EXPERIMENT 2

Response of soil CO_2 efflux and net ecosystem exchange to rainfall variability in peanut field

Sub-experiment 1: Mechanism and environmental control of soil CO_2 efflux following rainfall events in summer peanut field

INTRODUCTION

The increasing interest in global climate change and its link to carbon dioxide (CO_2) and other greenhouse gases has fueled the atmospheric and agricultural science to study how soil fit into the global carbon cycle. Soil are now to be significant source of CO_2, hold approximately twice as much carbon (1500 Pg) as the atmosphere (780 Pg) and releasing about 68 Pg year^{-1} (Raich and Schlesinger, 1992). Interest in the factors that control soil CO_2 efflux is growing because of the potential for changing climate, including temperature and rainfall, influenced the seasonal variation in soil CO_2 efflux. Improved understanding the mechanisms and quantification of the variations in soil CO_2 efflux is essential for better managing soil CO_2 efflux potential to mitigate climate change.

Agricultural soils have the potential for large amounts of carbon and support increasing carbon sequestration in the soil (Smith, 2004) but the carbon dynamics has been less reported. Most of the agricultural production systems in the world are rainfed systems. Especially, wheat and peanut crops have differences in productivity and rooting system. Thus, soil CO_2 efflux in ecosystem of both plants may respond differently to environmental factors. The CO_2 emission from agricultural soils altered by the frequency and duration of rainfall would enable us to predict the magnitude and direction of soil C contribution to atmosphere. Therefore, the information about the carbon dynamics and mechanisms of soil CO_2 efflux is critical for understanding response of fast-growth crops.

Soil CO_2 efflux has been widely simulated using continuous records of temperature moisture and other variables (Davidson *et al.,* 1998; Epron *et al.,* 1999). However, there is some evidence that changes in soil CO_2 efflux take place following rainfall event in forest and grassland (Liu *et al.,* 2002; Lee *et al.,* 2004; Jarvis *et al.,* 2007; Chen *et al.,* 2008). Several studies have reported a significant increase in soil CO_2 efflux immediately after rainfall (Yuste *et al.,* 2003; Xu *et al.,* 2004; Huxman *et al.,* 2004). While it is know that rainfall increases in soil CO_2 efflux are caused by the enhanced microbial activity and/or population, the enhanced decomposition of labile C and increases in root activity (Broken *et al.,* 1999; Lee *et al.,* 2004). Other hypothesis contend that shape increases in soil water potential may instead cause microbes to rapidly oxidize cytoplasmic solutes, in doing so release a large increases in soil CO_2 efflux (Fierer and Schimel, 2003). However, there is still uncertainty about the mechanisms responsible for producing soil CO_2 efflux by rainfall. Since many surface soil experiences large seasonal fluctuations in moisture content, short-term increases in soil CO_2 efflux after rainfall are likely to be a common occurrence in many soil. In agricultural file, where rainfall event and irrigation are infrequent and soil is dry for few weeks, the effect of rainfall may contribute a significant proportion of the total annual soil CO_2 efflux from surface soil. The few models have incorporated rainfall effects in estimating the variation of soil CO_2 efflux.

This study, patterns of soil CO_2 efflux in response to summer rainfall in a peanut field are described here. Continuous measurement of soil CO_2 efflux was conducted to capture the rapid response of soil CO_2 efflux to rainfall events and soil water content. Soil CO_2 efflux was measured using an automated soil chamber. The objectives of this study were to: (1) characterize dynamic pattern of soil CO_2 efflux in response to rainfall; and (2) assess the influence of soil water content on soil CO_2 efflux.

MATERIALS AND METHODS

The research was carried out at the University of Georgia's Southwest Georgia Research and Education Center in Plains, GA, USA during May 2007 to September 2007.

Site description

The study was conducted at the University of Georgia's Southwest Georgia Research and Education Center in Plains, GA, USA (32.050° N, 84.367° W; elevation 152 m). Mean annual precipitation is 1246.1 mm and mean annual temperature is 24.2 °C. Peanut (*Arachis hypogae* L., var. Georgia green) was planted in early May, 2007. Sowing density of peanut was140 kg per ha and seeds were planted on 91 cm inter-rows. There was no fertilization applied. The peanut was frequently irrigated at the appearance of wilting to avoid drought on May 9, 23 and 31, July 24 and August 12. The field was harvested on 24 September 2007 and peanut yield was about 1,451.49 kg per acre.

Soil type was a sandy clay loam. The soil for planting peanut is composed of 56% sand, 12% silt, and 32% clay with a bulk density of 0.97, 0.9054% of C, 0.086% of N and 3.06% of organic matter.

Soil CO_2 efflux measurement

Soil surface CO_2 efflux was measured with soil automated chamber in the peanut field in the period of May to September 2007 (Fig. 3.1). Soil surface CO_2 flux was continuously measured at one location using a 0.20 m long-term soil automated chamber (Li-8100-101, Li-Cor Inc., Lincoln, NE). The soil collar (thick-walled 0.20 m PVC sewer pipe) was inserted into the soil to a depth of approximately 0.03 m. The collar was installed at least 24 hr prior before the start of the measurement and was left on the field through the study period. The increase in CO_2 concentration in the chamber placed on the soil surface was measured every 30 minutes for 2 minute and then stored to an internal compact flash card.

Figure 3.1 Soil automated chamber (Left) and control unit box (Right) for soil CO_2 efflux measurement on the peanut field.

Environmental measurements

Soil temperature was measured with Type-E thermocouples at depths of 0.02, 0.05, 0.08 and 0.030 m. Volumetric soil water content was measured at depths of 0-0.04, 0.04-0.08 and 0.08-0.030 m at the same location using time-domain reflectometers, TDR (CS616, Campbell Scientific Inc., Logan, UT). Rainfall was measured above the canopy with a tipping bucket rain gauge (TE525, Campbell Scientific Inc, Logan, UT). The observation were taken every second and then stored as 5 min average in the datalogger (CR1000, Campbell Scientific Inc., Logan, UT).

Data processing

Generally, soil temperature and soil moisture are considered the most influential environmental factors controlling soil CO_2 efflux. To examine the response of the soil CO_2 efflux on soil water content, the non-linear regression was applied using the quadratic function.

$$F(\theta) = a + b\theta + c\theta^2 \qquad (1)$$

where $F(\theta)$ is soil CO_2 efflux (μmol $m^{-2}s^{-1}$), θ is the volumetric soil water content (m^3m^{-3}) and a, b and c are coefficients estimated by non-linear regression.

All statistical analyses were performed using Origins package, Version 7 (Origins Cooperation, Massachusetts, USA). Unless otherwise stated, significant differences of all statistical test were evaluated at the level $\alpha = 0.05$.

RESULTS

Seasonal patterns of soil CO_2 efflux, soil temperature and soil water content

Figure 3.2a shows the seasonal pattern of daily mean soil CO_2 efflux and rainfall in the peanut field for 93 days from May to September 2007. Figure 3.2b shows the daily mean volumetric soil water content and soil temperature. Daily mean soil CO_2 efflux changed from 1.25 to 7.78 $\mu molm^{-2}s^{-1}$. The variation in soil surface CO_2 efflux had a seasonal pattern that more closely resembled that of volumetric soil water content at 0.02-0.05 m than soil temperature. On any day, there was little difference in average daily soil temperature. The daily soil temperature at 0.05 m varied from 24.4 °C to 30.29 °C (Fig. 3.2).

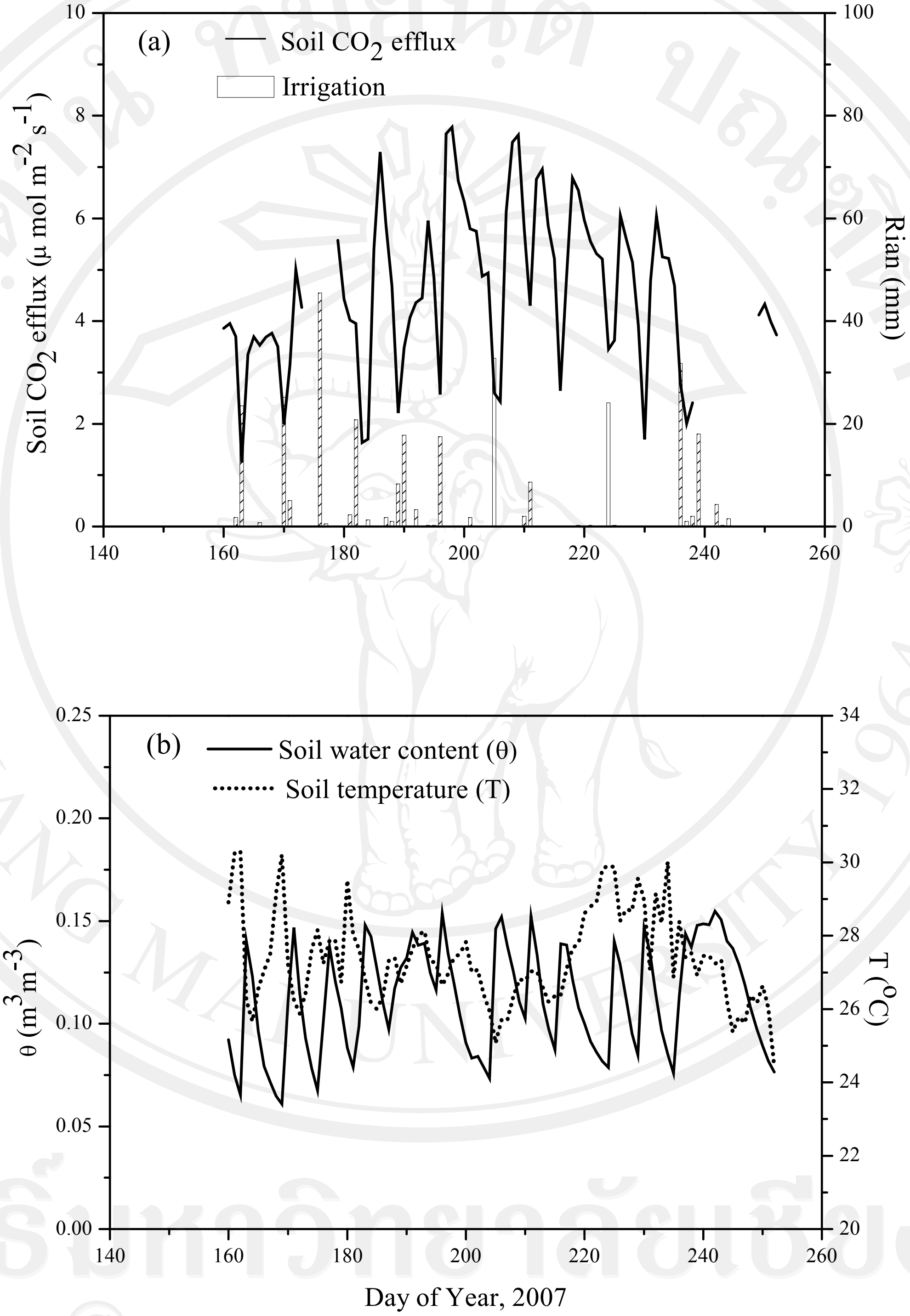


Figure 3.2 The seasonal pattern of soil CO_2 efflux, and rainfall (a), and soil temperature at 0.05 m depth and volumetric soil water content at 0.02-0.05 m depth in peanut field.

