Efflux of CO₂ from soil in Norway spruce stands of different ages: A case study

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ABSTRACT

Efflux of CO₂ from soil is a major component of the terrestrial ecosystem and plays an important role in the global carbon cycle. In this study the efflux of CO₂ from soil was measured in three stands of Norway spruce. We investigated differences in the efflux of CO₂ from soil in different age classes of the forest: two young (YR and YBK) and one old (OR) stand, during the growing season in 2010. The lowest amount of soil CO₂ released was recorded in OR (14.9 t ha⁻¹), which was just over half that recorded in the young stands. There were no significant differences in total soil CO₂ released recorded in YR and YBK (29.3 and 27.2 t ha⁻¹). Efflux of CO₂ recorded in YR and OR during July was low because of lack of rain. When the efflux of CO₂ from soil in OR and YR, respectively, was estimated on the basis of the soil moisture measured at YR, the modelled cumulative amount of soil CO₂ released increased by 10.9 and 11.4%. Our results indicate that the age of a stand can be an important and easily obtained factor for predicting the amount of soil CO₂ released at the regional level.

Keywords: spruce forest, Picea abies, soil temperature, moisture, respiration

Introduction

Soil respiration is the second-largest flux of carbon in terrestrial ecosystems and plays an important role in the global carbon cycle. It is estimated that 45–90% of forest ecosystem respiration is from soil cycling (Goulden et al. 1996; Boldstad et al. 2004; Guan et al. 2006). Therefore, soil respiration has a great effect on the atmospheric concentration of CO₂, and consequently, as CO₂ is one of the greenhouse gases, on global warming.

In the temporal dynamics of the efflux of CO₂ from soil, temperature and soil moisture are the most important factors. There is a mostly positive relationship between soil respiration and temperature and this relationship is often described as exponential (Davidson et al. 2006). Low and high soil moisture may limit the efflux of CO₂ from soil (Jassal et al. 2008).

As forests develop from young to mature stages, there can be changes in sources of organic carbon used in soil respiration, which includes assimilates (in roots), plant residues, rhizoh-deposits or soil organic matter (Kuzyakov et al. 2006). Age-related variation is recorded in, for example, soil organic matter (Saiz et al. 2006a), litter input (Klopatkova 2002) and root biomass (Fang et al. 1998). To estimate the efflux of CO₂ from soil on a large spatial scale would demand many different analyses and measurements of the various factors. Some of these can be similar for a given forest age class. Therefore, assessing the efflux of CO₂ from soil in forests of different ages is important for accurately estimating the global carbon balance.

In this study, we measured the efflux of CO₂ from soil in three Norway spruce (Picea abies (L.) Karst.) stands of different ages, including a 32- and a 110-year-old stand in an upland region and a 29-year-old stand at a mountainous location. The aim was to estimate the efflux of CO₂ from soil in the three tree stands of different ages and describe the seasonal course of the efflux of CO₂ from soil in these stands during the experimental season.

Material and Methods

Measurements were carried out in three Norway spruce forests in the Czech Republic at Bily Kriz and Rajec-Nemcice.

Bily Kriz is situated in the Moravian–Silesian Beskydy Mts. The stand (YR) was planted after clear-cut of a first-rotation forest that had grown on former pasture. Characteristics of the site and the stand are summarized in Table 1.

The efflux of CO₂ from soil was measured at eight positions using an automatic closed gasometrical system SAMTOC (Pavelka et al. 2004) from 1 May to 25 October 2010. Soil temperature was measured at a depth of 1.5 cm within each chamber (Pavelka et al. 2007). Precipitation in the area was measured using a MetOne 386 rain gauge (Met One Instruments, Inc., USA). Soil moisture was measured using a TRIME-FM 2/3 device (Mesa Systems Corp., USA) in a 0–32 cm profile.

Rajec-Nemcice is situated in Drahanska Upland. We studied two stands at this site – one 32 years old (YBK) and the other 110 years old (OR). The stands were established by reforesting clear-cut areas. Characteristics of the site and the stands are summarized in Table 1.

