Sub-experiment 2

The effect of drying and rapid rewetting of soil on CO_2 efflux

INTRODUCTION

Soil CO_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_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_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_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_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; 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 m^3 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 CO_2 gradient method

Field measurements

Two CO_2 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 CO_2 concentration probes to simultaneously measure soil temperature (T_S) and moisture. The soil CO_2 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.

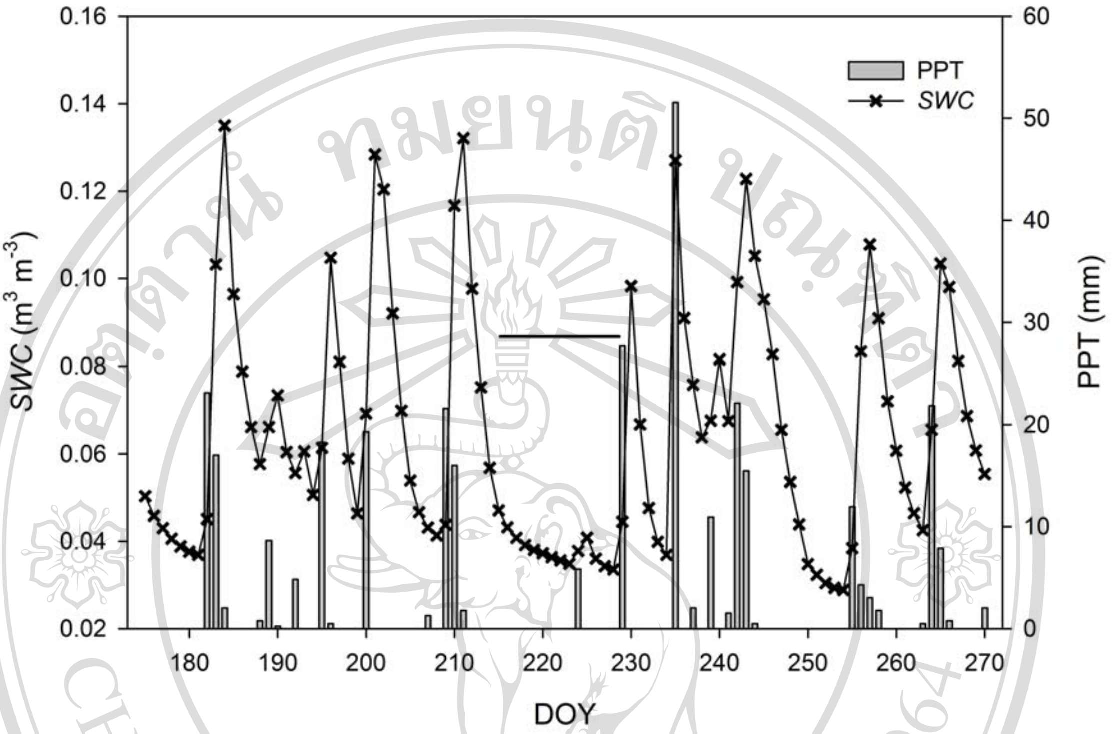

Figure 5.1 Daily averages of soil water content (*SWC*) at the depth of 2-5 cm and the daily total precipitation (*PPT*) over the course of the study. DOY means days of year. Horizontal bar shows the observation period.

Soil CO_2 efflux calculation

Soil CO_2 efflux calculation procedure was already discussed in the experiment 3.1. In order to compute ξ, the model that proposed by Moldrup *et al.* (1997) was used,

$$\xi = 0.66(\phi - SWC)\left(\frac{\phi - SWC}{\phi}\right)^{\frac{12-m}{3}} \text{ (Moldrup } et\ al.\text{, 1997),} \qquad (5.1)$$

where SWC is the volumetric soil water content, $\phi = \rho_b / \rho_m$ is the porosity (where ρ_b is the bulk density with a value of 1.19 g cm^{-3} in this site study and ρ_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):

$$F_s(T_s) = ae^{bT_s}, \qquad (5.2)$$

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:

$$Q_{10} = e^{10b}, \tag{5.3}$$

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:

$$F_s(SWC) = c + dSWC + fSWC^2, \tag{5.4}$$

where c, d and f are fitted parameters.

