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# Seasonal and inter-annual variability of soil respiration at Skyttorp, a Swedish boreal forest

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Master degree thesis in

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## Abstract

The ecosystem carbon balance is the net result of $CO_2$ uptake by photosynthesis and $CO_2$ emission through ecosystem respiration and soil respiration is a major part of ecosystem respiration. Soil $CO_2$ fluxes were continuously measured from August 2005 to November 2008 with an automatic chamber system at a boreal forest site in central Sweden to investigate the annual and seasonal variations of soil respiration ($R_s$) and its dependence on soil temperature and soil moisture. The soil temperature varied from -2 ℃ to 21 ℃ at 3 cm depth, and top 5-cm soil water content was in the range of 5 vol% to 40 vol%. There were no large variations of soil temperature among all the chambers on the annual time scale. The $CO_2$ fluxes in all chambers but one varied from 0 to 12 μmol $m^{-2}$ $s^{-1}$ in summer and from 0 to 5 μmol $m^{-2}$ $s^{-1}$ during winter. The fluxes in one chamber had larger fluctuations with the range of -4 to 24 μmol $m^{-2}$ $s^{-1}$ in summer time because of the influences of ground vegetation in the chamber. The variation of $CO_2$ fluxes tightly followed the variation of soil temperature on seasonal and inter-annual time scale. The temperature sensitivity $Q_{10}$ calculated on the annual time scale varied from 3.07 to 3.45 among 5 chambers. A positive correlation existed between $Q_{10}$ and soil water content when soil water content was in the range of 15 vol% to 30 vol%, and $Q_{10}$ was decreasing with increasing temperature. The $R_{10}$ (the soil respiration rate at 10 ℃) regression model provided good estimated $R_s$ in both daytime and nighttime. The photosynthesis rate of ground vegetation in the chamber was around 5 μmol $m^{-2}$ $s^{-1}$ by comparing the estimated $CO_2$ fluxes and measured $CO_2$ fluxes in the daytime. A decline of $R_s$ rate was found in one chamber when soil water content was higher than 33 vol% during growing season of 2008. The variation of $CO_2$ fluxes in the growing season was much higher than that of off season under the same soil moisture condition. The seasonal and inter-annual variability of soil $CO_2$ fluxes were mainly explained by 3-cm soil temperature variation at Skyttorp site.



**Key Words:**

$CO_2$ flux; Chamber system; Soil respiration; Skyttorp;

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# 1. Introduction

The boreal forest and associated peat-rich soils store nearly half of the global carbon because of the massive surface area and large soil C densities (Dunn et al, 2009; Pare et al., 2011). In boreal forest ecosystems, the highly developed organic layer is more sensitive to changes in temperature and soil moisture compared with the mineral layer that underlies it (Khomik et al., 2006). Projections of climate models show an increase in both temperature and precipitation at high latitude, which accordingly will change the carbon balance of boreal ecosystems through the influences of warmer climate on primary production, autotrophic and heterotrophic respiration (IPCC, 2007; Meehl et al., 2007; Savage et al., 2009, Wu et al., 2011). Soil respiration ($R_s$), a combination of root respiration ($R_{root}$) and microbial respiration ($R_{micro}$), is a major component of carbon fluxes from terrestrial biosphere to the atmosphere with contributing 30-80% of annual total ecosystem respiration in forests (Davidson et al.,2006b). In other words, the way of $R_s$ responding to the climate change is likely to impose significant impacts on the capacity of forest as a carbon sink and the atmospheric $CO_2$ concentration in the future (Gaumont-Guay et al., 2006). Since $R_s$ is an important component of global carbon cycle, it is necessary to fully understand the physical and biochemical processes involved in $R_s$ in order to accurately quantify carbon emissions from soil on different temporal and spatial scales and to evaluate effects of environmental change on soil carbon cycling.

## 1.1 Background

Soil is a complicated heterogeneous medium comprising diverse types of organic and mineral particles, aggregates, and numerous microbial organisms (Fang & Moncrieff, 1999). It is difficult to accurately quantify soil respiration and predict its response to climate change due to the complex belowground biological and physical processes of respiration and their interaction with the environment (Gaumont-Guay et al., 2006). In the past decades, many studies attempted to attribute the $CO_2$ sources into different components to investigate the relationships between the environmental controlling factors and $CO_2$ emission (Moyano et al., 2008). There are two main biogenic sources of $CO_2$ fluxes: respiration of root and rhizosphere microorganisms (autotrophic respiration); microbial decomposition of soil organic matter (SOM) and both above and below ground litter (heterotrophic respiration) (Hanson et al., 2000; Vincent et al., 2006). Boreal forest has a larger fraction of soil $CO_2$ fluxes that derive from SOM decomposition as compared with temperate and tropical forests (Subke et al., 2006). Gaseous diffusion and liquid phase dispersion were the main mechanisms of $CO_2$ vertical movements (Fang & Moncrieff, 1999). In past studies, temperature and soil moisture are presented as the dominant controllers to soil respiration rate, where temperature has a more substantial influence (Davidson et al., 1998; Gaumont-Guay et al., 2006; Vincent et al., 2006). In addition, substrate availability is an important factor for $CO_2$ production (Davidson et al., 2006a; Niinistö et al, 2011). Root and microbial biomass, soil acidity and texture also affect the soil $CO_2$ flux (Raich and Potter 1995; Raich and Schlesinger, 1992; Ryan et al., 1996). All these factors generally account for 80% of temporal variability of soil $CO_2$ flux (Longdoz et al., 2000).

A number of studies have examined the relationship between $R_s$ and soil temperature on different time scales. The production of soil $CO_2$ comprises chemical and biochemical reactions, and these reactions are temperature-dependent, so the temperature controls $R_s$ rate through its influence on enzyme kinetics (Davidson and Janssens, 2006). Different functions, such as power, exponential and sigmoidal et al, were applied to present the correlation between soil temperature and $R_s$ rate in the past studies (For details, see Lloyd & Taylor, 1994; Webster et al., 2009). For each study case, ecosystem modelers need to find the suitable function for the specific site. $Q_{10}$, the increase of soil respiration rate per 10 ℃ increase in soil temperature (Wang et al., 2010), has been commonly used in many studies to indicate the temperature sensitivity of $R_s$. The reported $Q_{10}$ values are roughly around 2-2.5, and for the cool temperate and boreal regions $Q_{10}$ is in the range of 4 to 6 on annual time scale (Davidson et al., 1998; Khomik et al., 2006). In the study of Chen and his colleagues (2010), $Q_{10}$ showed a strong seasonal and annual variation pattern, and its value decreased with soil temperature. It is worth to mention that if $Q_{10}$ is applied in the prediction of soil $CO_2$ emission without considering other environmental factors, such as soil moisture, it would possibly cause a significant error (Davidson et al., 1998).

Although soil temperature variations account for the majority of variations of $CO_2$ fluxes on seasonal and diurnal scale, soil moisture and other factors also partly control the $CO_2$ flux variation. Water content is considered as a key factor besides soil temperature in most studies (Davidson et al., 1998; Gaumont-Guay et al., 2006; Qi et al., 2002; Vincent et al., 2006). Low soil water content could restrain $R_s$ due to a reduced rate in microbial decomposition, because low water content can affect the diffusion of enzymes and substrates and reduce the mobility of micro-organisms (Sowerby et al., 2008). While high soil water content also can cause an inhibition of $R_s$ related to the transport and storage of $CO_2$ and/or oxygen ($O_2$) in the soil (Gaumont-Guay et al., 2006). Field capacity is generally the optimum soil moisture condition for respiration (Savage & Davidson, 2001). Some studies have shown that drought conditions could reduce soil respiration, but the magnitude of drought-induced reduction is still uncertain (Davidson et al., 1998; Martin & Bolstad, 2005; Savage & Davidson, 2001). Soil temperature and soil water content has a negative correlation, and $Q_{10}$ is also affected by soil water content (Davidson et al., 1998). Consequently, it is difficult to detect the independent effect of soil moisture on $R_s$. Soil water deficit could significantly limit the positive relationship between $R_s$ and soil temperature, which was proved by presenting a decreasing $Q_{10}$ with declining matric potential ($\psi$) (Conant et al., 2004; Jassal et al., 2008). The relationship between $R_s$ and soil moisture is demonstrated with quadratic, lognormal or superimposed Gompertz functions and soil temperature is incorporated in some of the functions. These models are based on the rate of microbial response to changes in moisture and a range of moisture conditions for optimum respiration (Webster et al., 2009).

Lately, the relationship between soil $CO_2$ flux and photosynthetic activity has started to attract attention from ecologists. The environmental factor - photosynthetically active radiation (PAR) connects to the photosynthetic activities for both trees and ground vegetation. Carbohydrates are assimilated in the leaves by photosynthetic activities and then are transported through phloem down to the roots for root respiration or releasing to soil (Kuzyakov and Gavrichkova,

2010). There is a time lag between photosynthesis and soil $CO_2$ emission due to the transport of assimilated carbon from leaves to root, and the effusion of exudates from root cells to the rhizosphere (Davidson and Holbrook, 2009; Kuzyakov and Gavrichkova, 2010). The range of time lag also depends on other factors, such as species of plants, growth stages of plants, microenvironment for the roots, the microbial community and so on. Since PAR above canopy usually correlates with soil temperature on a diurnal and monthly scale, its individual effect on soil respiration is difficult to evaluate (Moyano et al., 2008). There is a study reporting the coupling photosynthesis activity to soil $CO_2$ emissions through a large-scale tree-girdling experiment, it showed that the soil respiration decreased by 27% within 5 days (Högberg et al., 2001). Analysis of $^{13}CO_2$ in soil respiration in a mixed coniferous boreal forest stand revealed that 1-4 days are needed for C from canopy photosynthesis of trees to become available for root and rhizosphere respiration (Ekblad and Högberg, 2001).

Accurate measurement of the soil $CO_2$ flux is difficult due to the heterogeneity of soil itself, and presence of vegetation on the ground increases this heterogeneity (Lankreijer et al., 2009). The closed-dynamic-chamber system (CDCS) is the most direct and widely used approach of measuring $CO_2$ flux from soil surface with relatively good accuracy, though it contains several sources of errors due to chamber artifacts (volume of headspace, chamber height, air flow rate, chamber pressure, sampling time), weather condition (snow), and spatial heterogeneity (soil drainage class, vegetation type) (Davidson et al., 2002; Kutzbach et al., 2007; Lankreijer et al., 2009).

## 1.2 Aim and objectives

There are quite a few studies about net primary production and respiration for a whole boreal forest ecosystem based on the eddy-covariance technique or modeling (Lindroth et al., 2008; Tagesson et al., 2009). Some research of forest soil respiration based on chamber system has been conducted in Norunda, which is located in central Sweden (Widen & Majdi, 2001; Lankreijer et al., 2009). However, currently there is no specific study of soil respiration at Skyttorp, which is around 20 km from Norunda. Thus the investigation of soil $CO_2$ fluxes at Skyttorp is fairly meaningful, since $R_s$ varies both temporally and spatially on both of plot and landscape level, and changes vertically with soil depth as well (Maier et al., 2011).

The aim of this study is to investigate soil respiration measured with chamber techniques at the Skyttorp forest site from 2005 to 2008. The objectives of this study are:

1) To investigate annual/seasonal variations of soil $CO_2$ flux and its dependence on environment factors (soil temperature, soil moisture, and PAR).

2) To calculate annual and growing-season $Q_{10}$ with exponential function to determine the temperature sensitivity of $R_s$ and the correlations between $Q_{10}$ and environmental factors.

3) To analyze night time soil respiration to exclude the influences of photosynthesis to daytime

$CO_2$ fluxes in the closed transparent chambers and to extend the night $R_s$ to diurnal $R_s$ through an exponential model.

4) To examine the relationship of soil $CO_2$ flux with soil moisture through quadratic and hyperbolic model.

5) To examine the possible time lag between peak PAR above canopy and peak soil $CO_2$ flux.

# 2. Materials and Methods

## 2.1 Study site

The study site is located at Skyttorp (60°7'N, 17°5'E), about 20 km east of Norunda, Sweden (Olofsson et al., 2007). Norunda (60°5'N, 17°29'E, alt. 45m) is a long-term field site with a 106 meters central tower in the forest for carrying on research activities (Jansson et al, 1999). Norunda and Skyttorp have hemiboreal climate with annual mean air temperature of 5.5°C and an annual sum of precipitation of 527 mm. Skyttorp is a 40-year-old stand boreal forest, the tree density is 1023 per hectare; the dominating species are Pinus sylvestris and Picea abies; the soil type is sandy podzolic glacial till; the forest floor is mainly covered with dwarf shrubs (*Vaccinum myrtillus; Vaccinium citis-idaea*), grasses and mosses (Lindroth et al., 2008). The growing season generally extends from mid-April until the second half of October (Widen & Majdi, 2001).

## 2.2 Soil respiration measurements

Soil respiration was measured by an automatic chamber system from August 2005 to November 2008. The chamber system contained of six transparent chambers, which were placed on steel collars installed in the soil and all the chambers were not moved during whole time of measurement. Six chambers were connected to a central box with an infrared gas analyzer (IRGA LI-820, LI-COR lnc, Lincoln, NE, USA), valves, a pump and a data logger (CR10X, Campbell Scientific, Logan, UT, USA). The air was circulated through a valve system between each chamber and the gas analyzer. Each chamber measurement cycle was five minutes. The lid of chamber was open with activated fan and air circulating between chamber and gas analyzer in the first two minutes. The lid was then closed for three minutes and $CO_2$ concentration was recorded for 6 or 18 times during the closure time. After sampling, the lid was opened and the system switched to the next chamber in the sequence. At the end of each chamber measurement, average soil temperature and average soil moisture and average PAR were recorded for each of the chambers. From 30$^{th}$ January 2006 to 23$^{rd}$ May 2007, $CO_2$ concentration was recorded six times during 3 minutes sampling in each of the chambers. From 23$^{rd}$ May 2007 to 18$^{th}$ November 2008, there were 18 records of $CO_2$ concentrations during the closure time for each chamber. Air flow of this system was 10 L/min. A linear regression was

applied on the continuously increasing $CO_2$ concentration with time in the closed chamber to determine the $CO_2$ flux rate. The chamber system was rebuilt in May of 2007, and the time resolution of this system had been improved when the concentration measurements of each sampling changed from 6 to 18 times within every 3 minutes. Based on the biases of measured $CO_2$ fluxes in chamber 1, the detection accuracy for $CO_2$ fluxes was around $\pm 1$ μmol $m^{-2}$ $s^{-1}$ before 23rd May 2007 and the detection accuracy narrowed down to $\pm 0.5$ μmol $m^{-2}$ $s^{-1}$ after resetting the system.

The soil temperature was measured at 3~4 cm below the ground with thermocouple wires. PAR was measured with a PAR sensor (JYP 1000, SDEC, Reignac-Sur-Indre, France) which was placed in the chamber. Soil moisture was detected in the top 5 cm layer of the soil with soil moisture sensors (ThetaProbe ML2x, Delta-T Devices, Cambridge, UK) inserted in the soil with an angle (20 °). The sensor output in mV was recalculated to volumetric water content by a generic function for organic soils from the manual. The function was:

**Water content θ (vol%) = 0.055*Theta (mV)-2** **Eqn 1**

## 2.3 Data sorting

The available data is from August 2005 to November 2008. Chamber 1 was not connected during the whole time of measurement, so available data for $CO_2$ flux analysis was only from 5 chambers. Before June 2006, the data had long time gaps, and the chamber system had low accuracy for $CO_2$ concentration measurement with the value of $\pm 3$ μmol $m^{-2}$ $s^{-1}$. The data from June 2007 to November 2008 had good regression and the performance of chamber system was increased after the rebuilt of system. As mentioned in chapter 2.2, there were 18 readings of $CO_2$ concentrations in 3 minutes sampling for each chamber since June 2007. Though the accuracy of measurements was improved, errors still existed in the data. Those errors are mainly due to malfunctions of the system during the measurements. For instance, the lids of chambers could not tightly close because of the snow pack or the pressure of the chamber went extreme high or extreme low. Appendix 1 shows the criterions for sorting data and the percentage of good data for further analysis. The criterions are created based on the overall quality of data and the accuracy of chamber system itself. The percentage of valid data was above 80% from July 2007 to November 2008. However, July and August of 2008 were exceptional (the system only worked 2 days in July and 9 days in August).