The dynamic pattern of soil CO_2 efflux in response to rainfall event

The responses of daily soil CO_2 efflux to three rainfall events in the peanut field are presented in Fig. 3.4. The daily soil CO_2 efflux in peanut field showed a similar response to the rainfall event in the wheat field and this response showed relatively short duration (Fig. 3.3). An immediate response in soil CO_2 efflux caused by rain events is an observed reduction in the efflux, and then reached a peak value within 2 days after rainfall. Subsequently, soil CO_2 efflux appeared to be declined to pre-rainfall levels on 3 days after rainfall on DOY 163 (vegetative stage), 7 days after rainfall on DOY 196 (flowering stage), and 4 days after rainfall on DOY 210 (Pod filling stage). For example, nearly 85-90% decrease in soil CO_2 efflux was observed following 25.29 mm and 10.66 mm rainfall events on DOY 163 and DOY 210, respectively. Soil CO_2 efflux exhibited a nearly 14.92% increase following a rainfall event (18.02mm) on DOY 196 and nearly 7.12% increase following a rainfall event (24.38 mm) on DOY 210. The peak rate of soil CO_2 efflux was highest at the flowering stage and soil CO_2 efflux was up to 1.5 times higher than soil CO_2 efflux at the day before rainfall. While there was no significant differences in magnitude of increase in soil CO_2 efflux between the day before and 2 days after rainfall at the vegetative stage and the pod filling stage.

Soil CO_2 efflux varied significantly with all growth stages, but no significant differences in soil water content were observed during and 24 hr after rainfall (Fig. 3.5). Nonetheless, this did not lead to an immediate increase in soil CO_2 efflux. There were also no significant differences in the magnitude and duration of increase in soil water content between growth stages. Soil water content of all growth stages increased rapidly after rainfall and followed by gradual decreased. Soil water content decreased to background levels on 5 days after rainfall on DOY 163, and 3 days after rainfall on DOY 196 and DOY 210. The results showed the increased in soil CO_2 efflux after rainfall could be attribute to a rapid decrease in soil water content.

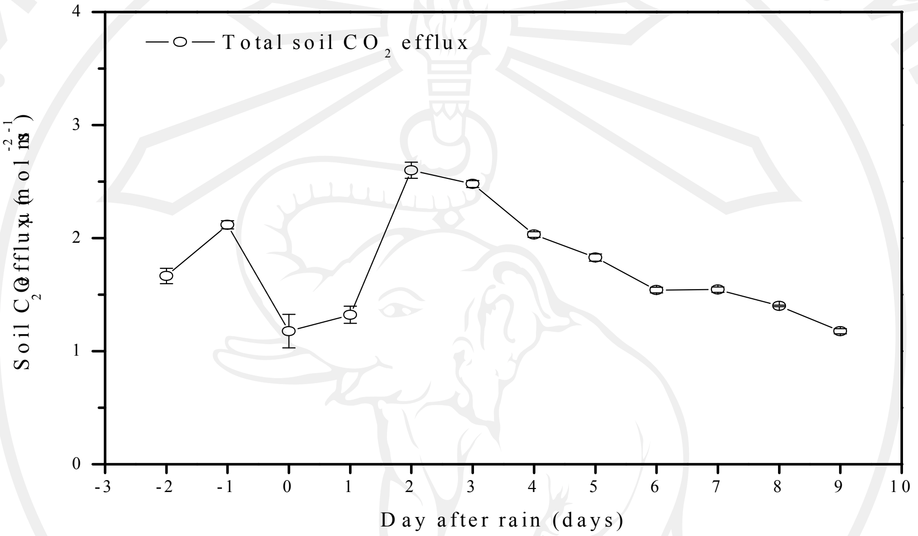


Figure 3.3 Examples of soil CO_2 efflux response to rain event in wheat field. Shown are mean and standard errors for 24 hr period. The day -1 represents 24 hr before the rainfall and the day 1 represents 24 hr after rainfall.

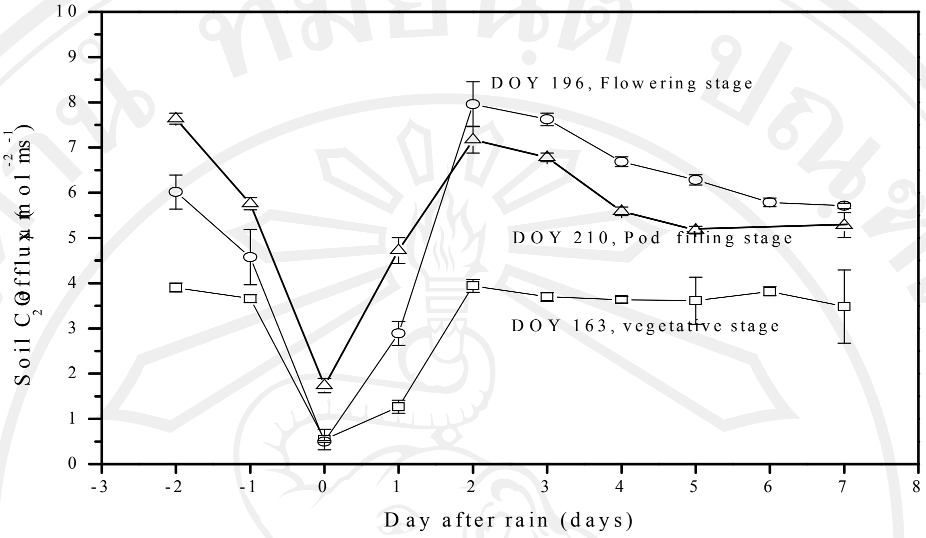


Figure 3.4 Total soil CO$_2$ efflux before, and 7-days period following rainfall events on DOY 163, DOY 196, and DOY 210. Shown are mean and standard errors for 24 hr period. The day -1 represents 24 hr before the rainfall and the day 1 represents 24 hr after rainfall.

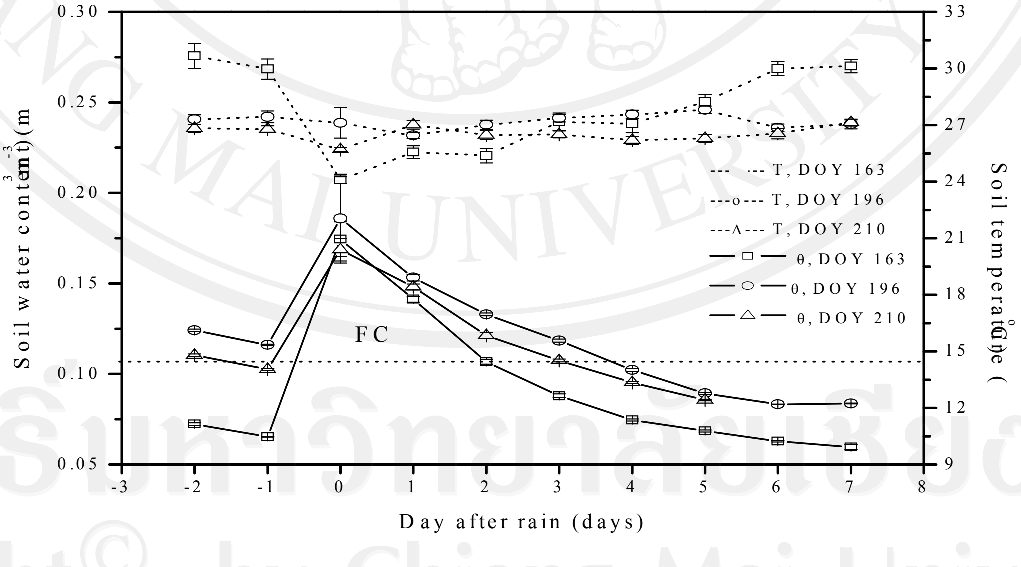


Figure 3.5 Soil volumetric water content at 0.02-0.05 m depth (FC, field capacity) and soil temperature at 0.05 m depth on DOY 163, DOY 196, and DOY 210. Shown are mean and standard errors for 24 hr period.

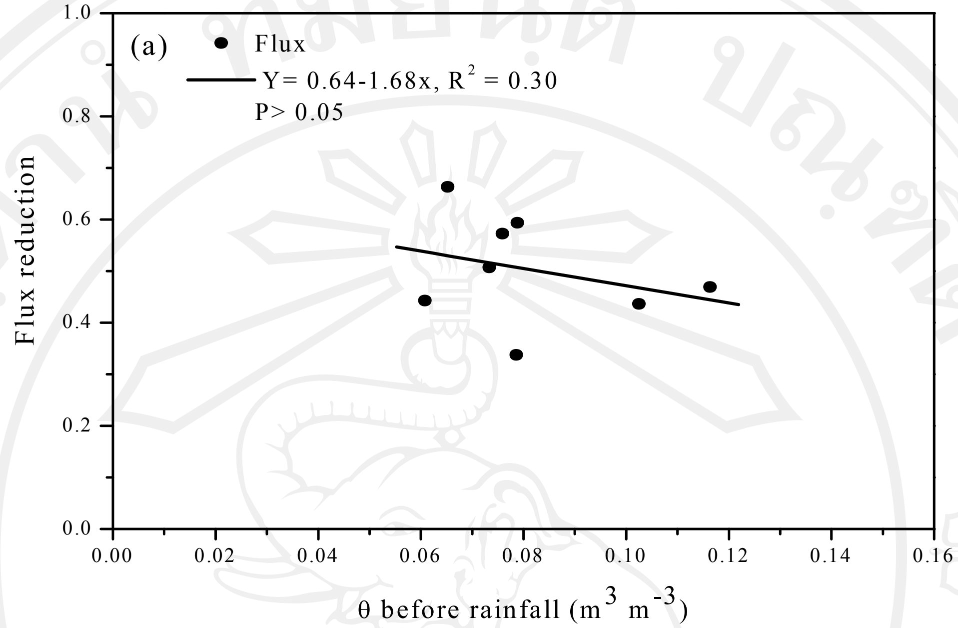
Effect of rainfall events on the response of soil CO_2 efflux to soil water content

There were eight rainfall events in peanut field, which could be used to compare pre- and post-rainfall soil CO_2 efflux in order to understand the decrease in the soil CO_2 efflux when rain falls. To calculate the relative flux reduction on day of rainfall, the normalized decrease in soil CO_2 efflux following rainfall was calculated as:

$$Flux\,reduction = \frac{(F_0 - F)}{F_0} \tag{2}$$

where by F_0 is daily soil CO_2 efflux before rainfall event (μmolm^{-2} s^{-1}) and F is a soil CO_2 efflux on the day of rainfall occurred.

The soil water content and soil CO_2 efflux before rainfall were found to be influence on the flux reduction (Fig. 3.6a, b), although this relationships were not strong. Nevertheless, soil CO_2 efflux on the day of rainfall occurred was decreased whether soil was dried or wetted before rainfall.