RESULTS AND DISCUSSION

Responses of soil CO_2 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 CO_2 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 m^3 m^{-3}), the variation in soil respiration was closely related to those in T_s, *SWC* and soil CO_2 concentration (Figure 5.2). The evidence that soil water stress strongly limited F_s was observed. Soil CO_2 efflux and soil CO_2 concentration decreased with decreased *SWC* and increased T_s (Figure 5.2).

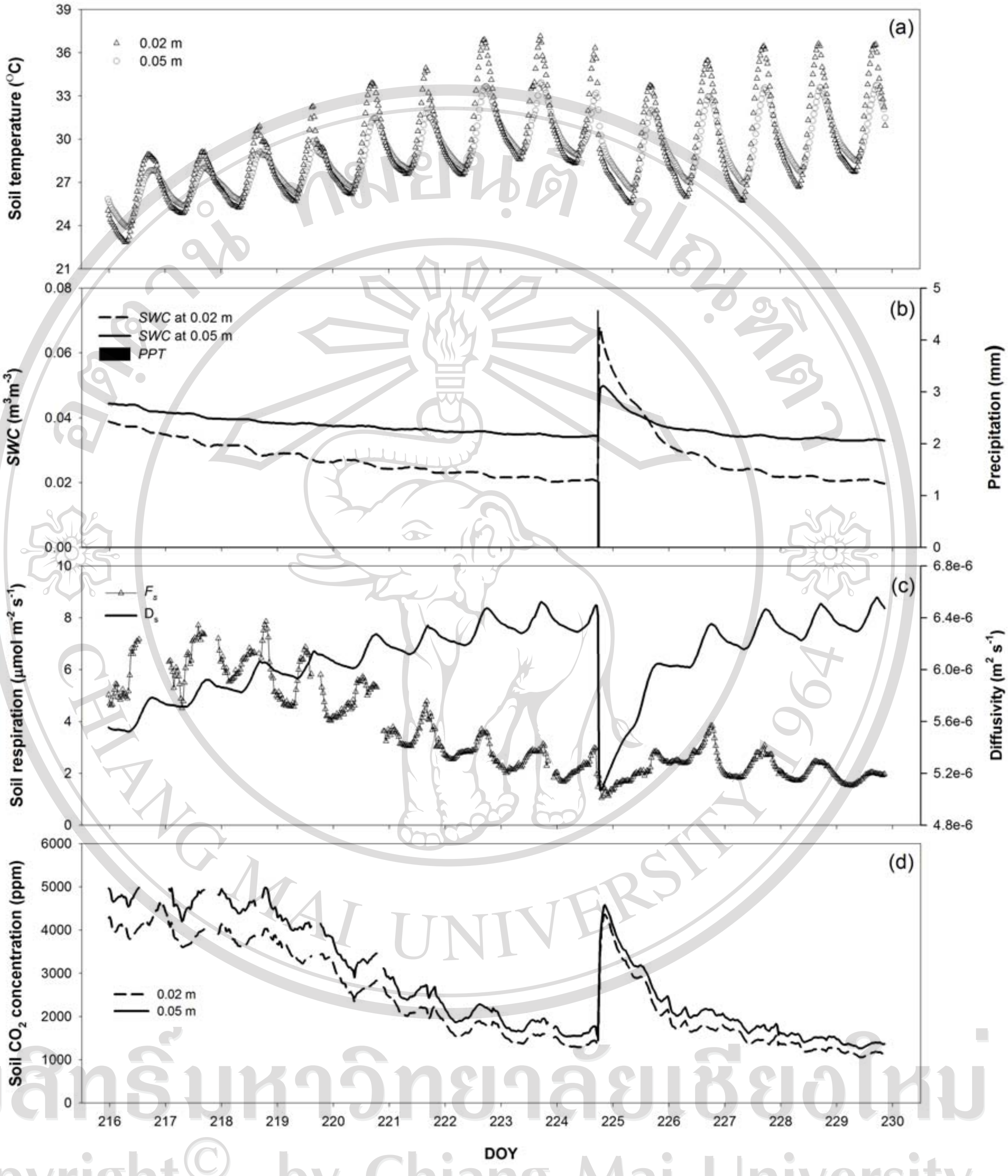

Figure 5.2 Diurnal pattern of (a) soil temperature at the depth of 0.02 and 0.05 m, (b) soil water content (*SWC*) at the depth of 0.02 and 0.02-0.05 m and the half-hourly total precipitation (*PPT*), (c) soil respiration (F_s) and soil diffusivity (D_s), and (d) soil CO_2 concentration at the depth 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 CO_2 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 CO_2 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 CO_2 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 CO_2-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 CO_2 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* ($SWC \leq 0.037$ m^3 m^{-3}, $0.037 < SWC \leq 0.039$ m^3 m^{-3}, and $SWC > 0.039$ m^3 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).

