable daily temperature amplitude (Fig. 1). On the day of measurements, the amplitude of air temperatures was from 5.2°C at 5:00 to 22.0°C at 14.00 ($Cv = 44\%$). The thermodynamic inertness of the soil relative to the air leads to the shift in the temperature fluctuations by about 9 h. According to our measurements during one day, the emission intensity displayed significant correlation with the air temperature ($r^2 = 0.505$; $p < 0.05$) (Fig. 5). Our measurements of the emission intensity under oak stands on August 10, 2014 (unpublished data) also showed a significant exponential dependence of the emission intensity on the air temperature.

## CONCLUSIONS

Mixed *Pinus koraiensis*–broadleaved forests in the southern part of the Sikhote-Alin Range (the Przhevalsky Mountains) under conditions of the temperate monsoon climate are characterized by the specific regime of soil respiration with the high portion of the summer efflux (more than 50% of the annual efflux). The factors of soil temperature and moisture determine seasonal variability in the emission intensity by 50–70 and 10%, respectively. The maximum difference in the emission intensity between the model plots under stands of different ages reaches 36%. The specific summer emission averaged for all the test plots for three years of measurements comprises 5.64 ± 1.23 μmol/(m$^2$ s). It is considerably lower than the specific summer emission from the soil surface under oak stands in the same area. The daily dynamics of the efflux of carbon dioxide from the soils under Korean pine stands can be described by an exponential curve with the air temperature as an independent variable ($R^2 = 0.51$).

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