ความผันแปรในระหว่างปีของอัตราการหมุนเวียนคาร์บอนไดออกไซด์ ในดินนาข้าว จังหวัดสุโขทัย

นางสาวปริชาติ เวชยนต์

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INTERANNUAL VARIABILITY OF CARBON DIOXIDE CIRCULATION IN PADDY FIELD SOIL, SUKHOTHAI PROVINCE

Miss Parichat Wetchayont

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ปริชาติ เวชยนต์ : ความผันแปรในระหว่างปีของอัตราการหมุนเวียนคาร์บอนไดออกไซด์ในดินนาข้าว จังหวัดสุโขทัย (INTERANNUAL VARIABILITY OF CARBON DIOXIDE CIRCULATION IN PADDY FIELD SOIL, SUKHOTHAI PROVINCE) อาจารย์ที่ปรึกษาวิทยานิพนธ์: ผู้ช่วยศาสตราจารย์ ดร.สมชาย นาคะผดุงรัตน์, 130 หน้า. ISBN 974-17-6978-4

การศึกษาความผันแปรในระหว่างปีของแก็สคาร์บอนไดออกไซด์จากดินในนาข้าว จังหวัดสุโขทัย มีวัตถุประสงค์เพื่อติดตามการเปลี่ยนแปลงและประเมินค่าการปลดปล่อยก๊าซคาร์บอนไดออกไซด์จากดินจากอิทธิพลของอุณหภูมิและความชื้นในดิน ซึ่งตรวจวัดโดยวิธี closed chamber technique ในปี พ.ศ. 2546 ในการตรวจวัดทุกครั้งจะเก็บข้อมูลความชื้นดินโดย TDR และอุณหภูมิดินด้วย Temperature probe ที่ระดับความลึก 5 เซนติเมตรจากผิวดิน นอกจากนั้นได้ทำการเก็บตัวอย่างดินจากผิวพื้นจนถึงระดับความลึก 30 เซนติเมตร เพื่อนำไปวิเคราะห์คุณสมบัติทางเคมีของดิน จากการทดลองพบว่าความผันแปรของการปลดปล่อยก๊าซคาร์บอนไดออกไซด์ของดินมีค่าสม่ำเสมอตลอดทั้งปี โดยในเดือนมกราคมมีระดับสูงกว่าปกติเล็กน้อย แล้วลดอัตราการปลดปล่อยก๊าซคาร์บอนไดออกไซด์มาที่ระดับปกติในเดือนกุมภาพันธ์ ยกเว้นเดือนกรกฎาคม พบว่ามีค่าสูงกว่าปกติ การวิเคราะห์ได้แบ่งเป็น 2 ช่วง คือ dry period ในช่วงเดือนมกราคมถึงเดือนกุมภาพันธ์และเดือนพฤศจิกายนถึงเดือนธันวาคม (อัตราเฉลี่ย 528.58 mg CO_2 m^{-2} h^{-1}) ส่วน wet period จะอยู่ในช่วงเดือนมีนาคมถึงเดือนตุลาคม (อัตราเฉลี่ย 299.12 mg CO_2 m^{-2} h^{-1}) จากการศึกษาพบว่า ตลอดปีอุณหภูมิดินมีความผันแปรน้อยแต่ความชื้นดินจะผันแปรตามการตกของฝน ดังนั้น ปัจจัยหลักที่จำกัดการปลดปล่อยก๊าซคาร์บอนไดออกไซด์จากดินในช่วง dry period คือ ความชื้นในดิน ส่วนอุณหภูมิดินเป็นปัจจัยรอง ในทางกลับกันในช่วง wet period พบว่ามีความสัมพันธ์กับปัจจัยศึกษาทั้งสองต่ำ แต่ยังพอสรุปได้ว่า ปัจจัยหลัก คือ อุณหภูมิดิน และปัจจัยรอง ได้แก่ ความชื้นดิน ผลการวิเคราะห์การถดถอยพบว่า การปลดปล่อยก๊าซคาร์บอนไดออกไซด์จากดินมีความสัมพันธ์กับอุณหภูมิและความชื้นดินแบบไม่เป็นเส้นตรงในทั้ง 2 ช่วงการวิเคราะห์ ได้สมการสองตัวแปรโดยประยุกต์จาก Arrhenius equation และค่าการปลดปล่อยแก็สคาร์บอนไดออกไซด์รวมตลอดปีจากดินนาข้าว จังหวัดสุโขทัยในปี พ.ศ. 2546 มีปริมาณ 2.99 kg CO_2 m^{-2} y^{-1} คำนวณจากข้อมูลที่ตรวจวัด และ 2.89 kg CO_2 m^{-1} y^{-1} โดยคำนวณจากสมการ dry period (1.53 kg CO_2 m^{-1} y^{-1}) และ wet period (1.36 kg CO_2 m^{-1} y^{-1})

ภาควิชา ธรณีวิทยา	ลายมือชื่อนิสิต...................................
สาขาวิชา โลกศาสตร์	ลายมือชื่ออาจารย์ที่ปรึกษา..............................
ปีการศึกษา 2547	ลายมือชื่ออาจารย์ที่ปรึกษาร่วม........................

 # # 4472328223 :MAJOR EARTH SCIENCE

KEY WORD: SOIL RESPIRATION / PADDY FIELD / SOIL TEMPERATURE / SOIL WATER CONTENT / CLOSED CHAMBER TECHNIQUE / SUKHOTHAI PROVINCE

PARICHAT WETCHAYONT: INTERANNUAL VARIABILITY OF CARBON DIOXIDE CIRCULATION IN PADDY FIELD SOIL, SUKHOTHAI PROVINCE. THESIS ADVISOR: ASSISTANT PROFESSOR SOMCHAI NAKAPADUNGRAT, Ph.D. 130 PP. ISBN 974-17-6978-4

Interannual variability of soil respiration was investigated in a paddy field, Suhkothai Province in northern Thailand. The objectives of this research were to monitor the variation in soil respiration in paddy field and to evaluate both soil temperature (Ts) and soil water content (SWC) functions as predictors of soil respiration. Soil respiration was measured with closed chamber technique throughout an annual cycle in 2003. For each measurement date, soil water content was taken in the top 5 cm, using time domain reflectometry (TDR) and soil-surface temperature also was recorded in the same depth, using a temperature probe. Also soil sample from surface to 30 cm depth soil core (5 cm diameter) was collected for each measurement. Variation on SR exhibited highest in January, the later month quite steady except for the extremely high respiration rates in July, in particular dry period (528.58 mg CO_2 m^{-2} h^{-1} overall mean) from January to February and from November to December and wet period from March to October (299.12 mg CO_2 m^{-2} h^{-1}). During measurement period, Ts slightly varies but SWC large changes corresponding with rainfall pattern. For the dry period, SR rates were mainly limited by SWC. Ts is minor factor influence. Whereas, in the wet period, SR rates were poorly correlated with both Ts and SWC, however Ts also seem be the most effectors and SWC still be minor factor even though shows a bit correlation. The best fitted equations were reconstructed base on Arrhenius equation as bivariate nonlinear relationships for both of the dry and the wet period. Total annual of SR to be 2.99 kg CO_2 m^{-2} y^{-1} by using measured data and 2.89 kg CO_2 m^{-1} y^{-1} estimated by integrating the model outputs in part of the dry (1.53 kg CO_2 m^{-1} y^{-1}) and wet period (1.36 kg CO_2 m^{-1} y^{-1}).

Department Geology	Student's signature……….……………
Field of study Earth Science	Advisor's signature………..……………
Academic year 2004	Co-advisor's signature……..……………

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CHAPTER I

INTRODUCTION

1.1 Motivation

Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise (IPCC, 1998). In addition to warming, increases in sea level and changes in precipitation distribution, including more frequent floods and droughts. These changes, over time, are referred to broadly as the result of climate change, and its effects on our future environment require a better understanding and quantification of the processes supporting global change. An integrated view of climate change considers the dynamics of the complete cycle of interlinked causes and effects across all sectors concerned (Figure 1.1).

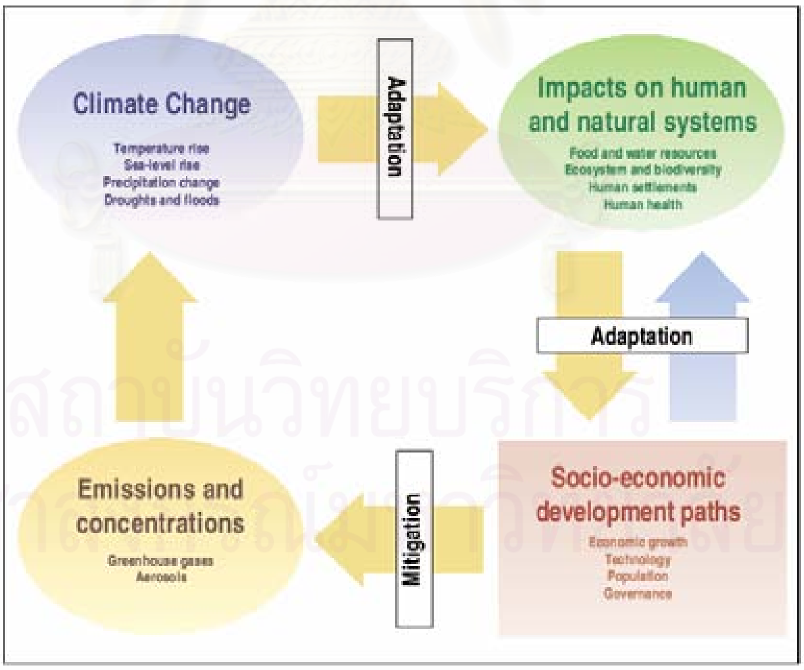

Figure 1.1 Representation of an integrated assessment flowchart for considering impact of climate change. The yellow arrows showed the cycle of cause and effect among the four quadrants shown in the figure, while the blue arrow indicates the societal response to climate change impacts. Source: IPCC (1998)

The Earth's climate system has indicatively changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activities. The growing scientific approval is that this warming is largely the result of emissions of greenhouse gases (i.e., carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)) from human activities including industrial processes, fossil fuel combustion, and changes in land use, such as deforestation. Might be in future warming suggest a global increase of 1.4ºC to 5.8ºC by 2100.

1.2 The cause of CO_2 selection

Human activities have increased the atmospheric concentrations of greenhouse gases and aerosols since the pre-industrial era. The atmospheric concentrations of greenhouse gases reached their highest recorded levels in the 1990s, generally due to the combustion of fossil fuels, agriculture and land use changes. An increasing of observations gives a collective picture of a global warming and other changes in the climate system. The increase in surface temperature over the 20th century for the Northern Hemisphere is likely to have been greater than that for any other century in the last thousand years. Insufficient data are available prior to the year 1860 in the Southern Hemisphere to compare the recent warming with changes over the last thousand years. Temperature changes have not been uniform globally but have varied over regions and different parts of the lower atmosphere.

Long records of past changes in atmospheric composition provide the context for the influence of green house gas emissions. Figure 1.2 a, b and c showed changes in the atmospheric concentrations of CO_2, CH_4, and N_2O over the past thousand years. The ice core and firn data for several sites in Antarctica and Greenland (shown by different symbols) are supplemented with the data from direct atmospheric samples over the past few decades (shown by the line for CO_2 and incorporated in the curve representing the global average of CH_4). The estimated positive radiative forcing of the climate system from these gases is indicated on the right hand scale. Since these gases have atmospheric lifetimes of a decade or more, they are well mixed, and their concentrations reflect emissions from sources throughout the globe. All three records showed effects of the large and increasing growth in greenhouse gases emissions during the Industrial Era. In particular, CO_2 is the highest concentration in the atmosphere and the highest radiative forcing ability. Therefore, CO_2 is interested and selected to observe in this study.

