



PRELIMINARY RESULTS OF SOIL RESPIRATION IN BEECH, SPRUCE AND GRASSY STANDS

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Soil respiration constitutes the second largest flux of carbon between terrestrial ecosystems and the atmosphere. This study provides the preliminary results of soil respiration (R_s) observations in three different stands, including two types of young forest stands (beech and spruce) and grassy clearings. The average values of R_s ranged from 0.92 to 15.20 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in the beech stand, from 1.14 to 11.26 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in the spruce stand and from 0.96 to 12.92 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in the grassy stand, respectively during the whole measuring period. Maximum rates of R_s were observed on all stands at the beginning of August and minimum rates of R_s at the beginning of November. Soil CO_2 efflux exhibited a clear seasonality for all measured stands. Seasonal fluctuations of soil respiration for all stands are closely related to changes in soil temperature and soil moisture.

Keywords: *experimental site Vrchslatina, soil respiration, soil temperature, soil moisture*

1. Introduction

Soil respiration is a major source of CO_2 released by terrestrial ecosystems and constitutes the second largest flux of carbon between ecosystems and the atmosphere (RAICH and SCHLESINGER, 1992). Ecosystem respiration consists of both autotrophic (above and belowground plant respiration) and heterotrophic components, the latter reflecting (mostly belowground) microbial (and to a lesser degree animal) respiratory activity. Both respiration components depend on the respective substrate availability (photosynthate, litter and soil organic matter), providing a direct link between respiration and productivity (WAN and LUO, 2003). The most important abiotic influencing factors on ecosystem respiration are temperature (WOHLFAHRT *et al.*, 2005), through its effect on enzyme kinetics, and in the case of soil respiration, also soil water availability (DAVIDSON *et al.*, 2000; BAHN *et al.*, 2006).

Many soil characteristics vary significantly during a year (such as soil moisture, soil temperature, microbial activity, and mineral nitrogen) and are correlated with a relatively high spatial variability (GÖMÖRYOVÁ *et al.*, 2006). Spatial heterogeneity in forest soil results from

variable quality and quantity of litter input into soil variable abiotic conditions (precipitation, light, temperature) under different tree canopies at different times of year, differences in quality and quantity of stemflow and spatial differences in water and nutrient uptake by roots of trees, etc. (BRUCKNER *et al.*, 1999, STŘELCOVÁ *et al.*, 2006)

Although the primary mechanism for transport of CO_2 from the soil to the atmosphere is diffusion, transport may also be influenced by fluctuations in pressure, wind, temperature, and displacement by precipitation. There is a great deal of spatial and temporal variability in soil CO_2 flux due to its dependence on environmental conditions and the heterogeneity of soil. Chamber techniques are probably the most widely used means of measuring gas exchange between the soil and the atmosphere. The closed portable chambers offer the opportunity to investigate spatial variability of soil respiration and its controls. In ecosystems with high spatial variability, portable chamber systems are well suited in the search for controlling factors of soil respiration since many spatial replications ensure the full coverage of this variability (KNOHL *et al.*, 2008).

The aim of this study is the comparison of soil respiration (Rs) in three different stands, including two types of young forest stands (beech and spruce) and grassy clearings, during the vegetation period of 2012. Apparently, the young forest stands represented very different ecosystems from the grass community in terms of carbon sequestration and cycling.

Two hypotheses have been tested:

H1: Does soil temperature and water content influence soil respiration?

H2: Are there differences in soil respiration between spruce, beech and grassland?

2. Methods

2.1. Site description

The Experimental Site Vrchslatina was established at the beginning of the 2009 growing season. A more detailed description (site, meteorological characteristics) of the whole experimental site has been published by KONÓPKA *et al.* (2013).

