Carbon emission by soil respiration in a deciduous forest on the southern border of the taiga (Tatarstan, Russia)

Denis Tishin¹*, and Nelly Chizhikova¹

¹Kazan Federal University, Kazan, 420008, Russia

Abstract. Soil respiration contributes to the carbon emission losses of terrestrial ecosystems, so its accurate assessment is prerequisite to predict environmental risks resulting from Earth's climate change. Seasonal dynamics of carbon dioxide fluxes from the soil surface of broad-leaved forest of the Middle Volga region, located on the southern border of the southern taiga subzone, were measured during the growing season. The forest belongs to the polygon Karbon-Povolzhye (Zelenodolsky district, Republic of Tatarstan, Russia). Seven measurements were taken from May to October 2022 in five replicates. The average monthly carbon emission during the growing season and pre-winter period was 0.19±0.01 g C h/m². The largest emissions were observed at the end of June, the smallest – in September under the decreasing air and soil temperatures. Robust linear regressions were built to predict carbon emission depending on air temperature (n = 35, p < 0.001, r² = 0.37), temperature of soil at a depth of 1 cm (n = 35, p < 0.001, r² = 0.30), temperature of soil at a depth of 5 cm (n = 35, p-value < 0.01, r² = 0.18). The data on carbon flux by soil are presented for the first time for the forest ecosystems of the Middle Volga region. The resulting emission estimates can be used to calculate the total carbon balance for the forest ecosystems of the Middle Volga region.

1 Introduction

Monitoring of carbon dioxide (CO₂) emissions from soils provides the valuable estimates for determining carbon cycles in the biosphere, which is especially important in the context of global climate change [1-2]. Evaluation of carbon dioxide released by soil under different conditions will contribute to accurate forecasting of soil carbon dioxide emissions under possible climate change scenarios, which can be used to reduce the environmental risks of the negative impact of climate change on the Earth's ecosystems.

Soil carbon flux studies published around the world cover various ecosystems and spatial scales: the global scale studies [3-4]; the forest habitats of various spatial scale [5-7]; the arable lands under various management [8-10].

The works on greenhouse gas emissions conducted in forest ecosystems of the European part of Russia cover the northern taiga zone and soddy-podzolic soils in

* Corresponding author: kpfuecoology@gmail.com
coniferous-deciduous forests [11-12], coniferous forest of middle [13-14] and southern taiga zones [15-18], mixed forests of southern taiga [19-20].

The studies on soil carbon fluxes in deciduous forests of the European part of Russia are rare. There is no published data on soil respiration for Volga region and for the territory of the Tatarstan Republic, especially for its broadleaved ecosystems, but the deciduous forests have a different intensity of root respiration and differ from coniferous ones in vegetation and climate, which form their own microbial, fungal soil communities that determine soil respiration [21]. For example, [22] showed that broad-leaved forests are characterized by higher carbon dioxide emissions compared to coniferous forests.

2 Materials and methods

Aims and scopes. The purpose of this study was to assess the seasonal soil emission of CO2 in a broad-leaved forest with the inclusion of coniferous trees of the carbon polygon “Carbon-Povolzhie” (Volga carbon) during the growing season of 2022. The resulting estimates on carbon emissions can be used to calculate the total carbon balance of forest ecosystems of the Middle Volga region.

This study is the first step towards assessing the contribution of soil respiration to the carbon balance of broadleaved forests of Middle Volga region, so the current stage included the following works:

- Selection a representative forest area on the carbon polygon and description of its soil and vegetation.
- Determining of sampling locations in the selected area for measuring soil carbon dioxide emissions and preparing sites for measurement.
- Measurement of the temperature of the environment.
- Estimation of carbon emissions through the release of carbon dioxide by the soil for certain months and the entire growing season.
- Assessing of the relationship between expected soil carbon emissions and environment temperature through linear regression.

Study area. Field studies were conducted in the broad-leaved forest of the carbon polygon “Carbon-Povolzhie” (Zelenodolsky district, Republic of Tatarstan, Russia) (Figure 1A) located in the 50th quarter of the Aishinsky district forestry, site coordinates N 55.844168; E 48.798718.