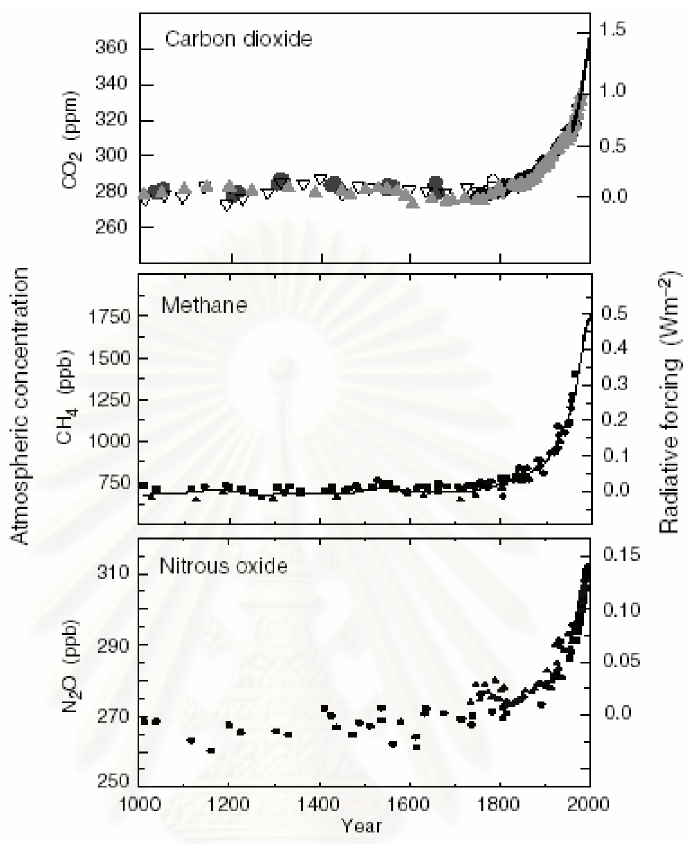

Figure 1.2 The records of past changes in atmospheric concentration and the radiative forcing of CO_2 (a), CH_4 (b) and NO_2 (c)
Source: IPCC (2005)

The concentration of CO_2 in the atmosphere has rapidly increased since the industrial revolution and released the greenhouse gases to disrupt global climatic patterns continuously. Some analyses suggest that increases in atmospheric CO_2 can be mitigated by change in soil carbon storage; however, soil respiration (SR) may increase as the result of increases of CO_2 in atmospheric (Jenkinson *et al.,* 1991; Nakayama *et al.,* 1994, Schlesinger, 1977). Many studies about this impact have paid attention on above ground tree responses and have shown that increasing concentrations of CO_2 in atmospheric may lead to change forest ecosystems (Ceulemans *et al.,* 1999; Bazzaz, 1990).

The current concentration of CO_2 (in parts per million, ppm) in the atmosphere has increased by about 30% since the start of the industrial revolution around the middle of the 19th century (Figure 1.3) and is continue releasing greenhouse gases to disturb global climatic patterns. Temperatures at the Earth's surface increased by an estimated 1ºF (0.6ºC) over the 20th century. The 1990's were the hottest decade of the entire century, in 1998, and 2001 were two of the hottest years ever recorded (Figure 1.4). Increasing of atmospheric CO_2 concentration and temperature are the similar trend, indicated that temperature raising caused by atmospheric CO_2 concentration. Therefore, recent global circulation models include potential increases in atmospheric CO_2 concentration and temperature (Cox *et al*., 2000), and changes in the distribution of precipitation and evaporation (Mitchell *et al*., 1999; Dai *et al*., 2001).

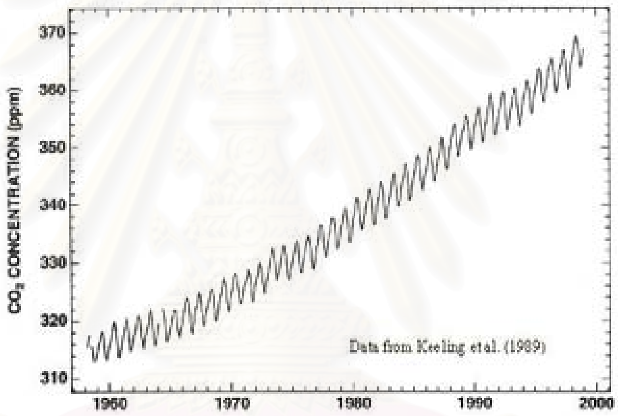

Figure 1.3 Global CO_2 concentration (ppm) of the air at the summit of Mauna Loa, Hawaii (19° 32′ N, 155° 35′ W), from 1958 to 2000
Source: Keeling *et al.* (2001)

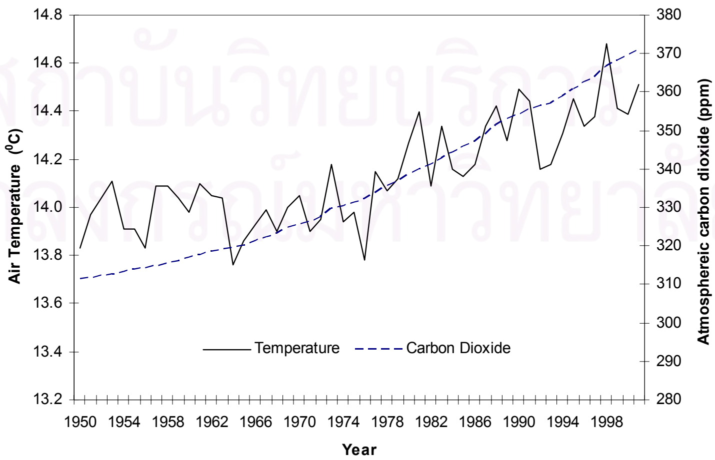

Figure 1.4 Global average temperature rise at earth's surface and atmospheric concentrations of carbon dioxide, 1950-2001
Source: Keeling *et al.* (2001)

The result of CO_2 emissions from human activities including industrial processes were exactly known, while the CO_2 emissions from ecosystem still lack of understanding. Plants are one of important components in the global carbon cycle. Each year they withdraw carbon (in form of CO_2) from the atmosphere through photosynthesis and release to the atmosphere through both plant and microbial respiration. The processes of photosynthesis and respiration are strongly affected by climatic conditions, particularly temperature and precipitation. Soil respiration (SR) is the loss of carbon (in the form of CO_2) from soils as a result of both microbial decomposition and root respiration. Both temperature and moisture play an important role in determining SR rates.

SR could result in understanding the nature and extant of the role played by soil in the CO_2 cycle. In order to completely understand the role of soils in absorbing CO_2, we need to understand the fundamental processes controlling soil carbon content. Several issues have emerged recently to focus questions on the role of soils in the global carbon cycle over a decade to century time scales. First, soils have historically played the roles of both sources and sinks of carbon associated with changes in land management including agricultural management. Second, how climatic changes influence soil carbon stores knowing that organic matter decomposition rates are linked to soil temperature (Ts) and soil water content (SWC). Third, soils contain the largest active terrestrial carbon pool on earth, and contribute 10 times more CO_2 to the atmosphere than fossil fuel combustion through SR (Schlesinger, 1997). Despite recent achievements, many quantitative gaps are still present in knowing the relative size of soil carbon pools and the mean residence time of carbon in the soil. For example, in the conversion of virgin soils to a cultivated state; the exact part of the carbon cycle is affected by this process remains unknown (Trumbore, 2000).

1.3 The cause of Paddy field selection

Further more, the impact of the climate change on SR is largely unknown. Since SR is a major mechanism controlling soil carbon pools a through understanding of influence factors of this process is essential before we can determine how much CO_2 that emitted from soil.

According to the role of soils in the global carbon cycle in section 1.2, the land management is one of the fundamental processes controlling soil carbon content. Since more than 52% of agricultural land use in Thailand was paddy field (National Statistical Office, 2003). There are a few studies on SR in Thailand, however, it still be unconcern in the paddy field. Therefore, understanding the nature and extant of the SR role played by rice in the CO_2 cycle become interesting. Moreover, the paddy field where settled the micrometeorological instruments became interesting. Because that supposed to use the micrometeorological data related with our SR data to find out the purpose. The micrometeorological towers under the GEWEX Asian Monsoon Experiment (GAME) project were installed at 4 sites, Lampang, Suhkothai, Phisanulok and Nakornrachasima. Sukhothai site was selected to measure SR because our aim was focused on paddy soil and this site was less data lose problem due to electric city drop.

1.4 Objectives

1. To monitor the interannual variation of soil respiration (SR) in paddy field, Sukhothai Province.
2. To evaluate the effects of Soil Temperature (Ts) and Soil Water Content (SWC) on SR.
3. To evaluate the annual emission of CO_2 from paddy field in Sukhothai Province, Thailand.

1.5 Scopes of work

1. Assumption of SR is total CO_2 flux that emit from soil.
2. Measure monthly CO_2 emission from soil in Paddy field, Sukhothai Province, Thailand in 2003.
3. Measurements are based on the closed chamber technique.

CHAPTER II

BACKGROUNDS AND LITERATURE REVIEW

2.1 Carbon cycle and soil carbon dioxide emission

Bush (2000) gave the definition of the carbon cycle. The carbon cycle maintains atmospheric CO_2 concentrations through the continuous uptake CO_2 by plants and their respiration of carbohydrate storage. The diagram on Figure 2.1 shows the carbon cycle with the mass of carbon, in Petagrams of carbon (1 Pg C = 10^{15} grams C), in each sink and for each process, if known. The amount of carbon being exchanged in each process determines whether the specific sink is growing or shrinking. For instance, the ocean absorbs 92 Pg C more from the atmosphere than it gives off to the atmosphere. All other things being equal, the ocean sink is growing at a rate of 92 Pg C per year and the atmospheric sink is decreasing at an equal rate. But other things are not equal. Fossil fuel burning is increasing the atmosphere's store of carbon by 5.5 Pg C each year, and the atmosphere is also interacting with vegetation and soil.

The decomposition cycle also is extremely important component in the carbon cycle. Decomposers feed on dead organic matter and respiration the carbon from the corps approximately 50 Pg C per year and withdraw CO_2 from atmosphere for primary production in similar amount about 51 Pg C per year. The chemical reaction of respiration calls for oxygen that is used as CO_2 is released. Thus the release of CO_2 from decomposers in the soil is called soil respiration (SR). This CO_2 is released into the atmosphere, where it may once again be used in photosynthesis. An alternate way for a plant body part is eaten by herbivore. The herbivore either releases CO_2 via respiration, dies, and is respired by decomposers, or becomes food for a predator, and so cycle goes on. It is the ultimate way of every carbon molecule in our bodies to be respired and returned to the atmosphere as CO_2, unless a dead body is fossilized.

