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Discussions

Interactive comment on "Seasonality in a boreal forest ecosystem affects the use of soil temperature and moisture as predictors of soil CO_2 efflux" *by* S. M. Niinistö et al.

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Reply to Referees 1 and 2 on question on soil temperature

This reply together with separate replies to Referees 1 and 2 earlier, will form our final reply as authors.

We fully agree with Referees that an appropriate depth for measuring soil temperature is not constant in all seasons and conditions, and that monitoring of soil temperatures at different depths to cover the CO2 producing soil profile is useful. We also agree that measuring temperature of the surface layer, i.e. organic layer influenced the difference in the perceived levels of soil CO2 efflux at a given temperature between the early and

late season. In the new version of the manuscript, we will discuss this thoroughly. In the following, we reply to Referees' questions about temperature and discuss the question of temperature in detail. Corresponding modifications that we plan to carry out in the new version of the manuscript are included. We are ready to shorten this discussion in the manuscript later if necessary.

This study cannot give a thorough answer to how to take into account a temperature gradient within the soil profile, and how much the depth at which the temperature was measured affected apparent seasonality of temperature response that we observed. A reverse hysteresis with temperatures measured deeper in soil column is an interesting aspect of this question. All in all, the questions raised by the Referees are very interesting. It was good that the Referees suggested that we look into this question more carefully than we had in the earlier version of the manuscript that had only a short reference to this question in Discussion.

I. Temperature measured in the organic layer (horizons Oe+Oa)

At the beginning of the study, we chose to measure soil temperature with a hand-held probe inserted into organic humus layer because the surface (organic) layer had been identified as the layer in forest soils in which most of CO2 was produced and where a large proportion of fine root biomass was found (e.g. Bowden et al. 1993). The temperature of surface layer had also been successfully used in modelling of temperature response in a previous study carried out in our research group (Pajari 1995, at Mekrijärvi site).

We intended to measure temperature of the organic layer and because the organic humus layer (horizons Oe + Oa) was quite thin, 2.5 cm in average at our study site, temperature was thus measured at quite a shallow depth, at 1-2 cm in the organic humus layer, close to the surface of mineral soil. The depth of the litter layer (horizon Oi) consisting of dead moss and other litter that lay on top of the organic humus layer, was in average 5.7 cm thus we measured the temperature at an average depth of 7 cm from the top of the litter layer.

In more recent literature, several studies have similarly found that temperatures close to surface were better predictors of soil CO2 efflux in boreal forests than temperatures deeper in soil (e.g. Gulledge and Schimel 2000, Bond-Lamberty et al. 2004). Surface layer temperature at depth of 2 cm (Bond-Lamberty et al. 2004) and at 5cm from the forest floor surface (Gulledge and Schimel 2000) had been compared with temperature measured at 10 cm. On the contrary, Schlentner and Van Cleve (1985) found that temperature at 15 cm depth was a better predictor of soil CO2 efflux than the temperature at soil surface, at organic-mineral soil interface or at 30 or 60-cm depth in (cold) Alaskan forests. It is, however, sometimes difficult to know when reading research articles in which layer soil temperature has been measured (i.e. organic or mineral) and where the depth has been measured from (we are not referring the studies quoted above).

More recently, Reichstein et al. (2005) and Davidson et al. (2006) have emphasized the contribution of the organic (surface) layer to the total soil CO2 efflux and to its seasonal and interannual variation. This is supported by our finding on the good correlation ($p<0.02$, $n=19$) between a two-month average of soil CO2 efflux and root mass (fine roots, living roots and all roots) in the organic layer of collars on Plots 2 and 3 at the end of our experiment at the end of October 1999 (unpublished results to be included in our manuscript in preparation on spatial variability of soil CO2 efflux at our site). There were no apparent correlation between soil CO2 efflux and fine or living root mass in the upper 5 cm of mineral soil, but a weak correlation between efflux and all roots ($p=0.06$, $n=19$).

In Finnish conditions, Kähkönen et al. (2002) emphasized that observed mineralization of carbon mainly located in the humus layer in all seasons, both during the warm summer of 1997 as well as during the rainy and cool summer of 1998. Similarly, Pumpanen et al. (2003b) estimated that most of the soil CO2 emissions originate from the organic humus layer in Finnish boreal forests throughout the year.