With regard to the content of the paper we attach a more detailed soil characterization. The site is situated in the geomorphological unit Veporské vrchy Mts., subunit Sihlianska plateau, which is composed mainly of porphyric granodiorites, biotite tonalites and granites. Cambisols were developed from this parent material. The soil properties at the research site are favourable and it is classified as Cambisol (Humic, Eutric). The textural class of the fine earth fraction is qualified as sandy loam. Though the rock fragments content is relatively high (about 30 – 35 volume percent in the whole assessed soil profile), almost all of the rock fragments are in the fraction fine gravel (0.2 – 0.6 cm) and so it does not influence the soil properties negatively. Soil reaction is only slightly acid. Values of pH measured in hydrosuspension were between 5.1 and 5.4 and values measured in CaCl₂ extract were between 4.3 and 4.6 (gradually decreasing towards the soil surface). The content of soil organic

carbon (SOC) is high (above average for forest soils in Slovakia). In A horizon the SOC content is almost 7% and even at a depth of 50 to 100 cm it is about 1%. It has a positive effect on the soil structure and consistency. The total carbon storage in soil to a depth of 100 cm was calculated as 197 t ha⁻¹. The C/N ratio values also indicate good quality of soil organic matter.

The young forest stand consisting of a mosaic of pure European beech patches, pure Norway spruce patches, both naturally regenerated after shelter cut with a mean age of about 12 years, and grassy gaps dominated by *Calamagrostis epigejos* (L.), were selected. The total size of selected plots were approximately 0.7 ha and represented a mixture typical for naturally regenerated forests; groups of varying density with a few scattered gaps dominated by *Calamagrostis epigejos* (L.).

The five circular plots in beech and five in spruce patches were established in 2009. Specifically, a radius of the plots in the beech stands varied between 0.8 and 1.0 m, respectively between 0.7 and 1.0 m in the spruce stands. All trees inside the plots were labelled and basic tree characteristics were measured. Moreover, in 2010, our studies were enhanced by the inclusion of grassy plots with *Calamagrostis epigejos* (L.) as a dominant species. Hence, we established five square shaped plots of 3 × 3 m and subplots of 0.25 × 0.25 m for detailed measurements and sampling. The criteria as well as the reasons for the selection of individual plots are described in detail by KONÓPKA *et al.* (2013).

2.2. Soil respiration measurements

Soil respiration was measured using the LI-6400XT portable photosynthesis system (LI-COR Inc., Lincoln, Nebraska) fitted with a 6400-09 soil CO₂ flux chamber (Figure 1). The system volume (including gas analyzer optical bench) is 991 cm³ and the measured soil area is 71.6 cm². The CO₂ and water vapour analyzers are attached directly to the chamber and mixing in the chamber headspace is achieved with the gas analyzer mixing fan



Fig. 1. Details of portable photosynthesis system Li 6400XT with a 6400-09 soil CO₂ flux chamber (left) and soil collar (right)

and the associated manifold. During a measurement, chamber air is withdrawn at the top of the chamber through the analyzer inlet duct and enters the optical path of the gas analyzer. Air is returned from the gas analyzer through the analyzer outlet ducts to the manifold near the soil surface. Soil CO₂ flux measurements were made using a soil collar inserted 3 cm into the soil as an interface between the soil and the chamber. The LI-6400 soil CO₂ flux measurement system has been designed to minimize perturbations in the soil-atmosphere CO₂ concentration gradient (GARCIA *et al.*).

The soil respiration was measured episodically (every two weeks), within four hours (midmorning) on each measuring day. The individual measurements were realized repetitively from the end of April to the beginning of November 2012 for a total of 12 replicated measurement dates. Three soil collars (Figure 1) were used for soil respiration measurements on each circle (beech and spruce) or square (grass) plot. In all, the measurements were done using 45 plastic collars (inner diameter of 10 cm) as we installed 3 collars per plot, i.e. 15 pieces for every ecosystem.

To reduce plant respiration, within the area covered by each collar, all newly growing aboveground parts of plants had been removed at the beginning of the measuring season. This procedure was carried out only in the grass stands, because spruce and beech stands are practically without ground vegetation. The grass species *Calamagrostis epigejos* (L.) produces tall grass blades, up to 120 cm which would cause problems in the respiration chamber. Soil respiration fluxes were expressed in μmol CO₂ m⁻² s⁻¹. The seasonal course of soil respiration for each stand was estimated.

Soil temperature (at -10 cm) was measured automatically using the Pt1000 A-class temperature sensors on two beech (bp1, bp2), two spruce (sp1, sp5) and two grassy (gp2, gp5) plots. Data acquisition was made with a MicroLogT3 (CZ) datalogger, manufactured by EMS (www.emsbrno.cz). One hour averages were stored. Soil temperature was also monitored simultaneously with soil CO₂ efflux with a thermocouple soil temperature probe (LICOR 6000-09TC) inserted in the soil to a depth of 10 cm near the soil flux chamber.