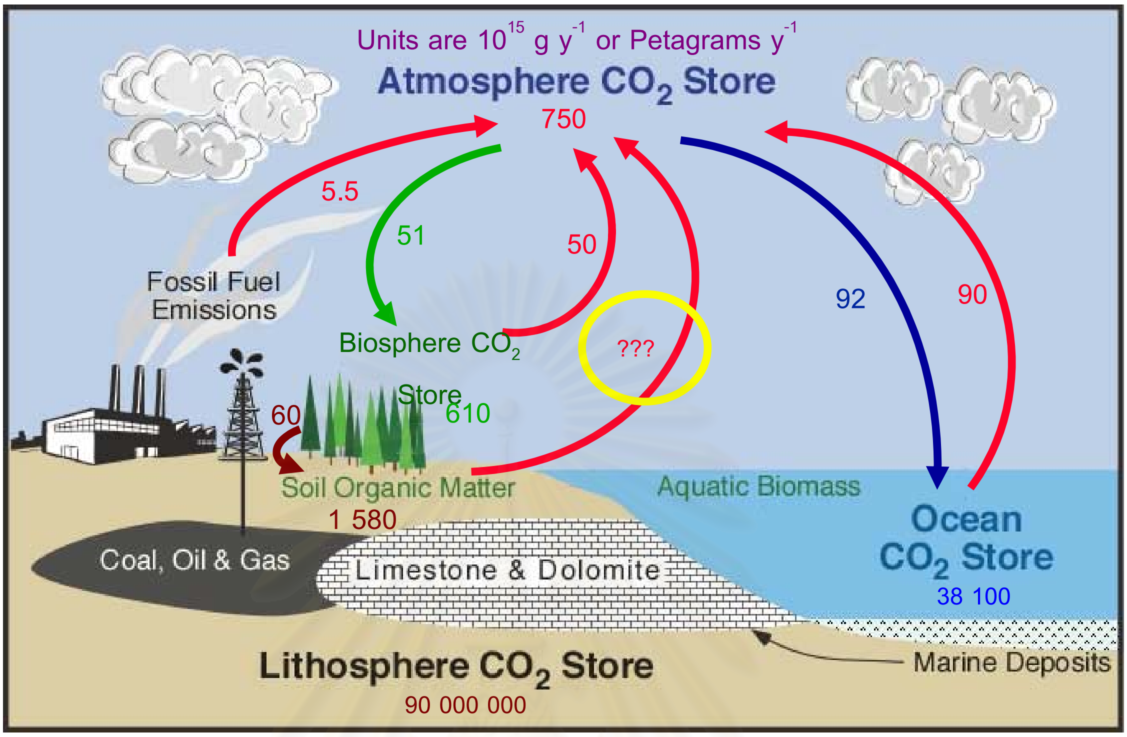

Figure 2.1 The carbon cycle and carbon dioxide emission
Source: National Science Foundation (2005)

2.1.1 Soil

Global total carbon flux from soil is estimated to be between 50 and 75 Gigatons (C) y^{-1} (Raich and Schlesinger, 1992). The deep ocean is considered the largest pool of the global carbon-cycle and soil is considered to be the second largest pool in the global carbon cycle, as well comprising more than twice from the estimated pool of carbon in living biomass. In particular importance is the soils in the boreal region, which are form the largest soil organic matter reserve, due to low soil temperatures (Ts) (Rayment and Jarvis, 2000).

Soils are an important component of the global carbon budget for several reasons. Firstly, as shown in Figure 2.1 soil is the greatest reservoir containing about twice the amount of carbon as the atmosphere, i.e. 1500 Pg of carbon in soils vs. 750 Pg of carbon in the atmosphere (Watson *et al*., 1990), and the results are an important global carbon reservoir. Secondly, soils contribute carbon to the atmosphere through plant root respiration and decomposition of soil organic matter by soil microorganisms that transform organic plant inaccessible carbon to the inorganic plant accessible form (CO_2). There upon after photosynthesis, CO_2 which emits from soil, soil respiration (SR) is the second largest flux of carbon in most terrestrial ecosystems (Davidson *et al*., 1998). It has been hypothesized that small climatically induced changes in SR could rival the annual fossil fuel loading of atmospheric CO_2 (Jenkinson *et al*., 1991; Raich and Schlesinger, 1992).

In addition, Schlesinger (1977) reported that forest and mineral soil in temperate forests, accounted for 45% of the total ecosystem carbon storage. Recently, Rhoades *et al.* (2000) also added the contribution of tropical soils to an increased emission of CO_2 from terrestrial ecosystems and showed that 32% of the global soil carbon (including the above and below ground storage) is contained in tropical soils. As Mielnick and Dugas (1999) suggested, soil contributes carbon to the atmosphere through plant root respiration and decomposition of soil organic matter by soil microorganisms that transform organic plant-inaccessible carbon to the plant-accessible form (CO_2). Moreover soil contains twice amount of carbon in the atmosphere and therefore it is an important component of the global carbon budget.

Maria (2003) suggested that most of the carbon is stored below ground; soil has a central role in the carbon cycle. Therefore, it is important to measure how the carbon exchange of the soil varies in the short term, and to estimate its impact in the longer term. The concept of SR refers to the flux of CO_2 at the soil surface, quantified as the amount of CO_2 given off by living organisms and roots in the soil.

However, knowing only the size of the reservoir of carbon stored in soils is not enough to predict its influence on atmospheric CO_2 concentrations. Changing in the carbon balance between atmosphere and the terrestrial ecosystems could significantly affect to the CO_2 level in the atmosphere. Carbon cycle in a terrestrial ecosystem can be recognized as a circulation of carbon among the atmosphere, organisms and soil as carbon pools.

2.1.2 Soil respiration

Carbon storage in soil is regulated balancing between above ground and below ground production. The above ground, primary production is considered the main source of organic matter for most soils.

The CO_2 is fixed by photosynthesis that is transferred from the above ground parts of living plants to the soil via litterfall and through translocation to the roots and from the roots into the soil as illustrated on Figure 2.2. Microbes utilize the carbon compounds which transformed from root derivation for energy production and biosynthesis. The functioning of soil ecosystems is possible only through the microbial activity which drives the nutrient cycling in soil and which uses the production of root-derived carbon.

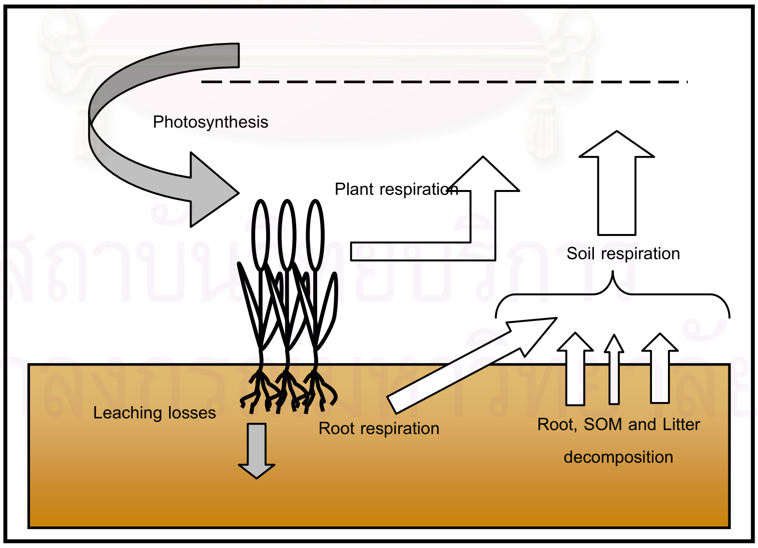

Figure 2.2 Carbon dioxide cycle in agricultural ecosystem and the soil respiration.

Source: Van Veen *et al.*, 1991

Toland and Zak (1994) also mentioned that the large portion of the CO_2 flux emitted from soil as a result of the decomposition of the below ground litter and plant root respiration. Root respiration is defined to all processes occurring in the rhizosphere following the definition of Wiant (1967) who stated that "root respiration includes all respiration derived from organic compounds originating in plants including all respiration of living root tissue, the respiration of symbiotic myccorrhizal fungi, associated microorganisms, decomposing organisms operating on root exudates and recent dead root tissues in the rhizosphere".

Pajari (1993) and Blanke (1996) defined the SR as consist mostly of the CO_2 produced by soil microorganisms and the roots of plants. The activity of microorganisms performing decomposition is mainly regulated by Ts, soil moisture content, and the availability of nutrients and energy sources, that is the chemical composition of the organic material in the soil at 0.6 m below canopy layer. Similar to Maria (2003) who defined that soil respiration, or soil surface CO_2 flux, is one of the two main mechanisms which carbon is transferred from the soil to the atmosphere.

Jenkinson *et al.* (1991) mentioned that soil respiration provides the main carbon flux from ecosystems to the atmosphere and is therefore an important component of the global carbon balance. Rates of soil respiration are known to be highly sensitive to Ts and soil moisture content and thus a future warmer climate may increase the flux of CO_2 from the soil.

Early studies of soil respiration by Lundegardth (1927) and others were performed generally in the laboratory or under agronomic conditions. Only in recent years has the complexity of the heterotrophic processes in the soil has been decoded. Soil respiration is the process by which the CO_2 produced by soil microorganisms and plant roots is released at the soil surface (Witkamp and Frank, 1969; Rochette *et al.,* 1991; Akinremi *et al.,* 1998). Soil respiration is the major pathway of ecosystem carbon flow and can contribute a significant fraction of the CO_2 fixed by photosynthesis. Reiners (1968) compared the forest floor to a major area of heterotroph activity and considered it a heterotrophic subsystem of the forest.

Kelting *et al*. (1998) addressed that the issue of three biologically relevant compartments among carbon is transferred in soils: root tissue, rhizosphere, and root-free soil. The most easily distinguished is the root tissue compartment, consisting of living roots bounded by the soil matrix. The rhizosphere compartment is more disperse, being populated by a relatively large microbial community (Hanson *et al.* 2000), which utilizes root-derived organic matter as the primary energy substrate. The third compartment, known as the root-free soil compartment consists of a smaller microbial community, which obtains its energy from the root turnover, and organic matter from above ground litter via secondary products diffused into the root-free soil.

Most investigators have found that it is difficult to quantify the contribution of roots to the total forest floor respiration. One approach suggested by Edwards and Sollins (1973) was to measure CO_2 evolution from upper root-free horizons, while measuring oxygen uptake from roots separated from portioned, lower horizons. Another procedure described by Hanson *et al.* (2000) was the root exclusion method that indirectly estimated root contribution to total soil CO_2 flux rates, by measuring SR with and without the presence of root. Much of the variability in these estimates might originate from the variety of measurement techniques, each with its unique set of limitations. Some estimates of total root respiration include soil disturbance and an extrapolation of the rates from individual roots to a whole system. Other estimates do not reflect conditions found in natural environment, depending on data from laboratory studies or greenhouses (Andrews *et al.,* 1999).

2.1.3 Soil CO_2 emission process

Knowledge of soil processes is also required to determine the effects of land use and land cover changes (Inter-Agency Committee on Global Environmental Change, 1996). Two major processes control CO_2 emission from the soil: the production of CO_2 in the soil and its transport from the soil to the atmosphere. The transport of trace gases within the soil has been studied previously and a sound theoretical base has been developed. Several mechanisms of gas and vapor transport can be distinguished in a porous medium like soil for example Knudsen diffusion, multi-component molecular diffusion and viscous flow (Thorstenson and Pollock, 1989; Massmann and Ferrier, 1992).

Usually, in soil pore when Oxygen (O_2) concentration gets lower than 2%-3% and CO_2 concentration rise to 5%-10%, the exchanging between O_2 in the atmosphere and CO_2 in soil will be occur (Faculty of Agriculture, 2001). However, ordinary gaseous diffusion and adjectives flow are considered to be the most important mechanisms (Freijer and Leffelaar, 1996), with the contribution from liquid phase diffusion being more significant than that from gaseous diffusion when soils are close to saturation (Sceimunek and Suarez, 1993). A mass balance model for the soil is commonly used (with different assumptions or simplifications about gas transport in the soil) to quantify CO_2 flux and the spatial distribution of CO_2 within the soil (Hendry *et al*., 1993; Sceimunek and Suarez, 1993; Wood *et al*., 1993). In a process-based model of CO_2 flux from the soil, the greatest uncertainty arises in describing CO_2 production and its dependence on soil conditions and no existing model is completely appropriate.

The release of CO_2 from the soil surface is the result of a number of complex processes, including CO_2 production, gas transport, and interactions between physical and biological factors within the soil. The relative importance of individual processes or factors in controlling CO_2 flux will vary in different ecosystems and under different climate conditions.