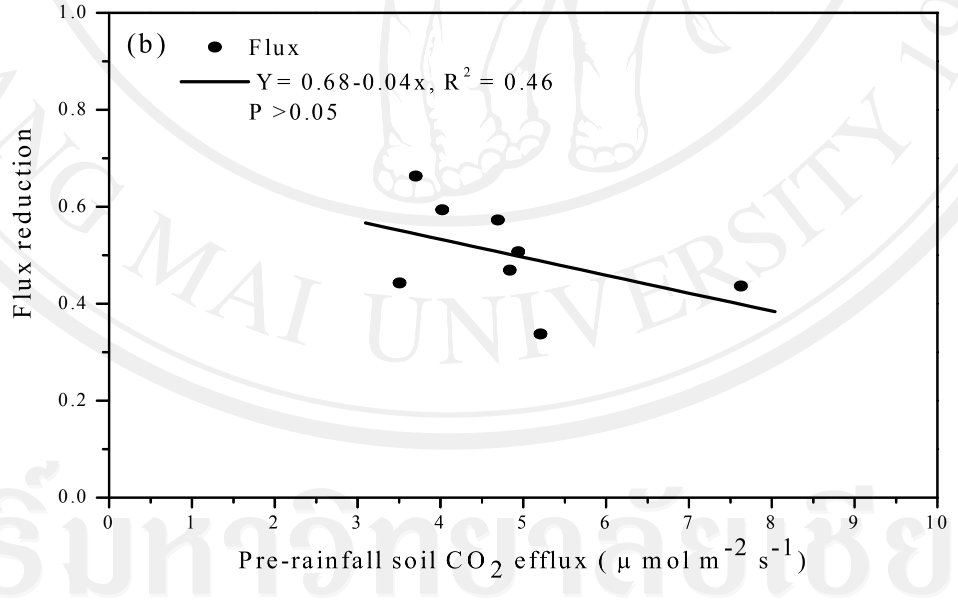


Figure 3.6 The relationship between the flux reduction and the soil water content (θ) before rainfall (a); and pre-rain soil CO_2 efflux (b).

Model analysis

The model was used from previous experiment simulating the response of soil CO_2 efflux caused by rainfall. Equation (3) describes how soil CO_2 efflux (F, μmol $m^{-2}s^{-1}$) changes with time (t, day) after rainfall, with t = 0 as the day when rainfall stops.

$$F = b_0 + b_1 (\frac{t}{\tau})^2 e^{\frac{-t}{\tau}} \tag{3}$$

where F is the soil CO_2 efflux after rainfall (μmol$m^{-2}s^{-1}$), b_0 is the base respiration, or soil CO_2 efflux on the day when rainfall stops (μmol$m^{-2}s^{-1}$), b_1 is a coefficient that determines the maximal enchantment of soil CO_2 efflux after rainfall, and τ is a coefficient that indicates the dynamic time constant, which determines how long it takes for soil CO_2 efflux to decline to 1/e (e is the base for natural log) of its peak value(day).

The dynamic pattern of soil CO_2 efflux in response to rainfall was best described by equation (3) with R^2 = 0.67-0.83 (Table 3.1). Also, this pattern was similar to the results from previous experiment in a wheat field. The dynamic time constant (τ) was varies with rainfall event. The rainfall amount was influenced how long CO_2 loss after rainfall (indicated by the dynamic time constant). The time constant of soil CO_2 efflux were increased linearly with amount of rainfall with R^2= 0.82 (Fig. 3.7), suggesting that the magnitude of CO_2 respired after rainfall may remain high for several days due to a slower drying of the surface soil with increasing amount of rainfall.

Table 3.1 Parameters of the exponential decay model of Equation 2 in peanut filed. Abbreviations: b_0 is soil CO_2 efflux on the day when rainfall stops (μmol $m^{-2}s^{-1}$); b_1 is a coefficient that determines the maximal enchantment of soil CO_2 efflux after rainfall and τ is a coefficient that indicates the dynamic time constant (day).

Rain event (amount of rain, mm)	b_0	b_1	τ	R^2
DOY 163 (25.29 mm)	1.72	4.22	1.47	0.78
DOY 196 (18.02 mm)	3.49	8.83	0.99	0.83
DOY 210 (10.66 mm)	3.60	6.90	0.76	0.79
DOY 224 (24.38 mm)	2.30	6.41	1.12	0.67

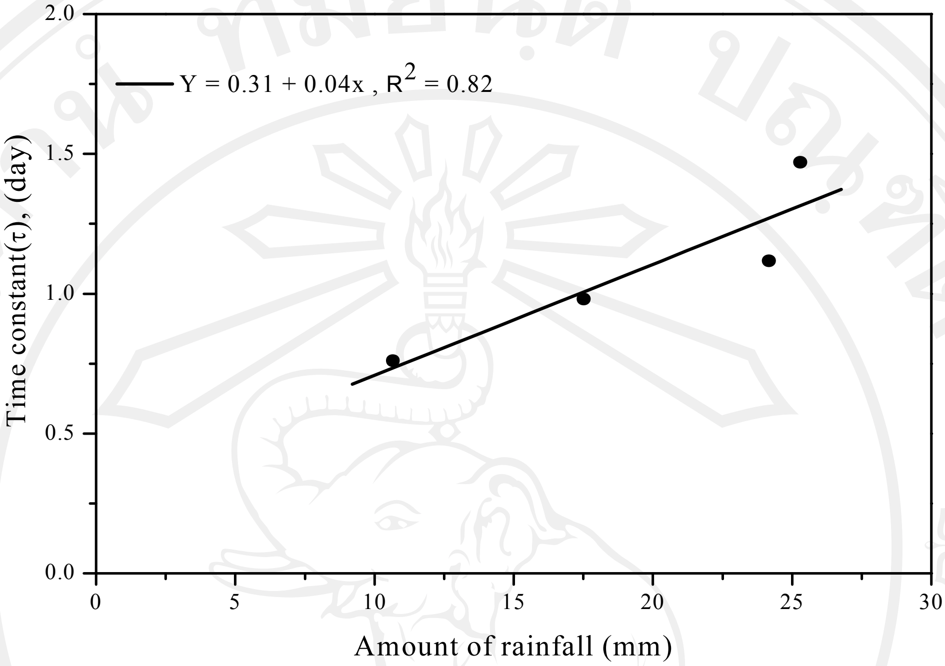


Figure 3.7 The relationship between time constant (τ) of soil CO_2 efflux and amount of rainfall.

Effect of soil water content on soil CO_2 efflux

There was no significant correlation between daily soil CO_2 efflux and soil temperature due to soil temperature during study small fluctuated between 24 and 31 °C. Therefore, soil temperature seemed to be less important in controlling in soil CO_2 efflux in current study. In contrast, soil water content is one of the important environmental factors affecting soil CO_2 efflux. In order to quantify the relationship between soil CO_2 efflux and soil water content, regression analysis was conducted using the quadratic function. The quadratic function explained 36% of the variation in the soil CO_2 efflux with $R^2 = 0.36$ (Fig. 3.8) after removes the soil CO_2 efflux data on 1 to 3 days after rainfall. The week correlation between soil CO_2 efflux and soil water content was due to the fact that the soil CO_2 efflux is an overall effect of multiple factors including soil temperature and soil water content. The week correlation may also be caused by rainfall variation. Rainfall increased soil water content which, in turn, stimulated soil CO_2 efflux as showed high soil CO_2 efflux on 1-3 days after rainfall.

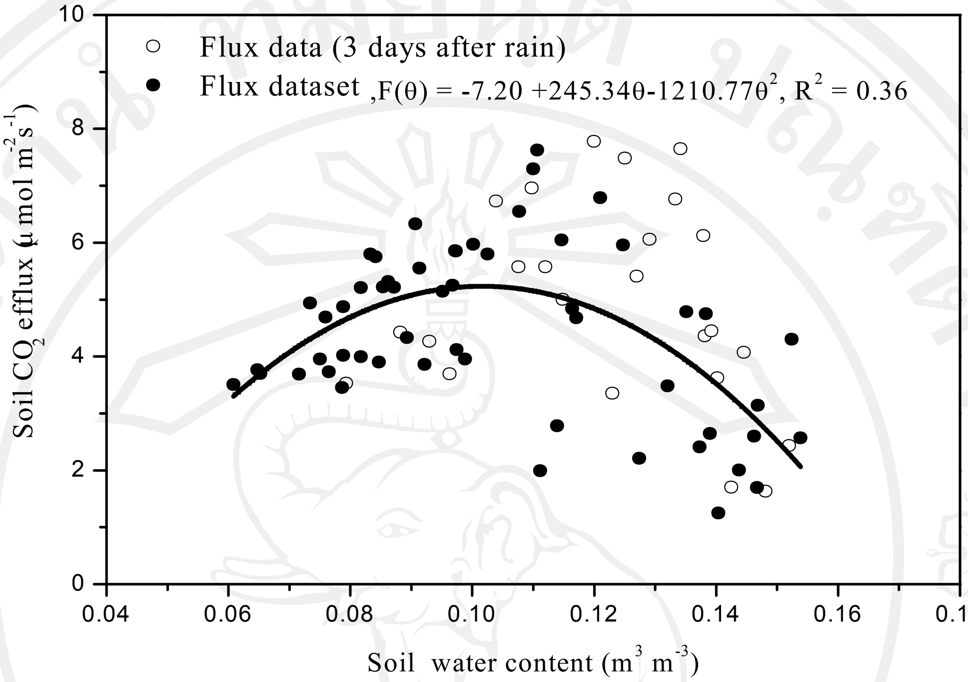


Figure 3.8 The relationship between daily mean soil CO_2 efflux and soil water content at 0.02-0.05 m depth. (c). Lines are fitted to Equation 3.

DISCUSSION

The pattern of soil CO_2 efflux between wheat and peanut

The dynamic pattern of soil CO_2 efflux in response to rainfall was showed increased immediately after rainfall, reached a peak and then gradually decreased. The general shape of the response of soil CO_2 efflux to rainfall is described well by an exponential decay as in Equation 3, very similar to that resulting from the wheat experiment show in Figure 3.4. These results were also consistent with previous studies conducted in grassland and forest (Liu *et al.,* 2002; Tang *et al.,* 2005). In this study, however, these responses quickly returned to near pre-rainfall soil CO_2 efflux levels following even large rainfall amount. Thus, the responses of soil CO_2 efflux of rainfall in peanut field were short lived. With in range of amount of rainfall considered here, rainfall event will significant influenced the season variation in soil CO_2 efflux.

Reduction of soil CO_2 efflux during rainfall

Independent of the effect of the water supply on the source of the CO_2, an immediate response in soil CO_2 efflux on the day of rainfall occurred caused by rainfall event is an observed reduction in the efflux about 85-90%. This agreement with Buchmann *et al.* (1997) who found that rainfall events decreased soil CO_2 efflux by about 40% in rainforest when compared with non-rain periods. The increase in soil water content may be responsible for most of the decrease in soil CO_2 efflux. The rainfall increased soil water content which, in turn, inhibited soil CO_2 efflux. The negative relationship was found between the reduction of soil CO_2 efflux and the prior-soil water content (Fig. 3.6a). The prior-soil CO_2 efflux was also correlated to a reduction of soil CO_2 efflux (Fig. 3.6b). Although those relationships were not strong. These weak correlations may be due to growth stage of plant and amount of rainfall. However, the magnitude of the decrease in soil CO_2 efflux appears to depend on prior soil water content. In dry soil and low soil CO_2 efflux, the increase in soil water content due to the rainfall may large reduces the air-filled pore spaces available for CO_2 diffusion out of the soil. The immediate replacement of the air-filled pored by water that may form a cap and prevent CO_2 diffusion, leading to large decreases in soil CO_2 efflux. This is supported by the finding of Sotta *et al.* (2004) who reported that soil CO_2 efflux reduced 30% immediately after the rain event, caused by a reduction in the rate of diffusion of air within the top soil pore space. Huxman *et al.* (2004) also reported that vegetation development, phenology and initial soil water content would affect the responses of the soil CO_2 efflux to rainfall. This study suggested that the accumulation of water and initial soil CO_2 efflux has important consequences for decrease in soil CO_2 efflux *during* rainfall. The decrease in soil CO_2 efflux *during* rainfall observed in this study should be further examined as a potential mechanism contributing to soil CO_2 efflux during rainfall. This kind of result and opening to future research should definitely be re-iterated in the conclusions.