Soil water content (at -10 cm) was measured automatically using two Decagon soil moisture sensors on the same plots as soil temperature. Data acquisition was made with a MicroLogV3 (CZ) datalogger, manufactured by EMS (www.emsbrno.cz). One hour averages were stored.

2.3. Statistical analyses and modelling

All mean values, standard deviations, standard errors and confidence intervals (confidence level of 95%) were calculated using the statistical software package Statistica 10.0 (StatSoft, Oklahoma, USA). All reported statistical characteristics were calculated from 90 values represented by three collars per plots.

For modelling soil respiration in different stands (spruce, beech and grassy) we used exponential function:

$$EFFLUX = b_0 \exp(b_1 X_1 + \dots + b_n X_n)$$

where, b_0 – denotes the intercept of the function to which the curve approximates, $b_1 - b_n$ are regression coefficients to be estimated, and $X_1 - X_n$ are explanatory variables.

As explanatory variables, several weather parameters were selected: soil temperature (Tsoil) and soil water content (SWC).

To account for random variability between plots inside each stand, we applied nonlinear random-effects models using the package “nlme” in R (R Development Core Team, 2012).

For each type of stand, four models were tested:

- Basic models including either soil temperature or soil water content
 - m1 $EFFLUX = b_0 \cdot \exp(b_1 \cdot T_{soil})$
 - m2 $EFFLUX = b_0 \cdot \exp(b_1 \cdot SWC)$
- Advanced models including both soil temperature and water content and their interactions
 - m3 $EFFLUX = b_0 \cdot \exp(b_1 \cdot T_{soil} + b_2 \cdot SWC + b_3 \cdot T_{soil} \cdot SWC)$
 - m4 $EFFLUX = b_0 \cdot \exp(b_1 \cdot T_{soil} + b_2 \cdot T_{soil} \cdot SWC)$

For comparison between models and for the selection of the most probable one we used AIC (AKAIKE, 1974).

3. Results

Soil temperature and soil moisture

The seasonal course of measured soil temperature and soil moisture for the different stands is shown in figure 2 – 3. The highest soil temperature values were identified at the beginning of July and August during the measuring season on all plots. Volumetric soil water content varied between 2% and 35% in forest stand plots and between 3% and 28% in the grass plot. We saw a strong dependence on precipitation. From the beginning of August 2012 there was a more or less continuous rainless period of 44 days. This caused soil moisture to be lower than 5% of volumetric water content on all plots. The first rain (11 mm) occurred on 13th September after the drought period. This could be the cause of decreasing soil respiration, because the values of soil temperature were still stable (Figure 2 – 3). After an increase of volumetric water content in autumn, the soil respiration increased very little because of lower values of soil temperature.

Soil respiration

Soil CO₂ efflux exhibited a clear seasonality for all measured stands (Figure 2 – 3).

