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EFFECT OF MEASUREMENT TIME OF THE DAY ON THE RELATIONSHIP BETWEEN TEMPERATURE AND SOIL CO_2 EFFLUX

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Abstract

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In this study we investigated effect of the time of the day when manual measurements of soil CO_2 efflux are performed on estimates of seasonal sums of released carbon from the soil. We subsampled continuous measurement of soil CO_2 efflux into six sets of data in accordance to the time of the day when the measurements were taken – 0 h, 4 h, 8 h, 12 h, 16 h and 20 h. To estimate seasonal carbon flux from the soil we used continuously measured soil temperature and parameters R_{10} (soil CO_2 efflux normalized for temperature of 10 °C) and Q_{10} (the proportional change in CO_2 efflux caused by 10 °C increase in temperature) calculated from continuous measurements and from measurements taken at individual hours. Values of Q_{10} calculated from 12 h and 16 h data were lower than Q_{10} calculated from continuous measurements. On the contrary, Q_{10} at 0 h, 4 h, 8 h and 20 h were higher. Seasonal carbon flux from the soil based on 0 h, 4 h and 8 h measurements was overestimated compare to the flux calculated from continuous measurements. On the contrary, measurements at 12 h, 16 h and 20 h measurements underestimated the carbon flux. The under- or overestimation was significant for 0 h, 4 h, 8 h and 20 h data sub-sets.

soil CO_2 efflux, R_{10}, Q_{10}, *Picea abies*, seasonal carbon flux

Current soil CO_2 efflux measurement techniques include manual and automated chamber systems. Automatic systems have the great advantage that they measure continuously for a long period, regardless of the weather and time of day. However, automatic systems are more difficult to maintain, they generally require higher initial costs and its installation is also constrained by the supply of energy. Manual measurements can be easily implemented on a large number of positions and also at sites without the possibility of energy supply. The larger number of measurements, possible with the manual system, narrows the standard deviation of the mean, thus increasing the confidence in the site mean estimate with respect to spatial heterogeneity (Savage *et al.*, 2003). However, measurements can not be carried out in rainy weather conditions and so they do not capture the immediate response to increased soil moisture caused by rain (Lee *et al.*, 2004; Chou *et al.*, 2008). The majority of manual measurement is also performed only during the daytime.

Several studies have investigated what is the minimal frequency of soil CO_2 efflux measurement to estimate annual/seasonal cumulative CO_2 efflux (Parkin and Kaspar, 2004; Savage *et al.*, 2008). However, they did not take into account that also the time of the day, when measurements are carried out, can affect results (Parkin and Kaspar, 2003). CO_2 efflux changes during the day. The driving factor is mostly soil temperature, therefore, the maximum occurs often in early afternoon and minimum at night in dependence on the temperature changes. There can be, however, a time lag of maximum and minimum of CO_2 efflux behind maximum and minimum of the measured temperature in dependence of its depth (Parkin and Kaspar, 2003, Pavelka *et al.*, 2007).

Moreover, a cycle of manual measurements often starts from the same position. Measured characteristics at each position then differs not only in space but also in time.

The aim of this study is to assess the effect of the hour of CO_2 measurements on the parameter of temperature sensitivity of CO_2 efflux. We subsampled continuous measurement of soil CO_2 efflux into six sets of data in accordance to the time of the day when the measurement was performed. We also compared seasonal sums of released carbon calculated from continuous measurement and from subsampled data sets.

MATERIALS AND METHODS

Site description

Measurements were carried out in Norway spruce (*Picea abies* [L.] Karst) forest at the Ecological Experimental Study Site (EESS) Bily Kriz (49°30´ N, 18°32´ E, 890 m a. s. l.) situated in Moravian-Silesian Beskydy Mts., the Czech Republic. EESS Bily Kriz is characterized by mean annual (1998–2009) temperature of 6.8 ± 1.1 °C and precipitation of 1 318 ± 215 mm. The Norway spruce stand was planted in 1981 with 4 years old seedlings on the slope (13.5°) with SSW exposure. The soil type is Haplic Podzol (FAO classification).