PAR measured in the chambers was used to separate daytime and nighttime. When PAR < 1 μmol $m^{-2}$ $s^{-1}$, the data was assorted to be nighttime data. When PAR $\geq$1 μmol $m^{-2}$ $s^{-1}$, the data was assorted to be daytime data.

## 2.4 Methodology/calculation

### *2.4.1 Calculation of CO2 flux*

Raw $CO_2$ data was recalculated from ppm (umol/mol) to umol/$m^3$ by using the ideal gas law, and then a linear regression was applied on the continuously increasing $CO_2$ concentration as a function of time to obtain the slope coefficient ($K_c$). $CO_2$ flux was calculated from the slope coefficient combining chamber area and volume (Eqn2). The chamber area in this study was 0.235 $m^2$, and the volume of chamber was 0.095 $m^3$.

The data from the first 30 seconds after chamber closed were excluded from the analysis when calculating the slope coefficient, because it may include noise in the data as a result of small pressure differentials or other disturbances after closing the chamber (Davidson et al., 2002). The $CO_2$ concentrations in the first 30 seconds were usually lower than ambient $CO_2$ concentrations.

$$\mathbf{Fc = K^* \frac{V}{A} = \frac{Kc*P}{Kg*(Ts+Tk)} * \frac{V}{A}} \qquad \textbf{Eqn 2}$$

Fc: $CO_2$ Flux( μmol $m^{-2}$ $s^{-1}$)
K: slope coefficient (umol/$m^3$)
$K_c$: slope coefficient (umol/mol)
V: volume of chamber ($m^3$)
P: air pressure (101325 Pa)
$K_g$: gas constant (8.31 J $mol^{-1}$ $k^{-1}$)
$T_s$: soil temperature in each chamber (℃)
$T_k$: 273.15 k
A: area of chamber ($m^2$)

The calculation of slope coefficient, $CO_2$ fluxes, and $R_{10}$ is conducted by MATLAB R2010b (MathWorks, US). Statistical analysis and regression analysis are conducted in Microsoft Excel 2010 (Microsoft, US) and SPSS 17.0 (IBM, US).

### *2.4.2 Calculation of $Q_{10}$, $R_{10}$ and Estimated $CO_2$ flux*

The functions for calculating the temperature sensitivity $Q_{10}$ and the soil respiration rate at 10 ℃ $R_{10}$ are based on the method of Lloyd and Taylor (1994), functions are listed below (Eqn3, 4, 5).

$$\mathbf{R = Ae^{BT}} \qquad \textbf{Eqn 3}$$

R: soil respiration (μmol $m^{-2}$ $s^{-1}$)
T: soil temperature (℃)
A, B: constant coefficients (were calculated in this study based on R and T)

$$Q_{10} = Exp(10*B) \quad \text{Eqn 4}$$

B: is calculated from Eqn 3.

$$R = R_{10}\, e^{E_0\left(\frac{1}{283.15 - T0} - \frac{1}{T - T0}\right)} = R_{10}\, e^{308.56\left(\frac{1}{56.02} - \frac{1}{T - 227.13}\right)} \quad \text{Eqn 5}$$

T: soil temperature (k)
$R_{10}$: the respiration rate at 283.15k
$E_0$: 308.56 k
$T_0$: 227.13 k

### *2.4.3 Soil water content and flux*

In this paper, there are functions, the quadratic function (Wang et al., 2010) and hyperbolic function (Gaumont-Guay et al., 2006), being used to assess the relationship between the soil respiration rate and soil humidity.

Quadratic:

$$R = a\theta^2 + b\theta + c \quad \text{Eqn 6}$$

R: soil respiration (μmol $m^{-2}$ $s^{-1}$)
θ: the soil water content (vol%)
a, b, c: constant coefficients (were calculated in this study)

Hyperbolic:

$$R = x + y\theta + z/\theta \quad \text{Eqn 7}$$

R: soil respiration (μmol $m^{-2}$ $s^{-1}$)
θ: soil water content (vol%)
x, y, z: constant coefficients (were calculated in this study)

# 3. Results

## 3.1 Annual soil temperature, soil moisture and soil $CO_2$ flux

The analysis of annual $CO_2$ fluxes, soil temperature and soil moisture is based on data from June 2007 to November 2008 since this data set was found to be most reliable and have the

highest quality during the whole time period of measurement.

Fig.1 shows the variances of soil temperature at 3 cm depth for the six chambers respectively during this one and half years. There was a clear annual pattern in the diagram, soil temperatures started to increase in April and reached the high level during June, July and August. In summer, the temperatures could reach 21 ℃. The temperatures went down from late August and reached the low level in late December, kept this level until the beginning of April. The lowest temperature was around -2 ℃ during winter time, but soil temperatures kept above 0 ℃ for most of the time of a year. The magnitudes of temperature variances were higher in the summer than in the winter. The soil temperature was roughly in the range of 5 to 20 ℃ from May to late August, and from November to April the soil temperature was in the range of -2 to 5 ℃. Chamber 5 had a huge fluctuation in May of 2008. The variance patterns of soil temperature were similar with each other among these six chambers. There was no pronounced inter-annual variance based on the available soil temperature data from June 2007 and November 2008.

Soil moisture data in this study was the averaged top 5-cm soil water content (vol%), and the distributions of soil moisture for each chamber from June 2007 to November 2008 were displayed in Fig.2. The fluctuations of soil moisture from June to September were quite high, while during winter the soil water content kept a high level around 30 vol% with small variation. The differences of soil water content among these six chambers were greater than soil temperature during the same time period. There was a sharp decline of soil moisture in all six chambers around 20$^{th}$ December 2007, and bounced back to the high level after two days. This was possibly related to the drop of soil temperature. The soil water will be frozen when the temperature goes below 0 ℃, which results in a quick drop in soil moisture.

A sharp increase in the diagram of soil moisture indicates precipitation, and it is followed by a continuous decrease of soil water content due to infiltration and evapotranspiration before the next precipitation event. This variance was very obvious from May to October. Generally, there was no long drought time during this whole period because precipitation happened often every month and very few soil moisture data was below 10 vol% based on Fig.2. The soil water content of chambers 3, 5, 6 were in the range of 5 vol% to 40 vol% for the whole year. The soil water content for chamber 1, 2 and 4 from June 2007 to July 2008 were out of the expected range with high values of soil water content above 60 vol%. The soil type of Skyttorp is between sand and clay (chapter 2.1), which means the saturated soil water content is around 40 vol% (Campbell & Norman, 1998). There was a possibility that the soil moisture sensors were placed in peat soil which could cause high values in chamber 1, 2 and 4. In this report, the analysis was mainly focused on chamber 3, 5 and 6.

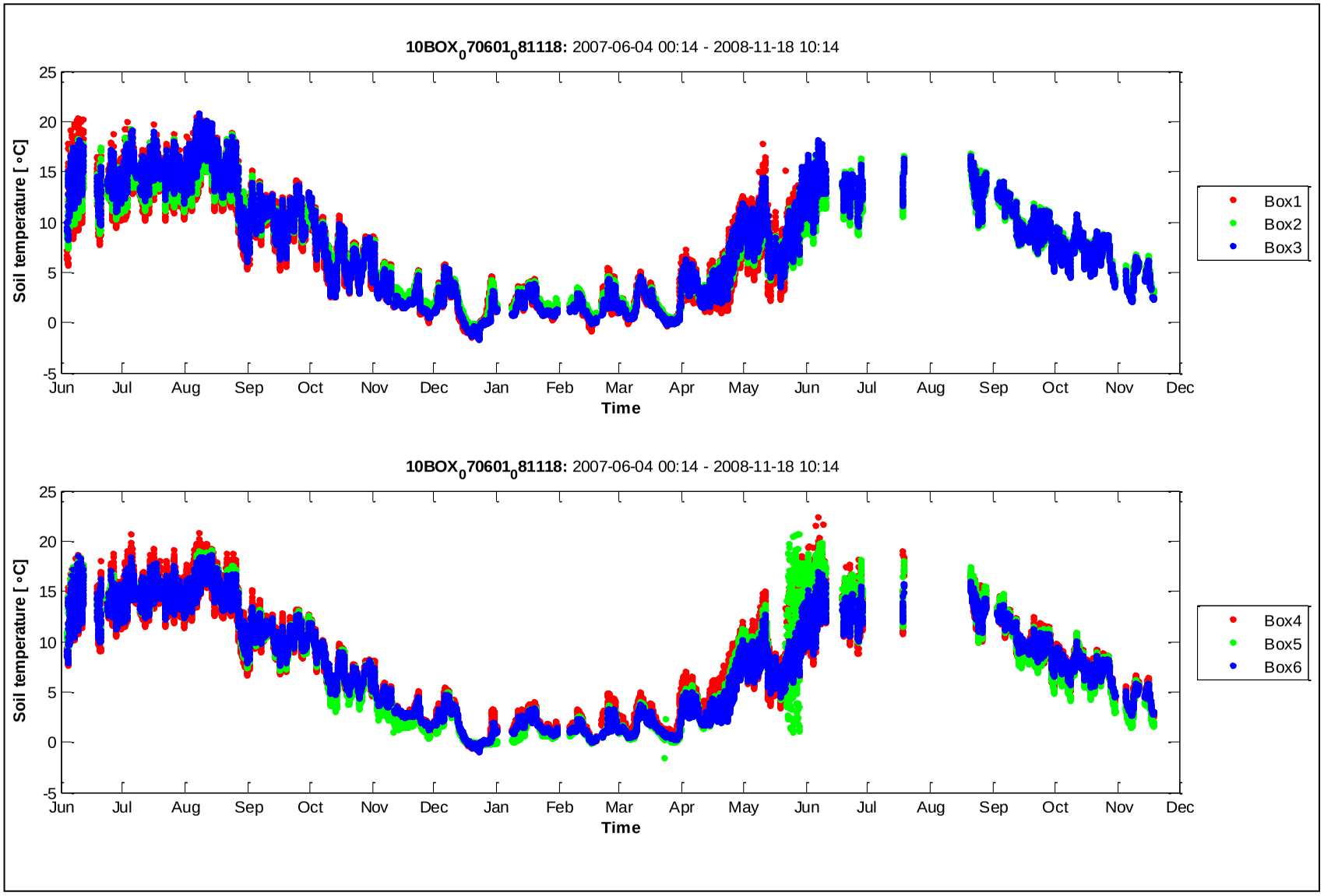


**Figure.1** The time series of soil temperature (°C) measured at 3 cm depth from June 2007 to November 2008.

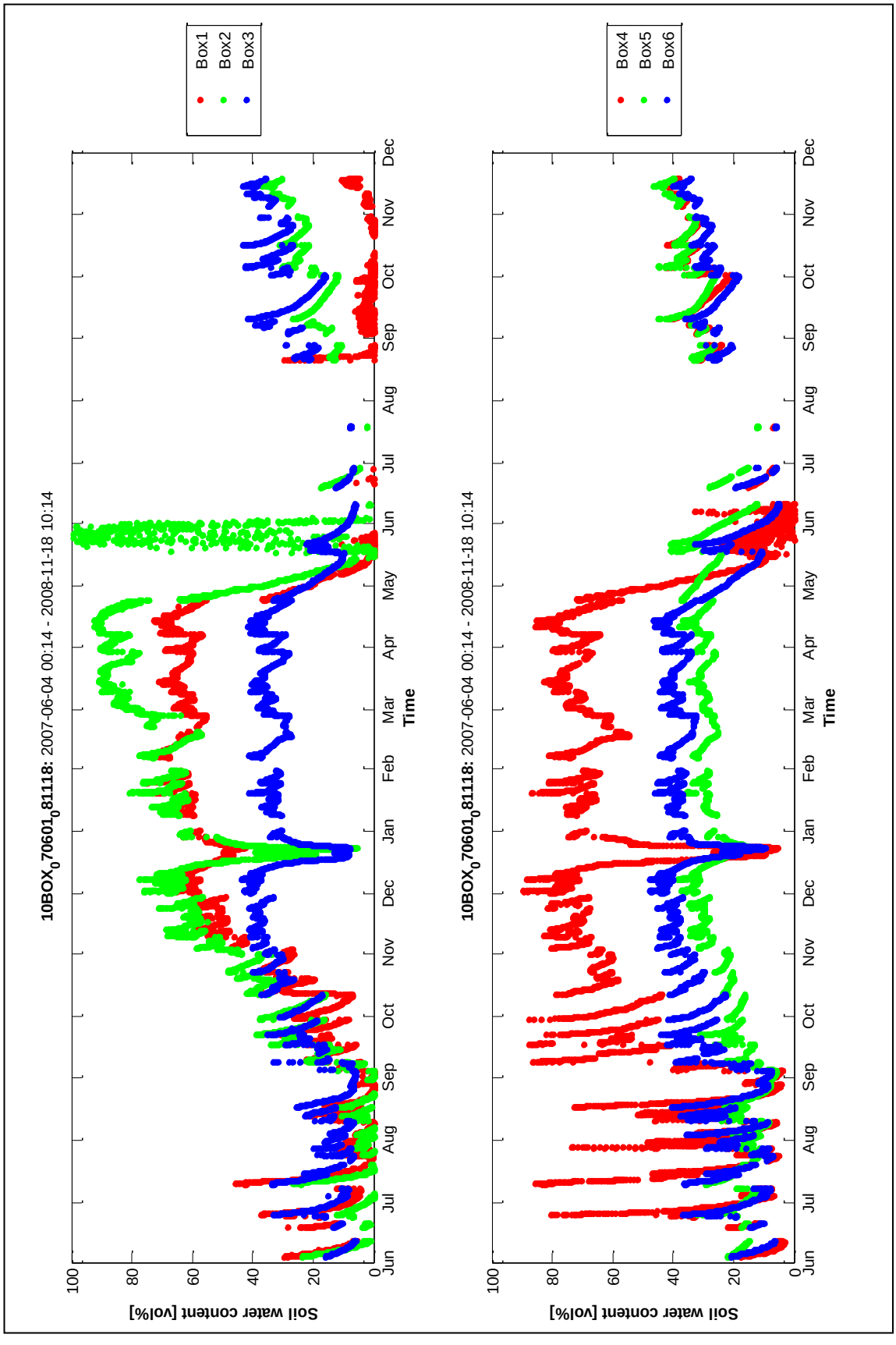


**Figure.2** The time series of soil water content (vol %) of the top 5 cm layer from June 2007 to November 2008.

The distributions of $CO_2$ fluxes for the five chambers are presented in Fig.3 from June 2007 to November 2008. Since chamber 1 was not connected, so the measurements of air circulating in a closed loop could not provide a slope coefficient (chapter 2.4.1) to calculate the flux for chamber 1.