2.2 Soil respiration measurement techniques

Chambers placed over the soil surface have been used to measure soil respiration (Lundegårdh, 1927; Reiners, 1968) and other trace gas emissions from soils (Ryden et al., 1979) for many decades. The accuracy of methods has been extensively reviewed (Bekku et al., 1997; Ewel et al., 1987; Rochette et al., 1997), with the general conclusion that some times overestimates of low fluxes and underestimates of high fluxes, but can be reliably calibrated for an intermediate range of fluxes. The Chamber technique can disturb the natural habitat (e.g. damage roots or vegetation, increase the temperature in the chamber) and cause high and erratic gaseous fluxes (Austin *et al*., 1998).

SR can be measured using several techniques. That is measured directly using either the chamber or micrometeorological techniques (Eddy covariance). Both techniques have their limitations. According to Janssens *et al.* (2000), accurate measurements of soil CO_2 flux can be taken only by a system that does not change soil respiratory activity, the CO_2 concentration gradient, or the pressure and air motion near the soil surface. Given the fact that the methods of measuring soil CO_2 flux might have large differences in accuracy, spatial and temporal resolution, and applicability, the option of a specific technique is in most cases an exchange between accuracy and feasibility (Janssens *et al*., 2000). In other hand, Matthias *et al*. (1980) summarized the advantages of chamber technique using for measurement N_2O flux that (i) it had high sensitivity and allowed detection of very small emissions of N_2O from unfertilized soils; (ii) its use was not limited to sites where electricity or special equipment was available; (iii) the chamber used was inexpensive and easy to fabricate, transport, and use. The chamber technique is based on several methods as following:

2.2.1 Chamber technique

2.2.1.1 Alkali absorption method

Alkali absorption method (AA-method) is where CO_2 that evolves from soil in a closed chamber is absorbed in a caustic solution (Witkamp, 1966; Kirita, 1971; Edwards and Ross-Todd, 1983). The AA-method has been adopted in much research for its convenience and capability to obtain many measurement plots (Kucera and Kirkham, 1971; Nakane, 1975; Buyanovsky *et al.*, 1986; Singh *et al.*, 1988). However, it has been suggested that the AA-method may underestimate or overestimate actual SR rates through suppressing CO_2 diffusion (Kucera and Kirkham, 1971; Freijer and Bouten, 1991) or through acceleration of the respiration rates under low CO_2 concentration in chamber (Koizumi et al., 1991; Nakadai et al., 1993).

Witkamp and Frank (1969) have categorized the chamber methods for measuring CO_2 evolution from soil, *in situ,* as either *static* or *dynamic.* Static methods are based on covering a known area of soil surface with an airtight chamber, and with a container of CO_2 absorbent (usually KOH) placed inside. After a measured period of time, the absorbent is removed, and the amount of released CO_2 is determined by analytical methods. Nay *et al*. (1994) pointed out the risk of using the static-chamber methods because of their tendency to overestimate small fluxes. On the contrary, a comparative study of static and dynamic closed chambers conducted by Rochette *et al.* (1991) suggested an underestimation of SR in the static chamber. Furthermore, depending on the range of fluxes, true differences in soil CO_2 flux could be nearly impossible to detect with this method.

2.2.1.2 Closed Chamber method

The Closed Chamber method (CC-method) using an infrared gas analyzer (IRGA) for measuring SR was examined, whereby CO_2 in a closed chamber; is sampled periodically and the flux is computed from the concentration that increase in the chamber (Matthias *et al*., 1980; Hutchinson and Cox, 1981; Rolston, 1986; Mariko *et al.*, 1994).

Two major factors which potentially cause errors were evaluated by Bekku *et al*. (1995): (i) volume of air sampled from the chamber; (ii) measuring period of time, were examined in laboratory experiments. Field measurements were also conducted with both the CC-method and the open-flow IRGA method (OF-method). They suggested that the air sample volume of air should be less than 0.2% of the volume of the chamber and the air within the chamber should be sampled several times within 20 min. The results of this study indicate that the CC-method is as effective for the measurement of the SR rates as the OF-method. Soil CO_2 fluxes were usually measured by using closed chambers covering small patches of soil (Rochette *et al.,* 1997; Janssens *et al*., 2000), although techniques based on the vertical gradient of CO_2 concentration in the soil air (De Jong and Shappert, 1972) or the atmospheric turbulence above the soil (Baldocchi *et al.,* 1988) have also been used.

In closed chamber IRGA systems, CO_2 evolution is determined by passing a stream of air through the chamber at a known rate of flow and then measuring the CO_2 content of the out flowing air by passing it either through an Infrared Gas Analyzer (IRGA) or CO_2 absorbant (Schwartzkopf, 1978; Janssens *et al*., 2000).

2.2.1.3 Open-flow infra-red gas analyzer method

Open-flow infra-red gas analyzer method (OF-method) whereby ambient air flows through a chamber, and CO_2 flux is calculated from the concentration difference between inlet- and outlet-air (Witkamp and Frank, 1969; Garret and Cox, 1973; Nakadai *et al*., 1993). The OF-method has been recently used with popularization of IRGA. However, it is less attractive for field measurements because this method requires expensive equipment and electric power supply (Bekku *et al*., 1995). Open-chamber systems have a constant airflow through the chamber, which is vented to the atmosphere, instead of being circulated (Schwartzkopf, 1978; Janssens *et al.,* 2000).

2.2.2 Micrometeorological technique

According to the chamber techniques that still have uncertainty, a new technique has been developed and known as the micrometeorological technique where the average flux is obtained from a large number of measurements from several sampling points over a larger area of interest.

Thus, micrometeorological technique or eddy covariance method has been applied to measure SR. Theoretical background of eddy covariance method has been available for more than half a century (Swinbank 1951). Its routine application, however, took another three decades for sufficient technological advances in instrumentation and digital computation. Some historical background of the routine field applications of this micrometeorological method is described in Baldocchi *et al*. (2001). Basically, the conservation equation (2.1) provides the framework for using the eddy covariance method for the direct measurement of vertical flux densities (*F*) of energy and matter such as CO_2 (*c*) (Raupach et al. 1999):

$$\underset{(I)}{\frac{\partial\left[\int cdz\right]}{\partial t}} = \underset{(II)}{F(z_1) - F(z_2)} - \underset{(III)}{\frac{\partial\left[\int ucdz\right]}{\partial x} - \frac{\partial\left[\int vcdz\right]}{\partial y}} + \underset{(IV)}{\int Pdz} - \underset{(V)}{\int kcdz} \qquad \text{----------(2.1)}$$

where : $F(z)$ = the vertical flux
z = the latitudinal wind velocity
u = the longitudinal wind velocity
v = the horizontal wind velocity
P = the production rate
kc = the destruction rate
v = horizontal wind velocity

If the site is homogeneous (neglecting horizontal advection, term *III* in the conservation equation), flat (neglecting mean vertical velocity) and stationary (neglecting the time-derivative for the scalar concentration, term *I*) with no sink/source for the scalar (neglecting terms *IV* and *V*), vertical flux for the scalar is computed from the covariance between the fluctuations of the vertical wind velocity (*w*) and the scalar (*c*) as equation (2.2) (Baldocchi *et al*. 1988):

$$F = \overline{w'c'} \qquad \text{----------(2.2)}$$

where : w' = the fluctuation of vertical wind velocity
c' = the fluctuation of CO_2 concentration

Over bar means time averaging (of typically 30-60 minutes). Turbulent fluctuations are computed as the difference between instantaneous and mean scalar quantities. The sign convention is such that positive flux represents a transfer away from the surface to the atmosphere, and negative flux denotes the reverse. When the conditions mentioned above are not satisfied, addition terms should be added to the flux computation (Paw *et al*., 2000).

The micrometeorological community is set to collect eddy flux data 24 hours a day and 365 days a year. However, in nature, missing gaps in the archived data are not uncommon. Typical data coverage is about 70% on an annual basis and thus the filling of missing data is necessary for defensible annual sums of net ecosystem carbon exchange, for instance. However the accuracy of micrometeorological technique required more experiment to establish. Therefore, the chamber techniques still be the basically method until now.

In this study, measuring soil respiration by using the CC-method to sample soil air and using IRGA for measuring SR rates. Because of the CC-method is suitable for this field measurement as it is simple, fast and able of obtaining many measurement plots.

2.3 Factors effecting on soil respiration

Because a small change in the magnitude of SR could have a large effect on the concentration of CO_2 in the atmosphere. Therefore, it is important to understand which factors control SR. According to soil respiration definition earlier, the process of respiration is strongly affected by climatic conditions, particularly temperature, precipitation and so on. Although, SR is the loss of carbon (in the form of CO_2) from soils as a result of both microbial decomposition and root respiration, the main source that generated soil CO_2 is microorganism activities. The effectors are the following:

2.3.1 Soil temperature

Temperature is an important parameter known to determine most of the major processes in the carbon cycle. It affects the allocation of carbon between roots and shoots (Farrar, 1988), respiratory losses of carbon by plants (Ryan, 1991), and mineralization potentials of the microbial populations (Ross *et. al.,* 1999). For SR, Ts is typically a reliable predictor of SR when no drought stress occurs (Fang and Moncrieff, 1999). Estimates of SR rates are frequently based on Ts because Ts has been determined as the primary factor controlling seasonal variations in plot scale measurements of SR (Trumbore *et al*., 1996; and Davidson *et al*., 1998). Many studies have indicated that Ts is a good predictor of CO_2 flux, e.g. Raich and Schlesinger (1992); Lee *et al*. (2002) and Cao *et al*. (2004). Edwards (1975) reported that 94% of the variability in the CO_2 flux from a forest floor and 90% from the mineral soil were accounted by the variation in temperature. Fitted as a simple quadratic model, and that the annual total CO_2 flux predicted from the mean temperature was less than 3% lower than that calculated from measured daily mean rates. However, Coleman *et al*. (1976) found that the variation in CO_2 flux was dominated by soil-water content in an arid grassland.

In a study about temporal and spatial variation of soil CO_2 flux in a Canadian boreal forest, Rayment and Jarvis (2000) concluded that Ts predominantly limited soil CO_2 respiration and other factors such as soil moisture had little effect. Agreement with Mathes and Schriefer (1985) and Scott-Denton L.E. *et al*. (2003) who reported that SR followed Ts pattern which represents a primary control on SR and showed a positive correlation with temperature at 5 cm depth.

The exponential function Q_{10} is commonly used to express the relationship between soil biological activity and temperature, although Holland *et al*. (1995) has shown that estimates of global SR are very sensitive to the selected Q_{10} value for various biomes. The most well know equation is Arrhenius equation that shown rate constants vary with temperature and activation energy as equation (2.3) below:

$$SR = A\exp\left[\frac{-Ea}{RT}\right] = A\exp(\beta Ts) \qquad \text{-----------(2.3)}$$

where : A = the equation constant

Ea = the activation energy in J mol^{-1}

R = the gas constant 8.31 J K^{-1} mol^{-1}

T = temperature in Kelvin

The increase in reaction rate per 10 degree. increases in temperature is known as the Q_{10}. The Q_{10} value defines the temperature dependence or sensitivity to temperature variation of SR (Gulledge and Schimel, 2000, Fang and Moncrieff, 2001) as equation (2.4) below:

$$Q_{10} = \frac{SR_{T+10}}{SR_T} = e^{10\beta} \qquad \text{------------(2.4)}$$

where :

A	=	the equation constant
β	=	the activation energy in J mol^{-1}
SR_T	=	the respiration rate at temperature T degree
SR_{T+10}	=	the respiration rate at temperature T+10 degree

Lloyd and Taylor (1994) and Raich and Potter (1995) noted that the Q_{10} value is frequently observed to change with temperature, with higher values typically found in colder climates. Most of the empirical relationships that have been established between field measurements of SR, soil moisture and Ts (Raich and Potter, 1995; Howard and Howard, 1993) tend to be site specific. Many studies indicated temperature effect on SR by using exponential equation and reported Q_{10} values as in the Table following:

Table 2.1 The Q_{10} values derived from Arrhenius equation in various land uses.