The territory is located on the southern border of the southern taiga natural zone in the Volga-Vyatka high-plain complex of dark coniferous-broad-leaved nemoral grass forests [23]. The climate of the region is temperate continental with cold winters and warm summers. Average annual temperature +5.2°C (1970–2021), January average temperature –10.4°C, July average temperature +20.8°C. Average snow depth is 30–40 cm. Atmospheric precipitation averages 584 mm per year (maximum in July up to 70 mm, minimum in March up to 33 mm) according to the average monthly data of the Russian Research Institute of Hydrometeorological Information – World Data Center [24].

This is an old-growth linden forest, where the age of Tilia cordata Mill. trees reaches 106 years. The forest stand encounters single trees Betula pendula Roth., Quercus robur L. and Picea × fennica (Regel) Kom. The understory is sparse, represented by Corylus avellana L. and Euonymus verrucosus Scop., Acer platanoides L. Dominants of the herbaceous layer are Aegopodium podagraria L. and Mercurialis perennis L.

The soil is soddy-podzolic on sandy and sandy loam deposits of the third floodplain terrace of the Volga River, the humus content in the A1 horizon is 1–2%. The thickness of the forest floor is 2–3 cm.
Methods. In 2022, seven intraseasonal emissions measurements were taken at the study site (May 17, May 31, June 15, June 29, July 26, September 6 and 21). The measurements were carried out during daylight hours, at 12 noon.

The assessment of soil fluxes of carbon dioxide was carried out by the "chamber method" [8] according to the change in CO$_2$ concentration in opaque cylindrical PVC chambers with a volume of 1.5 l and a diameter of 110 mm, permanently dug into the soil to a depth of 4 cm (Figure 1B). Five cameras were installed on the site at 2 m from each other. All ground vegetation inside the chambers was removed prior to digging, i.e., soil respiration measurements include carbon emissions from the forest floor and soil surface.

![Fig. 1. The phytocenosis of the study site in the linden forest of the carbon polygon (A). Plastic chamber with gas analyzer CD 210 (B).](image)

During the measurements, the chambers were hermetically covered with a lid combined with an infrared gas analyzer CD 210 (Wohler, Germany) and built-in fan for air mixing in the chamber (Figure 1B). This analyzer has a resolution of 1 ppm. The gas analyzer was calibrated before each measurement. The total exposure time for each chamber was 4 minutes. The first minute was required to stabilize the change in CO$_2$ concentration. The concentration was measured over next three minutes. The mass change of carbon $DC$ (contained in carbon dioxide fluxes of the chamber) during exposure was calculated according to the Mendeleev–Clapeyron equation (1):

$$DC = \frac{12 \cdot 10^{-6} \cdot DM \cdot P \cdot V}{8.314 \cdot (t + 273)}$$  \hspace{1cm} (1)

Where $DC$ – change in the mass of carbon in the chamber, g C; $12$ – molar mass of carbon, g C mol$^{-1}$; $10^{-6}$ – conversion factor from ppm to volume fractions, ppm$^{-1}$; $DM$ – change of CO$_2$ concentration in the chamber, ppm; $P$ – atmosphere pressure, Pa; $V$ – chamber volume, m$^3$; $8.314$ – universal gas constant, Pa m$^3$ K$^{-1}$ mol$^{-1}$; $t$ – air temperature, °C; $273$ – parameter for converting the air temperature in °C to °K.

The temperature of the surface air layer $T_{air}$ and soil at a depth of 1 cm $T_{soil1cm}$ and 5 cm $T_{soil5cm}$ was measured simultaneously using a Checktemp-1 device (HANNA instruments, Germany) with an accuracy of 0.1°C.

Several statistics on carbon emission and temperatures were calculated for each studied month of 2022 (Table 1), and robust regressions [25] were built to model the relationship between the average mass of emitted carbon and the temperatures of the surface layer of air and soil.
Statistics calculation, visualization and modeling of carbon fluxes in their relationship with temperature were carried out using author's scripts and packages in the R environment [26]. Robust regressions were built using the robustbase package [27] in the R environment.