Post-rainfall effect on soil CO_2 efflux

All of the rainfall events analyzed showed rapid and substantial increases in soil CO_2 efflux occurred on 1 day after rainfall, and then decreased gradually. Previous studies suggest that increases in soil CO_2 efflux is due to either, or both, the physical displacement of CO_2 in soil pores by water and enchanted microbiological activities of soil microorganisms and root activity with the increase in soil water content (Huxman *et al.,* 2004; Liu *et al.,* 2002; Borken *et al.,* 2003). The study of Steenwert *et al.* (2005) found that the activation of microbial activity might take several hours to day. In this study, soil CO_2 efflux was increased and reached a highest peak on 2 days after rainfall. It is likely that the increases in soil CO_2 efflux may due to microbial activity and less the expulsion of CO_2 rich air from the soil. The increases in soil CO_2 efflux after rainfall were either large or low in magnitude when compared with pre-rainfall soil CO_2 efflux, depending on growth stage of plant. Soil CO2 efflux at the flowering stage of peanut increased strongly after rainfall than that at the pod filling stage when soil water content was nearly field capacity level, suggesting that growth stage of plant also controlled soil CO_2 efflux loss after rainfall. There was no relationship between increases in soil CO_2 efflux after rainfall and the amount of rainfall. These results suggested that the soil microbial activity in this experiment could increase, decrease or have small net response to changes in amount of rainfall, presumably due to the moistening of surface soil.

The decline in soil CO_2 efflux following its peak can be well described by a nonlinear function as in Equation (3). The dynamic time constant of soil CO_2 efflux also showed difference among the four rainfall events. The dynamic time constant that represent how long CO_2 loss after rainfall was linear with amount of rainfall, suggesting that the magnitude of CO_2 respired after rainfall may remain high for several days due to a slower drying of the surface soil with increasing amount of rainfall. The increase in soil CO_2 efflux after rainfall was relatively short duration (5-6 days) in this study. Thus, the declination of wetted soil conditions of rainfall may have effects on short-term C losses in the field. These results suggested that soil water content may be an influenced factor for the decline in soil CO_2 efflux after rainfall. This is supported by the finding of Xu *et al.* (2004) who observed that the decline in soil CO_2 efflux was related with amount of rainfall. Lee *et al.* (2004) found that the slow decline of the litter CO_2 evolution rate with time following the wetting event was related to water loss.

Drying and rewetting effect on the soil CO_2 efflux

The rainfall events occurred several times during the peanut-growing season. One explanation is that the enhancement of soil CO_2 efflux after rainfall may caused by frequency of rainfall that increased microbial activity and root respiration. This result agree with Happer *et al.* (2005) reported that changes in frequency of rainfall throughout changes in soil water dynamics is more important in affecting soil CO_2 efflux. Drying and rewetting cycles can increase the availability of both C and N substrates and enhance microbial activity. The rapid rewetting of soil can increase availability of labile organic substrates through dead microbial and cell membranes and increase the microbial mineralization rate (Van Gestel *et al.,* 1992; Borken *et al.,* 2003; Fierer and Schimel 2003). Also Steenwerth *et al.* (2005) reported that drying and rewetting cycles within soil could significantly increase the soil microbial community and soil C availability depending on soil nutrient status, the specific environmental conditions at the field, the time interval between water additions, and interactions of microbial with soil biota. Thus, frequency of rainfall events may induce cycles of drying and rewetting within soil, causing increased variation in soil CO_2 efflux.

Soil temperature and soil water content influence on soil CO_2 efflux

The relationship of soil CO_2 efflux with soil temperature and soil water content involves complex interactions depending on the relative limitation of each variable to both microbial and root activity. Soil temperature has been found to explain much of the variance in soil CO_2 efflux (Davidson, 1998; Xu and Qi, 2001). In this study, there was no significant correlation between daily mean soil CO_2 efflux and soil temperature. The data did not fit a traditional respiration model well such as Lloyd and Taylor (1994) equation and an exponential function because soil temperature during study small fluctuated between 24 and 31 °C and appeared neither extremely high nor extremely low (Fig. 3.2). Therefore, soil temperature seemed to be less important in controlling the season variation in soil CO_2 efflux in current study.

In contrast, in the environmental with relative stable temperatures or markedly seasonal dry periods, soil CO_2 efflux can be predicted reasonably well using only soil water content (Keith *et al.,* 1997; Epron *et al.,* 2004). In this study, soil water content exerted the determinant control in the seasonal variation of the soil CO_2 efflux when soil temperature was almost nearly constant during study period. Although the relationship between soil CO_2 efflux and soil water content was not strong due to high fluctuation in soil water content by rainfall. However, the effect of soil water content on soil CO_2 efflux depends on the range of soil water content. As soil water content increases, soil CO_2 efflux generally increases, but the inhibition of soil water content on soil CO_2 efflux is significant only at its above a critical value (0.105 m^3 m^{-3}).

The large soil CO_2 efflux was found on 1 to 3 days after rainfall events, associated with the rapid increase in the soil water content due to frequent rainfalls (Fig. 3.8), open circle symbol. These scatter values was due to difference in plant growth state and amount of rainfall. It is clear that soil water content was the most important factor for carbon decomposition and root activity after rainfall. This result agree with Liu *et al.* (2002) who found that the lasting periods of higher soil CO_2 efflux after rainfall appeared to be controlled by the soil water content. The high soil CO_2 efflux after rainfall may due to the high frequency of rainfall events leads to large efflux. The frequency of rainfall events tended to increase the activity of the soil microorganisms in the soil and the activity of plant and root (Knapp *et al.,* 2002; Fay *et al.,* 2003). Thus the high fluctuation in soil water content by frequency of rainfall events in this study period may play an important role in the variation in soil CO_2 efflux. The high frequency of rainfall events may have a larger impact on soil CO_2 efflux. When high rainfall variability occurred, it might be important to incorporate the frequency of rainfall and soil water content into a predictive model of soil CO_2 efflux.

Sub-experiment 2: Seasonal variation of net carbon dioxide exchange in summer peanut

INTRODUCTION

The increasing concentration of atmospheric CO_2 require a better understanding of ecosystem fluxes, factors that determine the magnitudes of fluxes, the potential for mitigation and the feedbacks of ecosystems on climate. The CO_2 exchange between crop and atmosphere is a major driver of atmospheric CO_2 fluctuations. However, the amount of carbon stored in and emitted or removed from the agroecosystem depends on crop type, management practices and soil and climate variable. Studies have indicated that crop respond sensitively to change in climate, particularly to change in precipitation (Anthoni *et al.*, 2003; Moureaux *et al.,* 2006). Therefore, understanding how climate variability, particularly rainfall variability influences the CO_2 exchange in peanut field, can be valuable, not only the improve knowledge on the mechanisms that control the CO_2 fluxes but also to anticipate possible impacts of climate change scenarios and give the modelers a batter basic to improve and validate their model.

In recent years, many studies have used eddy covariance techniques to measure net ecosystem exchange of CO_2 (NEE), and the resultant NEE data provide valuable information related to photosynthesis period and gross primary production (GPP) of ecosystems (Falge and Baldocchi *et al.,* 2002; Falge and Tenhunen *et al.,* 2002). However, flux tower sites only provide integrated CO_2 flux measurements over footprints with sizes and shapes (linear dimensions typically ranging from hundreds of meters to 1 km) that vary with the tower height, canopy physical characteristics and wind velocity (Osmond *et al.,* 2004). There is still lack of detailed information on carbon exchange (gross primary production, GPP; ecosystem respiration, Re) and the influence of controlling factors in key agroecosystem.

Photosynthesis and its response to primary drivers (temperature and light) are relatively well understood at the leaf level and in environmental chambers. However, given the very high leaf area and significant variability in vertical and horizontal light interception with in crop ecosystem, it is significant challenge to upscale carbon assimilation fluxes to regional scale. Compared to forest and grassland ecosystems, agroecosystem are more artificially controlled through changing cropping systems, fertilization, and irrigation in order to improve production. The CO_2 exchange studies done in crop ecosystems show that the net ecosystem exchange is mostly controlled by temperature, soil moisture, biomass, and leaf area index (LAI) (Prueger *et al.,* 2004; Suyker *et al.,* 2005; Zhang *et al.,* 2006). No year-round gas exchange study has been done in peanut ecosystem. The carbon exchange between crop and the atmosphere may also greatly influence by cultivation practices, field management and meteorological conditions. Since carbon fluxes respond differently to environmental forcing variables and their perturbations, it is essential to investigate separately environmental parameters affect the plant photosynthesis and ecosystem respiration. Even more uncertain is how net ecosystem exchange of CO_2 and it components, gross primary production (GPP) and ecosystem respiration (Re) of peanut ecosystem vary in a seasonal basis.

The objects of this study was to quantify the seasonal distribution of GPP and Re in peanut during a growing season and to examine how carbon exchange is controlled by environmental drivers, especially rainfall. The hypothesis of this study is that seasonal variation in GPP and Re in peanut crop are largely driven by soil moisture and by vegetation characteristics, such as biomass and LAI.

METERIALS AND METHODS

The research was carried out at the University of Georgia's Southwest Georgia Research and Education Center in Plains, GA, USA during May 2007 to September 2007.

Eddy-covariance flux measurement

During the 2007 summer, micrometeorological measurements were carried out over a irrigated peanut field. Eddy-covariance fluxes were measured using the same procedure as sub-experiment 2 in Chapter 3. The eddy covariance sensors were mounted at a height of 1.5 m above the ground. The tower placement in the field provides a fetch over a continuous crop with 400m to the south and 220m to the west. The prevailing winds during the summer are from the south to southwest.

Supporting measurements

Along with the eddy-covariance technique, standard meteorology and soil parameters were measured continuously with an array of sensors, included net radiation (Model NR-LITE, Kipp and Zonen USA Inc., Bohemia, New York), rainfall (tipping-bucket raingauge,TE525, Campbell. Scientific, Logan, UT), relative humidity and temperature (CS500, Campbell. Scientific, Logan, UT). Soil heat flux was measured with two heat flux plates (HFT3, Campbell Scientific, Logan, UT): one within the plant row and the second in the inter-row space, installed at 8 cm below the soil surface and were randomly placed within a few meters of the flux system. Soil thermocouples were placed at 0.02 and 0.08 m below the surface and above each soil heat flux plate to compute the storage component of the soil heat flux. Soil water content was measured by time-domain reflectometers (CS616, Campbell. Scientific, Logan, UT) to permit calculation of heat capacity. All data was recorded on datalogger (CR1000, Campbell. Scientific, Logan, UT), and then 30 min average data was stored.

Leaf area index (LAI) was determined at 7 days intervals around the flux system with a leaf area meter (LAI-2000, Li-COR Inc., Lincoln, NE).

Flux calculation

The 30-min mean CO_2 fluxes were calculated from the 10 Hz time series data. Before covariance calculation the time series were de-spiking and linearly detrended. The fluxes were three-dimensional coordinate rotations (Wilczak *et al.,* 2001) to align the sonic anemometer axis along the long-term streamlines and WPL-correction (Webb *et al.,* 1980). Following the sign convention in the atmospheric flux community, positive flux covariance represent net carbon gain by the atmosphere and loss from the ecosystem; conversely, negative values indicate a loss of carbon from the atmosphere and gain by the ecosystem. The flux data were rejected following these criteria (1) wind direction, (2) rainy days, and (3) clam conditions. The nighttime net ecosystem exchange (NEE) was examined in relation to wind friction velocity (*u**). It is assumed that the u* threshold is located where the flux starts to level off as u* increases (Falge *et al*., 2001). In this study, the u* threshold about 0.1 m/s was used. The fluxes measurements when *u** was smaller than the threshold were removed from the dataset to minimize problems related to insufficient turbulent mixing (Fig.3.9).