Measurements

Measurements of CO_2 efflux from soil were carried out during the growing season (May–October) 2009. Measurements were done using automatic modified closed gasometrical (non-steady-state through-flow) system SAMTOC (developed at the Institute of Systems Biology and Ecology, the Czech Republic, Pavelka *et al*., 2004). The system consisted of eight respiration chambers and control units for chamber closing, infrared gas analyzer (Li-840, Li-Cor, Lincoln, NE, USA) and personal computer with a control software and an additional hardware. Eight respiration chambers had a cylindrical shape of 30 cm in diameter and 20 cm in height and was inserted about 3 cm into the soil. Moreover, soil temperature was measured in the depth of 1.5 cm within each chamber. The depth was chosen on the base of methodology of Pavelka *et al*. (2007). Soil CO_2 efflux was measured sequentially in all eight chambers after 10 minutes, so there are measurements every 80 minutes in each chamber.

Data analysis

Soil CO_2 efflux (R_S) was plotted against soil temperature (T_S) and this was fit by an exponential regression curve with the regression equation:

$$R_S = \beta \times e^{\alpha T_S}, \qquad [1]$$

where α and β are the regression coefficients.

Q_{10} (the proportional change in CO_2 efflux from 10 °C increase in temperature) was calculated (Linder and Troeng 1981) for each chamber for the whole growing season using equation:

$$Q_{10} = e^{10\alpha}, \qquad [2]$$

where α is the regression coefficient obtained from the previous equation.

Then, CO_2 efflux was normalized for the temperature of 10 °C (R_{10}) according to equation:

$$R_{10} = \frac{R_S}{Q_{10}^{\frac{T_S - 10}{10}}}, \qquad [3]$$

where R_S is the measured CO_2 efflux rate at temperature (T_S) of soil. R_{10} was determined for every measurements and then the seasonal average was calculated for all datasets.

Parameters Q_{10} and R_{10} can be used for estimation of CO_2 efflux response (R_M) on changes of continuously measured temperature using equation:

$$R_M = \frac{R_{10}}{Q_{10}^{\frac{10 - T_S}{10}}}. \qquad [4]$$

Finally, amount of the released carbon during the season was calculated from measured values of CO_2 efflux and from modeled CO_2 efflux using parameters (Q_{10}, R_{10}) from all data sets, that means from all data of continuous measurements, and from subsampled data for 0 h, 4 h, 8 h, 12 h, 16 h and 20 h.

Statistics were carried out in analysis software SigmaPlot 11.0. For data comparison one way repeated measures analysis of variance was used. Statistical significance was tested on the level α = 0.05.

RESULTS

The mean air temperature in the growing season 2009 (1. 5.–31. 10.) was 12.4 °C, mean soil temperature in depth of 1.5 cm was 10.6 °C, annual precipitation was 538 mm with 96 days when precipitation occurred.

From continuously measured data and from data subsampled for time 0 h, 4 h, 8 h, 12 h, 16 h and 20 h we calculated for each chamber mean seasonal soil temperature, parameter Q_{10}, mean seasonal R_{10} and determination coefficient of CO_2 efflux-temperature regression (R^2).

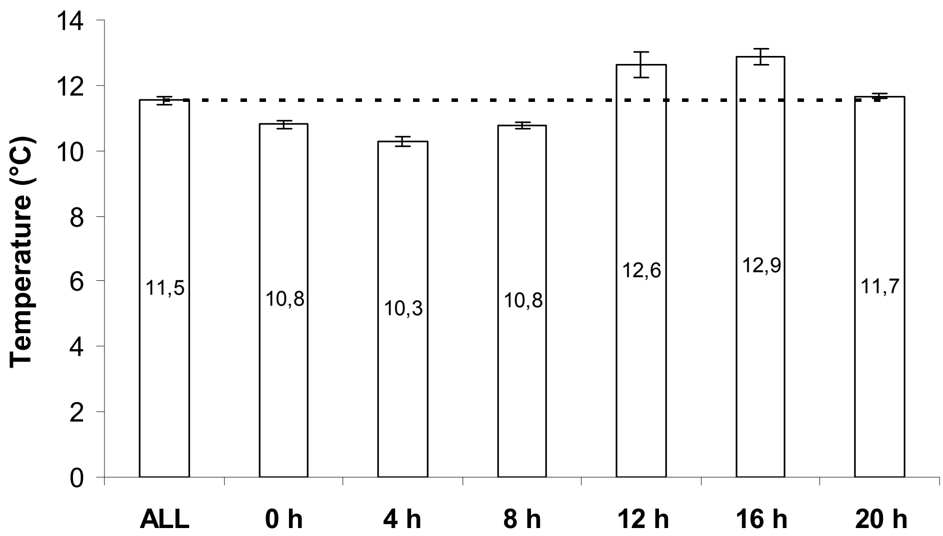
Mean seasonal temperature of soil was 11.5 °C (± 0.1) (Fig. 1). Mean seasonal temperature calculated for 0 h, 4 h and 8 h was significantly lower and for 12 h and 16 h significantly higher. There was no significant difference between temperature calculated from all data and temperature calculated for 16 h.