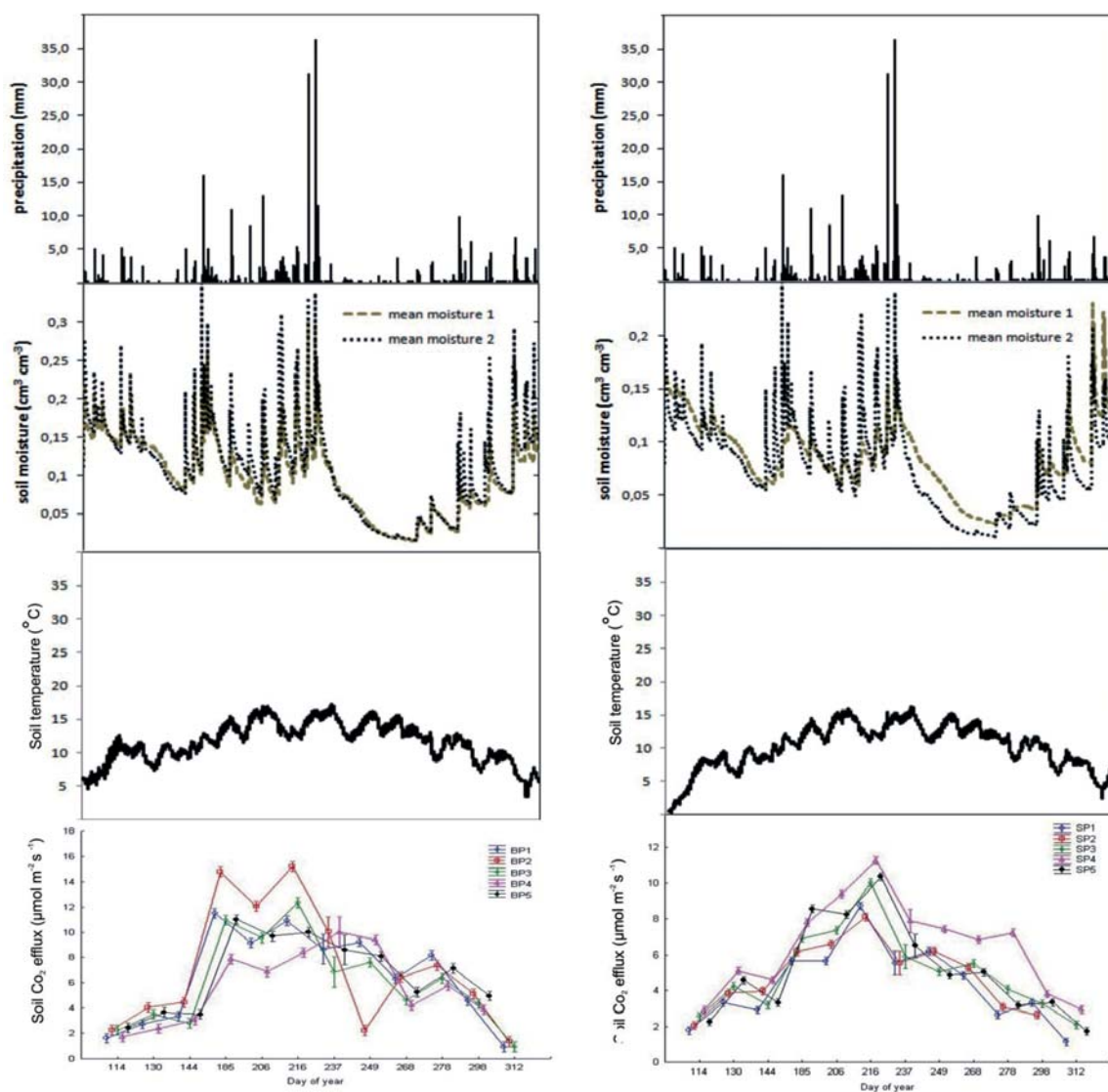


Fig. 2. Seasonal course of precipitation, soil moisture at 10 cm depth, soil temperature at 10 cm depth and soil CO₂ efflux measured on five beech ((bp1-bp5) – left) and five spruce ((sp1-sp5) – right) plots in 2012. Means and standard errors (bars) for soil CO₂ efflux represent measurements on three rings (n = 90) for each plot

Beech stand

The seasonal course of Rs showed two peak curves on all beech plots (Figure 2 – left). At the end of July a mild reduction in soil CO₂ efflux was observed. This reduction was associated with a decline in soil temperature, which reached values from 12.8 to 14.2 °C during the day. The increase of soil CO₂ efflux at the beginning of August can be attributed to the ascribed recovery of soil water content after the rainfall (129 mm per 9 days) and an increase in soil temperature to 16.4 °C.

The average values of soil respiration ranged from 0.92 to 1.34 µmol m⁻² s⁻¹ in November and from 8.39 to 15.20 µmol m⁻² s⁻¹ in August 2012 (Figure 2). The maximal differences (7.16 µmol m⁻² s⁻¹) in values of soil respiration rates between the beech plots were observed during day 248 at the beginning of September.

Model for beech stand

Table 1 presents the results from the final model estimation. The soil temperature and water content essentially contributed to the variability explanation, because the standard error was found to be small compared to the estimates and the p value rather low. The intercept denotes that the efflux starts from 0.81 and exponentially increases with the soil temperature and water content increase.