Measurements of the efflux of CO₂ from soil at OR were made at three positions using SAMTOC-II from 26 April to 8 November 2010. Soil temperature was measured at a depth of 4.5 cm inside each chamber (according to Rayment and Jarvis 1997). Measurements of the efflux...
of CO$_2$ from soil at Y$_R$ were made manually at 16 positions using a portable Li-8100 (Li-Cor, Inc., USA) from 23 April to 17 October 2010. Soil temperature was measured 1 cm alongside the positions at a depth of 4.5 cm during each CO$_2$ measurement. In addition, soil temperature at 4.5 cm was measured continuously for the entire season using a PT 1000 sensor (HITLd., CZ).

Soil moisture was measured at three positions in each stand using a CS616 Reflectometer (Campbell Scientific, USA) at 1 h intervals and over a profile of 0–30 cm. Precipitation was measured in an open area using a MetOne 370/375 rain gauge (Met One Instruments).

### Data Analyses

Efflux of CO$_2$ from soil ($R_S$) was plotted against soil temperature ($T_S$) and this was fitted by an exponential regression curve using the regression equation

$$R_S = \beta e^{a T_S}, \quad (1)$$

where $a$ and $\beta$ are the regression coefficients.

$Q_{10}$ (the proportional change in CO$_2$ efflux for a 10 °C increase in temperature) was calculated using the equation:

$$Q_{10} = e^{10a}, \quad (2)$$

where $a$ is the regression coefficient obtained from equation (1). For continuous automatic measurement data, $Q_{10}$ was calculated for each chamber for several short periods when the efflux of CO$_2$ from soil was not disturbed by rainfall. For manual measurement data, one value of $Q_{10}$ was calculated from all the measurements of the efflux of CO$_2$ from soil at different temperatures.

Then, efflux of CO$_2$ from soil was normalized for the temperature of 10 °C ($R_{10}$):

$$R_{10} = \frac{R_S}{Q_{10}^{T_{S} - 10}}, \quad (3)$$

where $R_S$ is the measured rate of efflux of CO$_2$ from soil at soil temperature ($T_S$). $R_{10}$ was determined for each measurement.

Missing data for the efflux of CO$_2$ from soil in the continuous measurements were replaced using the equation

$$R_M = \frac{R_{10}}{Q_{10}^{T_{S} - 10}}, \quad (4)$$

where values of $Q_{10}$ and $R_{10}$ were estimated from measurements for the periods of 3 to 5 d before and after the gap in the data.

Gaps in $R_{10}$ in the manual measurements from Y$_R$ were filled by interpolating the measured data. Then, mean efflux of CO$_2$ from soil was calculated for each day according to equation (4), where $T_S$ was replaced by values of mean daily soil temperature.

To exclude the effect of differences in rainfall at the two sites, we determined the effect of soil moisture on the efflux of CO$_2$ from soil and recalculated the efflux using soil moisture data collected at Y$_R$. We plotted the efflux of CO$_2$ from soil recorded at Y$_R$ against soil temperature. Then, the data were fitted with an exponential regression curve and residuals from the regression were estimated. These were plotted against soil moisture and logarithmic relationships of the residuals and soil moisture were estimated for four periods: 26 April–18 June, 19 June–17 July (with low precipitation), 18 July–4 October and 5 October–8 November. The equations for estimating the efflux of CO$_2$ according to soil temperature and moisture were defined on the basis of equation (1) and the logarithmic relationship of the residuals and the efflux of CO$_2$ from soil. Similarly, the data for Y$_R$ were recalculated (with one regression of the residuals on moisture).