Table 1. Statistics of carbon emission, air and soil temperatures in different months of 2022, calculated in this work.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Units</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_mean</td>
<td>g C m^{-2} h^{-1}</td>
<td>average monthly carbon emissions</td>
</tr>
<tr>
<td>C_{95lo}</td>
<td>g C m^{-2} h^{-1}</td>
<td>lower bound of the 95% confidence interval for average monthly carbon emissions</td>
</tr>
<tr>
<td>C_{95hi}</td>
<td>g C m^{-2} h^{-1}</td>
<td>upper bound of the 95% confidence interval for average monthly carbon emissions</td>
</tr>
<tr>
<td>T_airmean</td>
<td>°C</td>
<td>average monthly air temperature</td>
</tr>
<tr>
<td>T_{soil1mean}</td>
<td>°C</td>
<td>average monthly soil temperature at a depth of 1 cm</td>
</tr>
<tr>
<td>T_{soil5mean}</td>
<td>°C</td>
<td>average monthly soil temperature at a depth of 5 cm</td>
</tr>
</tbody>
</table>

### 3 Results

The seasonal dynamics of the intensity of soil CO₂ emission from May to October 2022 was measured. The average monthly carbon emission during the growing season and pre-winter period was 0.19±0.01 g C h^{-1} m^{-2}. The largest volumes of carbon emission with CO₂ fluxes were observed at the end of June and reached 0.26 g C h^{-1} m^{-2} (Table 2). The smallest emissions were in September-October 0.11 g C h^{-1} m^{-2} (Table 2). There was a decrease in air and soil temperatures (Figures 2 and 3). Interesting is the fact that the air and soil temperatures almost equalized at the end of July.

Table 2. Calculated statistics on carbon emissions, air and soil temperatures in 2022.

<table>
<thead>
<tr>
<th>Month</th>
<th>C_mean</th>
<th>C_{95lo}</th>
<th>C_{95hi}</th>
<th>T_airmean</th>
<th>T_{soil1mean}</th>
<th>T_{soil5mean}</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>0.20</td>
<td>0.14</td>
<td>0.27</td>
<td>16.6</td>
<td>11.8</td>
<td>9.7</td>
</tr>
<tr>
<td>June</td>
<td>0.23</td>
<td>0.15</td>
<td>0.31</td>
<td>21.1</td>
<td>14.5</td>
<td>13.0</td>
</tr>
<tr>
<td>July</td>
<td>0.25</td>
<td>0.17</td>
<td>0.34</td>
<td>25.0</td>
<td>19.0</td>
<td>18.0</td>
</tr>
<tr>
<td>September</td>
<td>0.11</td>
<td>0.10</td>
<td>0.13</td>
<td>12.2</td>
<td>11.0</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Fig. 2. Seasonal dynamics of carbon flux from May to September 2022.
Scaling the average monthly estimate of carbon emission from 1 m$^2$ to 1 ha of forest soil makes it possible to obtain estimates for 1 ha of soil: 1.9 kg C ha$^{-1}$ h$^{-1}$, or 6931 kg C ha$^{-1}$ for the growing season and pre-winter period (May-October).

The figures (Figure 4) show evident positive relationship between the variables, complicated by several outliers, so the relationship between carbon emission and environment temperature was estimated using robust linear regressions (eq. 2-3).
Robust linear regression for predicting carbon emissions \( C \) (g C h\(^{-1}\) m\(^{-2}\)) as a function of air temperature \( T_{\text{air}} \) (\( n = 35, p < 0.001, r^2 = 0.37 \)):

\[
C = 0.017 + 0.009 T_{\text{air}}
\]  
(2)

Robust linear regression to predict carbon emissions with soil temperature at the depth of 1 cm \( T_{\text{soil 1cm}} \) (\( n = 35, p < 0.001, r^2 = 0.30 \)):

\[
C = -0.017 + 0.014 \cdot T_{\text{soil 1cm}}
\]  
(3)

Robust linear regression to predict carbon emissions with soil temperature at 5 cm depth \( T_{\text{soil 5cm}} \) (\( n = 35, p\text{-value} < 0.01, r^2 = 0.18 \)):

\[
C = 0.034 + 0.012 \cdot T_{\text{soil 5cm}}
\]  
(4)

All regressions reported a statistically significant positive relationship between carbon flux and temperature of environment (Figure 4), although the coefficients of determination of all the models are low.

The resulting equations \(2, 3, 4\) can be used for a rough estimate of carbon fluxes from the soil surface depending on the temperatures of air and soil. The relationship of carbon emission with the temperature of the surface air layer (equation 2) is the most pronounced in comparison with models that take into account the contribution of the temperature of the top layers of the soil.

### 4 Discussion

As mentioned in the introduction, the presented field studies of soil carbon emission can be considered the first conducted in the Volga region. Therefore, it is of interest to compare our results with published data from similar studies conducted in close regions of the European part of Russia.

