EFFLUX OF CO_2 FROM SOIL IN NORWAY SPRUCE STANDS OF DIFFERENT AGES: A CASE STUDY

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ABSTRACT

Efflux of CO_2 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 CO_2 from soil was measured in three stands of Norway spruce. We investigated differences in the efflux of CO_2 from soil in different age classes of the forest: two young (Y_R and Y_{BK}) and one old (O_R) stand, during the growing season in 2010. The lowest amount of soil CO_2 released was recorded in O_R (14.9 t ha^{-1}), which was just over half that recorded in the young stands. There were no significant differences in total soil CO_2 released recorded in Y_R and Y_{BK} (29.3 and 27.2 t ha^{-1}). Efflux of CO_2 recorded in O_R and Y_R during July was low because of lack of rain. When the efflux of CO_2 from soil in O_R and Y_R, respectively, was estimated on the basis of the soil moisture measured at Y_{BK}, the modelled cumulative amount of soil CO_2 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 CO_2 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 CO_2, and consequently, as CO_2 is one of the greenhouse gases, on global warming.

In the temporal dynamics of the efflux of CO_2 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 CO_2 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, rhizo-deposits or soil organic matter (Kuzyakov 2006). Age-related variation is recorded in, for example, soil organic matter (Saiz et al. 2006a), litter input (Klopatek 2002) and root biomass (Fang et al. 1998). To estimate the efflux of CO_2 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 and understanding the efflux of CO_2 from soil in forests of different ages is important for accurately estimating the global carbon balance.

In this study, we measured the efflux of CO_2 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 CO_2 from soil in the three tree stands of different ages and describe the seasonal course of the efflux of CO_2 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 (Y_{BK}) 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 CO_2 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 Co., 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 (Y_R) and the other 110 years old (O_R). 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 CO_2 from soil at O_R 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

Dařenová, E., Fabiánek, T., Pavelka, M.: Efflux of CO_2 from soil in Norway spruce stands of different ages: A case study
European Journal of Environmental Sciences, Vol. 6, No. 2, pp. 98–102
https://doi.org/10.14712/23361964.2016.14

Table 1 Characteristics of the sites and the stands.

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

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 (HIT Ldt., 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

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

where a and β 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:

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

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}):

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

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

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

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_{BK}. We plotted the efflux of CO_2 from soil recorded at O_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).

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.

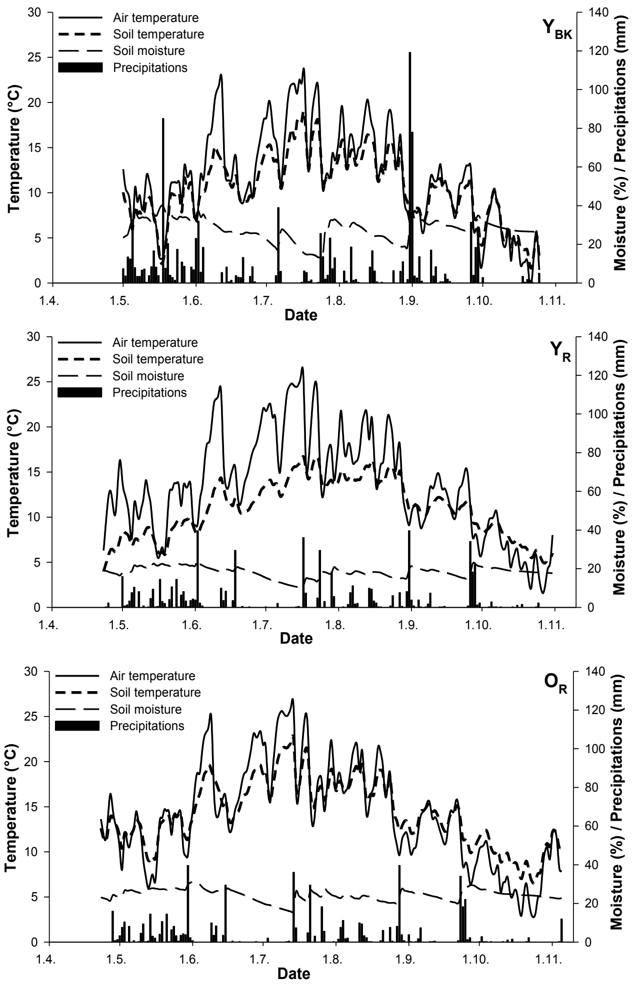

Fig. 1 Soil temperature, air temperature, soil moisture and precipitation in the young stand at Bily Kriz (Y_{BK}) and old (Y_R) and young (O_R) stands at Rajec-Nemcice.

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

	Y_{BK}	Y_R	O_R
Soil temperature (°C)	10.5	11.3	14.6
Air temperature (°C)	11.7	13.7	14.7
Soil moisture (%)	28.6	18.4	24.5
Total precipitation (mm)	1034	568	568

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_R 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

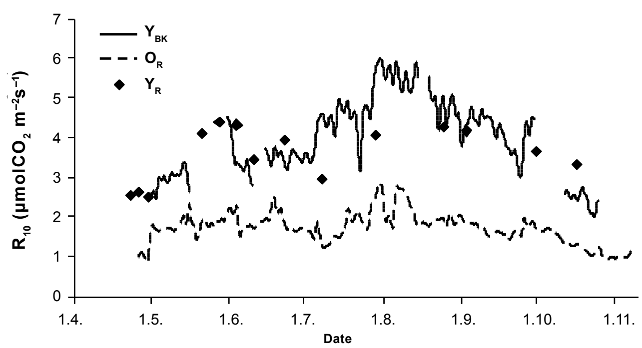

Fig. 2 Efflux of CO_2 from soil adjusted to a temperature of 10 °C (R_{10}) for the young stand at Bily Kriz (Y_{BK}) and the old (O_R) and young (Y_R) stands at Rajec-Nemcice.