### Table 1: Characteristics of the sites and the stands.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Bily Kriz $Y_{BK}$</th>
<th>Rajec-Nemcice $Y_R$</th>
<th>Rajec-Nemcice $Q_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude (m a.s.l.)</td>
<td>890</td>
<td>625</td>
<td>625</td>
</tr>
<tr>
<td>Mean air temperature (°C)</td>
<td>5.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>1318</td>
<td>717</td>
<td>717</td>
</tr>
<tr>
<td>Age (years)</td>
<td>29</td>
<td>32</td>
<td>110</td>
</tr>
<tr>
<td>Tree height (m)</td>
<td>14.9</td>
<td>13.6</td>
<td>31.6</td>
</tr>
<tr>
<td>Tree density (trees ha$^{-1}$)</td>
<td>1420</td>
<td>1888</td>
<td>609</td>
</tr>
<tr>
<td>Soil type (FAO classification)</td>
<td>Haplic Podzol</td>
<td>Cambisol</td>
<td>Cambisol</td>
</tr>
<tr>
<td>Carbon in organic layer (t ha$^{-1}$)</td>
<td>19.8</td>
<td>21.1</td>
<td>28.8</td>
</tr>
<tr>
<td>Carbon in mineral layers (t ha$^{-1}$)</td>
<td>100.0</td>
<td>92.6</td>
<td>169.3</td>
</tr>
<tr>
<td>Thickness of organic layer (cm)</td>
<td>8</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Thickness of mineral layers (cm)</td>
<td>42</td>
<td>55</td>
<td>42</td>
</tr>
</tbody>
</table>

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Statistical calculations were done using analytical software SigmaPlot 11.0 and SPSS 17.0. For data comparison one-way ANOVA and Games–Howell test (when a test of equal variance failed) were used. Statistical significance was tested with $\alpha = 0.05$.

**Results**

Environmental conditions (soil temperature, air temperature, soil moisture and precipitation) recorded at the different sites are presented in Fig. 1 and Table 2.

Table 2 Mean seasonal (1 May–25 October 2010) values of chosen characteristics and parameters.

<table>
<thead>
<tr>
<th></th>
<th>$Y_{BK}$</th>
<th>$Y_R$</th>
<th>$O_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil temperature (°C)</td>
<td>10.5</td>
<td>11.3</td>
<td>14.6</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>11.7</td>
<td>13.7</td>
<td>14.7</td>
</tr>
<tr>
<td>Soil moisture (%)</td>
<td>28.6</td>
<td>18.4</td>
<td>24.5</td>
</tr>
<tr>
<td>Total precipitation (mm)</td>
<td>1034</td>
<td>568</td>
<td>568</td>
</tr>
</tbody>
</table>

Efflux of CO$_2$ from soil was positively related to soil temperature at all sites. When analysing the continuous measurements recorded at $Y_{BK}$ and $O_R$, this relationship was stronger for $Y_{BK}$, with its coefficient of determination ($R^2$) equal to 0.58, than for $O_R$, with $R^2$ of 0.38. Values of $Q_{10}$ were 1.60, 2.25 and 1.82 for $Y_{BK}$, $Y_R$, and $O_R$, respectively. Mean daily $R_{10}$ at $Y_{BK}$ ranged between 2.0 and 6.0 μmol m$^{-2}$ s$^{-1}$ and increased at the beginning of the growing season. The maximum values were reached at the end of July and during August. At $Y_R$ and $O_R$, we recorded no increase in $R_{10}$ during June and July. This was possibly due to a lack of precipitation during this period. $R_{10}$ values were between 2.0 and 4.5 μmol m$^{-2}$ s$^{-1}$ at $Y_{BK}$ and 1.0 and 2.5 μmol m$^{-2}$ s$^{-1}$ at $O_R$ (Fig. 2).

The amount of CO$_2$ released from soil at $Y_{BK}$ was 27.2 t ha$^{-1}$ during the period 1 May–25 October 2010. The amount of CO$_2$ released from soil at $Y_R$ was 29.9 t ha$^{-1}$ during the season 23 April–25 October 2010 (29.3 t ha$^{-1}$ for the same period as that for $Y_{BK}$). The amount of CO$_2$ released from soil at $O_R$ was 15.6 t ha$^{-1}$ during the whole period (26 April–8 September 2010). This amount was 14.9 t ha$^{-1}$ for the same period as that for $Y_{BK}$ and was...
Discussion