Spruce stand

The seasonal course of Rs showed one peak curve on all the spruce plots (Figure 2 – right). During the whole season, no substantial reduction in soil CO₂ efflux was observed. The decrease of Rs values was associated mainly with a decline of soil temperature at the beginning as well as at the end of the vegetation period.

Table 1. Estimates of the final model (as selected using AIC) using nonlinear mixed-effects models applied to beech stand

Parameter	Estimate	Std.Error	DF	t-value	p-value
Intercept (b_0)	0.810029	0.214938	68	3.76867	<0.001
T soil	0.143342	0.017855	68	8.028094	<0.001
T soil*SWC	0.317725	0.075159	68	4.227389	<0.001

Table 2. Estimates of the final model (as selected using AIC) using nonlinear mixed-effects models applied to spruce stand

Parameter	Estimate	Std.Error	DF	t-value	p-value
Intercept (b_0)	1.078461	0.258038	68	4.179471	<0.001
T soil	0.10043	0.01144	68	-8.77882	<0.001
T soil*SWC	0.556326	0.108636	68	5.121032	<0.001

Daily average values of soil CO₂ efflux ranged from 1.78 to 2.91 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in April and from 8.13 to 11.26 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in August 2012 (Figure 2 – right). The highest differences in values of soil respiration rates between the spruce plots were observed during the 277th day at the beginning of October. The mild increase in soil CO₂ efflux during the beginning of October on plot 4 can be ascribed to the recovery of soil moisture.

Maximum rates of Rs were recorded on all spruce plots at the beginning of August, the values ranged from 8.13 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (ss2) to 11.26 $\mu\text{mol m}^{-2} \text{s}^{-1}$ (ss4).

Model for spruce stand

Modelling the efflux of the soil in the spruce stand showed a similar pattern to the beech stand (Table 2). A slightly higher intercept was found for this stand, but taking the standard error into account the difference is not a significant one. On the other hand, the influence of the interaction between soil temperature and water content was found to be higher than for the beech stand (compare the parameter estimates between the both).

Grassy stand

The seasonal course of Rs showed a fluctuating unstable two peaked curve on all of the grassy plots (Figure 3). A significant decrease in soil respiration was observed at the end of May. This reduction was associated with a decline of soil water content, which reached values of around 15%. A further strong reduction in soil CO₂ and efflux was observed at the end of July, similarly to the beech plots.

Daily average values of soil respiration ranged from 0.96 to 1.29 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in November and from 8.66 to 12.72 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in August 2012 (Figure 3). The maximal differences (6.46 $\mu\text{mol m}^{-2} \text{s}^{-1}$) in values of soil respiration rates between the grassy plots were observed during Julian day 248 at the beginning of September.

Model for grassy stand

Concerning the grassy stand, both the soil temperature and the interaction between the temperature and

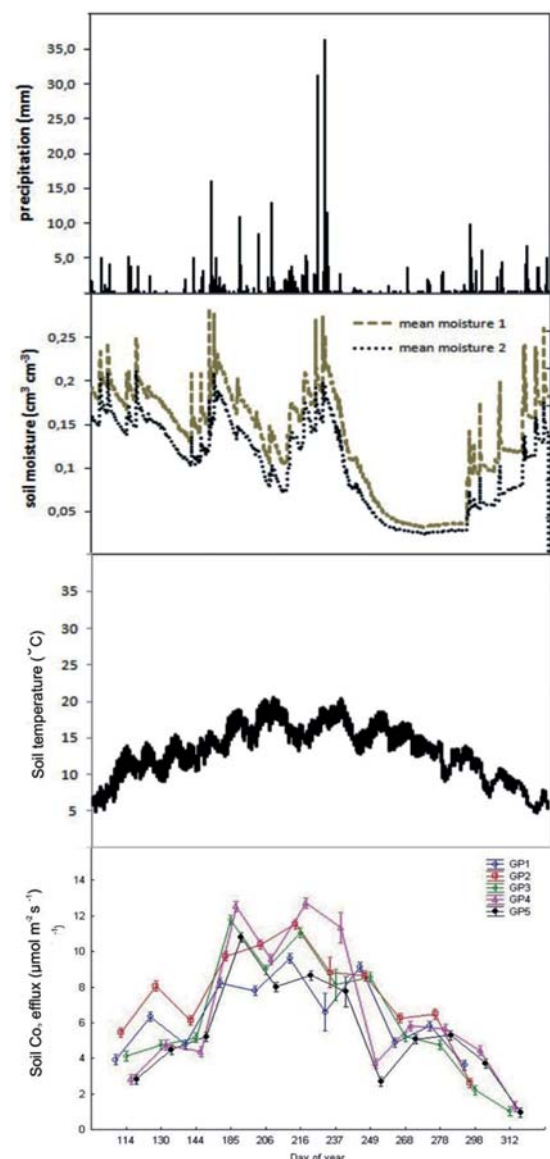
**Fig. 3.** Seasonal course of precipitation, soil moisture at 10 cm depth, soil temperature at 10 cm depth and soil CO₂ efflux measured on five grassy (gp1-gp5) plots in 2012. Means and standard errors (bars) for soil CO₂ efflux represent measurements on three rings ($n = 90$) for each plot