Arithmetic mean of parameter Q_{10} calculated for each of eight chambers obtained from all data of continuous measurement was equal 2.04 (± 0.24). Q_{10} calculated for 0 h, 4 h, 8 h and 20 h had a significantly higher value, and Q_{10} calculated for 12 h and 16 h was significantly lower (Fig. 2).

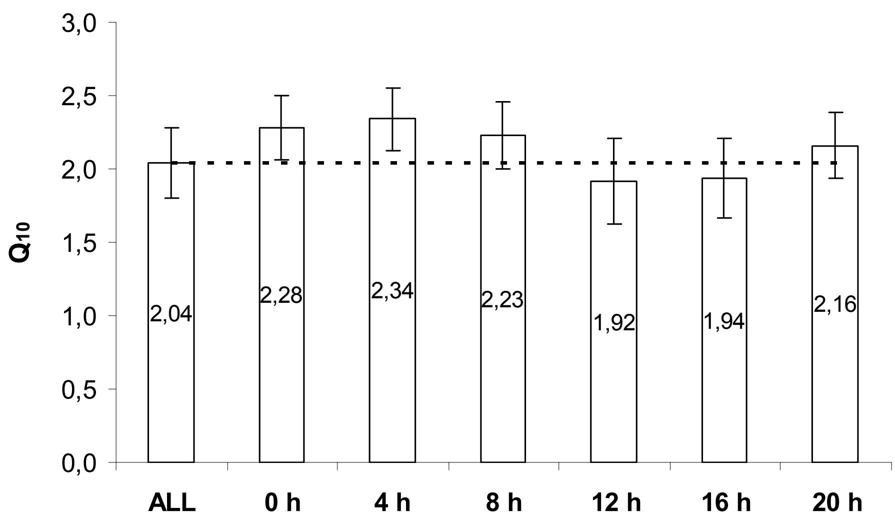
Average coefficient of CO_2 efflux-temperature regression (R^2) from eight chambers was quite low 0.49 (± 0.16) (Fig. 4). However, soil temperature and CO_2 efflux were in significantly tighter relationship for measurements at 0 h, 4 h and 20 h, and in significantly looser relationship at 12 h and 16 h when the soil temperature was the highest. Value of R^2 for measurements at 8 h was slightly higher.

Average seasonal R_{10} of eight chambers was equal 3.63 µmolCO_2 $m^{-2}s^{-1}$ (± 0.81). Values for 0 h, 4 h and 8 h were slightly above the average, and values for 12 h, 16 h and 20 h were slightly below the average. There was, however, no significant difference R_{10} calculated from all data set and from any of data subsets.

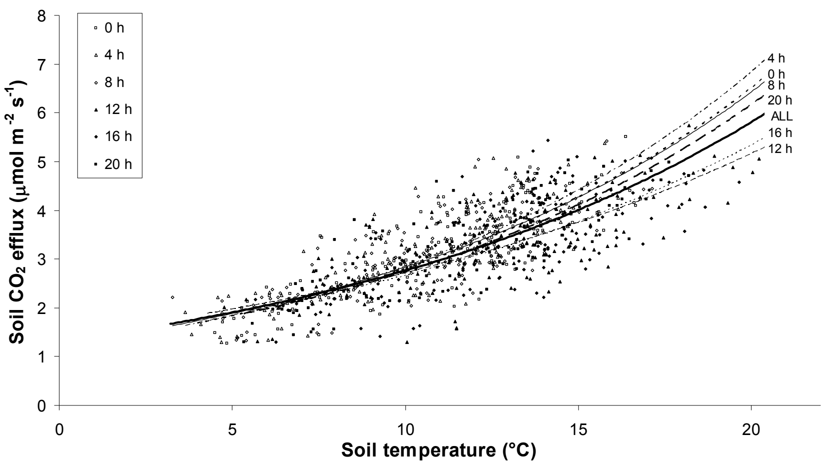
Parameters Q_{10} and R_{10} for individual time data sets were used for estimation of total carbon released from soil during the growing season 1. 5.–11. 10. 2010 using the equation [4]. The estimation was based on continuous measurements of soil temperature as a driving factor of CO_2 efflux. The average total amount of released carbon from eight chambers calculated directly from continuously measured values was 6.29 t ha^{-1} (±1.42) in the season 2009. There was no significant difference (< 0.3 %) in any chamber between seasonal carbon flux calculated from measured CO_2 efflux and CO_2 efflux