In this study, we measured the efflux of CO₂ from soil in three Norway spruce stands. Two stands (Y_BK and Y_R) were young and one was old (O_R). Efflux of CO₂ from soil standardized to 10 °C for Y_BK showed a seasonal trend. A similar trend with a maximum occurring in summer is reported for a pine stand in a study by Law et al. (1999), and these authors attributed the trend to fine root growth. Similarly, Yan et al. (2011) report that changes in fine root biomass is one factor influencing seasonal variation in the efflux of CO₂ from soil in young poplar stands. Epron et al. (2001) report a seasonal trend in temperature-normalized rhizospheric respiration in young beech forest with a maximum in July, at which time fine root growth was greatest. We did not record such a trend in R₁₀ at Y_R and O_R. This is most likely due mainly to the dry period in June and July, which reduced the efflux of CO₂ from soil due to the limited availability of water.

We recorded a significantly lower efflux of CO₂ from soil at O_R than at Y_BK and Y_R during the experimental season. Age-dependent efflux of CO₂ from soil is described in other studies, which involved stands of different ages. For example, increasing efflux of CO₂ from soil with age in pine or poplar stands is recorded (Wiseman et al. 2004; Zhang et al. 2011), but with a maximum stand age of 25 years. Kolari et al. (2004) describe a steep increase in the efflux of CO₂ from soil in 12 year old pine stands, after which it decreased until the age of 75 years. Luan et al. (2011) report an increase in cumulative growing season efflux of CO₂ from soil with age in oak stands (40–143 years). They explained the trend in terms of substrate availability and organic matter quality. Yan et al. (2011) report a decrease in the efflux of CO₂ from soil and R₁₀ in poplar stands from the age of 2 years to 12 years. This was explained as an effect of soil temperature, moisture and fine root biomass decreasing with age. Similarly, Saiz et al. (2006b) report a decreasing trend in the efflux of CO₂ from soil with age in spruce stands between 10 and 47 years old. They also report a decreasing trend in the fine root biomass with stand age and that the changes in the efflux of CO₂ from soil associated with variations in temperature and moisture were more obvious for the youngest stands. Klopatek (2002), too, points to the amount of fine root biomass as an important factor in age-related variations in the efflux of CO₂ from soil. He studied 20-year-old, 40-year-old and old-growth Douglas fir stands. The 40-year-old stand had both the lowest annual amount of carbon release through soil efflux and lowest fine root biomass. In old stands, there is usually a lower tree density than in young stands. Therefore, it can be difficult to separate the effects of age and tree density on the amount of fine root biomass (Borja et al. 2008). Fine root biomass was not assessed in our study, but we assume that this could have had an effect on the differences in the efflux of CO₂ from soil at the stands studied, as discussed above.

Concerning the effect of the differences in rainfall at our sites, we recalculated the CO₂ efflux at Y_R and O_R using the soil moisture recorded at Y_BK. A very important period was the drought in June and July when the regression of the residuals and moisture was steep. Under conditions of low water availability, soil moisture becomes the driving factor in the efflux of CO₂ from soil (Jassal et al. 2008). We measured soil moisture in a profile...
of 0–32 cm at Y_{BK} and 0–30 cm at Y_{R} and O_{R}. Moisture measurements at these depths can miss the changes in moisture in the shallow soil layers. The top layer of soil is very active in respiration and also sensitive to low rainfall, which may not affect soil moisture in deeper layers. This top-soil can also easily dry out.

Conclusions

In this study, the difference in the cumulative amount of soil CO₂ released in two young stands was much lower than the differences between that released in the young and old stands. The amount of CO₂ released by soil in the old stand was just over half that released in the young stands. From the comparison of the two stands located at the same site we assume an effect of stand age on the physical properties of the soil, such as soil temperature or moisture, due to changes in the structure of the aboveground biomass. Stand age can also generally influence other soil properties, such as the amount of soil carbon or root biomass. Although fine root biomass was not assessed in this study, we consider that stand age in combination with measurements of temperature and moisture can help to predict the amount of soil CO₂ released at the regional level.

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