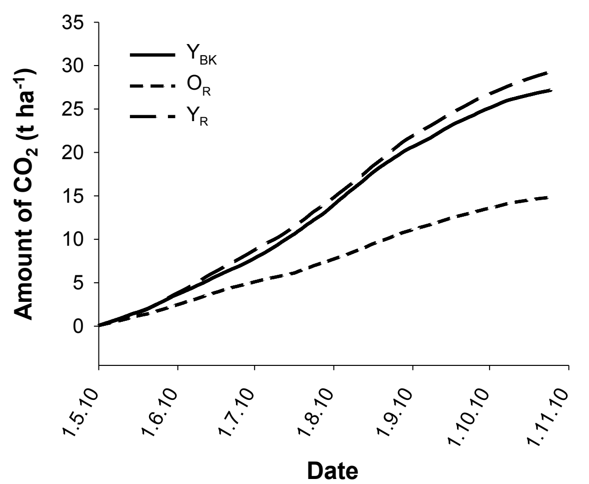

Fig. 3 Cumulative amount of CO_2 released from soil in the young stand at Bily Kriz (Y_{BK}) and the old (O_R) and young (Y_R) stands at Rajec-Nemcice from 1 May-25 October 2010.

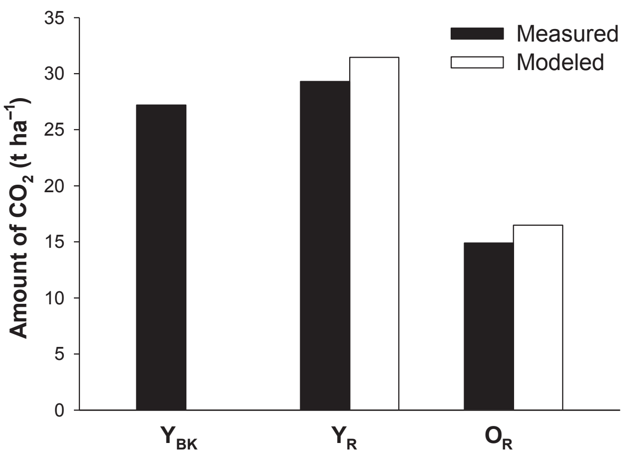

Fig. 4 Seasonal amount of CO_2 released from soil in the young stand at Bily Kriz (Y_{BK}) and the old (O_R) and young (Y_R) stands at Rajec-Nemcice during 1 May–25 October 2010. Black columns are measured data and white columns modelled amounts of CO_2 recalculated based on soil moisture recorded at Bily Kriz.

significantly less than at Y_{BK} and Y_R (amounting to 54.7 and 50.7% of the CO_2 production at Y_{BK} and Y_R, respectively). There was no significant difference between Y_{BK} and Y_R ($p = 0.058$) (Fig. 3).

To exclude the effect of the differences in rainfall at the two sites, we determined the effect of soil moisture on the efflux of CO_2 from soil at O_R and recalculated this to the soil moisture measured at Y_{BK}. The residuals of the efflux of CO_2 from soil from the regression of the relationship between the efflux of CO_2 from soil and temperature were statistically significant in their correlation with soil moisture in all four periods. The modelled data for the efflux of CO_2 from soil were in a good agreement with the measured data ($R^2 = 0.86$) and there was no statistically significant difference between measured and modelled efflux of CO_2 from soil (paired t-test, $p > 0.05$). When the efflux of CO_2 from soil was recalculated based upon soil moisture measured at Y_{BK}, the modelled seasonal (1 May–25 October 2010) amount of CO_2 released was increased by 10.9% to 16.5 t ha^{-1}.

The data from Y_R were recalculated in the same way but we used the regression of the residuals on moisture that was statistically significant. The modelled seasonal (1 May–25 October 2010) amount of soil CO_2 increased by 11.4% to 31.5 t ha^{-1} after recalculation based upon soil moisture recorded at Y_{BK} (Fig. 4).

Discussion

In this study, we measured the efflux of CO_2 from soil in three Norway spruce stands. Two stands (Y_{BK} and Y_R) were young and one was old (O_R). Efflux of CO_2 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 CO_2 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 R_{10} 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 CO_2 from soil due to the limited availability of water.

We recorded a significantly lower efflux of CO_2 from soil at O_R than at Y_{BK} and Y_R during the experimental season. Age-dependent efflux of CO_2 from soil is described in other studies, which involved stands of different ages. For example, increasing efflux of CO_2 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 CO_2 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 CO_2 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 CO_2 from soil and R_{10} 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 CO_2 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 CO_2 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 CO_2 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 CO_2 from soil at the stands studied, as discussed above.

Concerning the effect of the differences in rainfall at our sites, we recalculated the CO_2 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 CO_2 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 CO_2 released in two young stands was much lower than the differences between that released in the young and old stands. The amount of CO_2 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 CO_2 released at the regional level.

Acknowledgements

This work was supported by the Ministry of Education, Youth and Sports of CR within the National Sustainability Program I (NPU I), grant number LO1415. Authors wish to thank English Editorial services, s.r.o. (Brno, Czech Rep.) for revising the English language of this manuscript.

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