Sub-experiment 2

The effect of drying and rapid rewetting of soil on CO₂ efflux
INTRODUCTION

Soil CO\textsubscript{2} efflux or soil respiration ($F_s$) is a major component of the terrestrial carbon cycle (Davidson et al., 1999; Falk et al., 2005; Stolbovoi, 2003) because it constitutes up to about three-quarters of the total ecosystem respiration (Law et al., 2001). It has been recognized that relatively small changes in soil respiration induced by climate change can have large impact on atmospheric CO\textsubscript{2} concentration (Jenkinson et al., 1992; Raich and Schlesinger, 1992). To date, many measurements of $F_s$ have been made in various ecosystems to estimate how much CO\textsubscript{2} is released from the soil and to address the relationships between $F_s$ and environmental conditions (e.g. Borken et al., 2006; Davidson et al., 1998; Davidson et al., 2004; Davidson et al., 2008; Epron et al., 1999; Jassal et al., 2008; Jia et al., 2006). Soil temperature and soil moisture content are considered the most influential environmental factors controlling $F_s$ at the global scale (Raich and Schlesinger, 1992; Raich et al., 2002). Since increased altered global temperature and precipitation pattern in many regions of the world has been widely predicted (IPCC, 2007), CO\textsubscript{2} fluxes from soils are likely to be altered (Raich et al., 2002). It is thus important to understand which environmental factors control on $F_s$ and, moreover, how these factors affect CO\textsubscript{2} emissions from soils.

In the absence of drought stress, soil temperature is typically a reliable predictor of $F_s$ (Curiel Yuste et al., 2003; Drewitt et al., 2002; Moncrieff and Fang, 1999). However, other biotic and abiotic factors have been reported to influence $F_s$ such as soil water content (Davidson et al., 1998; Davidson et al., 2000; Epron et al., 1999).
1999; Jassal et al., 2008; Jia et al., 2006; Reichstein et al., 2002), soil organic matter quantity and quality (Cleveland et al., 2006; Schlesinger and Andrews, 2000; Taylor et al., 1989), root and microbial biomass (Han et al., 2007; Parkin et al., 2005; Vargas and Allen, 2008; Wang et al., 2003), and soil texture (Dilustro et al., 2005; Raich and Potter, 1995; Wang et al., 2003). In the presence of drought, the amount and distribution of precipitation have also been shown to control $F_s$ (Cable and Huxman, 2004; Cable et al., 2008; Chen et al., 2008; Curiel Yuste et al., 2003; Jarvis et al., 2007; Lee et al., 2002; Patrick et al., 2007). Rain exerts control during dry periods either by controlling soil water content pulses in surface layers where most of the biological activity occurs (Lee et al., 2002) or by stimulating soil CO$_2$ emissions in what is called the “Birch effect” or “drying and rewetting effect” (Birch, 1958; Birch, 1959; Borken et al., 1999; Borken et al., 2003; Davidson et al., 2000; Jarvis et al., 2007; Lee et al., 2002).

By far however, the measurements made in the above studies were done at a coarse resolution by weekly or even bi-weekly sampling and often miss the CO$_2$ pulses resulting from precipitation. Such studies may generate large uncertainties total seasonal and annual values of $F_s$. Therefore, a combination of high-temporal resolution measurements of $F_s$ using the soil CO$_2$ gradient method, soil moisture and temperature data is used in this study to elucidate the effect of rewetting of dried soil on $F_s$ in relation to environmental controls.
METERIALS AND METHODS

Site description

The experiment was conducted in a rainfed peanut field located in Unadilla, Georgia, USA in 2007. The details of site study were described in the experiment 1. Total rainfall at the study site during the period of the experiment was 327 mm (Figure 5.1). Soil water content (SWC) followed patterns of precipitation. Maximum daily average soil water content (0.135 m³ m⁻³) across the upper soil layer (0.02-0.05 m) occurred on DOY 184. This study focuses specifically on a 5.8 mm rain event that followed an intense drought period (DOY 215 to 229) (Figure 5.1).

Soil CO₂ gradient method

Field measurements

Two CO₂ probes (GMP343, Vaisala Corp., Vantaa, Finland) were installed horizontally with the diffusion slot downward at the depths of 0.02 and 0.05 m between the peanut rows from DOY 173 to DOY 272. We also installed custom-built chromel–constantan soil thermocouples at depths of 0.02, 0.05, 0.08, and 0.30 m and soil moisture sensors (CS616, Campbell Scientific, Logan, UT) at 0.02 and 0.02 to 0.05 m. The latter were co-located with soil CO₂ concentration probes to simultaneously measure soil temperature (Tₛ) and moisture. The soil CO₂ concentration, soil temperature, and soil moisture profile measurements were recorded to a datalogger (CR1000, Campbell Scientific, Logan, UT) at 5 min intervals and then 30-min average data are used in the present analysis.
Figure 5.1. Daily averages of soil water content (SWC) at the depth of 2-5 cm and the daily total precipitation (PPT) over the course of the study. DOY means days of year. Horizontal bar shows the observation period.
**Soil CO$_2$ efflux calculation**