Using actual soil temperatures and Q10's previously measured at the same site Kähkönen et al (2002) estimated that in May-October humus layer contributed 66% (1997) and 75%(1998) of the total sum of mineralized carbon for the soil core/profile of some 20 cm. During the winter period (November-April), however, a larger part originated from the illuvial layer too, so that the share of humus layer was about 60% of the total. Although this study of carbon mineralization covered only the upper 20 cm of the soil (upper 30 cm are considered usually the rooting zone), it emphasized that in boreal forests, interestingly, the humus layer is a very important source of soil CO2 efflux not only because of abundance of roots (that were excluded in the study by Kähkönen et al. (2002)) in that layer but also because of abundance of detritus and consequent microbial activity despite the fact that the humus layer in question is not necessarily thicker than a few centimeters.

We will add some of this discussion to Discussion (quoted later in this reply). We will also briefly clarify in Methods why we chose to measure temperature in the organic layer.

II. Correlation between temperatures measured by the weather station and those measured next to each collar

Starting in 1998 we had a weather station continuously running at the site, thus a possibility to monitor soil temperature continuously. In 1997, the weather station was not yet fully operating. The weather station recorded soil temperatures at 10 min intervals. We chose an equivalent depth to measure the temperature of the organic layer so that we would have continuous measurement of soil temperature to make use in estimation of annual total soil CO2 efflux. We used this depth then in modelling because we could thus use the soil CO2 efflux data from 1997 that lacked continuous soil temperature measurements at the site. An additional advantage was that we could fill any possible gaps (due to technical problems such as power cuts and thunderstorm damage) in temperature data derived from the weather station with a regression function using the temperature data collected with the hand-held probe next to each collar at the time of soil CO_2 efflux measurements. In all, there were very few gaps in temperature data from the weather station to be filled with the help of temperature manually measured next to collars on plots.

Readings from hand-held probe tended to have a slightly higher maximum temperature each year but differences between readings of the organic layer temperature from the hand-held probe and the weather station were small and correlation strong. Higher maxima most likely indicate that readings taken with a hand-held probe were influenced more by air temperature because the probe pushed vertically into porous uppermost organic layer kept was probably in a closer contact with air and its temperature. However, there was no indication that soil temperature measured adjacent to each measurement collar was a better predictor of variation in soil CO_2 efflux than soil temperature measured in a permanent location next to the weather station. Thus, soil temperature from the weather station was used in the models considered here except with any model containing observations from 1997 when weather station was not yet fully operating.

Temperature of the organic layer measured by the weather station close to Plot 1 correlated strongly with temperatures measured in the organic layer next to each collar for soil CO_2 efflux measurements on Plots 1-3: On occasions of soil CO_2 efflux measurements in 1998–1999, Spearman's rho was 0.97 and Pearson correlation 0.97 ($p<0.001$, $n=394$) between plot averages of temperature of the organic layer and the temperature of the same layer measured by the weather station. I.e. variation in soil temperature measured by the weather station explained 94% of the temporal variation of soil temperature averaged for each plot for soil CO_2 efflux measurements ($R^2=0.94$ of a linear regression analysis, $p<0.001$, $n=394$). Because of the good correlation between plot averages of organic layer temperatures and temperatures recorded at the same time by the weather station, we think that temperatures from the weather station were adequate to be used in modelling temporal variation of soil CO_2 efflux in this study.

To "Methods" (p.7, r.3), we will add a corresponding description of correlation between

temperatures of the organic layer measured next to each collar (or more precisely: plot averages of them) and those measured by the weather station at equivalent depth close to Plot 1. We will also add horizon definitions of Oe+Oa and Oi to the description of soil at the site on p.5, r.17-18.

Correlation between temperatures on Plots 1-3 is more difficult to estimate because plots were measured at least one hour apart (i.e. interval between a point of time when one had measured a half of the collars of one plot and the point of time when one had measured a half of the collars of the next plot) and temperatures of the organic layer varied easily by at least 1C from one hour to another in our climate (but in a consistant manner usually: increasing from the morning). For multivariable modeling, each plot average of soil CO_2 efflux was paired with soil temperature recorded by the weather station at the time point when a half of the collars was measured, or at least within 10 min from that time point. In modelling, these "pairs" of soil CO_2 efflux and soil temperature from all three plots were combined to have more observations and to cover different conditions. Thus, spatial heterogeneity of temperature of the organic layer between plots (i.e. between plot averages) was not included in this manuscript on temporal variation of soil CO_2 efflux. Variation in soil CO_2 efflux not explained by the models included variation between plots in general, as discussed in our earlier reply to Referee 1.