Data screening

To separate NEE into photosynthetic and respiration fluxes, NEE were divided into daytime and nighttime periods to develop non-linear regressions for evaluating environmental effects on NEE. All data records with solar altitude less than 0 were used to estimate ecosystem respiration (Re).

An eddy covariance system can rarely produce good quality data for 24 h a day. Several reasons exist for the occurrences of gaps (Falge *et al.,* 2001). Gap in half- hourly data were filled with empirical regressions for respiration and net CO_2 uptake derived for two weekly intervals. When daytime half-hourly values in peanut dataset were missing, the CO_2 flux was estimated as a hyperbolic function of income radiation. To minimize problems related to insufficient turbulent mixing at night, the CO_2 flux when u* was smaller than the threshold was estimates as an exponential function of temperature.

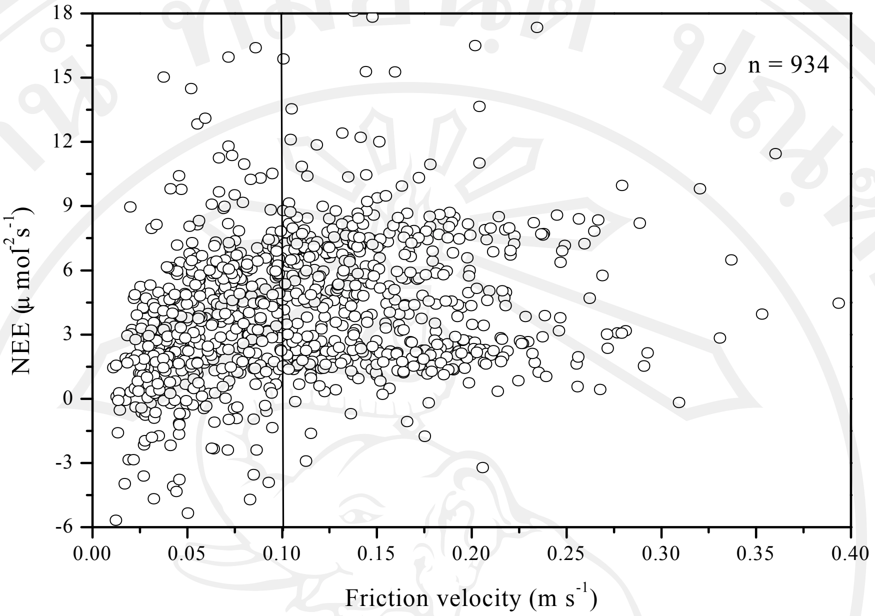


Figure 3.9 The nighttime net ecosystem exchange (NEE) versus the friction velocity in peanut.

Energy budget closure

Eddy covariance data quality was also assessed by analyzing the energy balance. Energy balance closure was examined every 30 min by comparing the sum of latent and sensible heat flux (LE+H), measured by eddy covariance against available energy (Rn-G-S), measured by other methods, where H represents sensible heat flux, LE represents latent heat, Rn represents net radiation, G represents soil heat flux and S represents the heat storage in the soil layer above the heat flux plates. The 30 min values of LE+H was plotted against Rn-G-S. The linear regression was (LE+H) = 0.91(Rn-G-S) + 26.95, $R^2 = 0.88$, $P < 0.0001$. The slope value was close to 1, indicating that eddy fluxes were in approximate balance with the available energy (Fig. 3.10).

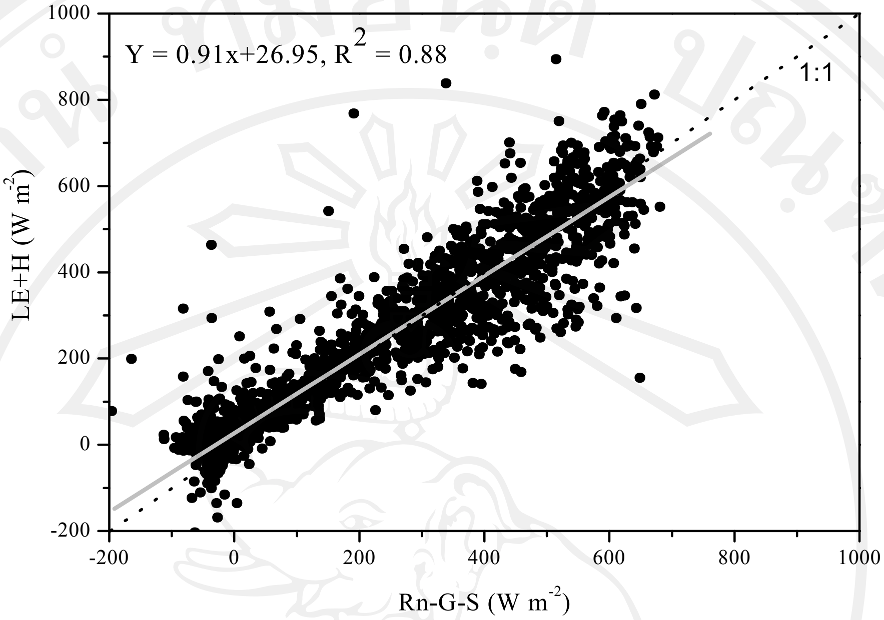


Figure 3.10 Energy balance closure at half-hourly scale in summer peanut growth period. Eddy covariance energy fluxes (LE+H) against available energy (Rn−G-S).

Statistical analysis and calculation

Multiple regressions and uncertainty analysis were calculated using the statistical software package Origin 7.0 and SigmaPlot 1.0 to assess the relationship of NEE with concurrent changes in the environmental variables (solar radiation, soil temperature and moisture).

RESULTS

Information on weather conditions, leaf area and aboveground biomass

Meteorological conditions in summer peanut during growing season are given in Fig. 3.11. The daily air and soil temperature in peanut field ranged from 22 to 31 °C. Total precipitation during peanut study period was 312.7 mm. Seasonal variation in soil volumetric water content followed the rainfall pattern and varied between 0.03 to 0.15 m^3m^{-3}. During the period of most rapid canopy growth, the peak value of GLAI was 6.07 m^2m^{-2} in peanut (Fig. 3.11b). Likewise, the above-ground biomass of peanut began to increase approximately 35 days after planting and the peak value was 49 g DM $plant^{-1}$ (Fig. 3.11c).

Diurnal change of CO_2 efflux (NEE) in the growing season

The average diurnal variations in NEE for each half hour in peanut field are shown in Fig 3.12 and shown daytime CO_2 uptake and nighttime CO_2 release. The half hour data were averaged from 0:00 to 23:00 per biweekly periods in the peanut growing seasons. The data were divided into seven periods in peanut field. Before morning the NEE moves from a positive value (release) to a negative value (uptake). During the daytime, when the carbon dioxide flux is directed from the atmosphere towards the plant canopy, the maximum flux occurs close noon (13:00). Because of the higher temperatures in the afternoon, the respiration loss is also higher in the afternoon which gives the curve a slightly asymmetric shape. The amplitude of the diurnal variation in NEE increased with growth and reached its peak around the mid-vegetative stage (DOY 196-209) and had maximum of NEE of -35 $\mu mol\ m^{-2}\ s^{-1}$. NEE during the early vegetative stage (DOY 154-167) fluctuated within ± 5 μmol m^{-2} s^{-1}. During the mid-vegetative stage, peanut field were converted to a CO_2 sink during two-thirds of the day. There is a net carbon uptake for nearly 11 hours per day. With in onset of senescence (DOY 224-251), daytime uptake decreased drastically, whereas nighttime release stay almost the same site as it was in the mid-vegetative stage.

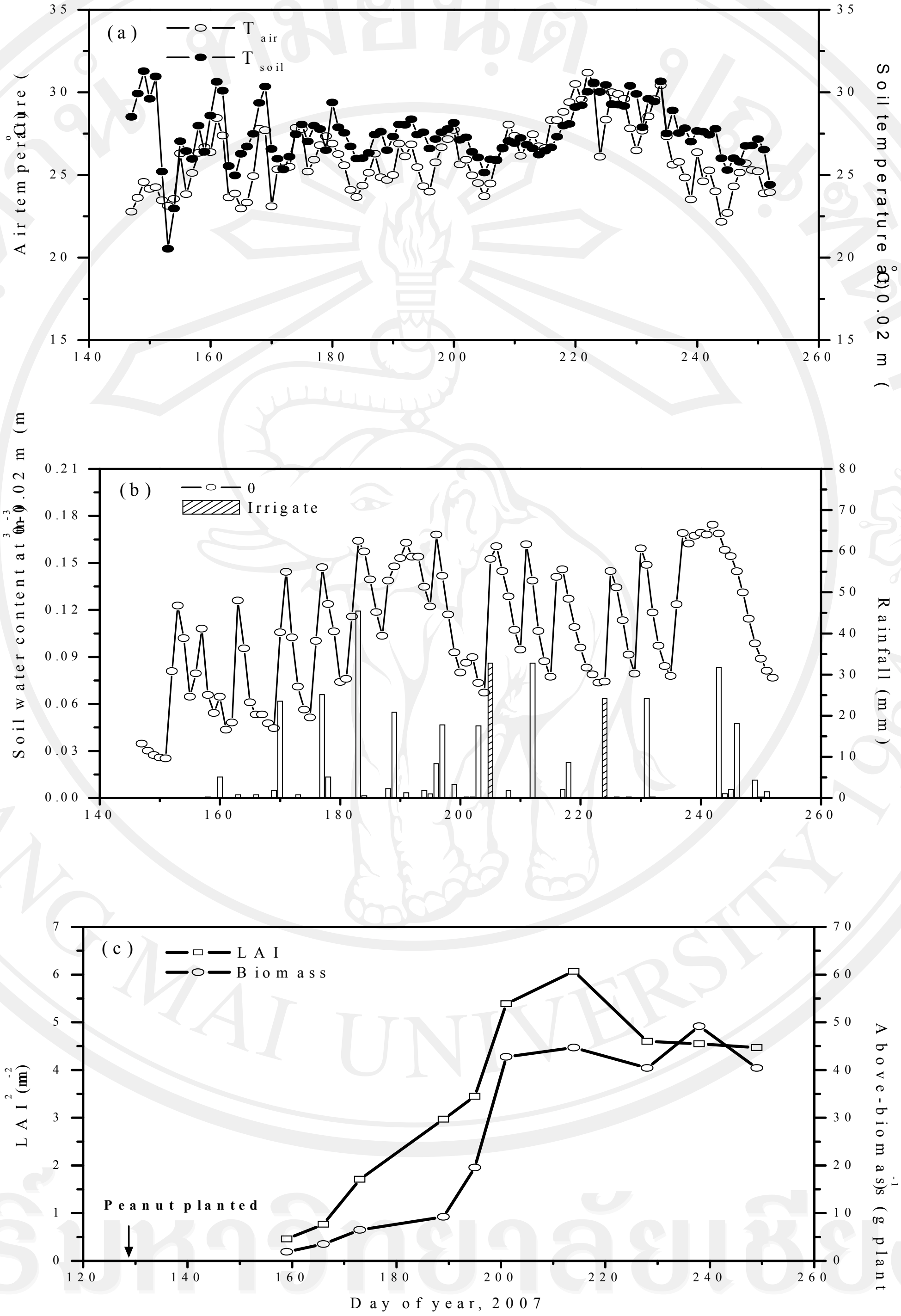


Figure 3.11 Daily mean air temperature, soil temperature and soil water content in the upper soil layer with rainfall and irrigation (a,) and weekly leaf area index (LAI) and aboveground biomass (c) during peanut growing seasons in 2007.