Land use	Q_{10}	References
Temperate mixed hardwood forest	3.9	Davidson, 1998
Flood plain		Gulledge and Schimel, 2000
Alder (1992)	1.9	
Whie spruce (1992-1993)	1.3	
Upland		
Birch/aspen (1992-1994)	1.3	
White spruce (1993-1994)	0.98	
Scotland		Fang and Moncrieff, 2001
Farmland	2.2	
Forest	2.9	
Alpine meadow, grazing		Cao *et al*., 2004
Light grazing	3.22	
Heavy grazing	2.75	

Table 2.1 was shown that the possible differential response of microbial and root respiration to temperature could also be reflected in the relatively high Q_{10} values noted in Davidson (1998) study. Because of the different temperature sensitivities showed by various components of SR, Q_{10} values vary considerable among ecosystems and across temperatures ranges. These components include respiration by live roots, associated mycorrhizae, root exudates and humified organic matter by soil heterotrophs (Trumbore *et al*., 1996). Atkin *et al*. (2000) explained that the response of root respiration to changes in temperature would be critical in determining the response

of vegetation to global environmental change. In trying to find out an answer for the prediction of the likely impacts of global warming on SR, it was suggested that short-term changes in temperature are likely to have a profound impact on root respiration. In an effort to test the abilities of describing the SR depend on temperature in different models and their limitations. Fang and Moncrieff (2001) demonstrated that linear equation gives a larger Q_{10} at low temperature and temperature decreases quickly. The exact nature of the relationship between respiration and temperature is still not perfectly clear, thus understanding how temperature affects SR is essential for predicting soil response to climate changes.

2.3.2 Soil moisture

Water is the solvent in which the molecules of life are dissolved, and the availability of water is therefore a critical factor that affects the growth of all cells. The availability of water for a cell depends upon its presence in the atmosphere (relative humidity) or its presence in solution or a substance (water activity). Soil microorganism accounted water that contain in soil as SWC. The water activity (A_w) of pure H_2O is 1.0 (100% water). Water activity is affected by the presence of solutes such as salts or sugars that are dissolved in the water. The higher the solute concentration of a substance, the lower is the water activity and vice-versa. Microorganisms live over a range of A_w from 1.0 to 0.7 (Kanthachod, 2002). Water activities in agricultural soils range between 0.9 and 1.0. Thus SWC is one of factors which necessary for microorganism activities.

SR could be altered by changed SWC since moisture affects rooting depth, root respiration, and soil microbial community composition. Scientists have discussed the effect of moisture availability on soil metabolic activity. Raich and Potter (1995) synthesized three phases of moisture effects on soil biota that were identified over time: 1) when soils are relatively dry, metabolic activity increases with increasing moisture availability; 2) when soil are 50-80% saturated, soil biological activity is almost at its potential; 3) when soils are to wet, oxygen deficiencies inhibit aerobic respiration.

Shoji *et al.* (2004) reported that the rate of SR in evergreen forest, north of Thailand is determined predominantly by soil moisture, not by Ts. Agree with Conant *et al.* (2001) who found that soil moisture was the main factor influencing soil CO_2 flux in three semiarid ecosystems in Arizona. It also may be affected by soil moisture conditions (Mathes and Schriefer, 1985). Unlike other results reported in some review articles, soil moisture showed a less limiting effect on the variability in SR rates. The influence of moisture content on SR is complicated through its effect on respiratory activity of roots and microbes on transport through the soil. The inhibition of soil moisture content on soil CO_2 flux is significant only at its lower (dry soil) or higher (wet soil). Moisture content has no obvious effect on respiration rates between dry and wet soil (Fang and Moncrieff, 2001).

2.3.3 Soil organic matter

Overall life must find in its environment, all of the substances required for energy generation and cellular biosynthesis. The chemicals and elements of this environment that are utilized for bacterial growth are referred to as nutrients or nutritional requirements. In order to grow in environment, microorganism must have an energy source, a source of carbon and other required nutrients, and a tolerance range of physical conditions (Kanthachod, 2002). The carbon requirements of organisms must be met by organic carbon (a chemical compound with a carbon-hydrogen bond) or by CO_2. Organisms that use organic carbon are heterotrophs and organisms that use CO_2 as a sole source of carbon for growth are called autotrophs.

Soil organic matter is considered to be another factor affecting SR. A few field experiments suggested that soil organic matter increases with elevated CO_2 (Schlesinger, 1977). Large accumulations of organic matter are expected where environmental factors (e.g. temperature) limit decomposers. Thus, increased delivery of labile organic matter to the soil could influence soil microbial communities and furthermore SR rates. It is expected that soils with high organic matter and high root and microbial activities would vent more CO_2 than do soils with low organic matter (Bazzaz and Williams, 1991).

Soil carbon was an anticipated variable in some models. Assume that the amount of microbial biomass carbon and carbon substrates available for decomposition are included in total soil carbon (Raich and Tufekcioglu, 2000). Studies by Kelting *et al*. (1998), Winkler *et al*. (1996), and Rayment and Jarvis (2000) showed that microbial respiration was correlated with the organic matter decomposition rates, the availability of carbon in the substrate, and especially with temporal changes in environmental variables such as temperature and moisture. Organic matter explained only 1.6% of the variation in the all regression models. Conventional management was shown to cause losses of organic matter (Buyanovsky *et al.* 1987).

2.3.4 Oxygen

Soil is a complex medium of an organo-mineral matrix of variable depth and because it supports a broad range of plants and microorganisms, reductionist approaches to modeling individual components of soil processes are extremely difficult (Davidson and Trumbore, 1998).

Oxygen is a universal component of cells and is always provided in large amounts by H_2O. However, some microorganisms display a wide range of responses to molecular oxygen O_2. An aerobe requires O_2 for growth; they use O_2 as a final electron acceptor in aerobic respiration. The response of an organism to O_2 in its environment depends upon the occurrence and distribution of various enzymes which react with O_2 and various oxygen radicals that are invariably generated by cells in the presence of O_2 (Kanthachod, 2002). All organisms can live in the presence of O_2 whether or not they use it in their metabolism. Therefore, O_2 is an important to drive aerobic microbial process to produce CO_2 in soil. Lee (2002) and Lee (2004) reported the sharp decrease in SR as resulted from the restriction of the soil air-filled pore space and respiration and increasing anaerobism.

2.3.5 pH

The pH, or hydrogen ion concentration, [H^+], of natural environments varies from about 0.5 in the most acidic soils to about 10.5 in the most alkaline lakes. Appreciating that pH is measured on a logarithmic scale, the [H^+] of natural environments varies over a billion and some microorganisms are living at the extremes, as well as every point between the extremes. Most free-living can grow over a range of 3 pH units, about a thousand changes in [H^+]. The range of pH over which an organism grows is defined by three cardinal points: the minimum pH, below which the organism cannot grow, the maximum pH, above which the organism cannot grow, and the optimum pH, at which the organism grows best. For most bacteria there is an orderly increase in growth rate between the minimum and the optimum and a corresponding orderly decrease in growth rate between the optimum and the maximum pH, reflecting the general effect of changing [H^+] on the rates of enzymatic reaction (Kanthachod, 2002). Microorganisms which grow at an optimum pH well below neutrality (7.0) are called acidophiles. Those which grow best at neutral pH are called neutrophiles and those that grow best under alkaline conditions are called alkaliphiles.

2.3.6 Ecosystem

Several scientists have discussed the relationship between net primary productivity (NPP) on SR (Raich and Potter, 1995; Maier and Kress, 2000). Predicted soil CO_2 emissions were positively correlated with NPP in various biomes, such as deserts, tundra, and grasslands (Raich and Potter, 1995). Since it influences the quantity of detritus supplied to the soil, soil microclimate and structure, and the overall rate of root respiration, vegetation is another factor affecting the rate of SR (Raich and Tufekcioglu, 2000). Changes in vegetation have been shown to have the potential to modify the responses of soil to environmental change. Raich and Tufekcioglu (2000) observed constantly greater SR rates in grasslands than in forests growing under similar conditions. The differences suggested that forest conversion to grassland would stimulate soil CO_2

emissions to the atmosphere. Grasslands may have more photosynthate available to allocate below ground than do forests trees.

A few findings indicate that SR rates in coniferous forests are lower than those in broad-leaved forests located on the same soil types (Weber, 1990; Raich and Tufekcioglu, 2000). In contrast, Raich and Potter (1995) found no consistent differences between SR rates in coniferous and broad-leaved forests. These divergent outcomes seem to be related to differences in C allocation patterns, litter quality, number of sites, and root respiration (Raich and Tufekcioglu, 2000). But the relatively small differences in SR rates between these vegetation types sustain the conclusion that climatic and substrate factors have the biggest impact on SR, with vegetation having a secondary effect only.

Rates of CO_2 evolution from soil a tallgrass prairie were reported to be highly correlated with temperature of the soil surface (Kucera and Kirkham, 1971). More recently, Mielnick and Dugas (1999) in an effort to quantify year-round soil CO_2 fluxes in a tallgrass prairie also found a strong relationship between soil CO_2 fluxes, Ts and soil moisture. Both Ts and moisture were combined into one equation that explained about 52% of the flux variance.

2.4 Interannual variability and Carbon dioxide emission amount

James *et al*., 2002 reported that the mean annual variations in global soil-to-atmosphere CO_2 flux over this 15-year period were estimated to be 80.4 (range 79.3-81.8) Pg C. Monthly variations in global soil CO_2 emissions followed closely the mean temperature cycle of the Northern Hemisphere. Interannual variability in estimated global soil CO_2 production is substantially less than that is variability in net carbon uptake by plants. Popescu (2001) informed that the mean SR rate measured over seven months sampling period in pine with mixed hardwoods, was 2.58 µmol m^{-2} s^{-1} while the carbon loss calculation from the soil over the same period added up to 575 g C/ m^2

As a result (Table 2.2) from Shoji *et al.* (2004), the roughly estimated annual SR rate was 2560 gCm^{-2} $year^{-1}$ in a tropical monsoon forest in northern Thailand, from 1998 to 2000. In addition Mielnick and Dugas (2000) estimated average annual soil CO_2-C fluxes, which were 1.6, 1.3, 1.2, 1.0, 2.1 and 1.5 kg CO_2 C m^{-2} yr^{-1} in 1993 through 1998, respectively in a tallgrass prairie, Taxus, USA. Lee *et al.* (2002) shows annual soil carbon fluxes in deciduous broad-leaved forest, Gifu, Japan during 1999 and 2000 estimated using models that both do and do not take rainfall effects into consideration. In the first estimation, annual carbon flux in 1999 and 2000 were 6.25 and 7.33 t C ha^{-1} $year^{-1}$, respectively. The second estimation gave considerably larger values, 7.54 and 8.49 t C ha^{-1} $year^{-1}$ for 1999 and 2000, respectively. Longdoz *et al.* (2000), Kurganova *et al.* (2002), Subke *et al.* (2002),and Liukang and Dennis (2003) to be reported varying from 0.68 kg C/m^2/y to 0.91 and 0.48 kg C/m^2/y in the grass land and forest. Other researchers found much smaller average annual SR rates, especially on low temperature climate such as Alaska, which ranging was less than 0.1 kg C/m^2/y (Shigeru *et al.*, 2000).

Table 2.2 The total annual CO_2 emission from various land use sources.