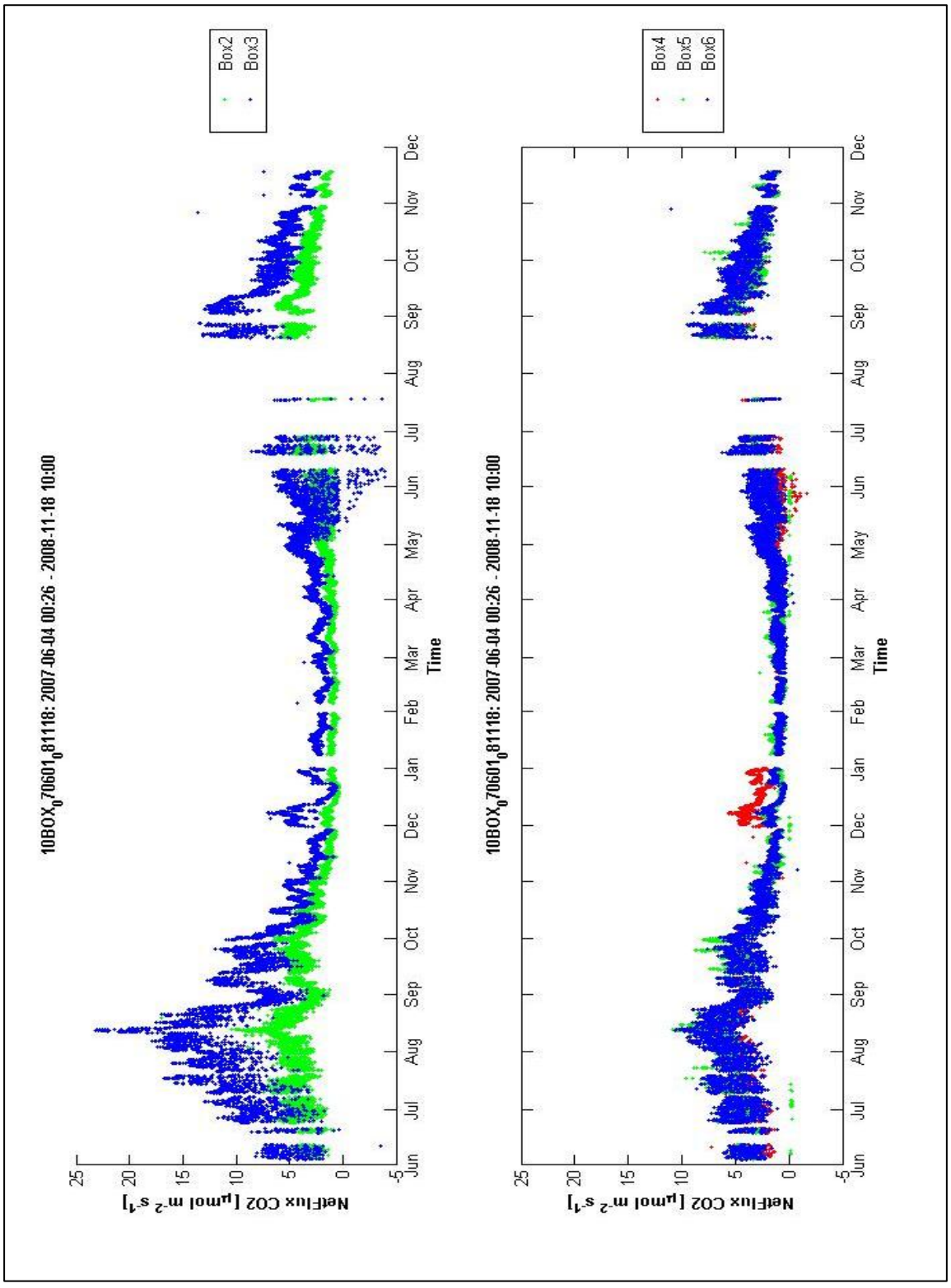


**Figure.3** The time series of soil $CO_2$ fluxes ( $\mu$ mol $m^{-2}$ $s^{-1}$) from June 2007 to November 2008.

The magnitudes of fluxes in chamber 3 were much higher than in the other four chambers especially during summer time. Roughly, the range of $CO_2$ fluxes for chamber 3 were from -4 to 24 μmol $m^{-2}$ $s^{-1}$ in the summer time and from 0 to 7 μmol $m^{-2}$ $s^{-1}$ in the winter time. Chamber 4 had several negative values in late May of 2008, and had higher $CO_2$ fluxes in December of 2007 compared with $CO_2$ fluxes of chamber 5 and chamber 6. For chamber 2, 5 and 6, the $CO_2$ flux variation was between 0 and 12 μmol $m^{-2}$ $s^{-1}$ in the summer time and between 0 and 5 μmol $m^{-2}$ $s^{-1}$ during winter-time. Comparing the fluxes of June 2007 with June 2008 in chamber 3, there were much more negative values in June of 2008. From January to April of 2008, the values and magnitudes of variations for $CO_2$ fluxes were much smaller than that in the summer. In the winter time, the fluxes of these five chambers were very close to each other.

## 3.2 The monthly distribution of soil temperature and soil moisture and $CO_2$ flux

The diagram below (Fig.4) indicates the monthly average soil temperature in 5 chambers from June 2007 to November 2008. There were two months data unavailable due to system malfunction, which were July and August of 2008. For the same month, the average temperature for each chamber was close with each other, as well as the standard deviation. Based on these data, the warmest month was August 2007 with the average temperature of 15 ℃ and the coldest month was December 2007 which had frozen soil for some days during this time period.

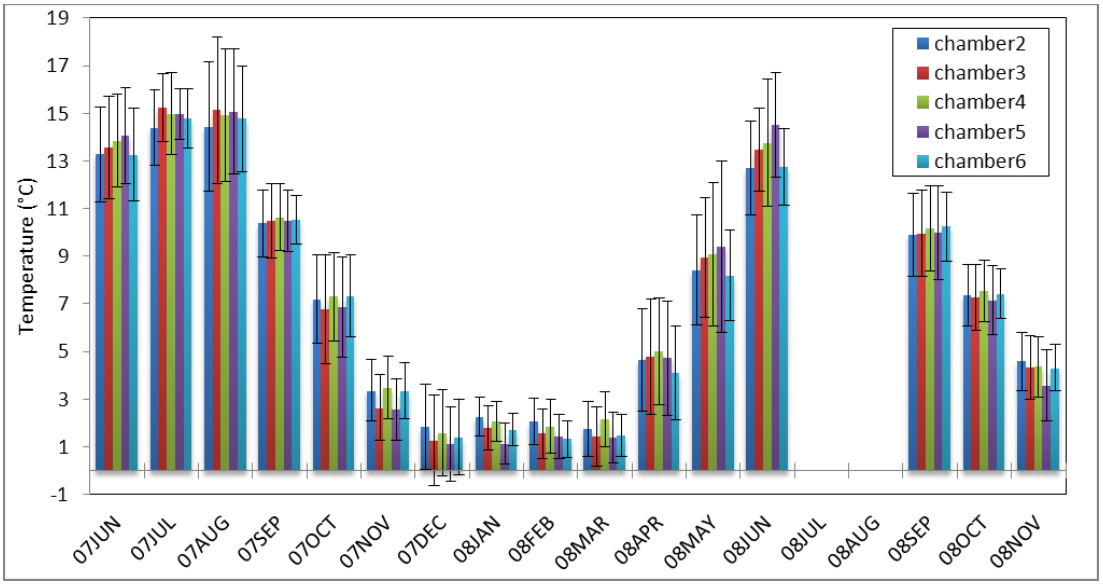


**Figure.4** Monthly average of soil temperature (°C) from June 2007 to November 2008. Bars present soil temperatures of each chamber and error bars present standard deviation. Chamber2 is in blue bar, chamber3 is in dark red bar, chamber 4 is in green bar, chamber5 is in purple bar, and chamber 6 is in light red bar.

The boxplot of soil temperature in chamber 5 indicates more details about soil temperature fluctuations in each month (Fig.5). The highest median temperature was in August 2007 with the value of 16 ℃ (red line in the box) and the lowest average was in December 2007 with the value close to 0 ℃, which was in accord with the results of Fig.4. The biggest variance of soil temperature happened in May 2008 with the range of 0 to 21 ℃, which was in accord with the results of Fig.1. The monthly soil temperature had smallest variance in January 2008 for chamber 5 with the range of 0 to 4 ℃. There were some extreme low values of soil temperature in June and August of 2007. The average soil temperature of November 2008 was higher than that of November 2007, which was probably due to there were only first 18 days data available in November 2008 instead of the whole month.

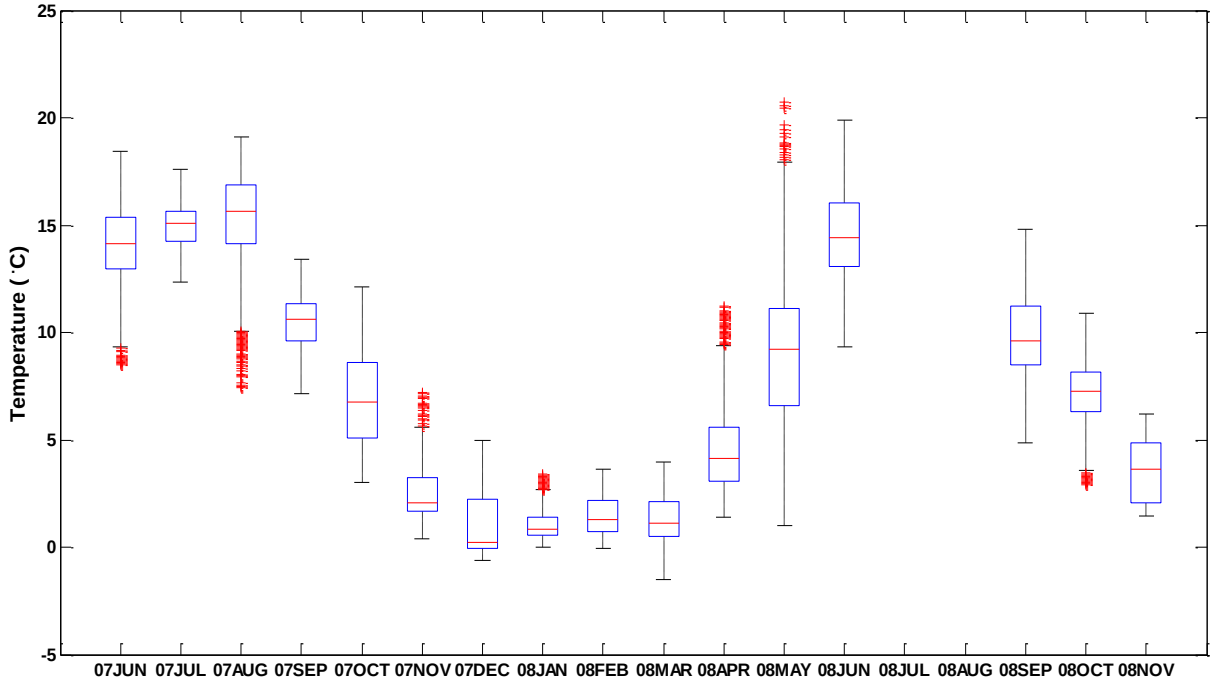


**Figure.5** A boxplot of monthly soil temperature (°C) from June 2007 to November 2008 for chamber 5. The lower and upper sides of the box denote the 25th and 75th percentiles of the data; the red horizontal line in the box shows the median of the data, the upper and lower whiskers display 90th and 10th percentiles of data. The red crosses present extreme values.

The monthly average soil water content for each chamber was below 45 vol% from June 2007 to November 2008 (Fig.6).The mean soil water content of off season was higher than that of growing season in all these three chambers. The soil water content in chamber 5 was much higher than in chamber 3 and chamber 6 during May and June of 2008. While from September 2007 to April 2008, the mean soil water content in chamber 5 was lower than in the other two chambers. The monthly mean soil temperature of chamber 5 in September 2008 was higher than that of September 2007. The same trend also happened in October and November between these two years.

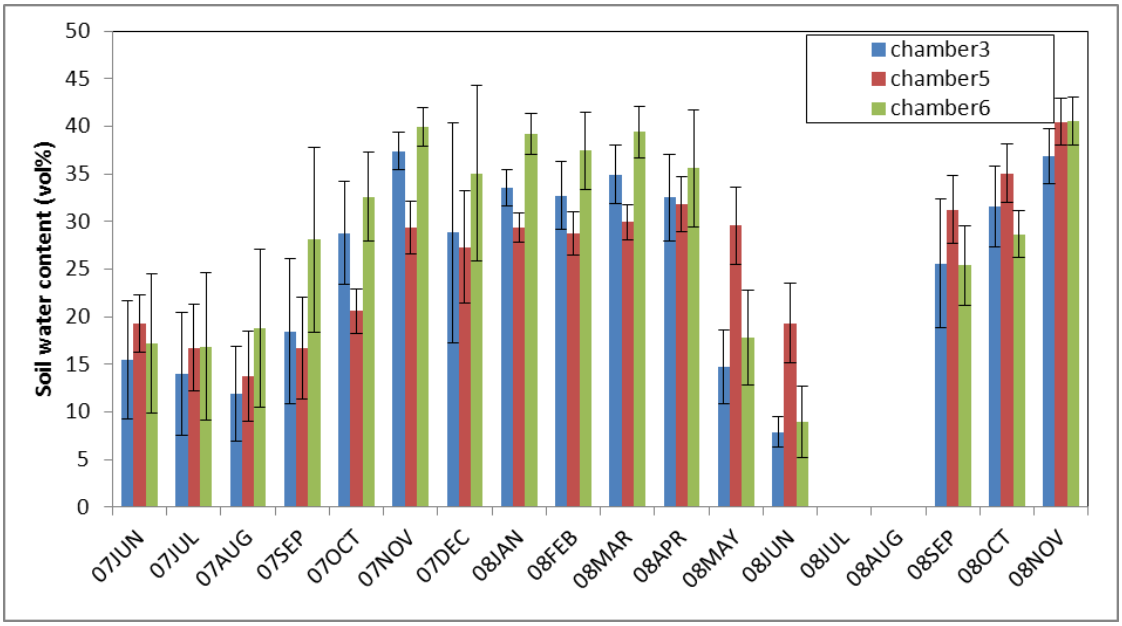


**Figure.6** Monthly average of soil water content (vol%) from June 2007 to November 2008. Bars present soil water content of each chamber and error bars present standard deviation. Chamber 3 is in blue bar, chamber 5 is in dark red bar, and chamber 6 is in green bar.

As Fig.7 shows, the soil water conditions for the same month of 2007 and 2008 varied considerably, for instance, the soil moistures of September, October and November of 2008 were much higher than the same time period of 2007, which was also exhibited in Fig.6. The highest monthly median soil water content was in November of 2008 with the value of 41 vol%, while the lowest mean soil water content was in August of 2007 with value around 14 vol%.

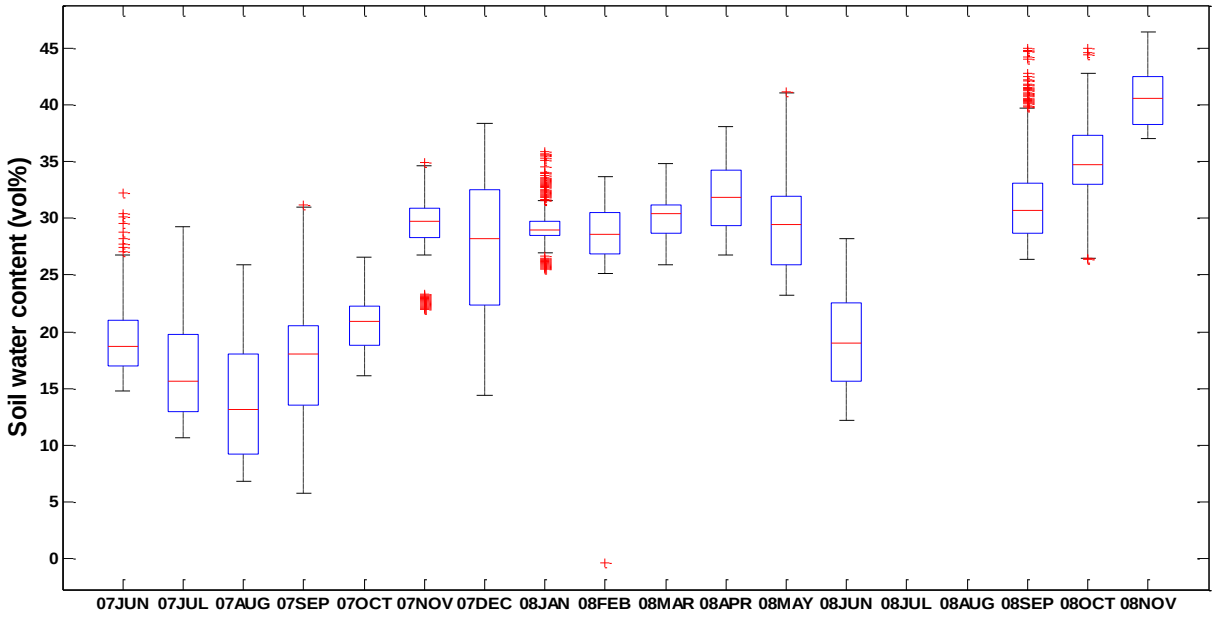


**Fig.7** A boxplot of monthly soil water content in vol% from Jun 2007 to Nov 2008 for chamber 5. The lower and upper sides of the box denote the 25th and 75th percentiles of the data, the red horizontal line in the box shows the median of the data, the upper and lower whiskers display 90th and 10th percentiles of data. The red crosses present extreme values.

Data from September and December in 2007 showed high variations comparing with the data of other months. There were some very high values in September and October of 2008.

There was a clear negative correlation between monthly averaged soil temperature and soil water content (vol%) in chambers of 3, 5 and 6 (Fig.8). In summer time, higher temperature responded to lower soil water content. In winter time, it was the other way around. The correlation between soil temperature and soil water content was significant at the 0.01 level in each chamber on the annual time scale and daily time scale, and chamber 3 had the highest correlation of 0.71 on the annual time scale.