The soil emission research reported in [11] was carried out in 2014, 2015 in Taezhny Log polygon which is in Novgorod region, the southern taiga zone. This is the spruce forest growing on the soddy-podzolic soils. Carbon emission in the CO\(_2\) flux was measured from April to November, average emission was 0.15 g C h\(^{-1}\) m\(^{-2}\), the maximum was reached in July–August. The results for the “Carbon-Povolzhie” polygon (average monthly carbon emission of 0.19 g C h\(^{-1}\) m\(^{-2}\)) are close to the estimates presented for the Taezhny log site, although somewhat higher.

The current data on soil emission at the “Carbon-Povolzhie” polygon are also twice as high as the results published by [13] on the carbon emission in the pine forest in the middle taiga and much higher than data reported by [12] on the mature bilberry–sphagnum pine forest.

This discrepancy is likely due, on the one hand, to the greater net primary productivity of broad-leaved forests in comparison with coniferous forests, as was shown in [28]. Similar ratios of soil respiration in broad-leaved and coniferous forests are shown by [28] as well. As shown in [12], excessive soil moisture blocks the activity of soil microorganisms and leads to decrease in carbon emission.

In [15-17] also noted that the most significant predictors of soil carbon dioxide emission in the spruce forest of the southern taiga natural zone are the air temperature aboveground and that of the top layer of the soil.

According to the results of [16] topsoil moisture, the precipitation during the preceding period is also recognized as significant, which my provide clues that local spatial moisture
heterogeneity resulting from past rains may have been a factor leading to significant heterogeneity in June carbon dioxide emissions measured in “Carbon-Povolzhie” polygon. The study [19] for mixed and broad-leaved forests on the border of the southern taiga and the zone of broad-leaved forests also supports the version of higher humidity at the moments of the highest carbon dioxide emission, reporting 1.3–1.4 times less carbon dioxide in the drier years. Also [29] showed for cool temperate deciduous broad-leaved (Quercus and Betula dominated) forest that rainfall events significantly increased soil CO$_2$ emission.

The spatial variability of soil emissions can be quite high since the distance to the trunks of dead standing trees can also be a significant factor due to the activation of respiration of pathogenic fungal flora in the rhizosphere zone [17]. As shown in [17], the level of ground emission in the zones of dry spruce forests steadily exceeded the control values by almost three times.

It is difficult to judge the patterns of soil respiration in studied carbon polygon based on one year of research. Long-term studies are essential, considering the weather conditions of a given year. According to long-term observations [30], the soil respiration in forest ecosystems of the southern taiga is decreasing. Existing global predictions in accordance with the RCP2.6 and RCP6 scenarios predict an increase in heterotrophic soil respiration, which is an important part of carbon dioxide emissions, in all bioclimatic zones, except for the southern taiga due to limitations in rainfall [31]. An analysis of climate trends in temperature, precipitation, humidity is inevitably required to create scenarios for soil change and respiration.

5 Conclusion

The soil carbon emission was assessed for deciduous forest growing at soddy-podzolic soils during the growing season of 2022. These are the first data on soil carbon emission losses for the forest ecosystems of the Middle Volga region. The main values of carbon fluxes were established; the average values are 0.19±0.01 g C h$^{-1}$m$^{-2}$. These values characterize soil respiration during daylight hours, varying depending on the current temperature of environment. Soil moisture was not considered in the work but could explain the spatial variability of soil respiration.

The relationship between the litter thickness and carbon dioxide emission was not considered in this work, because litter thickness is fairly spatially uniform, although litter and deadwood decomposition are another component of carbon dioxide emissions. The research can be extended by assessing emissions from the decomposition of large wood residues, as well as through a metagenomic analysis of soil to gain understanding which species or communities of microorganisms are involved in the decomposition of organic matter with subsequent release of carbon. All these are steps to estimate the overall carbon balance of forest ecosystems in the Middle Volga region.

Acknowledgement

This work was funded by the subsidy allocated to Kazan Federal University for the state assignment in the sphere of scientific activities, project No. FZSM-2022-0003. Assistance during the field work provided by Polina Kuryntseva is greatly appreciated.
References


7. A. Walkiewicz, P. Bulak, M. Brzezinska, M.I. Khalil, B. Osborne, Forests 12, 1, 226 (2021)


24. RIHMI-WDC. Baseline Climatological Data Sets, http:\\meteo.ru\english\data