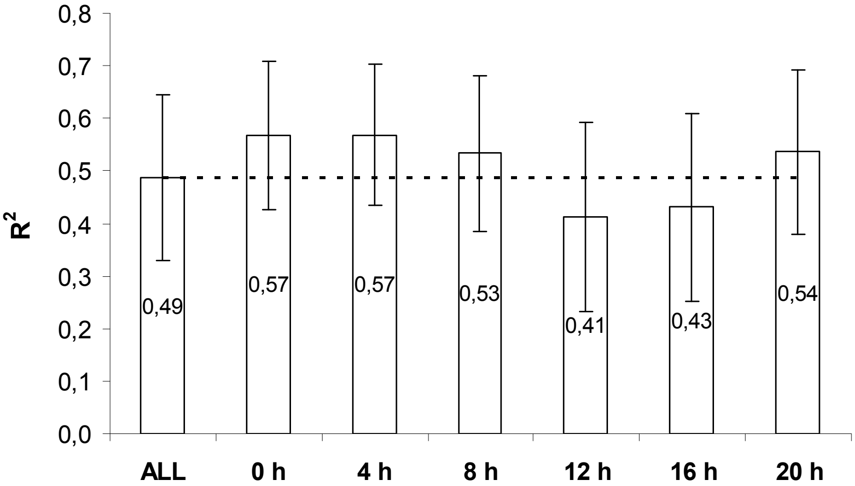
1: *Mean seasonal soil temperature from eight chambers from continuous measurements (ALL) and from measurements at individual hours. Dashed line means mean seasonal temperature calculated from all data of continuous measurement.*



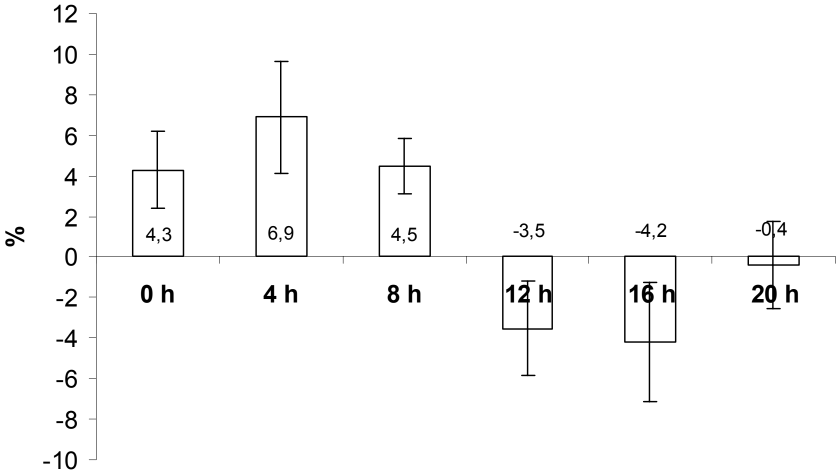
2: *Mean Q_{10} from eight chambers from continuous measurements (ALL) and from measurements at individual hours. Dashed line means value of Q_{10} estimated from all data of continuous measurement.*



3: *Exponential dependence of CO_2 efflux on soil temperature obtained from continuous measurements (ALL) and from measurements at individual hours*



4: *Mean determination coefficient of CO_2 efflux-temperature relationship (R^2) from eight chambers from continuous measurements (ALL) and from measurements at individual hours. Dashed line means mean R^2 estimated from all data of continuous measurement.*



5: *Percentage differences between the seasonal amounts of released carbon calculated from continuously measured CO_2 efflux and from modeled CO_2 efflux using parameters Q_{10} and R_{10} obtained from individual time data sub-sets* modeled using parameters calculated from the whole data set.