Land use	Total annual of SR (kg CO_2 C m^{-2} yr^{-1})	References
Tallgrass prairie, TX, USA (in year 1998)	1.50	Mielnick and Dugas 1999
Semi arid grassland, ND, USA	0.73	Fank *et al.*, 2002
Pine forest, Finland	3.33	Pumpanen *et al*, 2003
Mixed hardwood forest, Korea	1.07 – 1.25	Kang *et al*, 2003
Hill evergreen forest, Thailand	2.56	Shoji *et al.*, 2004
Grazing, China		Cao *et al.*, 2004
- light grazing	2.04	
- heavy grazing	1.53	

2.5 Soil respiration Model

SR has been reported to be influenced by many environmental factors, such as the quantity and type of live and dead biomass in the soil, Ts and moisture content (Bridge and Rixon, 1976; Chapman, 1979; Bridge *et al*., 1983; Rajvanshi and Gupta, 1986; Hogg, 1993; Qi *et al*., 1994). Suarez and Imunek (1993) described a sub model to define the relationship of the SR rate in terms of soil water potential, temperature, CO_2/O_2 concentration, depth in the soil and time. Although this model includes a larger number of biological processes than other previous models, some of the hypothesized mechanisms in the model remain uncertain, for example the dependence of SR on soil moisture content or the response to soil oxygen concentration.

Modeling of the variation in CO_2 flux or SR rate has long attracted the attention of ecologists but it is difficult to prove because soil is a complex medium consisting of a broad range of types of organo-mineral particles and aggregates and contains number of organisms exhibiting different physiological processes.

Numerous of the models published for describing or predicting SR by construction statistical regression model based on Arrhenious equation with specific climatic parameters such as temperature and precipitation (Rajvanshi and Gupta, 1986; Grahammer *et al*., 1991; Bridgham and Richardson, 1992; Peterjohn *et al*., 1994; Thierron and Laudelout, 1996). Raich and Schlesinger (1992) reviewed the data in the literature and derived a model to predict global variation of SR. The model reflected the global trend of annual soil CO_2 flux with temperature and precipitation and indicated that the global variation of SR is mostly accounted by the variation of temperature.

Hanson *et al*. (1993) developed an empirical model to predict SR rate by relating it to Ts, SWC and the percentage of soil coarse fraction. A modeling study using aggregated which mean monthly and yearly air temperatures was conducted by Kicklighter *et al*. (1994) to estimate regional SR rate from temperate forests. They found that the model provided good estimates of SR rates for different sites around the world regardless of forest types. The lack of a biological framework in regression models, however, makes it difficult to explain the roles of the environment on SR or carbon cycle in ecosystems.

Many models of decomposition of organic matter or of carbon dynamics in the soil included respiration rate as a component or a sub-model because CO_2 production is the final product of decomposition processes under many circumstances (Hunt, 1977; Ewel and Gholz, 1987; Wang and Polglase, 1995). Parton *et al*. (1987) developed the CENTURY model, which includes sub models of C and N cycling and plant growth, to describe the dynamics of soil organic matter. These decomposition models may also be used to estimate regional CO_2 flux from microbial respiration over a certain period and to predict the potential response of the flux to environmental conditions, for example increase in Ts due to global warming (Jenkinson *et al*., 1991; Wang and Polglase, 1995).

The response of SR to Ts is commonly expressed using different types of equations such as exponential (Winkler *et al*., 1996), Arrhenius (Lloyd and Taylor, 1994), or linear (Rhochette *et al*., 1991). Each of these models has been success in fitting data under specific occurrences. Valentini *et al*. (2000) suggested that Ts might not be a major factor controlling annual SR at the latitudinal scale. For larger geographic scales, SWC (Davidson *et al*., 1998; Xu & Qi, 2001a), soil substrate quality (Taylor *et al*., 1989; Dyer *et al*., 1990; Taylor *et al*., 1991; Aerts, 1997), vegetation (Buchmann, 2000; Raich and Tufekcioglu, 2000), and disturbance regime (Lytle and Cronan, 1998; Striegl and Wickland, 1998) also affect SR in forested ecosystems, perhaps more than Ts alone. Due to other factors than Ts exert some control over larger-scale spatial and temporal patterns of SR; considerable debate still exists over environmental factors which are the most influential regarding regional SR patterns, particularly SWC (Schlentner and Cleve, 1984; Oberbauer *et al*., 1992; Davidson *et al*., 2000). Topographically induced microclimates can affect SR rates by constraining micro site factors, such as Ts and SWC (Running *et al*., 1987; Western *et al*., 1998; Kang *et al*., 2000).

Table 2.3 lists fitted relationships between SR, Ts and SWC from different types of equations. Linear and power equations are simply empirical expressions of an increase in SR with increasing temperature without any theoretical basis. The linear equation gave a relatively poor fit for forest soil, based on the coefficient of determination of regression (R^2 = 0.763) but had a reasonable fit for farmland soil where respiration rate increased more slowly (R^2 = 0.848). Two kinds of power functions provided a better estimation. The quadratic model produces a better fit for Eucalyptus plantation soil (R^2 = 0.886) than with the forest-tundra soil (R^2 = 0.803).

Mielnick and Dugas (2000) combined the exponential Ts and quadratic soil water equations as a product in a multiple, nonlinear regression to predict SR. LEE *et al*. (2002) constructed a multiple polynomial regression model that included two variables (ST and SWC) according to the equation of Mielnick and Dugas (2000). Shoji *et al.* (2004) has been used model which reviewed by Raich and Schlesinger (1992), the measured rate of SR in terrestrial and wetland ecosystems, and the value reported here is as high as the highest they reported to estimate SR rates in the tropical rain forest in Thailand. They proposed a simple model describing the relationship between annual SR rate (SR, gC m^{-2} $year^{-1}$) and two climate variables, mean annual temperature (T, °C) and mean annual precipitation (P, mm).

Table 2.3 Equations were fitted by linear and nonlinear regression between SR, Ts and SWC in various studies

	Equation	R^2	Reference
Arrhenius:	$SR = 0.0307\ \exp\left[\dfrac{2.117\times10^{4}}{E(Ts+273.2)}\dfrac{Ts-10}{283.2}\right]$	0.90	Fang, 2001
	Linear regression		
Farm soil	SR = -0.143+0.0164Ts	0.85	Fang, 2001
Forest soil	SR = -0.176+0.0153Ts	0.76	
Thai hill evergreen forest	SR = 9.88*T* + 0.0344*P* + 0.0112*TP* + 268	-	Shoji *et al.*, 2004
	Exponential		
Hardwood forest	SR = 21.13 exp(0.137Ts)	0.80	Davidson *et al.*, 1998
Oak forest	SR = 0.84 exp(0.085Ts)	0.82	Rey *et a*l., 2002
Japan deciduous forest	SR = 95.083 exp(0.113Ts)	0.81	Lee *et al.*, 2002
Light Grazing	SR = 115.7 exp(0.117Ts)	0.55	Cao *et al.*, 2004
Heavy Grazing	SR = 90.21 exp(0.1016Ts)	0.68	
	Quadratic		
Eucalyptus plantation	SR = $-0.04SWC^2+1.04SWC-0.95$	0.88	Epron *et al.*, 2004
Forest-tundra	SR = $-0.04SWC^2+1.04SWC-0.95$	0.39	Sjögersten and Wookey, 2002
	Nonlinear regression		
Taxus Tallgrass prairie	SR = $[6.42\times\exp(0.087Ts)]\times2.12\times(SWC-0.10)\times(0.7-SWC)^{1.46}$	0.53	Mielnick and Dugas, 2000

CHAPTER III

METHODOLOGY

SR was influenced by several factors as mention before. The basically factors already well known is temperature. In recently, soil water content (SWC) becomes interesting and there are many studies that made effort to better understand SWC effect on SR. The importance of soil temperature and water in influencing soil microbial activity and the respiration rate of field soils has been established. However, information is limited as to the quantitative affects, measured in the field.

3.1 Site selection

Paddy field at Sukhothai province was chose due to there was the meteological tower, a kind of Automatic Weather Station (AWS) as shown on Figure 3.1, in which measured micrometeorological data such as soil temperature (Ts), soil water content (SWC), solar radiation, etc. The data were corrected every 5 min and then made an average 30 min to keep in the data locker. The experiment sites were located in non-irrigated paddy fields, Thailand. The study areas was carried out in paddy field at Sukhothai Province, Thailand which is located 17º 00´ 10´´N, 99º 49´ 53´´E and 50 meter elevated from sea level (Figure 3.2). Sukhothai Province is a small modern town about 427 km (267 miles) north of Bangkok. The area is flood plains in the valley of the Yom River which cover about 60 percent of province. The soil texture consists of sandy clay. The soil color is reddish gray and its pH 5.5 - 6.5. They have moderate to rather high soil fertility which is suitable to grow rice and upland crops. The 60 percent of land in Sukhothai is used for rice and 30 percent for the upland crops example maize, soybean, tobacco, sugar cane, cotton and sesame as well as fruits, vegetables and flowers. Many farmers grew mono crop (rice), few farmers developed integrated farm or mixed farming.

Figure 3.1 The meteological tower in 2003 at paddy field, Sukhothai, Thailand.

The site is characterized by a tropical climate with winter, summer and rainy season. In 2003, winter season started from late of November 2002 to the end of February and summer season started from the beginning of March to the end of May. Rainy season started from the beginning of June until the end of October. Annual precipitation is 883.7 mm, mean annual air temperature is 27.3º C, mean annual of maximum air temperature is 33.6º C, mean annual of minimum air temperature is 22.1º C (Table 3.1 and Figure 3.3) and mean annual soil temperature is 32.3º C.

Figure 3.2 The experiment site at Paddy field, Sukhothai, Thailand.
Source: Map Internet, Inc. (2004)

Table 3.1 Average monthly of rainfall and air temperature in 2003 at Sukhothai, Thailand

Month	Rainfall (mm)	Average Air Temperature (^{0}C)		
		Mean	Maximum	Minimum
January	10.5	23.6	30.2	17.3
February	1.2	26.1	33.6	18.9
March	50.7	28.1	34.2	20.9
April	2.4	31.2	37.6	24.0
May	50.8	31.0	36.7	24.5
June	203.0	27.7	32.9	24.0
July	152.3	28.1	33.7	23.9
August	124.6	28.3	33.4	24.6
September	250.7	27.3	32.3	24.3
October	37.5	27.4	33.4	23.8
November	0.0	26.2	33.6	21.4
December	0.0	22.5	31.1	17.6
Total	883.7	-	-	-
Average	-	27.3	33.6	22.1

Source: Thai Meteological Department (2003)

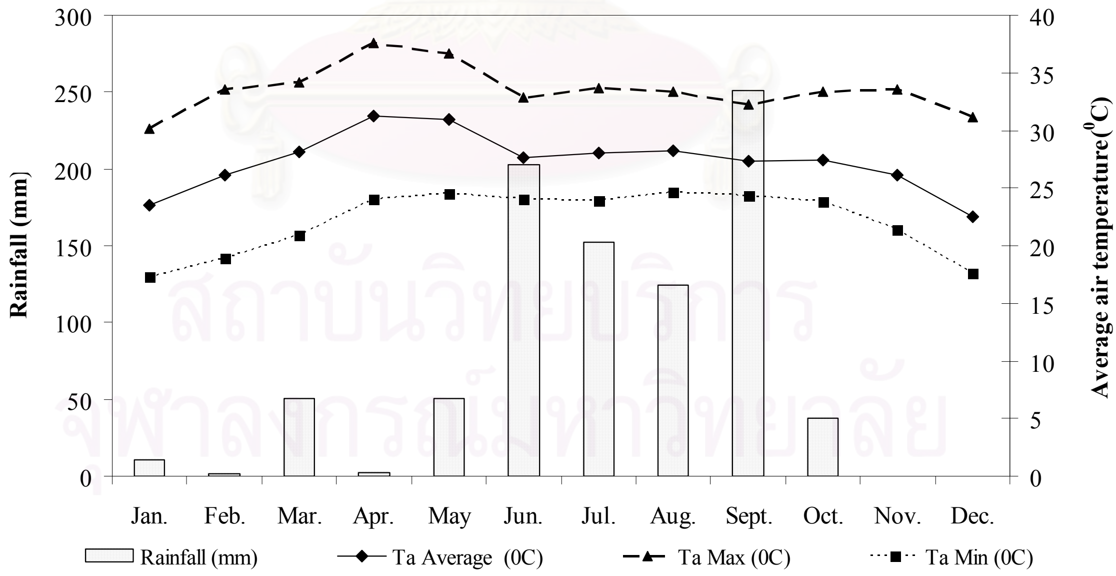

Figure 3.3 Climatic in 2003 at Non-irrigated paddy field, Sukhothai, Thailand. Source: Thai Meteological Department (2003)

Measuring CO_2 emits from paddy soil in 2003, after harvesting in December 2002 the measurement started in January with bare soil condition. And then the growing season is from early July to late December with rice species is "Chainat" (*Oryza sativa* L. cv. Chainat). After that rice was harvested in the end of December 2003. Moreover, the field was fertilized twice in 2003, first in September and second in November. In addition, micrometeorological data were collected from the various devices installed on the meteorological tower settled near the measurement area in an area of 40x20 m^2, and the setting was as illustrated in Figure 3.4. Parameters of concerns include SWC by TDR, solar radiation, soil heat flux, net radiation, wind speed, and canopy temperature.