Soil CO$_2$ efflux calculation procedure was already discussed in the experiment 3.1. In order to compute $\xi$, the model that proposed by Moldrup et al. (1997) was used,

\[
\xi = 0.66(\phi - SWC) \left( \frac{\phi - SWC}{\phi} \right)^{12-m} \text{ (Moldrup et al., 1997),} \tag{5.1}
\]

where $SWC$ is the volumetric soil water content, $\phi = \rho_b / \rho_m$ is the porosity (where $\rho_b$ is the bulk density with a value of 1.19 g cm$^{-3}$ in this site study and $\rho_m$ is the particle density of mineral soil with a typical value of 2.65 g cm$^{-3}$), and $m$ is constant equal to 3.

**Data Analysis**

Soil CO$_2$ efflux from the soil gradient method during DOY 215 to 229 was used to analyze which environmental factors control on soil CO$_2$ efflux. The exponential function was used to quantify the dependence of half-hourly soil CO$_2$ efflux on soil temperature at the 0.02 m depth (e.g. Boone et al., 1998; Davidson et al., 1998; Epron et al., 1999; Mielnick and Dugas, 2000):

\[
P_f(T_e) = ae^{bT_e}, \tag{5.2}
\]

where $a$ and $b$ are coefficients estimated by the non-linear regression. $a$ denotes the reference soil CO$_2$ efflux at 0 °C and $b$ provides an estimate of the $Q_{10}$ coefficient,
representing the degree of the dependence of soil CO$_2$ efflux on soil temperature. The latter coefficient was calculated according to the following equation:

$$Q_{10} = e^{10b}, \quad (5.3)$$

The quadratic function was used to quantify the dependence of half-hourly soil CO$_2$ efflux on soil water content in the 0.02-0.05 m soil layer:

$$F_s(SWC) = c + dSWC + fSWC^2, \quad (5.4)$$

where $c$, $d$ and $f$ are fitted parameters.
RESULTS AND DISCUSSION

Responses of soil CO₂ efflux to drying and rapid rewetting of soil

The variations of the major environmental conditions during the observation period are shown in Figure 5.2. Results show that $F_s$ was best correlated with $T_s$ at the 0.02 m depth and $SWC$ at the 0.02-0.05 m depth compared with these measurements made at the other depths (Figure 5.2). This is consistent with recent findings that most of the respiratory source strength of CO₂ in soils is generally concentrated near the soil surface (e.g. Jassal et al., 2005). Accordingly, $T_s$ at the 0.02 m depth and $SWC$ at the 0.02-0.05 m depth were used for describing $F_s$ dependence on $T_s$ and $SWC$. During dry conditions (DOY 216-224) when $SWC$ gradually decreased below the permanent wilting point (0.042 m³ m⁻³), the variation in soil respiration was closely related to those in $T_s$, $SWC$ and soil CO₂ concentration (Figure 5.2). The evidence that soil water stress strongly limited $F_s$ was observed. Soil CO₂ efflux and soil CO₂ concentration decreased with decreased $SWC$ and increased $T_s$ (Figure 5.2).
Figure 5.2  Diurnal pattern of (a) soil temperature at the depth of 0.02 and 0.05 m, (b) soil water content (SWC) at the depth of 0.02 and 0.02-0.05 m and the half-hourly total precipitation (PPT), (c) soil respiration ($F_s$) and soil diffusivity ($D_s$), and (d) soil CO$_2$ concentration at the depth of 0.02 and 0.05 m during DOY 215 – 229.
A sudden increase in soil water content due to rain on DOY 224 resulted in significant increases in soil CO2 concentration at both depths (Figure 5.2d). However, immediately after the rain stopped, $F_s$ decrease by 17% lower than $F_s$ before rain and gradually decreased and reached at the lowest values of 47% lower than $F_s$ before rain at an hour after the rain stopped (Figure 5.2c). This phenomenon can be attributed to a decrease in soil diffusivity since we observed the decrease in soil diffusivity in the top soil layer from 6.49 mm$^2$ s$^{-1}$ before rain to 5.07 mm$^2$ s$^{-1}$ immediately after the rain stopped (Fig. 2c). These results are consistent with previous findings from Smart and Penuelas (2005), Jassal et al. (2005), and Chen et al. (2005). After $F_s$ reaches its minimum, $F_s$ gradually increased and reached the peak of 3.82 µmol m$^{-2}$ s$^{-1}$ two days after rain and then decreased gradually (Figure 5.2c). Numerous studies have shown that the rapid rewetting of a dry soil by rain or irrigation can result in bursts of CO2 releases from the soil (e.g. Birch, 1958; Borken et al., 2003; Chen et al., 2008; Jarvis et al., 2007; Lee et al., 2002; Tang et al., 2005; Xu et al., 2004). Since surface soils experience large fluctuations in soil moisture content, the pulsed CO2 efflux after rewetting is likely to be a common occurrence. During a wetting-drying cycle, multiple mechanisms regulate $F_s$. It has been hypothesized that significant increase in $F_s$ following a rain event results from the displacement of CO2-rich air from within the soil (Liu et al., 2002). Rain pluses can activate microbial metabolism, resulting in an increase of $F_s$. The activation of microbial respiration might take anywhere from several hours to days (Steenwerth et al., 2005). Moreover, addition of water to an extremely dry soil can increase access to microbial substrate (Huxman et al., 2004). As the carbon source for CO2 released from soils, carbohydrate substrate quantity and quality play a critical role in controlling soil respiration (Wan and Luo, 2003). Prior to
the wetting event, the soil surface layer in this study site was extremely dry because of
the drought stress since DOY 216 (when SWC less than permanent wilting point).
Drying and rapid rewetting of soil can increase availability of labile organic substrates
through microbial death and cell lysis or by destabilizing soil aggregates making
physically protected soil organic matter accessible to microbes (Fierer and Schimel,
2003; Harper et al., 2005). Thus, the $F_s$ after rain at this site is likely trigger by a
stimulating of microbial activity and by enhancing the mineralization of organic
constituents after the prolonged dry conditions and rapid rewetting events.