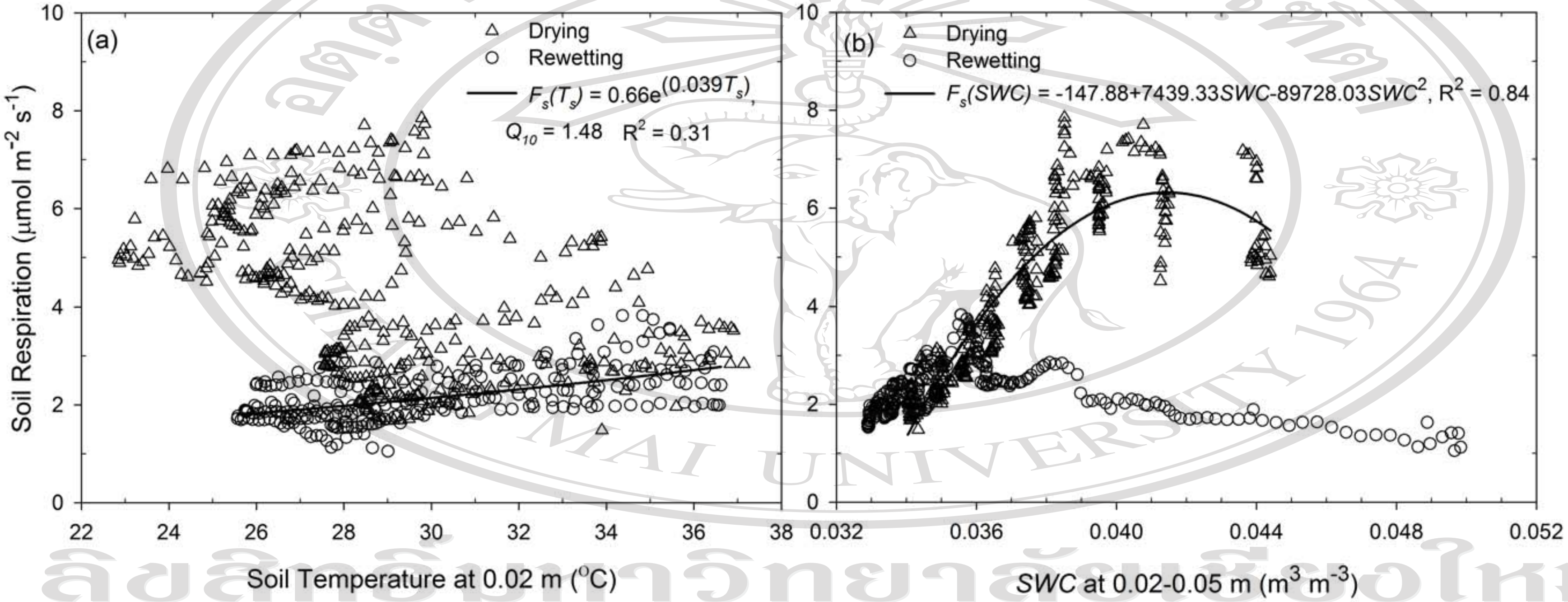

Figure 5.3 Relationship between the half-hourly soil CO_2 efflux and (a) soil temperature at 0.02 m depth and (b) soil water content at 0.02-0.05 m depth during drying period (DOY 216-224) and rewetting period (after a 5.8 mm rain event on DOY 224). The non-linear regression curves were fitted with Equation 5.2 and 5.4 for soil temperature and soil water content, respectively.