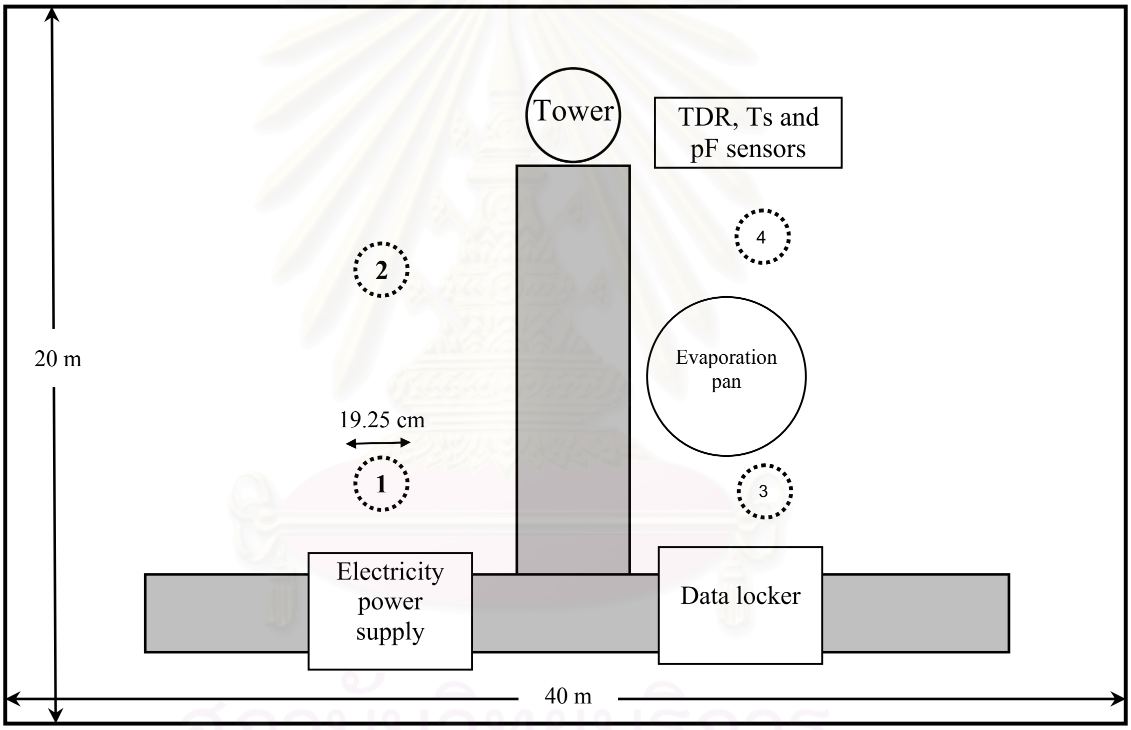

Figure 3.4 Measurement plot and the meteorological tower at paddy field, Sukhothai.

3.2 Data collection

3.2.1 Soil temperature

In each sampling time, soil temperature was recorded using a temperature probe in the top 5 cm nearby measurement point (Figure 3.5).

Figure 3.5 The closed chamber and thermometer.

3.2.2 Soil water content

According to the Sukhothai paddy field was installed the micrometeological instruments that included SWC sensor. For each measurement date, soil water content was taken on the top 5 cm, using Time Domain Reflectometry: TDR (Soil Moisture Equipment Corporation, 6050X1, Golena, CA). The TDR data was automatically recorded in data locker (Figure 3.6).

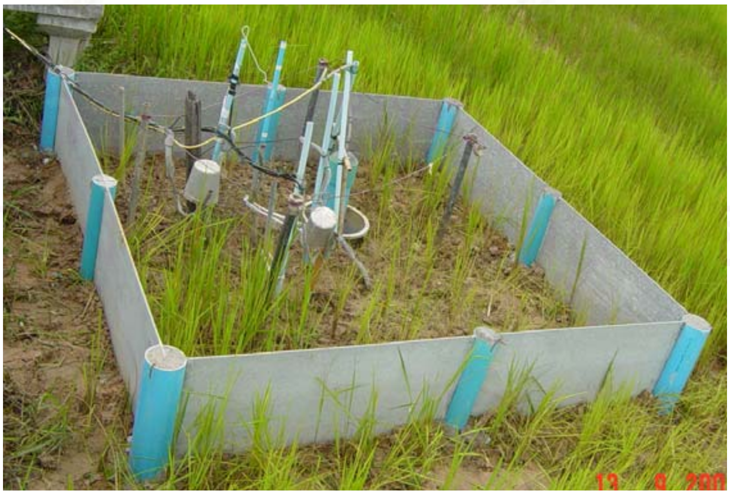

Figure 3.6 Time Domain Reflectometry (TDR).

3.2.3 Soil sampling collection

From April to December, soils were sampled in the last date of each month measurement. Soil samples were collected at 5, 10 and 30 cm of each measurement points in 2 kinds. First, soil core are undisturbed soil sample for measuring SWC and second is disturbed soil sample for chemical properties from sieved soil in plastic bag (Figure 3.7).

(a)

(b)

Figure 3.7 The core sampling: (a) soil samples and (b) soil sampling instrument.

3.2.4 Soil respiration Measurement (Air sampling)

SR was collected once a month in paddy field from January – December 2003 (except October because flooding in the paddy field, the closed chamber can not measured). Measurement was carried out continuously from 08:00 until 16:00, and 22:00, 24:00, 02:00 and 06:00 O'clock, three days in each time by closed chamber method (CC-method). And then analyze immediately at field by Infrared gas analyzer (IRG).

A technique used for measuring the rate of CO_2 emission from soil in this study is the CC-method. Due to the CC-method is simple, fast, comfortable to carry out to the field, able of obtaining many measurement points and most economical. The closed chamber used consists of plastic chamber, 16.2 cm in diameter, 19.25 cm in basal diameter, and 21.9 cm in height that was installed a small fan 12 V power supply and thermometer, as illustrated in Figure 3.8. The top of the chamber was fitted with an air sampling needle and stopper. The chamber was put on soil surface 3.9 centimeters depth in soil. The measurement points were kept free from any plant. Air in the chamber was sampled several times at certain time intervals (1, 3, 5 and 7 minute) by 5 ml with a needle-syringe through the stopper. The small fan was always operated the air sampling in order to homogenize CO_2 concentration in the chamber.

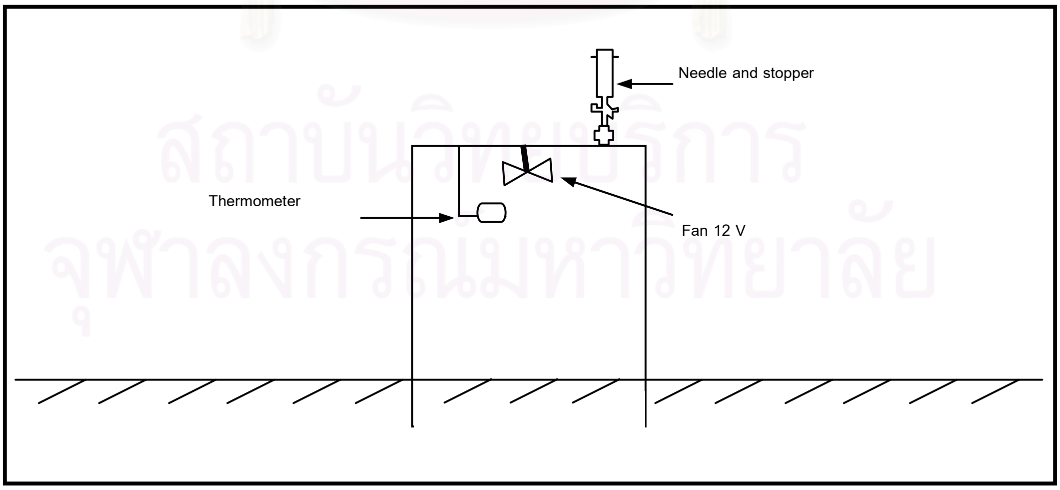

Figure 3.8 The closed chamber and inside composition.

3.3 Data Analysis

3.3.1 Soil CO_2 analysis

The sampling air was injected into a gas-line in which CO_2 free gas (N_2 gas 95%) at 300 ml/s passed through silica gel bottom to absorb H_2O and then went to flow meter to control flow rate (Figure 3.9). Next injection, the sampling air was sent to the Infrared Gas Analyzer (IRGA; Fuji Electric, Model ZFP9, Tokyo, Japan). The CO_2 concentration in the sampling air was determined by reading the height of the pulse monitored on a chart recorder (TOA, Tokyo, Japan) with the calibration curve of pulse height versus CO_2 concentration. The increase of CO_2 concentration in the chamber on time was calculated to the SR value from equation (3.4):

$$SR = 60 \times 10^{-6} \left(\frac{a\,\rho\,V}{S} \right) \qquad \text{------------(3.1)}$$

Where:
- SR = soil respiration rate (mg CO_2 m^{-2} h^{-1})
- a = the time rate of change of the CO_2 concentration in the chamber (μl l^{-1} min^{-1})
- ρ = air temperature inside the chamber (^{0}C)
- V = the volume of the chamber (m^3)
- S = the basal area of the chamber (m)

Specification of analyzer system

- Infrared Gas Analyzer (Model ZRC)
- Recorder by Yokogawa 3056 Pen recorder (L-19)
- Range used is 0.25 mV/cm
- Standard Nitrogen gas (N_2 99.9%)
- Standard gas (CO_2) 500 ppm
- Standard gas (CO_2) 1000 ppm

However the method for detecting CO_2 concentration was H_2O/CO_2 analysis based on an infrared absorption principle. This method can measure both CO_2 and water vapor with infrared beam, which traversed an open path between the sealed light source and detector and processed them into part per million (ppm) units of CO_2 and humidity which could be reported in various units such as vapor density, relative humidity or dew point temperature. Therefore we had to use silica gel and H_2O trapper to absorb H_2O from the air sample before it went through the IRG analyzer as Figure 3.10.