**Effect of drying and rapid rewetting of soil on the sensitivity of soil CO$_2$ efflux to
soil temperature and soil water content**

Soil temperature and soil moisture are the main factors driving $F_s$ in many
ecosystems. Their relative importance however is still controversial, especially in the
water-limited ecosystems (Huxman et al., 2004). The data of both drying and
rewetting period were pooled and found no significant relationship between $F_s$ and $T_s$
(Figure 5.3a) and SWC (Figure 5.3b). However, significant exponential curve and
quadratic curve could be established between $F_s$ and $T_s$ for the rewetting period
(Figure 5.3a) and between $F_s$ and SWC for the drying period (Figure 5.3b). Results
show that during the drying period when SWC was less than 0.042 m$^3$ m$^{-3}$, $F_s$
decreased dramatically (up to 80%) and SWC took over control of $F_s$. After rapid
rewetting of dry soil on DOY 224, the rain event stimulated $F_s$ and restored
temperature control over $F_s$, even though SWC in the surface layer was low. These
results are consistent with previous reports from Curiel Yuste et al. (2003) and
suggested that restoration of temperature control occurred when rain events
adequately rewetted the uppermost soil layer, where most of the respiratory activity occurred.

For the entire $F_s$ dataset during the drying period, with all $SWC$ levels grouped together, no single temperature function was found to describe the variations in $F_s$. By contrast, when data were grouped by degree of $SWC$ ($SWC \leq 0.037 \text{ m}^3 \text{ m}^{-3}$, $0.037 < SWC \leq 0.039 \text{ m}^3 \text{ m}^{-3}$, and $SWC > 0.039 \text{ m}^3 \text{ m}^{-3}$), the significant exponential relationships between $F_s$ and $T_s$ were found (Figure 5.4). Figure 5.4 shows that the slope of $F_s$ and $T_s$ curves decreased as $SWC$ decreased. The temperature sensitivity of soil respiration is often indicated by the $Q_{10}$, which describes the response of $F_s$ to elevated temperature (Lloyd and Taylor, 1994). $Q_{10}$ varies with $T_s$, $SWC$ and thus with seasons (Conant et al., 2004; Davidson et al., 2006; Scott-Denton et al., 2003). It was observed that the values of $Q_{10}$ decreased as $SWC$ decreased (Figure 5.4). A similar decline in $Q_{10}$ of $F_s$ with decreasing $SWC$ has been reported by Conant et al. (2004), Curiel Yuste et al. (2003), Jassal et al. (2008), and Wen et al. (2006). One reason for low $Q_{10}$ at low soil water content is that water stress increases diffusion resistance thus reducing contact between substrate and the extracellular enzymes and microbes involved in decomposition. Another reason for lower $Q_{10}$ under water stress conditions is decreased substrate supply (Davidson et al., 2006) which, in this case, was likely due to (a) the drying out of the coarse fraction in the active surface layer, and (b) the reduced photosynthesis, which decreases translocation of recent photosynthates to the rhizosphere (Högberg et al., 2001).
Figure 5.3  Relationship between the half-hourly soil CO\textsubscript{2} efflux and (a) soil temperature at 0.02 m depth and (b) soil water content at 0.02-0.05 m depth during drying period (DOY 216-224) and rewetting period (after a 5.8 mm rain event on DOY 224). The non-linear regression curves were fitted with Equation 5.2 and 5.4 for soil temperature and soil water content, respectively.
Figure 5.4 Relationship between the half-hourly soil CO$_2$ efflux and soil temperature at 0.02 m depth under different soil water content (SWC). The non-linear regression curves were fitted with Equation 5.2. The temperature dependence of soil CO$_2$ efflux on soil temperature expressed by $Q_{10}$ was calculated according to Equation 5.3.