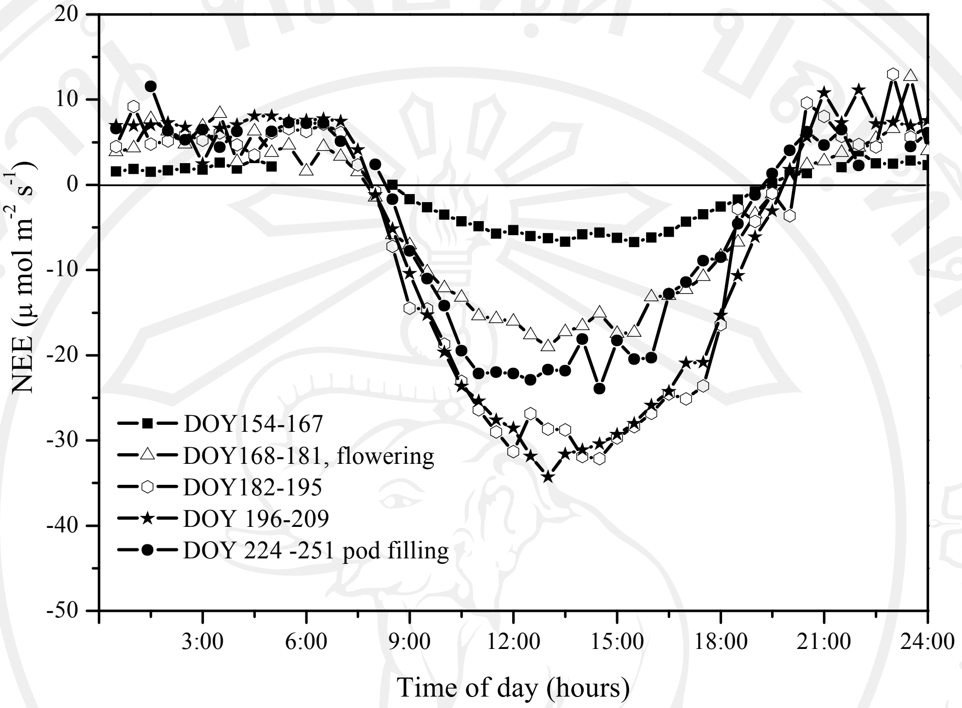


Figure 3.12 Example of diurnal variation in half-hourly mean net ecosystem exchange (NEE) in peanut field.

Response of daytime NEE and gross primary production (GPP) to biophysical and environmental factors

The relationship of the daytime NEE with net radiation was investigated based on their half-hourly average data. The response of daytime NEE to net radiation evolved with crop development (Fig. 3.13). To assess the response of daytime NEE to net radiation, Fig. 3.13 shows the light-response curve for short periods of the main stage of plant growth. More than 66% of the variation in NEE was explained by the change in solar radiation. The daytime NEE increased along with net radiation and increase as LAI increases when compared with the same values of solar radiation. The relationship of the daytime NEE with air temperature, soil water content and soil temperature were also investigated based on their half-hourly average data (Fig. 3.14). More than 43% and 41% of the variation in daytime NEE was explained by the change in air temperature and soil water content, respectively.

Measurements of NEE were used to estimate gross primary production (GPP). Growing season distribution of weekly-GPP is shown in Fig 3.15a. The seasonal distribution of weekly GPP follows that of the green leaf area. The peak GPP reached its peak (27.5 μmol $m^{-2}s^{-1}$) when LAI peak at 4.8 m^2m^{-2}. The weekly-GPP responded linearly to changes in LAI (Fig.3.15b). About 68% of the variation in GPP was explained by change in LAI. There was weak correlation between weekly GPP and amount of rainfall.

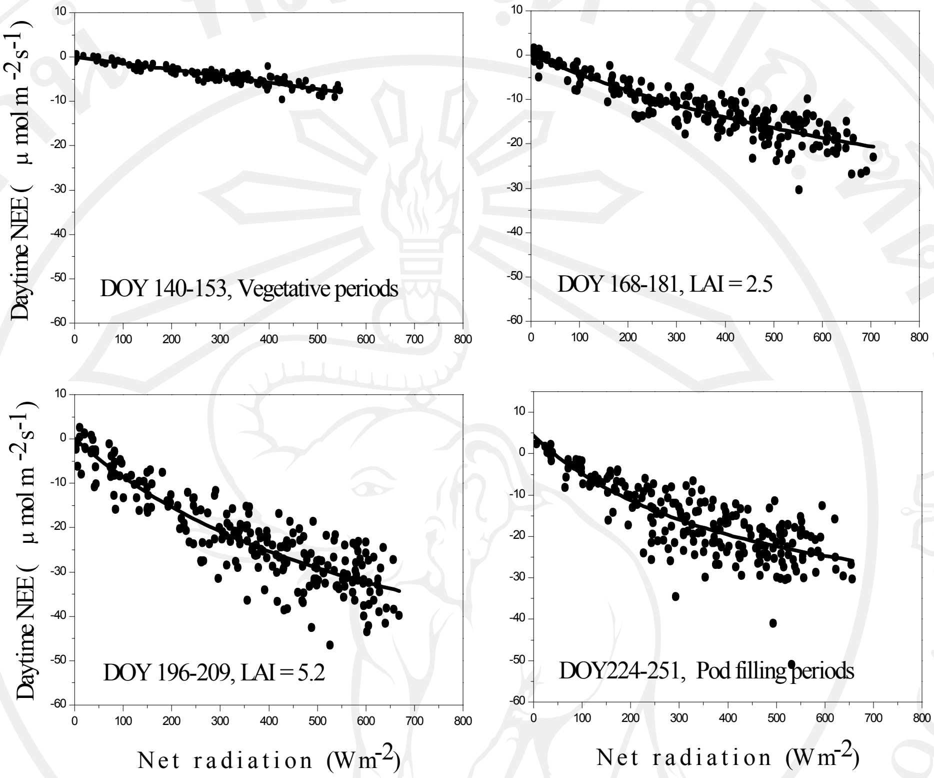


Figure 3.13 Example of light-response curves of daytime NEE at different growth stages of peanut.

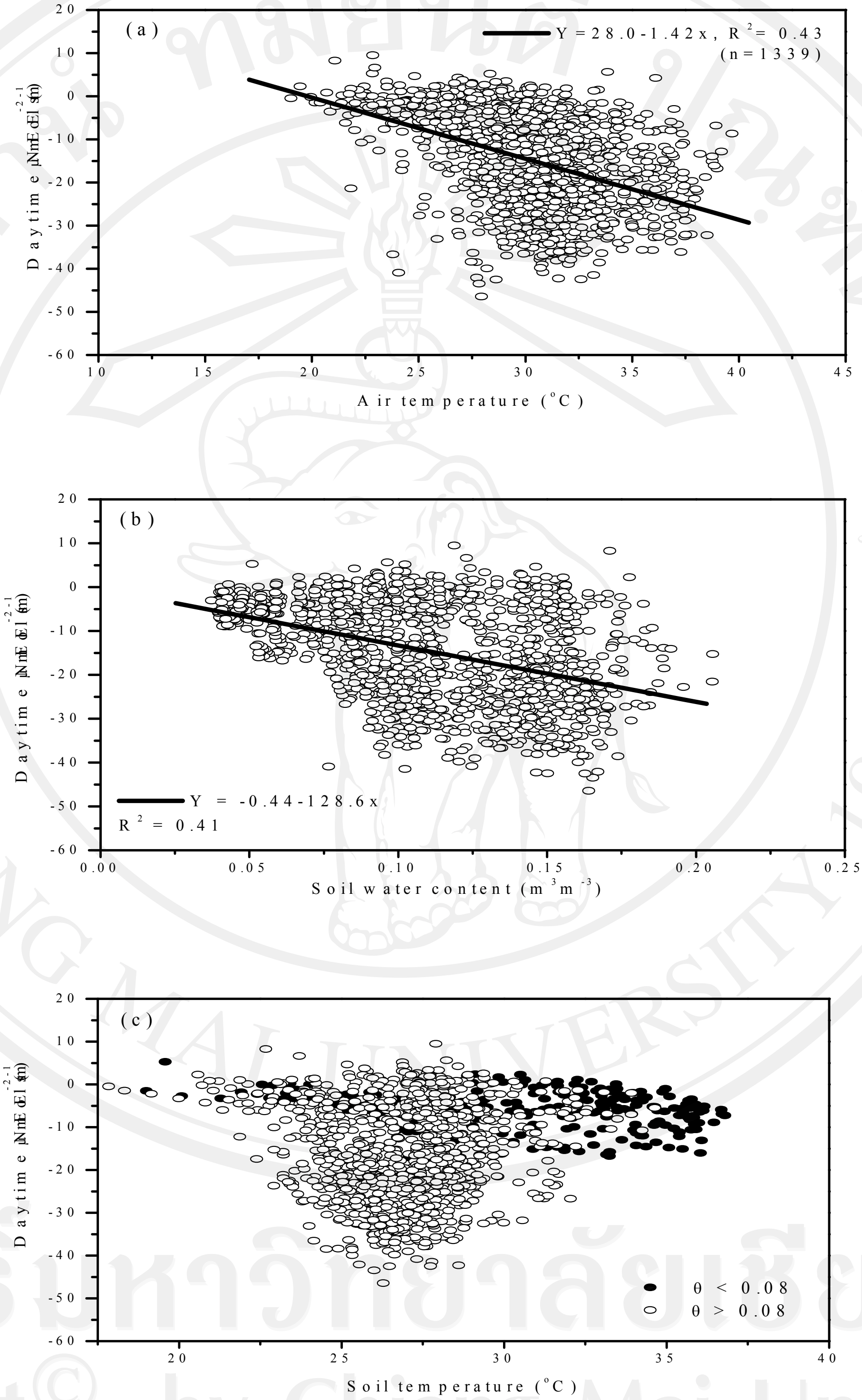


Figure 3.14 Response of daytime NEE to change in air temperature (a), soil water content at 0.02 m depth (b) and soil temperature (c).