Observed seasonal course of measured CO_2 efflux and CO_2 efflux modeled using parameters calculated from the whole data set, the model tended to underestimate CO_2 efflux during periods without rain, when the soil was dry, and to overestimate CO_2 efflux when rain events occurred and increased soil moisture.

The difference of the released carbon amount based on individual data sets from that based on continuously measured data reached up to 6.9%. A significant difference was found for the 0 h, 4 h, 8 h and 20 h data sub-sets. Generally, the models based on the measurements at 0h, 4h and 8h overestimated seasonal carbon flux, and models based on the measurements at 12 h, 16 h and 20 h underestimated seasonal carbon flux. The lowest difference (0.4%) was found for 20 h sub-sample (Fig. 5).

DISCUSSION

To model soil CO_2 efflux we used a relationship between soil CO_2 efflux and soil temperature. This relationship is often described by a simple exponential function (equation 1). A temperature sensitivity parameter (Q_{10}) can be determined from this relationship (Lloyd and Taylor, 1994). The parameter Q_{10} is commonly used for normalization of measured CO_2 efflux for a reference temperature (equation 3) to investigate other factors than temperature (Jassal *et al.*, 2008; Noormets *et al.*, 2008) or in carbon models to simulate soil or ecosystem respiration (equation 4) (Khomik *et al.*, 2006; Wang *et al.*, 2010).

The average value of Q_{10} estimated for the whole season for each from eight chambers was 2.04 (± 0.24). The parameter Q_{10} was estimated for temperature measured at a depth of 1.5 cm. Similar values were obtained also in other studies (Borken *et al.*, 2002; Saiz *et al.*, 2007) for spruce forest soil. The correct estimation of Q_{10} depends among others on the depth of temperature measurements. The value of Q_{10} tends to increase with the depth (Khomik *et al.*, 2006; Pavelka *et al.*, 2007; Graf *et al.*, 2008) as the amplitude of temperature dynamics in deeper soil layers decreases.

Estimated cumulative seasonal (May to October) carbon efflux from the forest soil based on continuous measurements was 6.3 t C ha^{-1}, which is comparable to other studies on spruce forests (Borken *et al.*, 2002; Bergeron *et al.*, 2009; Gaumont-Guay *et al.*, 2009). There was no significant difference (< 0.3 %) between seasonal flux calculated from measured CO_2 efflux and CO_2 efflux modeled using parameters calculated from the whole data set. The model, however, tended to overestimate CO_2 efflux when the soil was dry and CO_2 efflux was limited by water supply. On the other hand, the model tended to underestimate CO_2 efflux when rain increased soil moisture. These inaccuracies can be caused by dependency of Q_{10} on soil moisture and temperature (Qi *et al.*, 2002; Janssens and Pilegaard, 2003; Davidson *et al.*, 2007). When the soil moisture is too low, relationship of CO_2 efflux and temperature can be even decoupled (Yuste *et al.*, 2003). Estimation of one value of Q_{10} for the whole season can hide these effects.

The seasonal C flux obtained from data sub-sets differed up to 6.9%. The relatively small difference is due to the fact that the soil temperature was measured at optimal depth determined on the base of the methodology of Pavelka *et al.* (2007). In case that soil temperature was measured deeper than is the optimal depth, higher values of Q_{10} would be produced and consequently higher differences between models based on continuous measurement and measurements at individual hours would be obtained. The highest difference was for 4 h sub-sample the lowest for 20 h. Generally measurements at 0 h, 4 h and 8 h overestimated seasonal the carbon flux, and measurements at 12 h, 16 h and 20 h underestimated seasonal carbon flux.

Estimation of annual/seasonal cumulative carbon flux was in several studies estimated on the base of manual measurements with the period from days to a month (e.g. Davidson *et al.*, 1998; Epron *et al.*, 2004; Khomik *et al.*, 2006). The measured CO_2 flux was consequently extrapolated to 24 h and then interpolated between days when the measurements were performed (Parkin and Kaspar, 2004; Savage *et al.*, 2003, 2008). This method can inaccurately estimate carbon flux in dependence on the time of day at which the measurements were taken as CO_2 efflux changes during day (Flanagan and Johnson, 2005). For example Parkin and Kaspar (2003) found up to 40% overestimation of daily CO_2 flux when measurements were performed in the early afternoon. Unbiased daily CO_2 efflux occurred around 8:30 a.m. and 7:00 p.m. The authors also observed a decrease in inaccuracy of daily CO_2 efflux estimation when they corrected measured CO_2 efflux for daily average temperature using parameter Q_{10}.