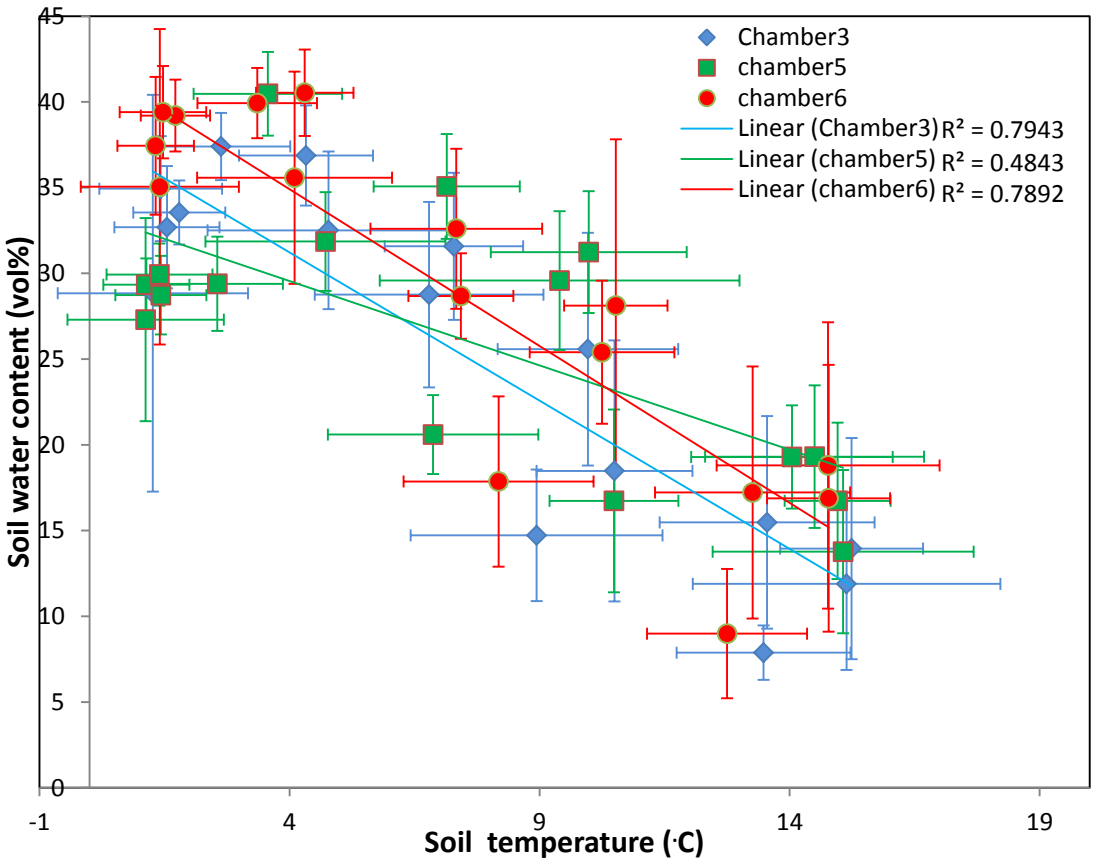


**Figure.8** A plot of monthly mean soil water content (vol%) and soil temperature (°C) for chamber 3(blue diamonds), chamber5 (green squares) and chamber6 (red dots).The blue line represents the trend line of chamber 3 with $r^2 = 0.79$. The green line represents the trend line of chamber 5 with $r^2 = 0.48$. The red line represents the trend line of chamber 6 with $r^2 = 0.79$. The horizontal error bars represent the stand deviation of soil temperature; the vertical error bars represent the stand deviation of soil water content.

As shown in Fig.9, the monthly mean $CO_2$ fluxes of August 2007 were the largest from November 2006 to November 2008. The fluxes of chamber 3 were much higher than the fluxes of other four chambers in every month except December 2007. The mean $CO_2$ flux of December 2007 in chamber 4 was quite high comparing with other months in the winter, and this large increase was also very clear in Fig.3. The mean $CO_2$ flux of each month from November 2006 to June 2007 was higher than the same time from November 2007 to June 2008. The monthly averaged $CO_2$ flux kept at the same level in each month during the off season, such

as the time period of November 2006 to April 2007, and the time period of December 2007 to March 2008. The $CO_2$ fluxes in chamber 4 and chamber 5 were quite close with each other in same month. The variances of $CO_2$ fluxes in each chamber were more pronounced in the summer, and comparatively smaller in winter.

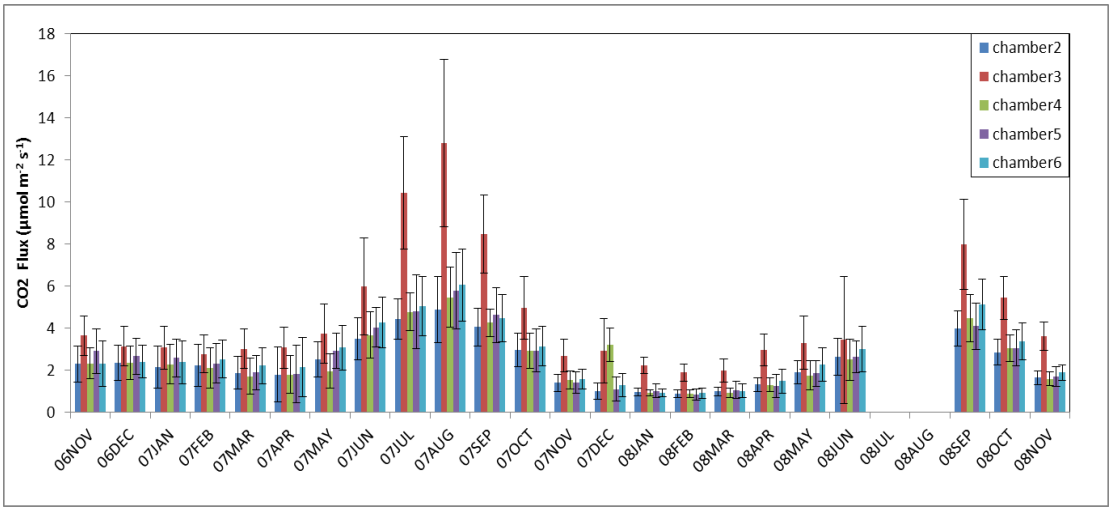


**Figure.9** Monthly averaged of soil $CO_2$ flux in µmol $m^{-2}$ $s^{-1}$ from November 2006 to November 2008. Bars present soil $CO_2$ flux of each chamber and error bars present standard deviation. Chamber 2 is in dark blue bar, chamber3 is in dark red bar, chamber 4 is in green bar, chamber 5 is in purple bar, and chamber6 is in light blue bar.

## 3.3 The relationship between soil respiration and soil temperature

The calculation of $Q_{10}$ (Eqn3 and 4) and $R_{10}$ (Eqn5) was based on four different time periods of data, June 2007 - May 2008 (annual), June - October 2007 (growing season), June-August 2007 (summer time), and December 2007 – February 2008 (winter time). It is partly shown in Table.1, the full results are shown in Appendix 2. The calculation of $R_{10}$ was only based on nighttime data in order to exclude the influences of photosynthesis of ground vegetation in the chambers during daytime, but the effect of respiration of ground vegetation in growing season could not be excluded in the night.

The annual $Q_{10}$ value varied from 2.63 to 3.45 in this study, which was well fitted in the reasonable range. The values of $Q_{10}$ in the summer were quite low and extremely high in the winter in every chamber. The coefficient of determination ($R^2$) for summer-time $Q_{10}$ in each chamber was below 0.5 and regression for winter-time $Q_{10}$ was slightly better except chamber 5. The annual and seasonal $R_{10}$ were also in the reasonable range except chamber 3. The $R^2$ of $R_{10}$ was generally better than for $Q_{10}$ for each chamber, mainly because the $R_{10}$ was only based on nighttime data. The values of $Q_{10}$ derived from nighttime data or daily data did not make a big difference, but the $R^2$ was slightly better if only nighttime data was used. During winter time period (Dec 2007 - Feb 2008), the exponential relationship between soil temperature and $CO_2$ flux for chamber 4 was not good with $R^2$ below 0.1.

**Table.1** The results of calculated $Q_{10}$ and $R_{10}$ for 5 chambers. $Q_{10}$ is the temperature sensitivity of soil respiration calculated from Eqn4, $R_{10}$ is the soil respiration rate at 283.15K calculated from Eqn5, $R^2$ is the coefficient of determination, and n is the numbers of data.

| Chamber No. | Time period | **$Q_{10}$** | | | **$R_{10}$** | | |
|---|---|---|---|---|---|---|---|
| | | $Q_{10}$* | $R^2$ | n | $R_{10}$* | $R^2$ | n |
| **2** | Jun 2007- May 2008 | 3.31 | 0.79 | 10538 | 3.53 | 0.87 | 6277 |
| | Jun 2007-Aug 2007 | 1.59 | 0.11 | 2400 | 3.7 | 0.58 | 920 |
| | Dec 2007- Feb 2008 | 6.46 | 0.65 | 2381 | 2.45 | 0.60 | 2030 |
| **3** | Jun 2007- May 2008 | 3.07 | 0.74 | 10403 | 7.46 | 0.87 | 5946 |
| | Jun 2007-Aug 2007 | 2.67 | 0.26 | 2455 | 7.98 | 0.59 | 913 |
| | Dec 2007- Feb 2008 | 10.79 | 0.59 | 2356 | 6.73 | 0.47 | 1897 |
| **4** | Jun 2007- May 2008 | 2.63 | 0.55 | 10170 | 3.82 | 0.71 | 5386 |
| | Jun 2007-Aug 2007 | 1.55 | 0.12 | 2264 | 3.81 | 0.62 | 750 |
| | Dec 2007- Feb 2008 | 1.84 | 0.02 | 2391 | 4.99 | 0.06 | 1791 |
| **5** | Jun 2007- May 2008 | 3.26 | 0.78 | 10211 | 3.69 | 0.83 | 5091 |
| | Jun 2007-Aug 2007 | 2.62 | 0.46 | 2414 | 3.66 | 0.56 | 710 |
| | Dec 2007- Feb 2008 | 7.25 | 0.36 | 2276 | 3.02 | 0.42 | 1641 |
| **6** | Jun 2007- May 2008 | 3.45 | 0.75 | 10281 | 4.38 | 0.92 | 5151 |
| | Jun 2007-Aug 2007 | 1.57 | 0.07 | 2460 | 4.6 | 0.73 | 713 |
| | Dec 2007- Feb 2008 | 8.02 | 0.37 | 2343 | 3.12 | 0.43 | 1708 |

* The statistical significance p-value < 0.001 for both $Q_{10}$ regression model and $R_{10}$ regression model in each chamber during different time periods.

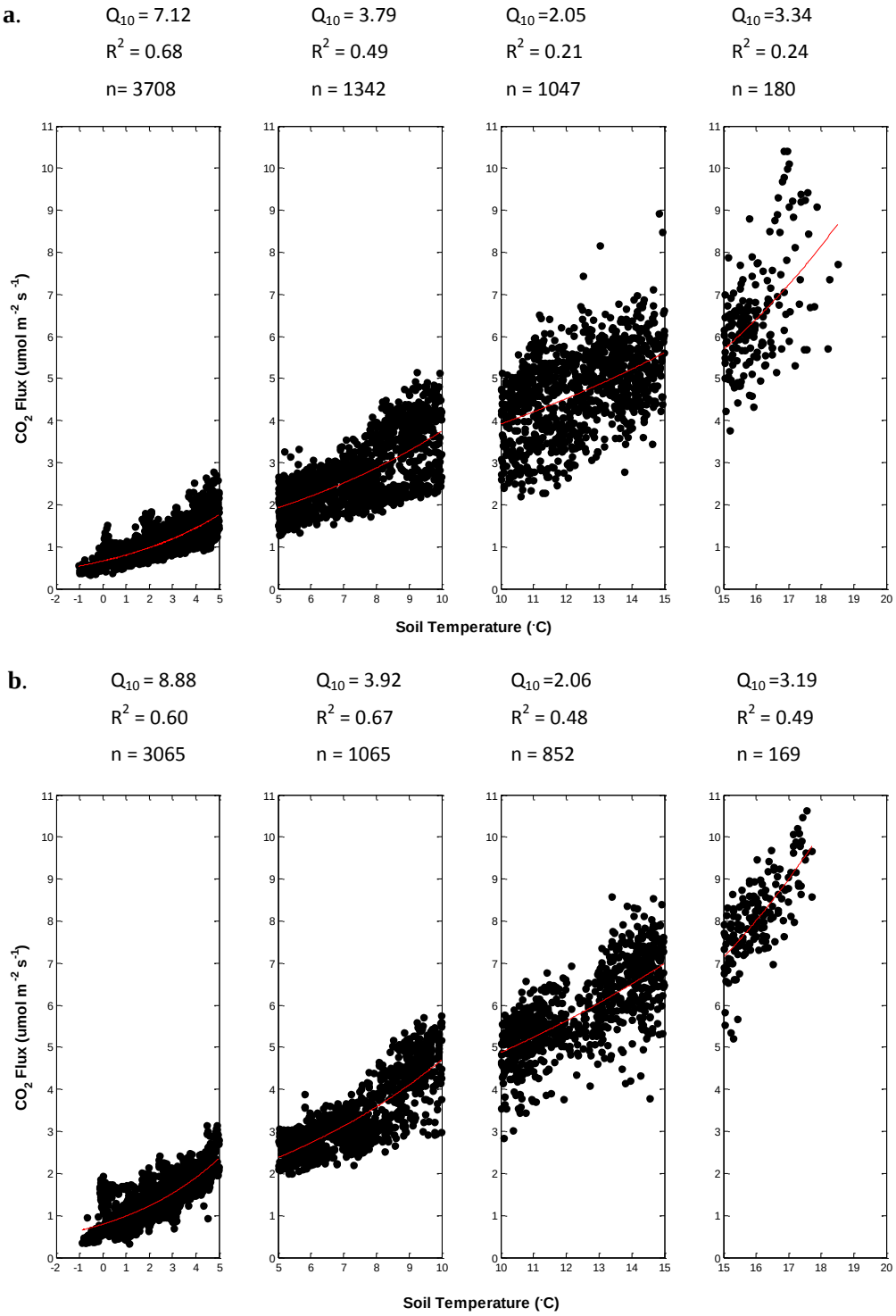


**Fig.10** The calculated $Q_{10}$ for chamber 2 (a) and chamber 6 (b) based on the nighttime data from June 2007 to May 2008. The temperature of first column is from -2°C to 5°C, the second column is 5°C to 10°C, the third column is from 10°C to 15°C, the last column is from 15°C to 20°C. $Q_{10}$ is the temperature sensitivity of soil respiration calculated from Eqn4, $R^2$ is the coefficient of determination, and n is the numbers of data.

Fig.10a represents the calculated $Q_{10}$ of chamber 2 and Fig.10b represents the calculated $Q_{10}$ of chamber 6 merely calculated from the night data. The first column contained all the data with

temperature was below 5 ℃; the second column contained all the data with temperature between 5 ℃ and 10 ℃; the third column contained all the data with temperature between 10 ℃ and 15 ℃; the last column contains all the data with temperature above 15 ℃. $Q_{10}$ was reduced with increasing temperature and the value of $R^2$ also decreased at the same time when the soil temperature was in the range of 0 ℃ to 15 ℃. For chamber 2, the $Q_{10}$ was declining from 7.1 to 2.1 with enhanced temperature. $Q_{10}$ was declining from 8.9 to 2.1 with enhanced temperature in chamber 6, but the $Q_{10}$ for temperature from 15 ℃ to 21 ℃ was higher than the $Q_{10}$ for temperature from 10 ℃ to 15 ℃. The ranges of $CO_2$ fluxes were expanding with rising temperature. When the temperature was below 15 ℃, this regression model worked well. When the temperature exceeded 15 ℃, the magnitudes of fluxes variation were quite high in a relatively narrow temperature range for chamber 2; thus the exponential function could not explain the relationship between temperature and soil $CO_2$ fluxes at high temperature level. There was a positive linear relationship ($r^2$=0.95) between soil water content and $Q_{10}$ for chamber 5 as Fig.11 shows, the lower temperature responded to high soil water content and high $Q_{10}$ value.