III. Difference between warming and cooling soil profiles and appropriate depth to measure soil temperature

We apologize for a hasty original reply to Referee 1 on temperatures measured deeper in soil than in the organic layer, i.e. close to the surface. We had made some previous analyses on partial data early on, and replied according to them. Now, we looked into the availability of the soil temperature data more carefully. A profile of soil temperatures was measured at four depths and at two locations by the weather station starting in June 1998. Before that our "old" weather station measured soil temperature at two depths.

We found out that we could combine temperature observations measured at 7 cm depth in mineral soil by an "old" weather station at the site in 1998 and temperature observations measured at 5 and 10 cm depth in mineral soil by the Vaisala weather station starting in June 1998, i.e. to have complete data series of mineral soil temperature at 7 cm depth for the snow-free periods in 1998 and 1999. We had originally thought that there were too many gaps in the data from the old weather station for it to be useful but it turns out that gaps were in the data from the other soil temperature probe, not from the one at 7 cm in mineral soil.

The 1998 measurements of temperature at 7 cm were used as they were in auxiliary analyses to test the effect of the measurement depth of soil temperature. There were no actual temperature measurements made at the exact depth of 7 cm in 1999, but corresponding temperatures were predicted based on a regression model built on the very strong correlation between mineral soil temperature at 7 cm and the average of mineral soil temperatures at 5 and 10 cm depth (Pearson correlation 0.998, $p<0.001$), with the organic layer temperature as an auxiliary predictor ($R2$ of the regression model=0.999, $p<0.001$, n=111). Because the temperature range in 1998 available for this regression model did not include temperatures below 4C, the low averages of temperatures at 5 and 10 cm were used as they were for early May in 1999.

Unfortunately, there were gaps in the data of mineral soil temperatures in July and September 2000, which made evaluation of any analysis/models based on mineral soil temperatures difficult, especially for autumn (September and October). As the evaluation data from Huhus in 2000 had very few observations for late autumn (i.e. October), complementary evaluation measurements from the Mekrijärvi site the same year had been essential. Regrettably, there were no corresponding data available on mineral soil temperatures for Mekrijärvi in 2000.

We will add to Methods (2.2. Measurement of soil $CO2$ efflux and temperature) p.7, r.3: "Temperatures of mineral soil were recorded by the weather station starting in 1998, with the most comprehensive series for temperature at 7 cm depth in mineral soil, i.e.

at 9 cm from the surface of organic humus layer or at 15 cm from the top of litter layer. There were some gaps in data in July and September 2000."

Although we could not thoroughly evaluate modelling results with temperatures at 7 cm by comparing them to the independent evaluation data from the year 2000, we will discuss the question of how the depth in which soil temperature affected our results presented in the manuscript.

We will thus add to Discussion (4.2 Seasonality of temperature response), p. 18, l.20 the following paragraphs:

"A similar hysteresis-type of pattern in the temperature response of the soil CO2 efflux has been observed in other forest studies with single-depth measurements of soil temperature during a snow-free period (e.g. Morén and Lindroth, 2000; Drewitt et al., 2002). A hysteresis of temperature response was also found in laboratory incubations of forest soils during warming and cooling treatments (Reichstein et al., 2005). Although most of the soil CO2 emissions have been estimated to originate from the organic humus layer in Finnish boreal forests throughout the year (Pumpanen et al., 2003b), the depth from which soil temperature is measured can cause seasonal differences in the perceived level of soil CO2 efflux at a given temperature (e.g. Drewitt et al., 2002). In addition to a possible discrepancy between the soil layer from which most of the CO2 originates and the soil layer in which temperature is measured, momentary temperatures in the surface soil may not reflect the conditions in which soil CO2 emissions have been produced and transported during a period preceding the measurements." (p.18, l. 20-23, as they were:) The greatest overestimations with temperature models in this study were thus often associated with cool conditions in May and October with afternoon surface temperatures that were noticeably higher than the morning temperatures.

to be added next: " In this study, a lack of appropriate temperature data prevented a thorough comparison and evaluation of models based on temperatures at different soil depths. The most comprehensive series of temperatures of the deeper soil layers was obtainable for the depth of 7cm in the mineral soil in 1998–2000, with some gaps in 2000. A similar data series was not available for the evaluation measurements made in Mekrijärvi. The fact that the temperature had been measured in the organic layer, i.e. close to surface, contributed for the most part to the observed greater level of CO2 efflux at a given temperature in October compared to May. Auxiliary analyses with mineral soil temperatures at 7 cm produced an opposite pattern. Similar reverse hystereses of the temperature response were observed for the surface and central temperatures of forest soil columns during warming and cooling treatments in laboratory (Reichstein et al., 2005). Yet in our study, the temperature of the organic layer was a better predictor of soil CO2 efflux in May than the temperature at 7 cm depth in mineral soil was. In October, variation in these two temperatures explained approximately an equal proportion of the variation in soil CO2 efflux. In modelling temperature response with multiple soil temperatures, temperature of the organic layer was the only predictor selected in a step-wise procedure of a regression analysis for May. For October, an inclusion of temperature at 7 cm in mineral soil as an auxiliary predictor did not notably improve the model fit although the inclusion was statistically supported (p=0.03 for an increase of 0.02 in R2). Inclusion did not change the difference in the level of CO2 efflux at a given temperature of the organic layer between May and October (as in Fig. 5b).