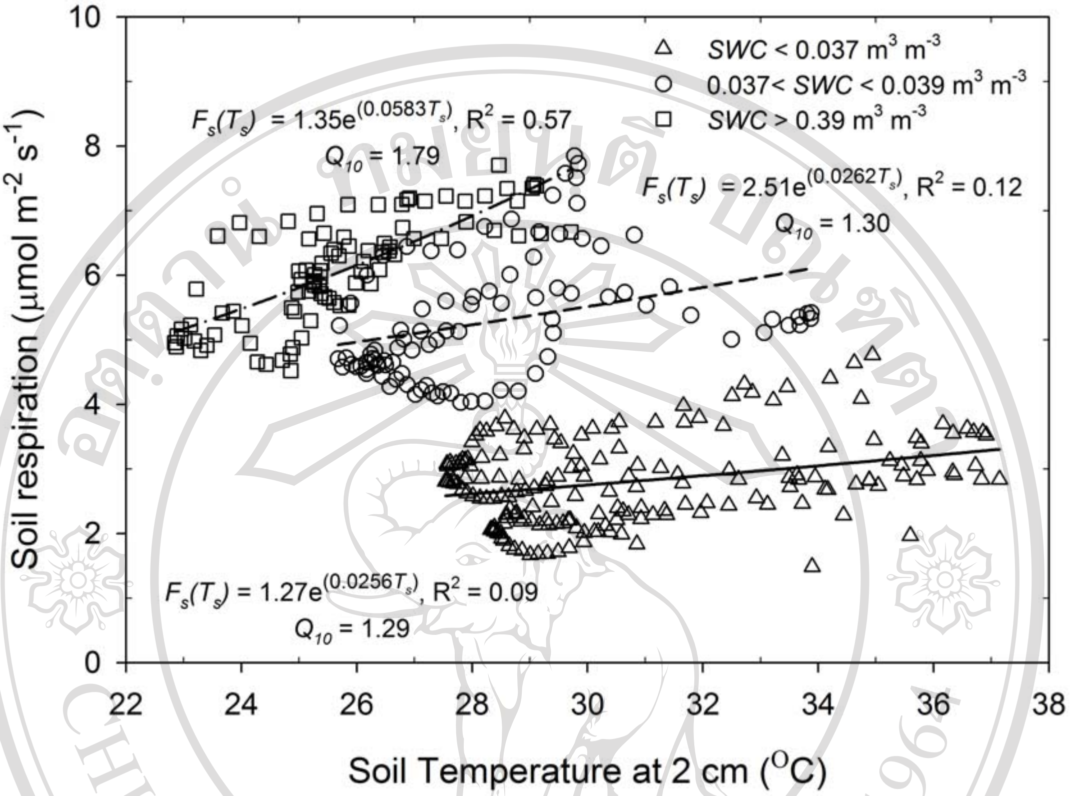

Figure 5.4 Relationship between the half-hourly soil CO_2 efflux and soil temperature at 0.02 m depth under different soil water content (*SWC*). The non-linear regression curves were fitted with Equation 5.2. The temperature dependence of soil CO_2 efflux on soil temperature expressed by Q_{10} was calculated according to Equation 5.3.