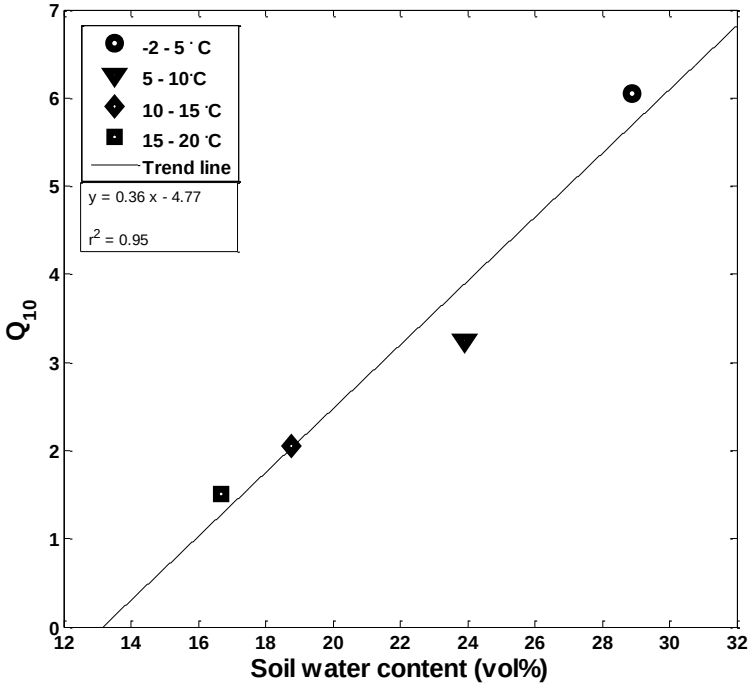


**Figure.11** The correlation between $Q_{10}$ and soil water content (vol%) for chamber 5 based on the annual data.

Fig.12 displays two of the regression results for chamber 3 and chamber 6 respectively, and chamber 6 had a high $R^2$ value above 0.9. The value of $R_{10}$ (7.46) for chamber 3 was almost two times higher than the $R_{10}$ (4.38) for chamber 6, which was possibly because of the higher organic layer. Both of these two diagrams show that when the temperature was below 1 ℃, the regression line was above all the data. The daytime soil respiration could be estimated by using measured daytime soil temperature and the calculated $R_{10}$ for each chamber (Eqn5). Fig.13 shows the correlations between estimated $CO_2$ fluxes and measured $CO_2$ fluxes, and the majority of estimated daytime soil respiration rate was higher than the measured soil respiration rate in chamber 3, 6 and other three chambers. In chamber 3, when the fluxes exceeded 17 μmol $m^{-2}$ $s^{-1}$, the estimated soil respiration rate which was calculated by Eqn 5 was lower than the

measured soil respiration rate both in the daytime and nighttime. For chamber 6, there was an excellent linear relationship between estimated $CO_2$ fluxes and measured $CO_2$ fluxes during night time, but most of estimated daytime soil respiration was higher when $CO_2$ flux in the chamber was below 8 μmol $m^{-2}$ $s^{-1}$. The fluctuations for the estimated fluxes were quite large when the measured soil respiration was between 2 and 6 μmol $m^{-2}$ $s^{-1}$.

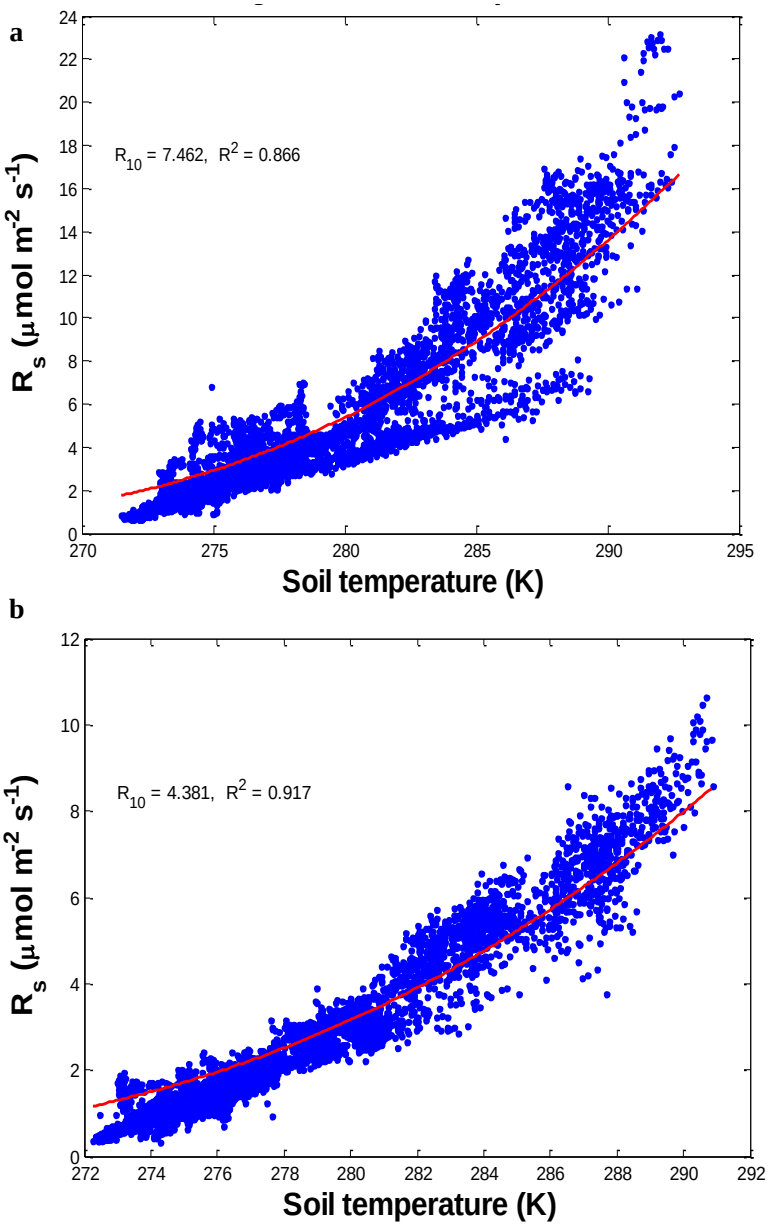


**Figure.12** A plot of soil $CO_2$ fluxes with temperature (K) in the nighttime for chamber 3 (a) and chamber 6 (b) based on data from June 2007 to May 2008. $R_{10}$ is the soil respiration rate at 10°C in μmol $m^{-2}$ $s^{-1}$; $R^2$ is the coefficient of determination.

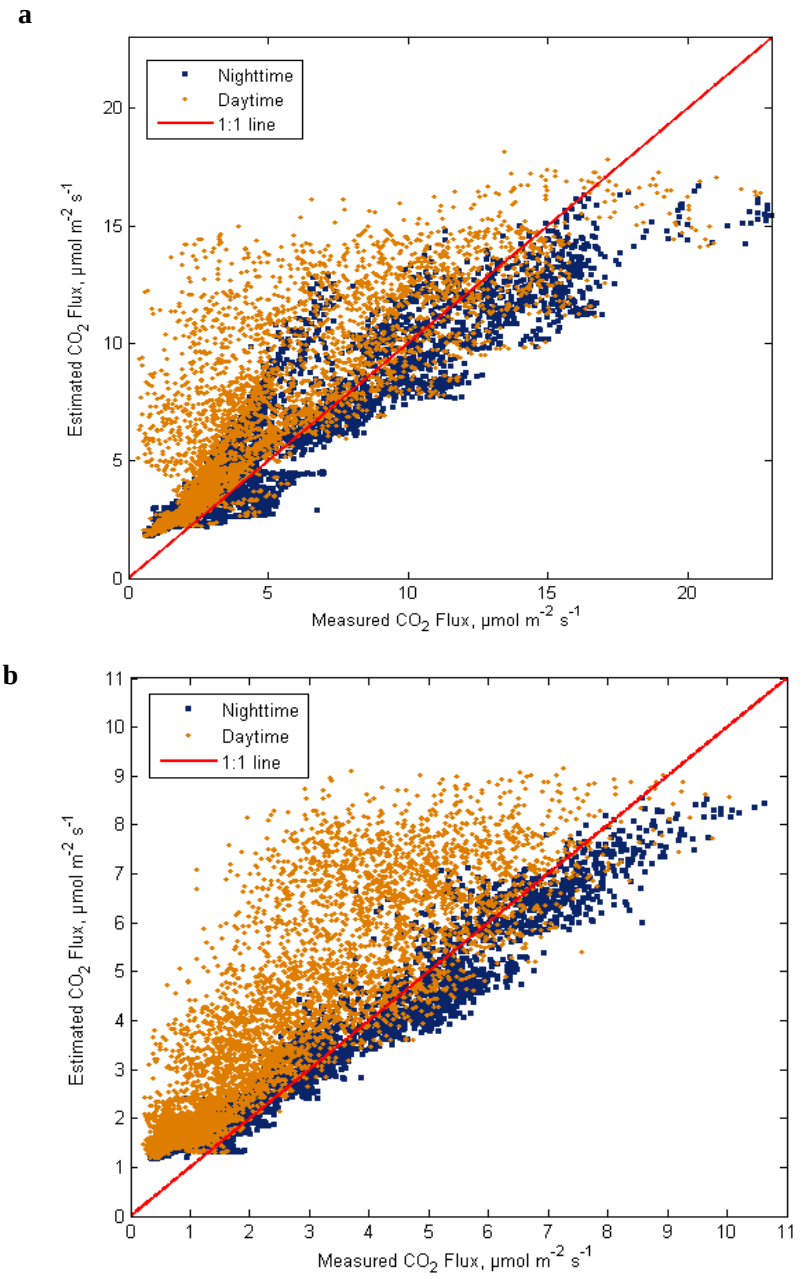


**Figure.13** The correlation between estimated $CO_2$ fluxes (µmol $m^{-2}$ $s^{-1}$) and measured $CO_2$ fluxes (µmol $m^{-2}$ $s^{-1}$) for chamber 3 (a) and chamber 6 (b), the red line denotes 1:1, the yellow dots represent daytime data, and the blue dots represents nighttime data.

Fig.14 offers another way to show the difference between estimated $R_s$ and measured $R_s$ during daytime. The patterns of residuals for chamber 3 and chamber 6 were quite similar, though the PAR of chamber 3 was lower than chamber 6. When PAR was above 25 µmol $m^{-2}$ $s^{-1}$ in chamber 3 and100 µmol $m^{-2}$ $s^{-1}$ in chamber 6 separately, all the residual was positive. The positive values indicated that the measured soil $CO_2$ fluxes were lower than the estimated. The residual became independent from radiation when the residual value was around 5 µmol $m^{-2}$ $s^{-1}$. This indicates the rate of photosynthesis in chamber 3 and chamber 6 was around 5 µmol $m^{-2}$ $s^{-1}$ in the day time.

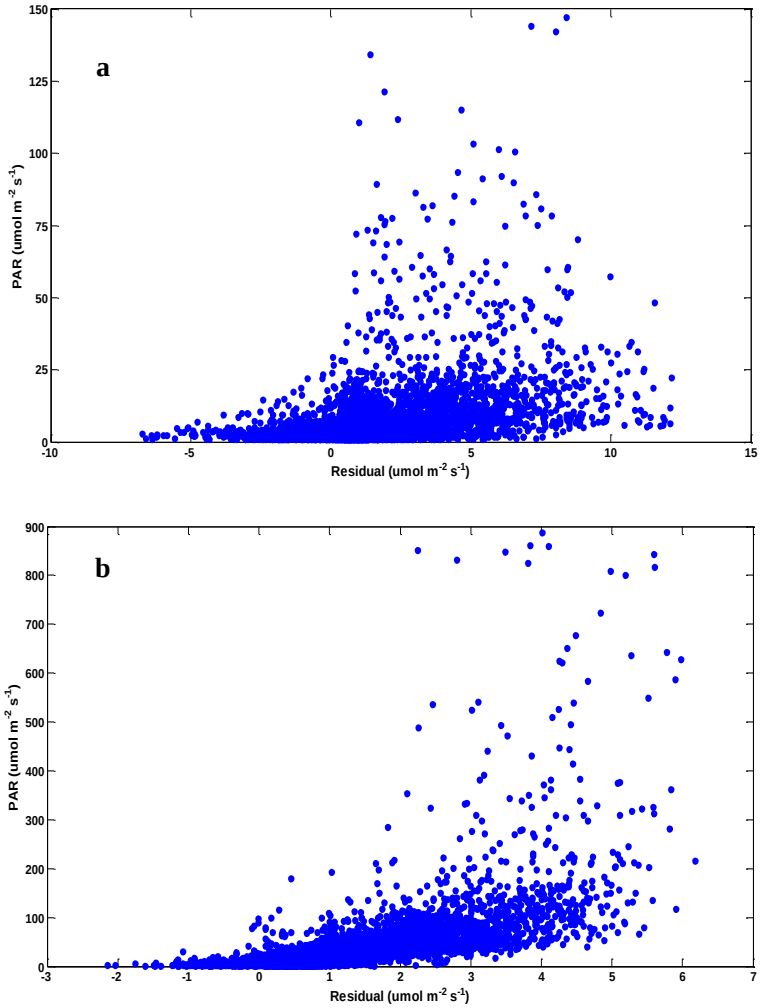


**Figure.14** A plot of PAR vs residual (estimated $CO_2$ flux – measured $CO_2$ flux) for daytime soil respiration for chamber 3 (a) and chamber 6(b).

Most of the estimated daytime $CO_2$ fluxes were higher than the measured $CO_2$ fluxes in chamber 3 via showing more negative values of residual (measured $CO_2$ flux - estimated $CO_2$ flux) for the daytime data(Fig.15a), while there were more positive daytime residual of $CO_2$ fluxes in chamber 6(Fig.15b). The daytime residual were independent from soil water content for both of chamber 3 and 6.The range of residual for nighttime $CO_2$ fluxes decreased with increasing soil water content in chamber 3, and the nighttime residual in chamber 6 also showed the same trend.

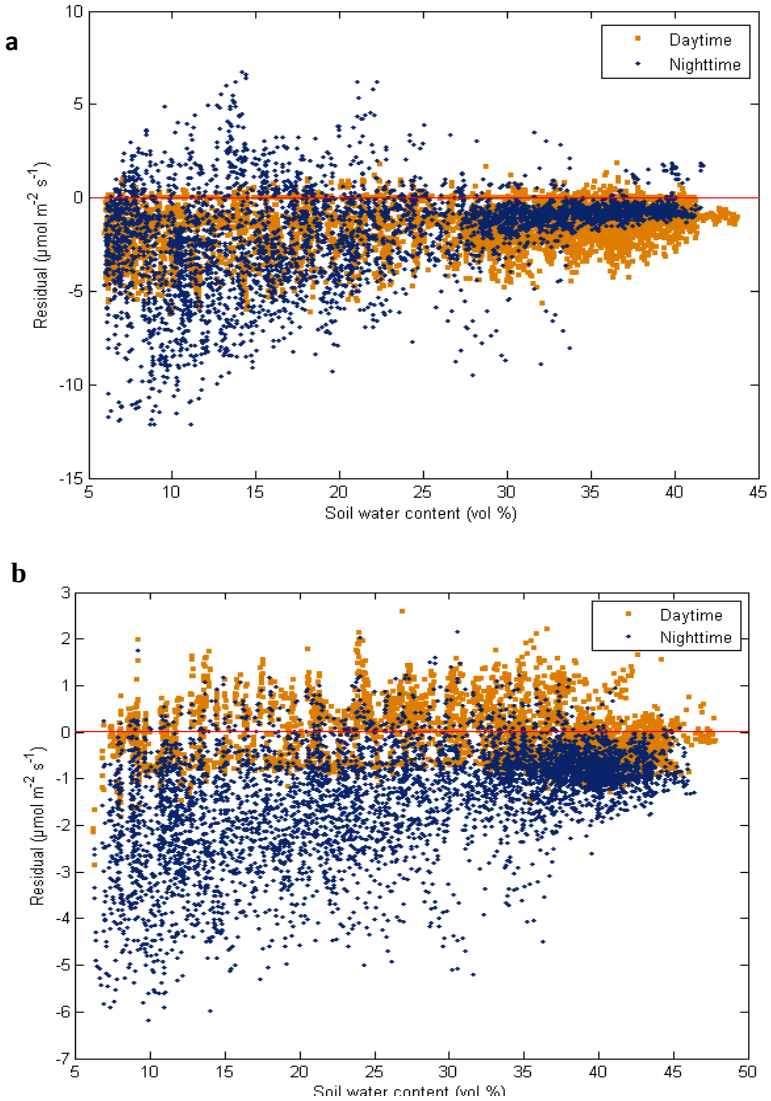


**Figure.15** A plot of residual (measured $CO_2$ flux - estimated $CO_2$ flux) vs soil water content on annual time scale for chamber 3(a) and chamber 6(b), the red line represents the value of 0.