The most appropriate depth to measure soil temperature is therefore not necessarily constant, as the soil CO2 efflux is influenced by the temperature of the soil column that should be taken into account as a whole (e.g. Morén and Lindroth, 2000). On the other hand, a contribution of the organic layer to soil CO2 efflux and its seasonal and annual variation have been found to be significant in many forest studies. Contribution has been estimated to be over 40% of the total annual soil CO2 efflux (Davidson et al. 2006b) and two thirds of the mineralized carbon of soil column samples (Kähkönen et al., 2002; Reichstein et al., 2005). However, combining temperatures at different depths, or a multi-layer approach such as applied by Pumpanen et al. (2003b), Re-

ichstein et al. (2005) and Davidson et al. (2006b), could be ideal, especially for a season-specific modelling. In continuous, multi-year modelling in a temperate forest, the partitioning of CO2 production by horizon did not, however, improve the overall prediction of soil CO2 efflux based on temperature functions (Davidson et al., 2006b).

It was, however, encouraging to find that according to our auxiliary analysis, the quadratic surface soil temperature and degree days model explained as much of the variation in soil CO2 efflux in 1998–1999 as did a model with a combination of the temperatures of the organic layer and that at 7 cm in mineral soil as predictors. On the other hand, models that included temperature measured in mineral soil could not be comprehensively evaluated with independent soil CO2 efflux data because of scarcity of the soil temperature data in 2000. Yet, our auxiliary analyses indicated that soil CO2 efflux was underestimated during the peak efflux in July–August also when the temperatures in the organic and topmost mineral soil layer were both included as predictors. The model with the temperatures measured at the two depths overestimated the soil CO2 emissions in spring and early summer i.e. in May and June, but its performance in autumn could not be tested against independent soil CO2 efflux data because of the lack of appropriate soil temperature data."

We will also add to Discussion (4.4 Multivariable approach) on p.21, r.17: "Although temperature of the organic humus layer was found to be a good predictor of soil CO2 efflux in this study, use of temperature from several depths could further improve the ability of models to predict CO2 efflux, especially during warming and cooling periods (Reichstein et al. 2005). Taking into account deeper soil layers would especially be advisable when soil CO2 emissions are modelled in similar boreal forests during late autumn or winter and during severe droughts (Pumpanen et al. 2003b)."

We have also modified the last sentence of the abstract to read: "Although soil temperature was a good overall predictor of soil CO2 efflux, possibly partly due to its proxy-like quality for covarying processes, consistent underestimation by the predictive models for the peak season corroborates recent findings concerning the importance of seasonal changes in carbon inputs to processes producing CO_2 in soil."

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IV. Some additional modifications to the manuscript (not related to the temperature question) as replies to Referees (those mentioned in the earlier replies to referees, Reply to Referee 1 and Reply to Referee 2, are not repeated here):

We will add in Methods on p. 6, r. 2: "A set of five new collar locations were chosen to replace five old locations on plots in 1998 to minimize effects of possible wear on measurement locations. No signs of wear was detected when the new and old locations were compared as measurements were continued on "rejected" old collar locations once a measuring day."

We will describe the spatial set-up of Plots and the weather station in more detail in Methods (p.5, l.20). Location of soil moisture measurements will be also clarified in Methods.

We will add to Methods (p. 8, l.6) and rephrase the chapter title accordingly to "2.3 Soil moisture and auxiliary measurements": "Needle litter was collected in netted buckets with a surface area of 0.15 m^2 at eight locations in the study area monthly or bimonthly, dried in the oven at 105°C for 24 h and weighted. In addition, the diameter growth of six pine trees (representing median of the diameter distribution of the study area) was monitored with continuously recording bands around tree trunks starting in 1999."

We will also add to Discussion (p.22, r.12): "Inclusion of additional, seasonally changing variables such as needle litter input in our models proved to be difficult partly because of different intensity of the measurements. Also, time lags after which these variables could be considered to influence soil CO_2 efflux, were difficult to define."

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