Table 3. Estimates of the final model (as selected using AIC) using nonlinear mixed-effects models applied to grassy stand

Parameter	Value	Std.Error	DF	t-value	p-value
Intercept (b_0)	2.021187	0.342306	65	5.90462	<0.001
T soil	0.082723	0.013209	65	6.262848	<0.001
T soil*SWC	0.113985	0.046057	65	2.474857	0.0159

Table 4. Comparison between four tested models at the spruce, beech, and grassy stands using AIC

Model	Spruce		Beech		Grassland	
	AIC	p (difAIC)	AIC	p (difAIC)	AIC	p (difAIC)
m 1	283.3627	0.0010	375.2946	0.0000	306.9956	0.1063
m 2	339.2561	0.0000	425.1943	0.0000	356.2646	0.0000
m 3	283.9555	0.0007	359.9409	0.0016	303.484	0.4078
m 4	269.5445	min	347.1238	min	302.7379	min

water content was shown to be lower than the previous types. However, the intercept was higher, which means that the efflux is much higher at the lower temperature (Figure 4).

Evaluation of the four models tested in the study showed that possibly, the most correct model from among those tested was model no. 4 for all types of stands (tab. 4). This model includes the soil temperature and the interaction between the temperature and soil water content. However, in the case of the grassy stand there is a probability of 40% that model no.3 is as good as model no. 4.

4. Discussion

The efflux of CO_2 from the soil is characterized by large seasonal fluctuations due to seasonal changes in root and microbial respiration. Although several biotic and abiotic factors influence root and microbial activity, the control exerted by temperature, and in some case moisture, is usually dominant. In the absence of water stress, variations in soil temperature account for most of the seasonal and diurnal variations in soil CO_2 efflux (JANSSENS *et al.*, 2003). Seasonal fluctuations of soil respiration were confirmed during our measurements for almost all the surveyed stands.

The highest soil respiration rate was observed in the beech stand ($15.20 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), followed by

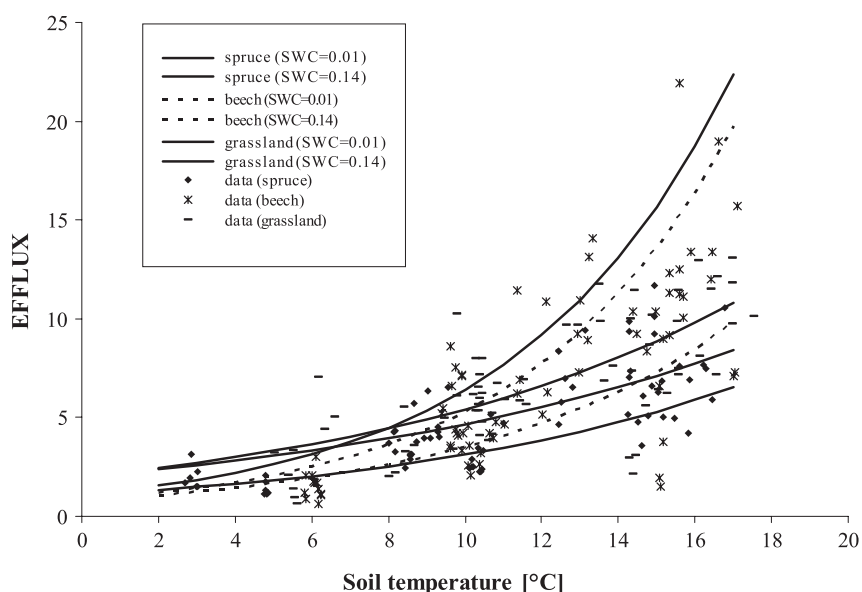


Fig. 4. Comparison of the EFFLUX between spruce, beech and grassy stands at different soil water contents (min = 0.01 and max = 0.14)

the grassy ($12.72 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) and spruce stands ($11.26 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) during the vegetation period.