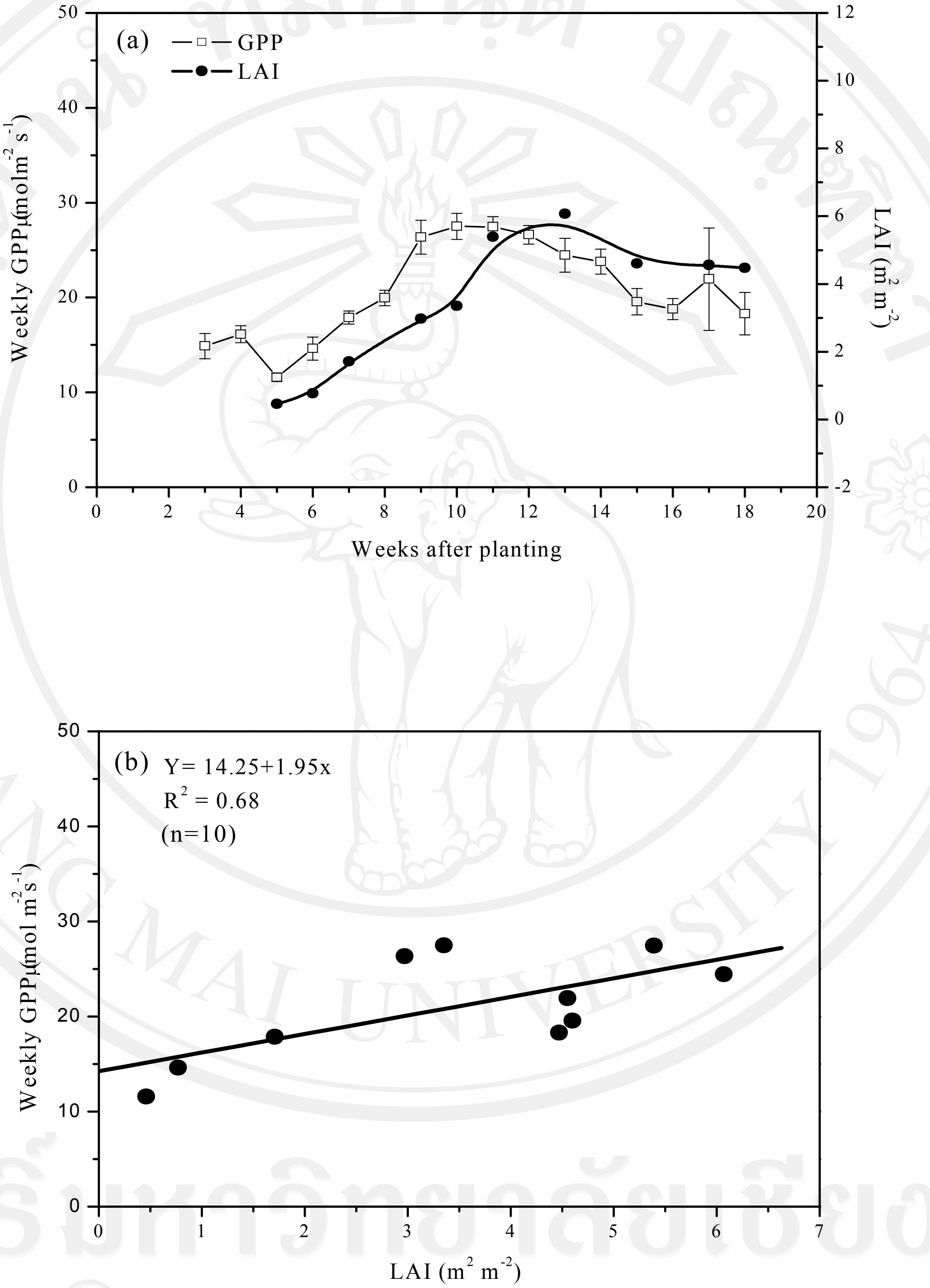


Figure 3.15 Seasonal variation of weekly-GPP in relation to leaf area index (LAI) (a), and the relationship between weekly GPP and LAI (b).

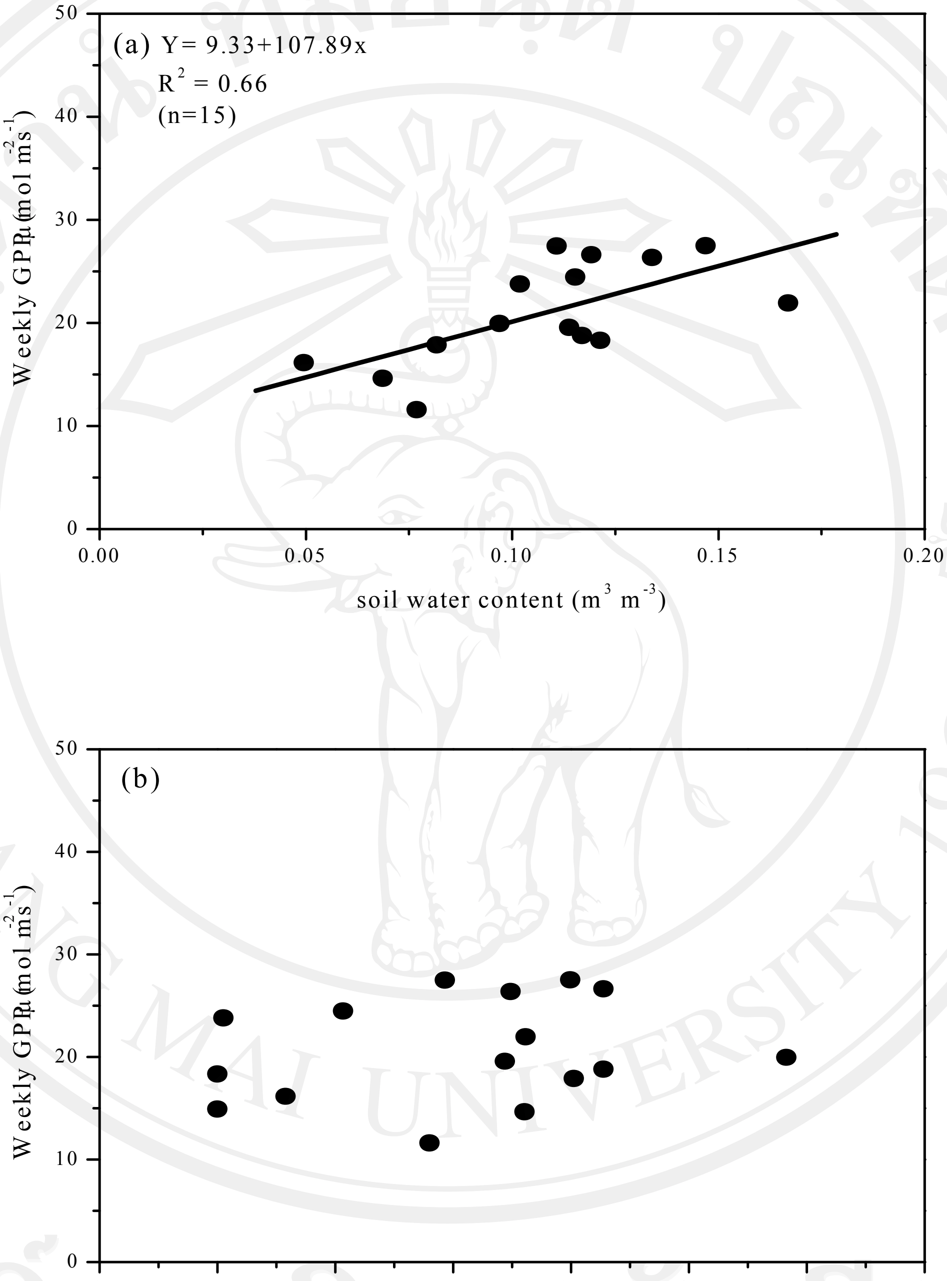


Figure 3.16 The relationship between weekly-GPP and soil water content at 0.02 m depth (a) and amount of rainfall (b).

Response of nighttime NEE to biophysical and environmental factors

Seasonal distribution of weekly-nighttime NEE or ecosystem respiration for peanut crops is given in Figure 3.17a. Like GPP, the distribution of ecosystem respiration showed a strong linkage with leaf area index (LAI). About 70% variation in ecosystem respiration was explained by the change in LAI (Fig. 3.17b). The relationship between ecosystem respiration and soil water content was described by linear function and explained only 56% of the variation in ecosystem respiration (Fig. 3.18a). In terms of amount of rainfall response, there was weak significant relationship between ecosystem respiration and temperature and amount of rainfall.

Evidence exists in the literature that plant respiration can be scaled from plant photosynthesis. When ecosystem respiration was plotted against GPP, there was a strong linear relation ($R^2 = 0.86$, Fig 2.19). This relationship indicates that ecosystem respiration was more closely related to the canopy photosysthetic activity than to soil temperature and soil water content

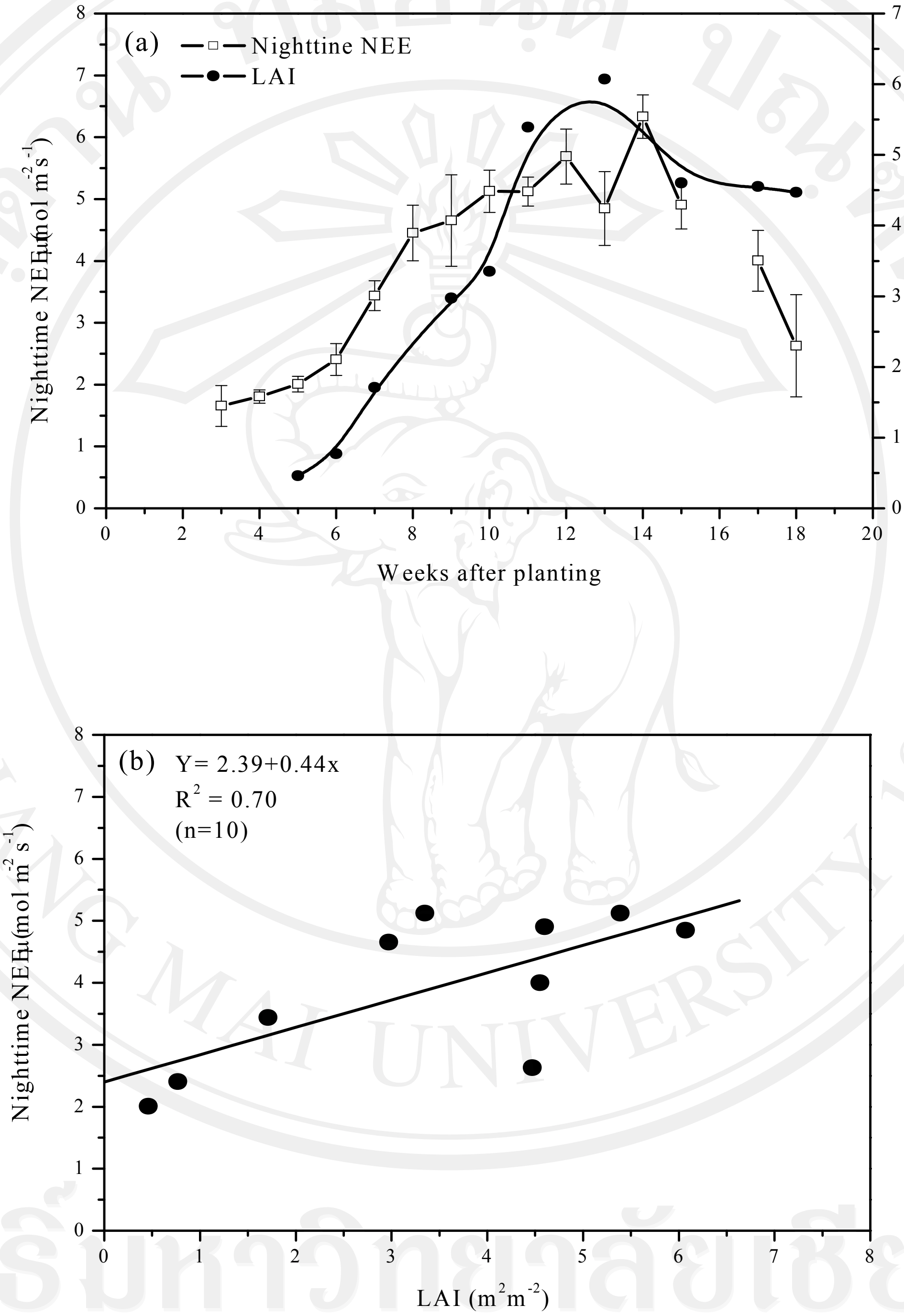


Figure 3.17 Seasonal variation of weekly-nighttime NEE in relation to leaf area index (LAI) (a) and the relationship between weekly-nighttime NEE and LAI (b).