## 3.4 The relationship between soil respiration and soil moisture

In this project, a quadratic function (Eqn6) and a hyperbolic function (Eqn7) were used for the examination. There was no good relationship found through these two commonly used models neither in growing season (April to October) nor in off season (November to March), all the $R^2$ values were below 0.4. The results are shown in Appendix 3. The correlation between soil water content and soil respiration rate was also examined for the whole time period (June 2007 to November 2008), and the regression values were better comparing with the seasonal analysis results. The outputs of quadratic function and hyperbolic function were very close with each other based on the regression values.

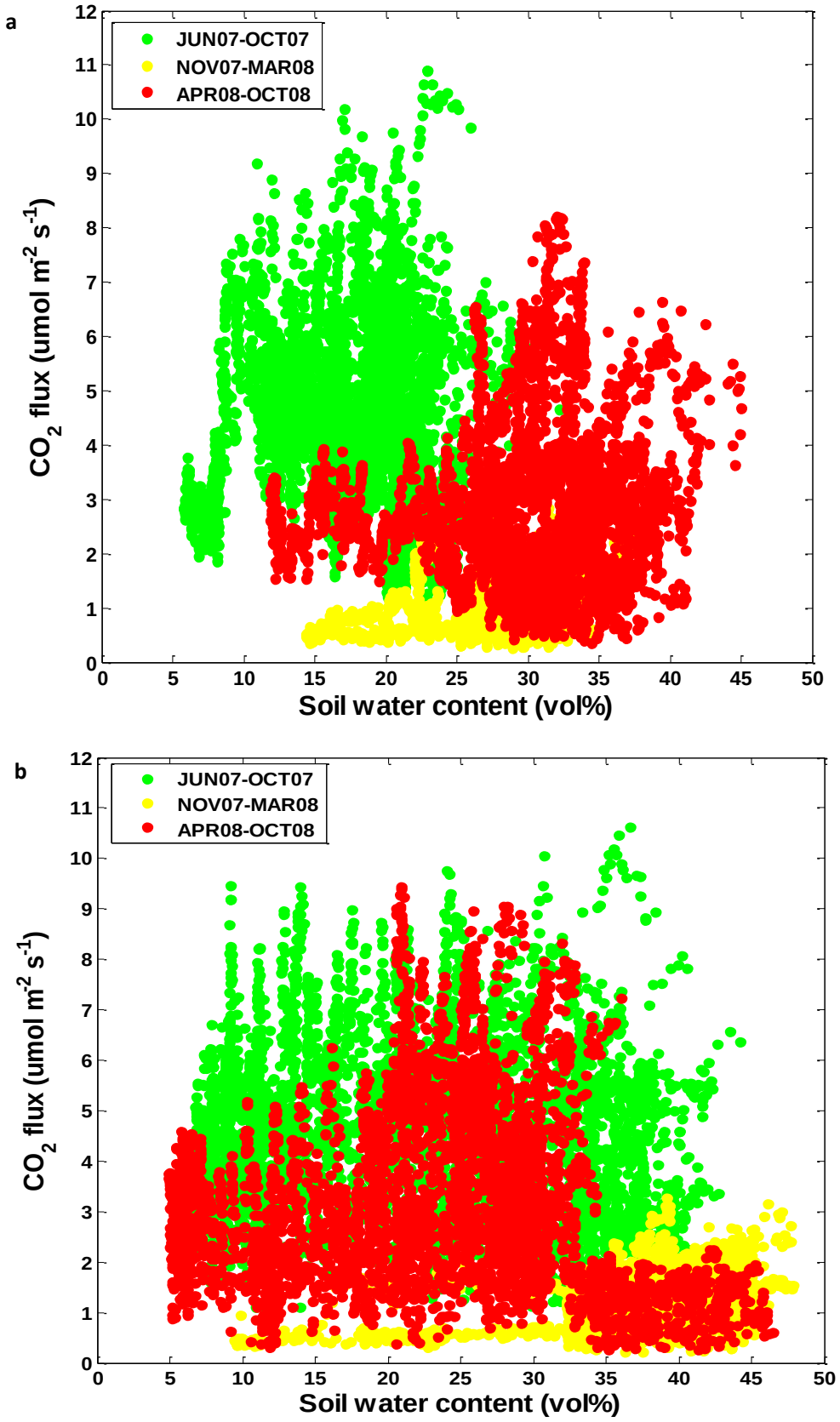


**Figure.16** A scatter plot of soil respiration (μmol $m^{-2}$ $s^{-1}$) as a function of soil water content for chamber 5(a) and chamber 6(b), the green dots represent data of June 2007 - October 2007; the yellow dots represent data of November 2007 - March 2008; the red dots represent data of April 2008 - October 2008.

Fig.16 indicates the scatter plots of soil water content and soil respiration rate for chamber 5 and chamber 6. In chamber 5, the highest soil water content happened during the growing season of 2008, and the highest $CO_2$ fluxes occurred in growing season of 2007 when the soil water content was between 10 vol% and 25 vol%. The highest $CO_2$ fluxes for growing season of 2007 and 2008 were quite close in chamber 6, and the highest soil water content occurred in the off season of late 2007 and early 2008. Both growing season and off season had higher soil water content range of 5 vol% to 48 vol% in chamber 6 comparing with the soil water content ranges for the three time periods in chamber 5. There was a decrease of $CO_2$ flux in chamber 6 when the soil water content exceeded 33 vol% during growing season of 2008. The variation of soil $CO_2$ fluxes was much higher in growing season than in off season referred to the same soil water content in both chambers. To exclude the influences of soil temperature and photosynthesis, Fig.17 shows the scatter plots of soil water content and soil respiration rate when the soil temperature was between 14 ℃ and 16 ℃ during night. The trend inclines to be logarithm instead of quadratic or hyperbolic in chamber 6, there was not a decreasing trend at high soil water content condition. The influences from wood density and organic matter layer to soil respiration rate could possibly conceal the relationship between soil moisture and $CO_2$ flux even though the effect of soil temperature was removed.

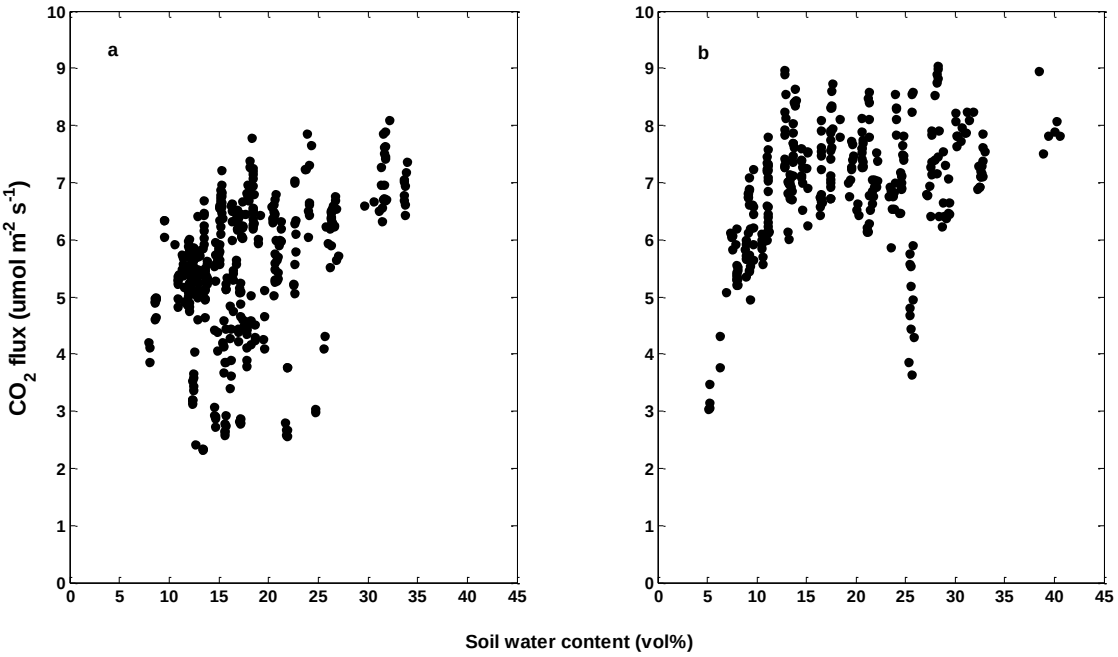


**Figure.17** A scatter plot of soil respiration (μmol $m^{-2}$ $s^{-1}$) as a function of soil water content (vol%) for chamber 5 (a) and chamber 6 (b) from June 2007 to November 2008 during night time when the soil temperature was around ± 15°C.

## 3.5 The relationship between soil respiration and PAR

Photosynthesis is tightly linked to photosynthetically active radiation (PAR), which partly determines the primary production of forest ecosystems. Fig.18 shows the incoming PAR

distribution above the canopy from June 2007 to November 2008 with a data gap between middle of July and middle of August in 2008. There was a strong seasonal pattern for the distribution; the radiation was as high as 1600 μmol $m^{-2}$ $s^{-1}$ from June to August, and it dropped below 200 μmol $m^{-2}$ $s^{-1}$ from November to February. Photosynthetic activities mainly happen in the growing season to accumulate carbon on the conditions of adequate PAR and relatively high air temperature and no soil water limit. The low air temperature and very low PAR limit the photosynthesis during winter time at Skyttorp.

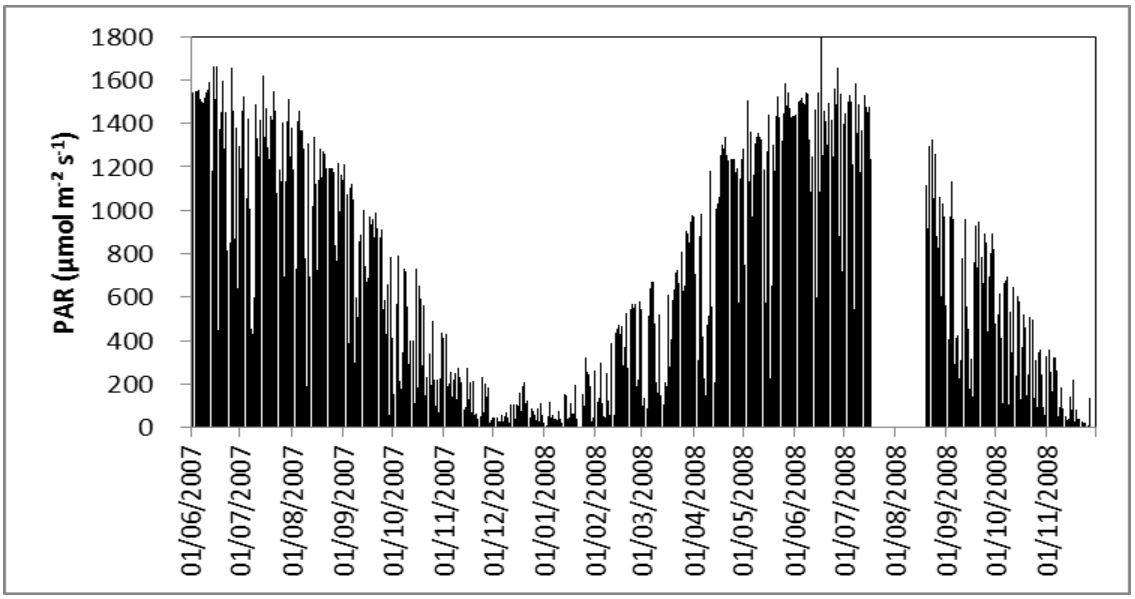


**Figure.18** Time series of incoming PAR from the tower in Skyttorp from June 2007 to November 2008

PAR detected from tower above canopy was significantly higher than the measured PAR in chambers below the canopy. Fig.19 also shows a seasonal pattern of PAR distribution in chambers, but there were large differences among these five chambers during growing season, and the PAR were generally below 30 μmol $m^{-2}$ $s^{-1}$ in off season. The PAR in chamber 2 and 3 were lower than that in another three chambers during the whole time period.