This sampling strategy with several days between measurements can also miss important changes in soil moisture such as e.g. fast increase caused by rainfalls. If the intervals between sampling days are too large, then the CO_2 flux response to rainfall may be inadequately characterized. Potential problems include underestimation of cumulative CO_2 flux if significant rainfall events are missed (Savage *et al.*, 2008), or overestimation of cumulative CO_2 flux if flux measurements performed following rainfall events are weighted too heavily because an un representative number of dry periods are included in the data set (Parkin and Kaspar, 2004). Savage *et al.* (2008) observed up to 23% difference between estimates based on continuous automated measurements and manual measurements carried out each week between 9 am and 3 pm.

Khomik *et al.* (2006) estimated annual respiration of boreal forest soil on the base of continuously measured temperature and manually measured CO_2

efflux measured once a month. This approach is not, however, suitable for sites with highly variable soil moisture, where water limited periods occur, and the model is not sensitive to tree physiology. (eg. variability in photosynthesis or root activity (Högberg *et al.*, 2001; Misson *et al.*, 2006).

In our study, estimation of the seasonal cumulative carbon flux on the base of continuously measured temperature and parameters Q_{10} and R_{10} seems to be sufficient. Although, the higher effect on the estimation has the intervals between measurements, the time of day at which the measurements are taken should not be neglected. For our studied ecosystem the best time for measurements and estimation of carbon flux was 8:00 pm (20 h) when parameters Q_{10} and R_{10} and especially average soil temperature were close to those calculated from continuous measurements. However, the most suitable time will be different for different ecosystems. Therefore, we recommend using an appropriate measurement design which eliminates measurement on particular position at the same time of day to minimize bias due to influence of time of day on relationship of temperature and soil CO_2 efflux.

SUMMARY

The aim of the study was to investigate the effect of the time of the day when manual measurements of soil CO_2 efflux are performed on the relationship of temperature and soil and on estimates of sums of released carbon from the soil during the growing season. Measurements were carried out in Norway spruce forest at the Ecological Experimental Study Site (EESS) Bily Kriz situated in Moravian-Silesian Beskydy Mts. Measurements of soil CO_2 efflux and soil temperature were taken during the growing season (May–October) 2009 using automatic modified closed gasometrical (non-steady-state through-flow) system SAMTOC. The continuous measurements were subsampled into six sub-sets of data in accordance to the time of the day when the measurements were taken – 0 h, 4 h, 8 h, 12 h, 16 h and 20 h. Parameters Q_{10} (the proportional change in CO_2 efflux caused by 10 °C increase in temperature) and R_{10} (soil CO_2 efflux normalized for temperature of 10 °C) were calculated from continuous measurements and from the sub-sets. These parameters and data from continuous measurements soil temperature were used to draw up a model for estimation of seasonal carbon flux from the soil. The model was based on an exponential relationship of CO_2 efflux and temperature.

Mean Q_{10} from eight chambers obtained from continuous measurement was 2.04. Values of Q_{10} calculated for 0 h, 4 h, 8 h and 20 h had a significantly higher value, and Q_{10} calculated for 12 h and 16 h was significantly lower. Average seasonal R_{10} of eight chambers was 3.63 $\mu molCO_2\ m^{-2}s^{-1}$. Values for 0 h, 4 h and 8 h were slightly above the average, and values for 12 h, 16 h and 20 h were slightly below the average. There was, however, no significant difference R_{10} calculated from all data set and from any of data sub-sets. The average total amount of released carbon from eight chambers calculated directly from continuously measured values was 6.29 t ha^{-1}. The difference of the released carbon amount based on individual data sets from that based on continuously measured data reached up to 6.9%. A significant difference was found for the 0 h, 4 h, 8 h and 16 h data sub-sets. Generally, the models based on the measurements at 0 h, 4 h and 8 h overestimated seasonal carbon flux, and models based on the measurements at 12 h, 16 h and 20 h underestimated seasonal carbon flux. The lowest difference (–0,4%) was found for 20 h sub-sample.

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