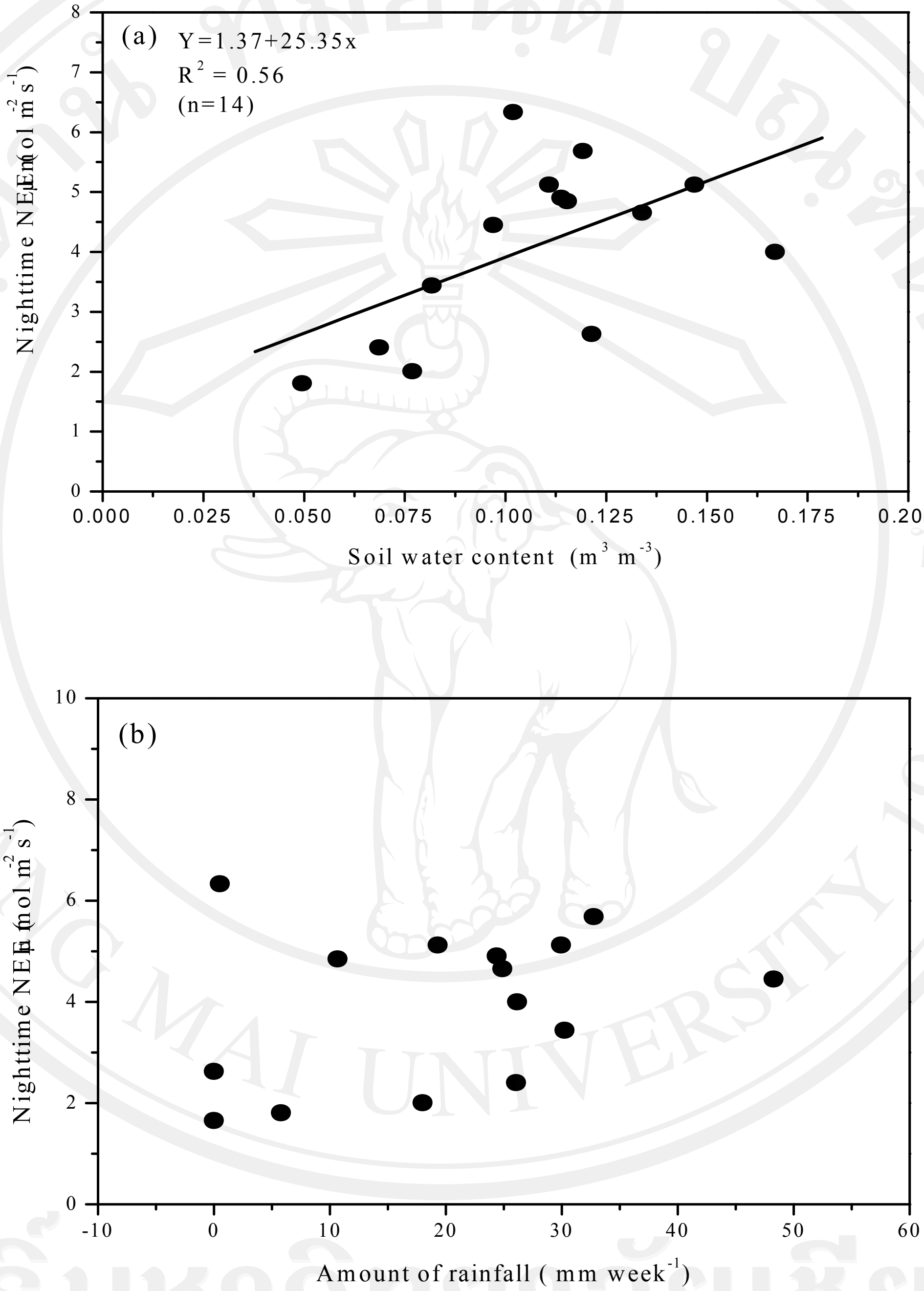


Figure 3.18 The relationship between weekly-nighttime NEE and soil water content at 0.02 m depth (a) and amount of rainfall (b).

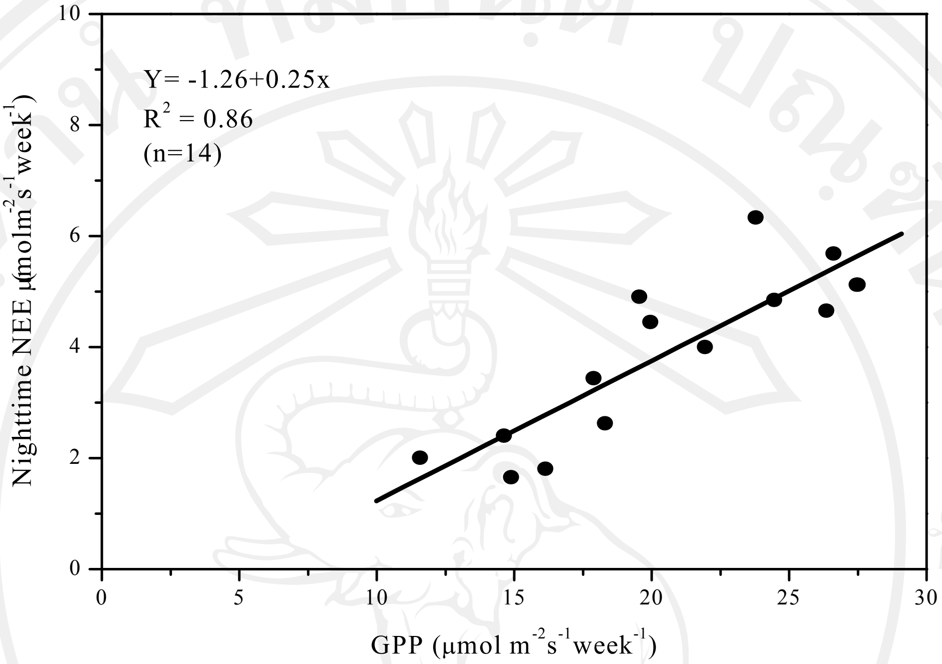


Figure 3.19 The linear relation between weekly gross primary production (GPP) and weekly nighttime NEE or ecosystem respiration.

DISCUSTION

Variation in seasonal pattern of GPP and ecosystem respiration

Seasonal variation of NEE measured by the eddy covariance technique was explained by those of GPP and ecosystem respiration as calculated using empirical models. The seasonal course of NEE was reflected in the differences of the phases and amplitudes in GPP and ecosystem respiration. The GPP was clearly apparent 3 weeks after leaf emergence and reached its maximum in 9 weeks after planting before the canopy was fully development. From 12 weeks after planting, GPP decrease. This decrease was not solely due to a radiation decrease but also to a canopy assimilation capacity reduction probably resulting from the increase of aged leaf relative area. The responses of daytime of NEE to air temperature and soil water content were investigated. Increased air temperature and soil water content enhanced the amount of half-hourly NEE net carbon uptake (Fig 3.12). This result suggested that photosynthesis at the study site was controlled by both air temperature and soil water content. The seasonal course of NEE was reflected in the differences of the phases and amplitudes in GPP and ecosystem respiration. Seasonal variation of GPP was mainly controlled by LAI, photosynthetic physiology and soil water content (Fig. 3.13 and 3.14). However, the strong dependence of weekly GPP on soil water content at surface soil (2-10 cm) indicated that soil water content is a batter predictor variable to NEE estimation at a peanut ecosystem. These results were consistent with the results of Kwon *et al.* (2008). They found that soil water availability was the main driving factor of growing season NEE under water limitation. Additionally, there are no relationship between GPP, ecosystem respiration and amount of rainfall. This might have been attributable to the frequency of rainfall. More frequent rain events occurred in the day time in this study. The explanation is that leaf surface wetness is reported to restrict CO_2 assimilation through stomatal regulation resulting from the loss of Rubisco (Hanba *et al.,* 2004). This is consistent with the work of Gaumont-Guay *et al.* (2006) who stage that the timing and frequency of rainfall was most important on soil respiration and ecosystem respiration than the amount of rainfall.

The seasonal variation of ecosystem respiration was determined mainly by soil water content (Fig. 3.16). This is consistent with the work of Chen *et al.* (2002) who examined seasonal variation in ecosystem respiration at the Howard Springs site and found that soil water content was the main influence on respiration rate. Flanagan and Johnson (2005) found that soil moisture was the dominant environmental factor that controlled seasonal and interannual variation in ecosystem respiration in grassland, when variation in temperature was held constant. Generally, ecosystem respiration is dependent on autotrophic (plant) and heterotrophic (microbe) activity, and both of these are controlled by environmental conditions (primarily temperature and water availability), and supply of carbohydrate and other substrates (Raich and Schlesinger, 1992; Davidson *et al.,* 1998; Janssens *et al.,* 2001). The lack of a relationship between ecosystem respiration and temperature in this study was likely due to the combination of difference factors. First, there are numerous sources of CO_2 for ecosystem respiration, each with their own controlling factors. Second, there was only a small range temperature during growing season (25-30°C). Therefore, soil water content appear to have played a more important role that temperature in explaining variability of both GPP and ecosystem respiration.

Weekly ecosystem respiration is strongly correlated with GPP, which explained 86% of variations in ecosystem respiration in the growing season. The ecosystem respiration was related to large GPP, the ratio of CO_2 uptake by photosysthesis to CO_2 release was almost linear because respiration should increase with photosynthesis. This result indicated that ecosystem respiration was more closely related to the canopy photosynthetic activity than to temperature. These results are in agreement with a number of recent studies that have demonstrated a close linkage between the photosynthesis activity and respiration. In Mediterranean annual grassland, Xu and Baldocchi (2004) showed that the interaction between soil moisture and plant activity was the dominant control on the magnitude of ecosystem respiration. Hirata *et al.* (2007) also found that ecosystem respiration was enhanced by the high photosynthetic activity of larch forest during growing season. Janssens *et al.* (2001) showed that soil and ecosystem respiration were strongly correlated to photosynthesis in several European forests, and that forest productivity had a larger effect than temperature in explaining variation in respiration rates among the different forests. This result suggested that the canopy photosynthesis is the best indicator of ecosystem respiration by controlling the substrate availability for autotrophic and heterotrophic respirations.

In summary, the seasonal distribution of weekly GPP of peanut was closely linked to the respective variations in green leaf area index on long time scales whereas GPP was strongly related to radiation on short-term time scales. The peak weekly GPP was 27 μmol $m^{-2}s^{-1}$. Peak in GPP were observed approximately 10 weeks after planting. The seasonal distribution of weekly ecosystem respiration also followed that of the LAI. Respective peak value of ecosystem respiration was 6.5 μmol $m^{-2}s^{-1}$.

However, these factors are often autocorrelated with the seasonal distributions of air/soil temperature and soil moisture and thus it is difficult to examine the dependence of ecosystem respiration on leaf area. The range of seasonal distribution of weekly ecosystem respiration was lower than that of the weekly GPP. This result indicated that seasonal distribution of weekly ecosystem respiration was mainly controlled by the canopy photosynthesis. The using the measured eddy covariance CO_2 flux, this method is used to monitor the net gain of carbon by the crop over the entire growing season reasonably well. Only one season of contrasting amount of rainfall was observed, much more years of research are needed to study the long term effects of altered rainfall timing on NEE.