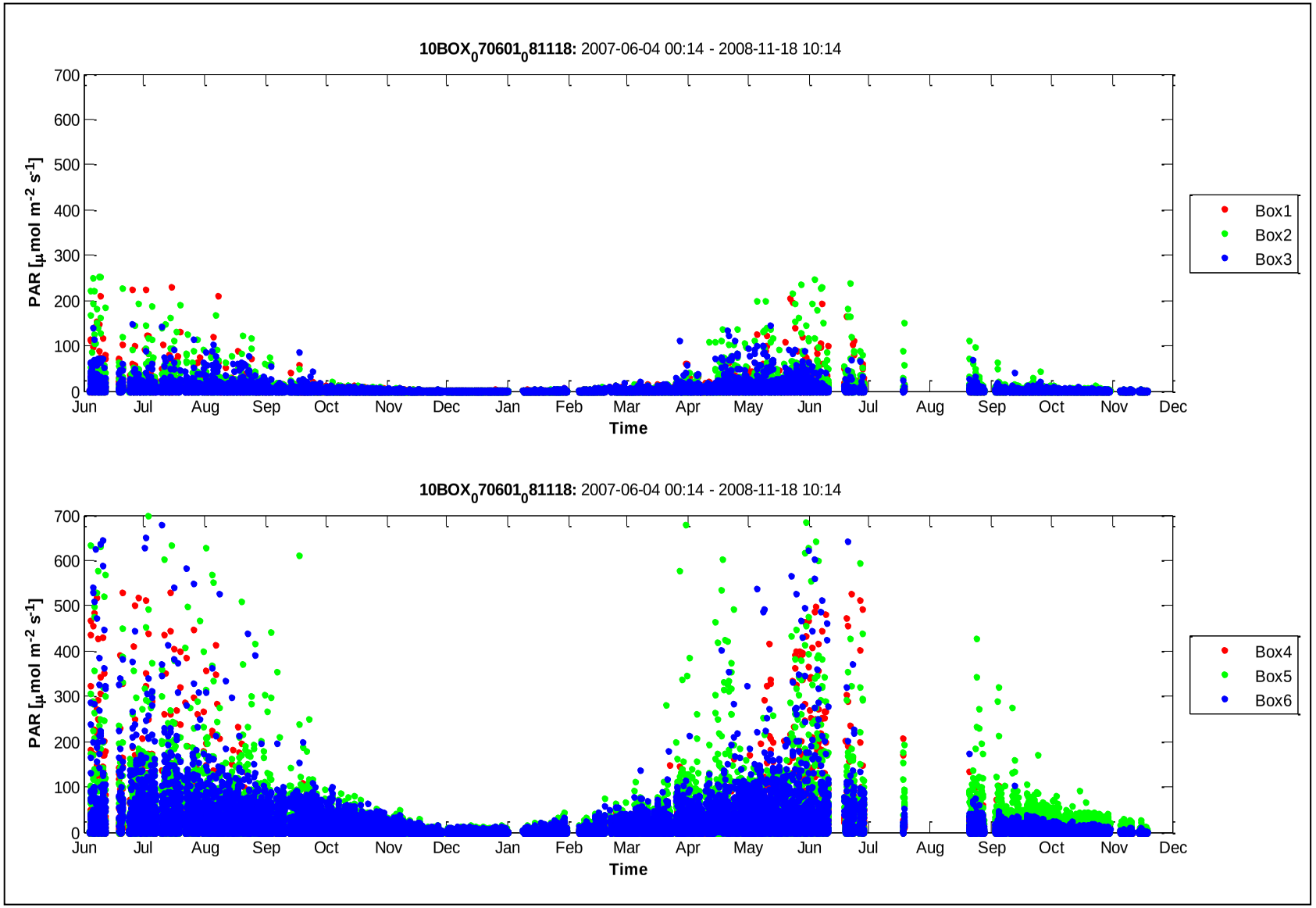


**Figure.19** Time series of PAR distributions in six chambers which were measured from June 2007 to November 2008.

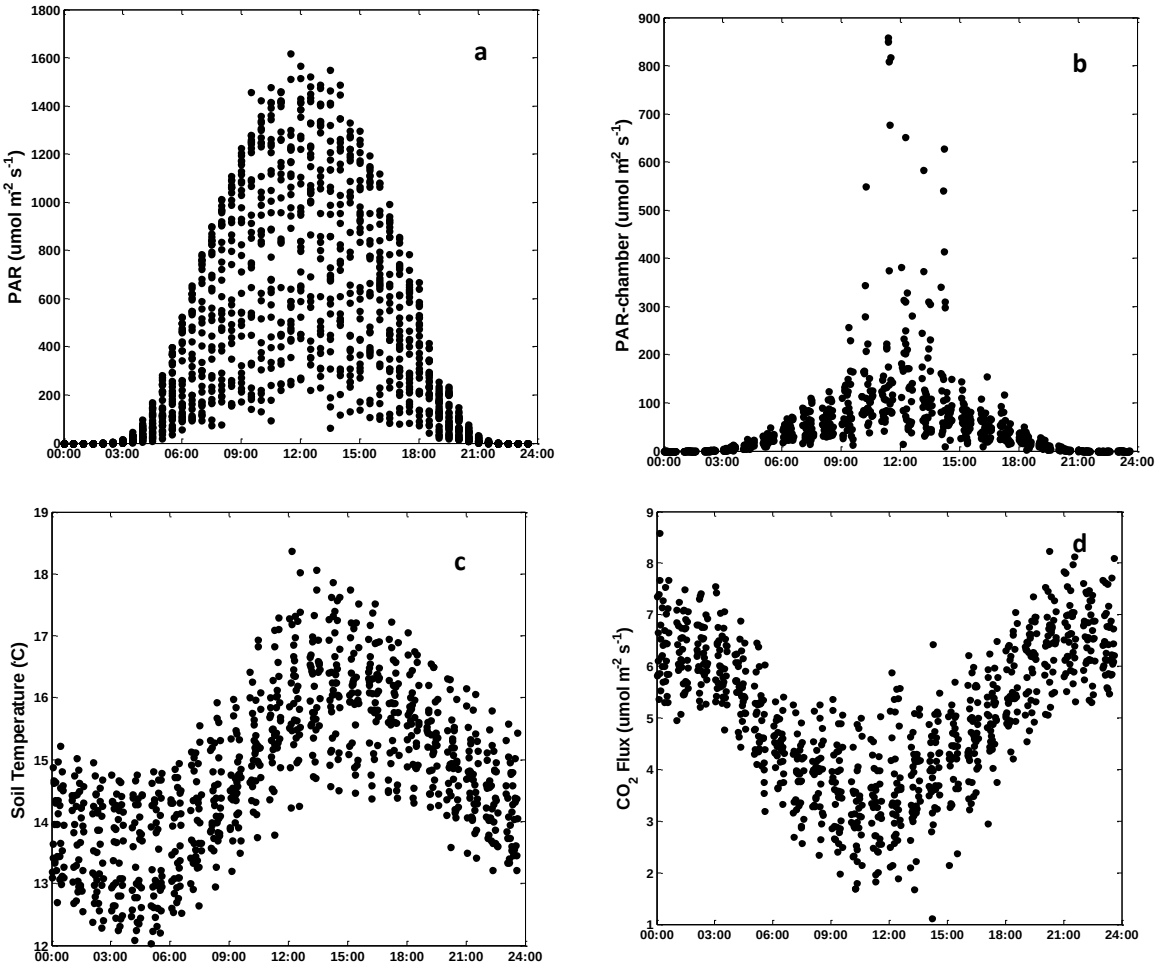


**Figure. 20** Daily distributions of tower PAR (a), chamber PAR (b), soil temperature (c), and $CO_2$ flux (d) for chamber 6 based on the data of July 2007.

PAR above the canopy reached the highest at around 12:00 in the middle of a day (Fig.20a), the same as PAR measured in the chamber (Fig.20b). The highest soil temperature occurred at around 15:00 in the afternoon, and the lowest soil temperature happened between 3:00 and 6:00 in the early morning (Fig.20c) during summer. The highest Rs rate measured in the chamber happened at around 21:00 in the night and reached the lowest level at noon (Fig.20d) in summer time. There were no clear daily patterns for soil temperature and soil CO2 fluxes in chambers during off season.

One of the aims in this project was to find the time lag between the peak PAR and the peak soil respiration based on the theory that assimilated carbon through photosynthesis takes time to transport from leaves to the root. In addition, the effusion of exudates from root cells to the rhizosphere and $CO_2$ molecules diffuse through soil medium up into the atmosphere also take time. Thus, there is probably a peak of $CO_2$ emission from soil following a peak of PAR within 5 days. But after examining the PAR measured on the tower, a PAR pulse between two time periods of overcast days was not found.

# 4. Discussion

## 4.1 Data sorting

The criterion for data sorting was based on the resolution of this closed-dynamic-chamber system, so even in the winter time after 23rd May 2007 the minimum $CO_2$ flux was set to be -0.5 μmol $m^{-2}$ $s^{-1}$ instead of 0 μmol $m^{-2}$ $s^{-1}$for sorting the data. During growing season, the minimums of $CO_2$ fluxes were set to be even lower with considering the effect of $CO_2$ uptake by vegetation. The criterion for each month, which based on the reasonable ambient $CO_2$ concentration and $CO_2$ flux ranges and $R^2$ values as well, is aimed to keep as much good data as possible. However, it is difficult to exclude all the bad data and keep all the reliable data at the same time through one simple criterion, since there are countless influences on continuous long time in-situ measurement. Fig.1 shows that soil temperature data for chamber 5 in the late of May 2008 has error, the soil humidity data for chamber 2 and chamber 4 from June 2007 to June 2008 contain errors as well (Fig.2).The output of the ThetaProbe soil moisture instrument used is a voltage signal which depends on the soil's dielectric constant, so it is very sensitive to the surrounding conditions around the probes. Air pocket, stones and even soil density and composition can have major influence on the values of output. So for the same sampling spot, the way of placing the probe is critical to the results of soil water content.

## 4.2 Range of soil $CO_2$ flux and its variation

There is no report of soil respiration for Skyttorp so far. The ranges of measured $CO_2$ fluxes in this study are close to some previous studies in Norunda site apart from the fluxes in chamber 3, which has a much higher fluxes range during growing season. The study of soil respiration in Norunda from May to October of 1999 by Widen and Majdi (2001) showed the range of soil $CO_2$ efflux was between 1.2 and 10.5 μmol $m^{-2}$ $s^{-1}$. The study result of soil and ground vegetation respiration from Lankreijer et al (2009) at Norunda forest was in the range of 1 to 8 μmol $m^{-2}$ $s^{-1}$ from mid-September to mid-November of 2005.

There is vegetation growing on the forest floor in the warm season, consequently the measured soil respiration in the closed chamber includes both soil respiration and ground vegetation respiration. During daytime in the growing season, the vegetation uptakes $CO_2$ through photosynthetic activity, which could exert substantial influences on results of $CO_2$ fluxes in the chambers. The gross photosynthesis of ground vegetation in the chamber could be estimated by extrapolating the nighttime respiration to daytime values and take the difference with the measured $CO_2$ fluxes (Lankreijer et al., 2009; Morén and Lindroth, 2000; Reichstein et al., 2005). Chamber 3 is a good example to explain the influences of vegetation on the measured $CO_2$ fluxes. As Fig.3 indicates, the soil respiration rate of chamber 3 could reach above 15 μmol $m^{-2}$ $s^{-1}$ in August 2007. The high values of $CO_2$ flux possibly derived from the combination of soil respiration and vegetation respiration, or caused by a rapid increase in fungal respiration or

other biological factors (Niinistö et al., 2011). The negative values of $CO_2$ fluxes in chamber 3 (June 2008) could be explained by that the uptake $CO_2$ by vegetation through photosynthetic activity exceeded the emissions of $CO_2$ from soil and vegetation respiration. Therefore, these negative values were supposed to only take place in daytime. While the measured soil respiration rate was higher in chamber 3 than the other chambers in night during the growing season because of the vegetation respiration. Chamber 4 also contained negative values of $CO_2$ fluxes in late May 2008. It is worth to point out that there were less negative values in June 2007 comparing with the $CO_2$ fluxes of June 2008 in chamber 3; while the maximum of $CO_2$ fluxes were similar for these two months. One possible reason is that some negative data were excluded during data sorting. But after checking the raw data, there were still much more negative values in June of 2008. The soil temperature was quite similar between these two months, but the soil moisture was lower in June of 2008. One speculation is that the vegetation types changed over one year in chamber 3, there were more fungi growing in 2007 summer while in 2008 there were grasses growing in the chamber because moist soil benefited fungi growing. Or the microbial community instead of ground vegetation changed with time caused lower heterotrophic respiration rate in 2008. Another assumption is that the drier conditions partially reduce the soil respiration. The averaged soil water content of June 2007 was 15 vol%, and it was 9 vol% in chamber 3 for June 2008. So even these two time periods keep the same level of $CO_2$ uptake by vegetation, the overall results could incline to more negative values in June of 2008 which has a relatively lower soil respiration. As Fig.9 showed that the averaged $CO_2$ flux of each month from November 2006 to June 2007 was higher than the same time from November 2007 to June 2008. This study site was thinned in 2005, which could bring more plant residues to the soil to decompose in 2006. The position of each chamber was not changed since the measurement started. The amount of input of carbon to the soil in each chamber was decreasing with time because of the lid of chamber blocking part of leaves or residues of plant falling inside of chamber, which was possibly one reason to explain why the $CO_2$ flux in one chamber from November 2007 to June 2008 was lower when comparing with the flux of same time period from November 2006 to June 2007.

As mentioned above, there was vegetation growing in chamber 3 during the growing season. The vegetation possibly blocked the PAR sensor placed in the chamber, which could explain what Fig.19 showed that the PAR measured in chamber 3 was lower than the other chambers. During winter time, PAR for each chamber was close to zero, which indicated the photosynthetic activities stopped in chambers. So in the winter time, the $CO_2$ fluxes measurements are almost purely soil respiration. However, it does not mean that the measurements in winter are more accurate, because the snow pack could cause influences on $CO_2$ fluxes. The magnitude of influence depends on the characteristics of snow pack, such as volume and density. In addition, low $CO_2$ flux requires high resolution of measurements.

The highest soil respiration rate happened in August (Fig.3) after the maximum solar radiation in June (Fig.18) and after a long time period with high soil temperature from June to Mid-August (Fig.1). One explanation is that 95% percent of annual carbon is accumulated in the six warmest months for a Swedish boreal Scots pine forest, thus the rapid increases in photosynthesis in the early growing season could offer more photosynthates for root respiration

(Keel et al., 2006, Niinistö et al, 2011). So the highest soil respiration rate occurs in the late summer when both root respiration and microbial decomposition reach high level. The occurrence of peak $CO_2$ fluxes could possibly vary from different forests and different sites under different climate conditions. Low temperature is the main reason for reducing soil respiration rate in winter time for boreal forest ecosystem (Niinistö et al., 2011), and there is low vegetation activities on the forest floor, therefore, the variations among each chamber and each month are very small. While the monthly averaged $CO_2$ fluxes for chamber 3 during winter time were still larger than that of other chambers. As discussed above, there was vegetation existing in chamber 3 during growing season, so more organic soil was developed from ground vegetation remains. The decomposition of larger organic matter content possibly leaded to the larger $CO_2$ flux in chamber 3 even in the winter time. The underground root biomass in the chamber varied from each other, it could be possible that the root biomass in chamber 3 was higher than that in other chambers. In the past studies, the contribution of root respiration to the total soil $CO_2$ flux was estimated between 10 to 90% depending on the types of ecosystem and the adopted method (Bhupinderpal-Singh et al., 2003; Hanson et al., 2000). The research of Bhupinderpal-Singh et al (2003) showed that root respiration was not as sensitive as heterotrophic respiration by measuring root and microbial respiration separately in response to a 6℃ drop of soil temperature during 20 days. Therefore, the root respiration in chamber 3 probably contributed a larger part to the total soil respiration, which could explain why the larger monthly averaged $CO_2$ fluxes occurred in chamber 3 during winter time.

## 4.3 Response of $R_s$ rate to soil temperature and soil moisture

The seasonal variation of soil temperature and $CO_2$ fluxes are consistent, while there is a negative linear relationship between soil temperature and soil water content (Fig.8). Temperature is an indicator of the potential evapotranspiration to the atmosphere, and there was a positive linear relationship between air temperature and potential evapotranspiration (Mckenney & Rosenberg, 1993; Shaw & Riha, 2011). In the summer time, both of air temperature and evapotranspiration rate are high, and soil water content will consequently decrease because of the high evapotranspiration rate in summer.

No good relationship was found between soil respiration and soil moisture through the quadratic and hyperbolic models on different time scales. The soil water content was in the range of 5 vol% to 48 vol% for chamber 3, 5 and 6 from June 2007 to November 2008, and more than 90% of the data had soil water content over 10 vol%. We speculate that soil water content is not the controlling factor to soil respiration in this study site. Soil moisture becomes a controlling factor to soil respiration rate only at very high and very low moisture levels, and the threshold values seem to be site-specific (Lellei-Kovács et al., 2011). The very dry conditions can affect the diffusion of enzymes and substrates and basic mobility of micro-organisms (Sowerby et al., 2008); but there is no drought time period to show a pronounced limitation of microbial decomposition underground to reduce the soil respiration rate in this study. On the other hand, high soil water content in winter could dissolve more $CO_2$ in the water thus reduce actual $CO_2$ fluxes (Lellei-Kovács et al., 2011). The soil respiration rate is quite low during

winter, thus the negative effect of high soil water content on $CO_2$ fluxes is possibly diminished. In chamber 5, the maximum $CO_2$ fluxes occurred when soil water content was around 22 vol% both in winter time and summer time (Fig.16a), but there is no such trend occurring in chamber 3 and chamber 6. One explanation for this difference among chambers is that ThetaProbe is very sensitive to its surrounding, so slight differences in the soil texture could produce big differences in the output of soil moisture. The other reason could be that the optimal soil water content for $R_s$ rate varies spatially since it is related to wood density and topsoil N content (Vincent et al., 2006).

The annual $Q_{10}$ value varies from 2.63 to 3.45 in this study, which is well fitted in the reasonable range. For chamber 2, the $Q_{10}$ is declining from 7.12 to 2.05 with enhanced temperature. This is in line with all the studies about soil temperature sensitivity, which is declining with increasing temperature (Niinistö et al., 2011; Gaumont-Guay et al., 2006; Lloyd & Taylor, 1994; Janssens & Pilegaard, 2003). But the exponential model does not work well on the data containing daytime measurements. In summer, the range of soil temperature probably is very narrow, while the $CO_2$ fluxes show a relative high variation in the daytime because of influences of ground vegetation. It also indicates that when the temperature is above 15 ℃, the other environmental factors, such as soil water content, substrate availability and microbial communities, probably exert greater influences on soil respiration rate.

The positive correlation between $Q_{10}$ and soil water content (Fig.11) has been found in different forest ecosystems, but it only exists in an intermediate soil water content range between the low threshold and high threshold (Wang et al., 2010, Wang et al., 2006). The study of Curiel Yuste et al (2003) revealed that the temperature sensitivity of soil respiration would decrease when soil water content decreases to less than 15 vol%. This is because of that the temperature dependence for $R_s$ would decline when soil water content becomes a limiting factor. Another study of temperate Douglas-fir forest by Jassal et al (2008) showed that when the soil water content was between 11 vol% and 22 vol%, the $Q_{10}$ was positively correlated with soil water content. The averaged soil water content displayed in Fig.11 is between 16 vol% and 29 vol%, so this range probably is between the low and high thresholds for this study site.