CATER and OGRINC (2011) stated that the CO_2 flux rates ranged from minimum averages of $2.3 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (winter) to maximum averages of about $7 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (summer) at all the investigated locations in the Slovenian young beech forests. EPRON *et al.* (1999) argued that soil CO_2 efflux varied greatly during the year, from less than $0.5 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in winter, to more than $4 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in summer in young beech forests. The average values of soil respiration varied from $0.92 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in November to $8.39 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in August in our young beech forest stand.

An interesting overview of maximal soil respiration values obtained in European grasslands has been published by BAHN *et al.* (2008). Our measured data of maximal Rs for grassy stands are comparable with those referred to in this paper.

The spruce stand showed, virtually during whole season, the lowest measured maximum value in Rs. Our measured maximal Rs values in spruce stands ($11.26 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), however, are higher than published by PAVELKA and JANOUŠ (2001) or SUBKE *et al.* (2003) ($5.15 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) in comparable conditions. The reason is that they presented daily averages of soil respiration, like most of the literature; we present actual average or maximal of soil respiration values.

Soil respiration exhibited pronounced spatial variations in all our studied stands. Similar results were published by MATTEUCCI *et al.* (2000) who compared spatial variability of soil respiration within 3 different forest sites (beech, spruce, mixed).

The dependence of soil respiration on soil temperature has been frequently described (LLOYD and TAYLOR, 1994). Our study confirms this dependency. The respiration increased exponentially with the temperature increase. Therefore we applied an exponential regression function. Some authors applied linear or sinusoidal regressions between soil CO_2 efflux and soil temperature (RAICH, SCHLESINGER, 1992; BEN-ASHER *et al.*, 1994; FAN *et al.*, 1995), in most of the studies exponential function was used (BOONE *et al.*, 1998; DAVIDSON *et al.*, 1998; BUCHMANN, 2000).

We also found out that soil water content significantly influences the soil respiration rates. In many studies soil temperature alone was sufficient to explain seasonal variations of soil respiration (BURTON *et al.*, 1998; GANSERT, 1994; HANSON *et al.*, 1993; BUCHMANN, 2000). Several authors suggest that under certain conditions, precipitation or soil moisture significantly influence respiration (CONANT *et al.*, 1998; BUCHMANN *et al.*, 1998).

5. Conclusion

This study provides the preliminary results of actual soil respiration in three different stands. The study confirms the differences in soil respiration between the

surveyed stands. The testing of four different models resulted in the selection of the most suitable model for the calculation of soil respiration from soil temperature and soil water content data for all types of stands. Furthermore it was discovered that soil temperature and soil water content significantly influences soil efflux rates. Finally, it should be noted that the presented results are the first showing soil respiration measurements using soil respiration chambers in young forest stands in the territory of Slovakia.

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Resumé

Cieľom príspevku je kvantifikovať a porovnať priebeh respirácie pôdy v troch rozdielnych ekosystémoch; smrekovom, bukovom a trávnom ekosystéme, ktoré sú súčasťou Výskumného objektu Vrchslatina, počas vegetačnej sezóny v roku 2012. Výsledky poukazujú na výraznú sezónnu dynamiku respirácie pôdy na všetkých sledovaných plochách. Najvyššie hodnoty Rs sme zaznamenali na všetkých plochách na začiatku augusta, najnižšie zas na začiatku novembra. Okrem toho boli zaznamenané výrazné rozdiely v hodnotách rýchlosti pôdnej respirácie nielen medzi ekosystémami, ale aj medzi jednotlivými plochami. Boli testované a vybrané rovnice pre kalkuláciu pôdnej respirácie na základe teploty pôdy a obsahu vody v pôde.