The exponential regression model could explain the relationship between soil respiration and soil temperature during night time with high $R^2$ value above 0.8 for chamber 3 and chamber 6 on annual time scale. Fig.13, which shows the correlation between measured $CO_2$ fluxes and modeled $CO_2$ fluxes for both nighttime and daytime, exhibits that the estimated daytime soil respiration by Eqn5 is higher than the measured soil respiration for both chamber 3 and chamber 6. This is due to the fact that measured soil respiration is the result of emitted $CO_2$ from soil deducts the uptake of $CO_2$ by ground vegetation through photosynthesis in the daytime. Fig.13 also shows that the estimated $CO_2$ fluxes are lower than the measured $CO_2$ fluxes in the nighttime when the soil respiration rate is high, this could be explained by the vegetation respiration in the night enhances the measured soil $CO_2$ emission. The soil temperature was measured at 3cm depth in this study, and 3cm-depth soil has higher temperature variation comparing with deeper soil layer. This is because of that the topper soil layer tightly follows the variation of net radiation on the ground. So the 3-cm soil temperature

could rise quickly in the daytime when the solar radiation reaches ground, and it also decreases faster during night when the ground heat flux needs to transport upward. As previously mentioned, more than 75% of soil $CO_2$ flux is created in the top 20 cm soil (Jassal et al., 2005).Therefore, 3-cm soil temperature is generally higher than the averaged soil temperature of whole soil layer for $CO_2$ production during daytime, while it is lower than the average temperature of whole soil respiration layer in the nighttime due to the delay of temperature signal transporting downward into the soil. Consequently, the estimated $CO_2$ fluxes are higher in the daytime and lower in the nighttime than the measured $CO_2$ fluxes. The residuals, which derived from modeled soil $CO_2$ fluxes subtracting the measured $CO_2$ fluxes, became positive with the rising PAR in chambers during daytime (Fig.14). This is because of that Eqn5 could not take account of the reducing effect of photosynthesis on the soil $CO_2$ emissions in chambers. Therefore, for the same temperature, the estimated $CO_2$ fluxes could be higher or lower than the measured $CO_2$ fluxes, which depends on the vegetation constitution in chambers and season time. Temperature sensitivity is higher at low temperature and decrease with rising soil temperature (Lloyd& Taylor, 1994; Widen, 2002), so $R_{10}$ decreases with increasing soil temperature. While $R_{10}$ was used as a fixed constant in Eqn5 when calculating $CO_2$ fluxes. So this equation systematically leads to underestimates of fluxes at low temperatures and overestimates fluxes at high temperature.

Soil temperature and soil moisture is closely related, hence, it is difficult to examine temperature dependence and moisture dependence of soil $CO_2$ emissions separately. Therefore, a bivariate model that contains both soil temperature and soil moisture could be better to explain the relationship between $R_s$ rate and these two environmental factors. In the study of Vincent et al (2006), a log normal distribution was included in a bivariate model (Appendix 4) for analyzing spatial and seasonal variations of $R_s$ in a temperate deciduous forest and obtained good fitting for the whole data set. The ranges of parameters in the bivariate model (a-the normalized soil respiration at both 10℃ and optimal soil water content; b-temperature sensitivity factor; c-the optimal water content for soil respiration; d-coefficient describing the shape of the relationship between $R_s$ and soil water content) from the reference (Vincent et al., 2006) were applied for this study site, but no useful results were obtained. But if suitable parameters ranges are found, this bivariate model would be a great tool.

## 4.4 Response of $R_s$ rate to PAR

The only approach applied in this study to find the time lag between the peak of soil respiration and the peak PAR above canopy was examining the time series of tower PAR data and $CO_2$ fluxes data. But it was failed to find a peak PAR between two time periods of overcast days from the available data. Even if a peak PAR above canopy was found, the time lag between $R_s$ and PAR could possibly not be found through this simple method. The dependence of $R_s$ on photosynthesis is because the photosynthetic process provides carbon source for root respiration (Tang et al., 2005). While the photosynthesis and respiration of ground vegetation exerts big influences on the chamber measured soil respiration. Therefore, the connection between photosynthetic activity and soil $CO_2$ emission could possibly be masked by the

influences of ground vegetation and other $CO_2$ sources which are independent of photosynthesis (decomposition of litter and SOM) (Kuzyakov et al., 2010). So as to investigate the time lag between photosynthetic activity and root-derived respiration, a partitioning method such as tree-girdling (Högberg et al., 2001) or isotope ($\delta^{13}C$) analysis (Ekblad & Högberg, 2001) is necessary to quantify the time required for carbon transformation from canopy photosynthesis to become available for root respiration.

# 5. Conclusion

The seasonal variability of soil $CO_2$ fluxes could be mainly explained by the seasonality of 3-cm depth soil temperature at Skyttorp during this time period. The temperature sensitivity $Q_{10}$ was decreasing with enhanced soil temperature when the temperature was in the range of 0 to 15 ℃. The $Q_{10}$ exponential function (Eqn4) worked well when soil temperature was below 15 ℃, and the variation of fluxes was enhanced because of ground vegetation when soil temperature was higher than 15 ℃. During growing season, the photosynthetic activity could cause negative $CO_2$ fluxes in chambers in daytime, and the measured soil respiration in nighttime contained soil $CO_2$ emission and ground vegetation respiration. There was a positive correlation between $Q_{10}$ and soil water content when soil water content was in the range of 15 vol% to 30 vol%. Overall, $R_{10}$ regression model (Eqn5) provided good estimation of $R_s$ in both of daytime and nighttime. The effect of photosynthesis to the measured soil respiration rate in chamber 3 and 6 was around 5 μmol $m^{-2}$ $s^{-1}$. No evidence of influences from soil water content on soil respiration was found except there was a decrease of $CO_2$ flux in chamber 6 when the soil water content exceeded 33 vol% during growing season of 2008. Because of the influences of ground vegetation in growing season, the highest and lowest $CO_2$ fluxes could happen under the same soil moisture condition. Probably soil moisture was not the limiting factor for soil respiration in this study site. The time lag between soil respiration and photosynthesis has not been found either through the time series analysis of $CO_2$ fluxes from soil and PAR above canopy.

To investigate the dependence of $R_s$ on environmental factors, more detailed and continuous measurements of environmental factors are necessary due to the complexity of soil underground. Such as the soil temperature profile, soil water content profile and water table, $CO_2$ sources production, soil organic material density, wood density, and gross primary production of forest ecosystem. Soil temperature profile could offer the best correlation between soil $CO_2$ emissions and soil temperature at a certain layer, the same as soil water content profile. The interactive effects of soil temperature and soil moisture on Rs could be further investigated with the help of a bivariate model. The isotope analysis is useful to track the carbon from canopy photosynthesis to become available for root respiration. The $R_s$ rate is also related to substrate availability and soil bulk density and N content. $R_s$ is not only part of carbon cycle of a whole forest ecosystem, it also coupled with the gross primary production. In addition, another challenge for this investigation is decoupling the influences of each environmental factor. Automated chamber system provides continuous measurements of $CO_2$ fluxes with good accuracy, but the effects of photosynthesis and autotrophic respiration from ground vegetation during growing season should be excluded.

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# Appendices

## Appendix 1

The criterions for data sorting from June 2006 to November 2008. Ambient $CO_2$ is the range of ambient $CO_2$ concentration (ppm), $R^2$ is the coefficient of determination, $CO_2$ Flux min is the lower limit of $CO_2$ flux (μmol $m^{-2}$ $s^{-1}$), $CO_2$ Flux max is the upper limit of $CO_2$ flux (μmol $m^{-2}$ $s^{-1}$), n1 is the number of selected data, and n2 is the number of raw data. Percentage is n1/n2.

| Date | Ambient $CO_2$ | $R^2$ | $CO_2$ Flux min | $CO_2$ Flux max | n1 | n2 | Percentage |
|---|---|---|---|---|---|---|---|
| 2006-06 | 340-550 | >=0.8 | -6 | 14 | 973 | 1198 | 81% |
| 2006-07&08 | 340-700 | >=0.8 | -10 | 20 | 3030 | 4003 | 76% |
| 2006-09 | 370-700 | >=0.9 | -7 | 25 | 2796 | 3493 | 80 % |
| 2006-10 | 380-680 | >=0.81 | -7 | 17 | 3620 | 4901 | 74% |
| 2006-11 | 370-500 | >=0.6 | -5 | 7 | 2237 | 4819 | 46% |
| 2006-12 | 370-450 | >=0.7 | -1 | 6 | 1232 | 4694 | 26% |
| 2007-01 | 350-440 | >=0.6 | -1 | 8 | 741 | 3727 | 20% |
| 2007-02 | 340-440 | >=0.5 | -1 | 5.5 | 1091 | 5041 | 22% |
| 2007-03 | 360-470 | >=0.6 | -1 | 7 | 1644 | 5703 | 29% |
| 2007-04 | 350-490 | >=0.6 | -5 | 7 | 1678 | 4260 | 39% |
| 2007-05 | 370-500 | >=0.6 | -3 | 8 | 2417 | 3794 | 64% |
| 2007-06 | 360-550 | >=0.8 | -4 | 12 | 3633 | 5662 | 64% |
| 2007-07 | 360-700 | >=0.9 | -4 | 24 | 6435 | 7736 | 83% |
| 2007-08 | 370-680 | >=0.9 | -0.5 | 18 | 2921 | 3507 | 83% |
| 2007-09 | 370-560 | >=0.9 | -0.5 | 13 | 4820 | 5799 | 83% |
| 2007-10 | 360-550 | >=0.9 | -0.5 | 8 | 4803 | 5779 | 83% |
| 2007-11 | 370-480 | >=0.9 | -0.5 | 5.1 | 3797 | 4631 | 82% |
| 2007-12 | 390-465 | >=0.8 | -0.5 | 7.1 | 5003 | 6060 | 83% |
| 2008-01 | 390-440 | >=0.8 | -0.5 | 4 | 3499 | 4232 | 83% |
| 2008-02 | 390-460 | >=0.8 | -0.5 | 5 | 3275 | 3985 | 82% |
| 2008-03 | 390-460 | >=0.8 | -0.5 | 4 | 4842 | 5927 | 82% |
| 2008-04 | 360-560 | >=0.9 | -0.5 | 7 | 4741 | 5811 | 82% |
| 2008-05 | 350-481 | >=0.9 | -2 | 6 | 4936 | 6080 | 81% |
| 2008-06 | 330-510 | >=0.9 | -5 | 9 | 2760 | 3428 | 81% |
| 2008-07 | 370-515 | >=0.9 | -4 | 7 | 130 | 175 | 74% |
| 2008-08 | 360-660 | >=0.9 | -0.5 | 14 | 1257 | 1512 | 83% |
| 2008-09 | 350-590 | >=0.9 | -0.5 | 13 | 4445 | 5335 | 83% |
| 2008-10 | 350-520 | >=0.9 | -0.5 | 10 | 4804 | 5774 | 83% |
| 2008-11 | 360-480 | >=0.9 | -0.5 | 7 | 1637 | 1989 | 82% |

# Appendix 2

The results of calculated $Q_{10}$ and $R_{10}$ for 5 chambers. $Q_{10}$ is the temperature sensitivity of soil respiration calculated from Eqn4, $R_{10}$ is the soil respiration rate at 283.15K calculated from Eqn5, $R^2$ is the coefficient of determination, and n is the numbers of data.

| Chamber No. | Time period | $Q_{10}$ | | | $R_{10}$ | | |
|---|---|---|---|---|---|---|---|
| | | $Q_{10}$ | $R^2$ | n | $R_{10}$ | $R^2$ | n |
| **2** | Jun 2007 - May 2008 | 3.31 | 0.79 | 10538 | 3.53 | 0.87 | 6277 |
| | Jun 2007 – Oct 2007 | 1.71 | 0.34 | 4279 | 3.86 | 0.72 | 2056 |
| | Jun 2007-Aug 2007 | 1.59 | 0.11 | 2400 | 3.70 | 0.58 | 920 |
| | Dec 2007- Feb 2008 | 6.46 | 0.65 | 2381 | 2.45 | 0.60 | 2030 |
| **3** | Jun 2007 - May 2008 | 3.07 | 0.74 | 10403 | 7.46 | 0.87 | 5946 |
| | Jun 2007 – Oct 2007 | 2.35 | 0.50 | 4277 | 7.98 | 0.80 | 2022 |
| | Jun 2007-Aug 2007 | 2.67 | 0.26 | 2455 | 7.98 | 0.59 | 913 |
| | Dec 2007- Feb 2008 | 10.79 | 0.59 | 2356 | 6.73 | 0.47 | 1897 |
| **4** | Jun 2007 - May 2008 | 2.63 | 0.55 | 10170 | 3.82 | 0.71 | 5386 |
| | Jun 2007 – Oct 2007 | 1.87 | 0.47 | 4144 | 3.93 | 0.81 | 1788 |
| | Jun 2007-Aug 2007 | 1.55 | 0.12 | 2264 | 3.81 | 0.62 | 750 |
| | Dec 2007- Feb 2008 | 1.84 | 0.02 | 2391 | 4.99 | 0.06 | 1791 |
| **5** | Jun 2007 - May 2008 | 3.26 | 0.78 | 10211 | 3.69 | 0.83 | 5091 |
| | Jun 2007 – Oct 2007 | 2.16 | 0.59 | 4291 | 3.95 | 0.62 | 1718 |
| | Jun 2007-Aug 2007 | 2.62 | 0.46 | 2414 | 3.66 | 0.56 | 710 |
| | Dec 2007- Feb 2008 | 7.25 | 0.36 | 2276 | 3.02 | 0.42 | 1641 |
| **6** | Jun 2007 - May 2008 | 3.45 | 0.75 | 10281 | 4.38 | 0.92 | 5151 |
| | Jun 2007 – Oct 2007 | 1.93 | 0.35 | 4332 | 4.69 | 0.88 | 1716 |
| | Jun 2007-Aug 2007 | 1.57 | 0.07 | 2460 | 4.60 | 0.73 | 713 |
| | Dec 2007- Feb 2008 | 8.02 | 0.37 | 2343 | 3.12 | 0.43 | 1708 |

# Appendix 3

The results of calculated constant parameters for quadratic and hyperbolic functions. a,b,c are coefficient constants for Eqn 6, x,y,z are coefficient constants for Eqn 7. $R^2$ is the coefficient of determination.

| Time period | Chamber No. | Range of soil water content (Vol/Vol) | Quadratic | | | | Hyperbolic | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | a | b | c | $R^2$ | x | y | z | $R^2$ |
| Jun2007-Oct2007 | 3 | 0.06-0.40 | -121.9 | 31.4 | 8.0 | 0.19 | 20.7 | -41.7 | -0.6 | 0.21 |
| | 5 | 0.06-0.32 | -87.8 | 28.4 | 2.5 | 0.02 | 10.1 | -18.8 | -0.4 | 0.05 |
| | 6 | 0.06-0.44 | -37.1 | 14.3 | 3.7 | 0.06 | 8.8 | -10.9 | -0.3 | 0.08 |
| Nov2007-Mar2008 | 3 | 0.08-0.44 | 38.3 | -11.9 | 1.9 | 0.39 | -3.6 | 14.9 | 0.3 | 0.36 |
| | 5 | 0.14-0.38 | 24.1 | -8.6 | 1.6 | 0.12 | -2.0 | 1.9 | 0.2 | 0.11 |
| | 6 | 0.09-0.48 | 12.8 | -4.4 | 1.0 | 0.19 | -1.4 | 5.7 | 0.2 | 0.18 |
| Apr2008-Oct2008 | 3 | 0.06-0.43 | -79.5 | 41.9 | 0.3 | 0.11 | 8.3 | -5.5 | -0.4 | 0.08 |
| | 5 | 0.12-0.45 | 14.5 | -5.8 | 3.2 | 0.01 | 0.7 | 4.9 | 0.2 | 0.01 |
| | 6 | 0.05-0.46 | -67.9 | 30.2 | 0.5 | 0.20 | 7.1 | -10.2 | -0.3 | 0.09 |
| Sep2008-Nov2008 | 2 | 0.12-0.37 | -56.3 | 15.0 | 2.8 | 0.34 | 11.7 | -24.9 | -0.6 | 0.36 |
| | 4 | 0.21-0.43 | -90.2 | 50.4 | 3.2 | 0.11 | 23.8 | -36.0 | -2.7 | 0.12 |
| Jun2007-Nov2008 | 3 | 0.06-0.44 | -38.0 | 2.0 | 0.7 | 0.21 | 13.7 | -25.9 | -0.3 | 0.22 |
| | 5 | 0.06-0.46 | 33.5 | -26.5 | 7.2 | 0.20 | 5.9 | -11.1 | -0.0 | 0.19 |
| | 6 | 0.05-0.48 | -54.2 | 20.0 | 2.4 | 0.30 | 9.6 | -17.1 | -0.4 | 0.29 |

# Appendix 4

The bivariate model applied in the study of Vincent *et al* (2006):

$$R_s = a\exp\left[-\left(\frac{\ln\left(\frac{Ws}{c}\right)}{d}\right)^2\right] \exp[b(Ts-10)]$$

$R_s$: soil respiration (μmol $m^{-2}$ $s^{-1}$);
$W_s$: soil water content ($m^3/m^3$);
$T_s$: soil temperature (℃);
a: the normalized soil respiration at both 10 ℃ and optimal soil water content;
b: temperature sensitivity factor;
c: the optimal water content for soil respiration;
d: coefficient describing the shape of the relationship between Rs and Ws.

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