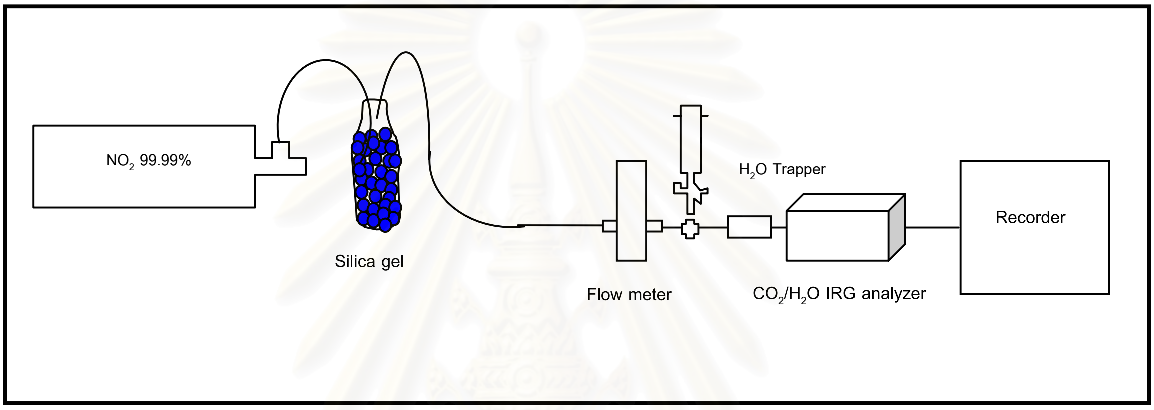

Figure 3.9 The system flow for the Infrared Gas Analyzer (IRG).

Figure 3.10 The infrared gas analyzer (IRG).

3.3.2 Soil sample analysis

In each measurement during April to December, soil sample were collected once a month after measurement. For January to March, we can not kept soil sample because lack of instrument.

3.3.2.1 Soil volumetric water content

Soil sample at 5, 10 and 30 cm depth (7 cm diameter) was collected at each sampling location. Soil cores were corrected for SWC which was measuring by TDR. SWC were measured by gravimetric method from each soil core sample. And the SWC was calculated from differential weight of wet and dry soil cores using equation (3.2) as the following:

$$SWC = \frac{Wet\ wt - Dry\ wt}{Dry\ wt} \times \frac{100}{V} \qquad \text{------------(3.2)}$$

Where:	SWC	=	soil water content (SWC: %V)
	Wet wt	=	weight of wet soil, before dried (g)
	Dry wt	=	weight of dry soil, after combusting the samples at 110^{o} C for 24 h (g)
	V	=	the volume of soil core container (m^3)

3.3.2.2 Soil texture

Additionally, another soil samples were passed through a 2 mm sieve to remove rocks and coarse roots; then finer roots were hand picked from each sample. Soil texture, was determined using the hydrometer method.

3.3.2.3 Soil Carbon and Nitrogen content

Soil Carbon (C) and Nitrogen (N) contents were determined on a Perkin–Elmer 2400 Carbon Hydrogen Nitrogen Analyzer: CHN Autoanalyzer (Perkin–Elmer, St Joseph, MO) (Figure 3.11) according to the machine's standard operating instructions and samples were weighed on a Perkin Elmer AD6 analytical scale (20 mg soil).

Figure 3.11 Carbon Hydrogen Nitrogen Analyzer (CHN).

3.3.3 Statistical Analysis

The experiment was conducted as a randomized point design with plot physical factors. All analyses were executed on data from the 4 points collected one year period in Thailand. Statistical differences were considered significant at $p \leq 0.05$. Regression analysis was also used to determine the relationship between SWC, Ts, and SR rates.

All of the data was divided into two groups which were classified by measurement of rainfall and SWC. The first group contains data from January to February and from November to December, which amount of rainfall was equal or less than 10 mm and SWC level was equal or less than 15%. The second group contains data from remaining days of the same year which amount of rainfall was more than 10 mm and SWC was more than 15%. These two groups will be called in term "Dry period" and "Wet period" respectively.

In addition, both univariate (Ts or soil water content) and bivariate models (SWC and Ts) were fitted against SR data using nonlinear regression analysis. Criteria for a valid model were a maximum coefficient of determination (R^2), a minimum root mean square error (RMSE) and no bias in the distribution of the residuals (Dapper and Smith, 1966).

CHAPTER IV

RESULTS AND DISCUSSION

The variability of SR rates was studied one year period. The data was divided into "Dry period" and "Wet period" for regression analysis in order to fine out the relationship between SWC, Ts, and SR rates and any equation to predict SR rates on similar sites.

4.1 Soil Characteristics

Soil at 5, 10 and 30 cm depth were sampled from paddy field and brought back to analyze in laboratory from April to December in 2003. Based on the amount of each soil particle size, the analytical procedures by which the percentages of the various soils were defined by United States Department of Agriculture (USDA) textural triangle (Appendix A Figure 1). The soil type was sandy clay, indicated that was fine-textured soils in which averaged porosity about 37.71% (Table 4.1). The particle size analysis gave 24.75% clay, 50.26% sand and 24.99% silt, and the bulk density was between 1.2 and 1.9 g/cm^3. Particular, the physical properties shows low of water and air permeability. Paddy soil was high ability to hold the water that reduced air-filled porosity in which made the suitable condition for rice planting. The total soil carbon (C) and soil nitrogen (N) also were analyzed and gave mean value of 0.61% C and 0.10% N as shown the monthly content in Figure 4.1. In general, C:N ratio that is most suitable for microbial activity and gave the result as high decompose and high produced CO_2 was to be 24 (Kanthachod D., 2002). In our study, soil C content was greater than soil N content particular C:N ratio slightly high in April and May after that steadily low in August and September. And highest was in November and December because low N content due to N consumption by rice plants during growing period that produced higher SR rates than the months which lower C:N ratio.

Table 4.1 The characteristics of soil in the paddy field, Sukhothai province in 2003.

Soil characteristics	Composition
Soil texture: sandy clay	% clay =24.75%
	% sand =50.26%
	% silt =24.99%
Average Bulk density (g/cm^3)	1.49
Porosity (%)	37.71

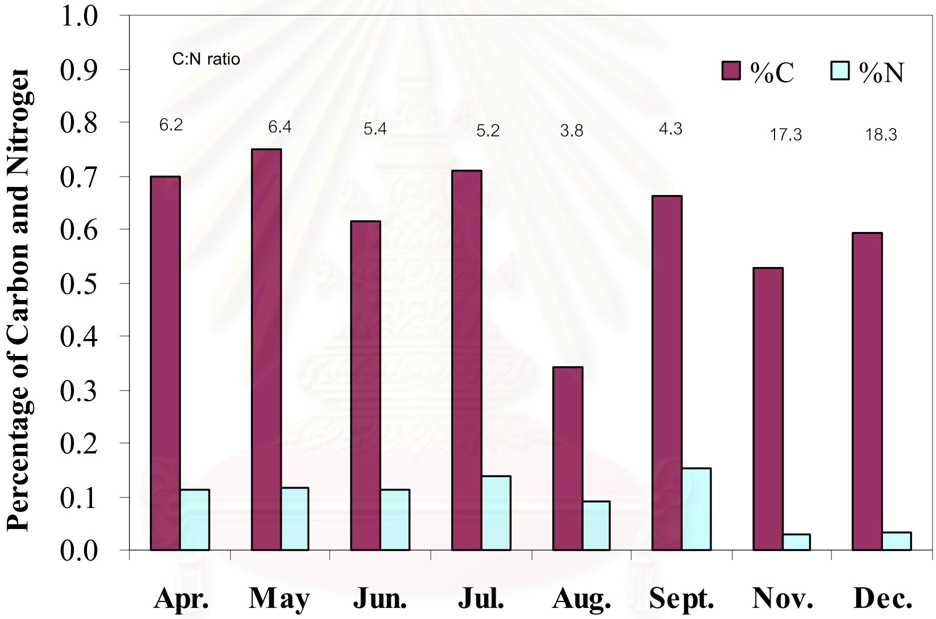

Figure 4.1 Soil Carbon and Nitrogen content, and C:N ratio in Paddy soil.

4.2 Soil temperature and soil water content

Annual variations of air temperature (Ta), Ts, precipitation and SWC in the 2003 are shown in Figure 4.2 and Figure 4.3, respectively. Ts was measured in this measurement along with the soil surface temperature which was the temperature at the top 5 cm of the soil by side the chamber. Ts at 5 cm depth increased slowly from January until March and then increased steadily become highest at 33.4^{0}C during March until May, after that decreased rapidly in June and then decreased slowly again from September until December and reached lowest value of 26.4^{0}C. The average annual Ta and Ts were about 27.3°C and 31.3°C, respectively. In Paddy filed, Ts was exhibited relatively higher than Ta during the wet period. That caused by Relative Humidity (RH) in the air during the wet period was higher than in the dry period. Ta inhibits from temperature increasing by heat capacity of water. While soil surface was heated by direct sunshine and radiated energy from water vapour in the air without plant covering, thus heat was accumulated in soil and showed higher Ts than Ta. SWC (% by volume: %V) of the top 5 cm ranged from 4.6% to 41.6% and averaged 21.7% for the four plots. Accumulated rainfall during the study period was 883.7 mm. Both Ts and SWC varied markedly with period. Ts showed inverse correlation with SWC from January to May while in June to December, Ts trend was coincided with SWC trend. Because of no rain event during measurement in January to May had, thus SWC declined as increasing Ts.

The dry period starts from January to February in the beginning of 2003 year and from November to December in the late of year. During the dry period, the amount of rainfall is very small (11.7 mm) over the study area and soil moisture was lost by evaporation, so soil was dry condition. During the 7 months of wet period, Ts increased steadily from March until May after that Ts declined in June and then steady. Corresponding to the pattern of precipitation, the soil moisture content was high from March to October and low from November to February. Soil condition in wet period is exhibited hot and moist. Therefore, SWC generally varies according to rainfall pattern as SWC decreases during the rest of rainfall and increases when rainfall occurrences.

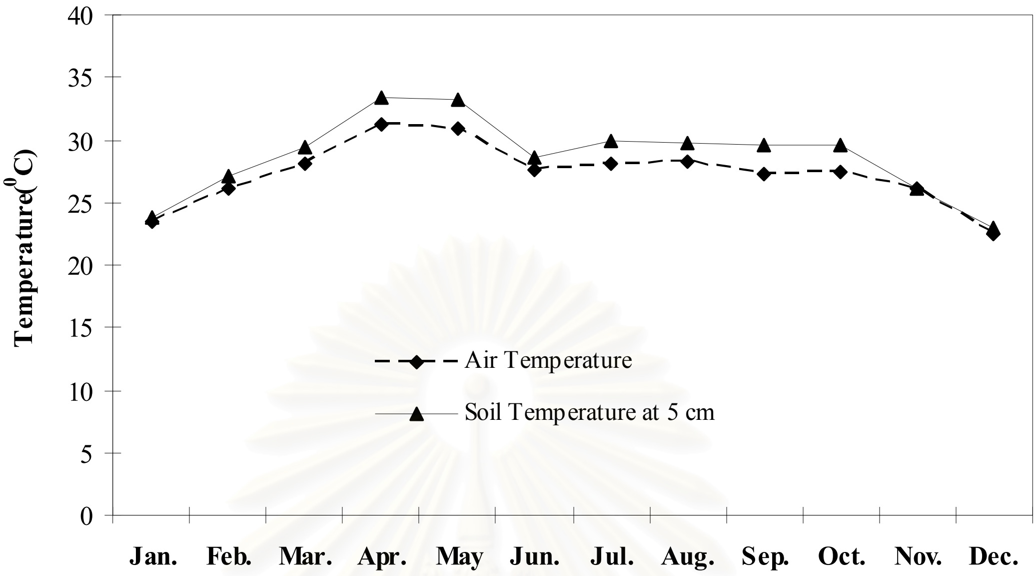

Figure 4.2 Air temperature (Ta) and soil temperature (Ts) at 5 cm depth in 2003 at Sukhothai.

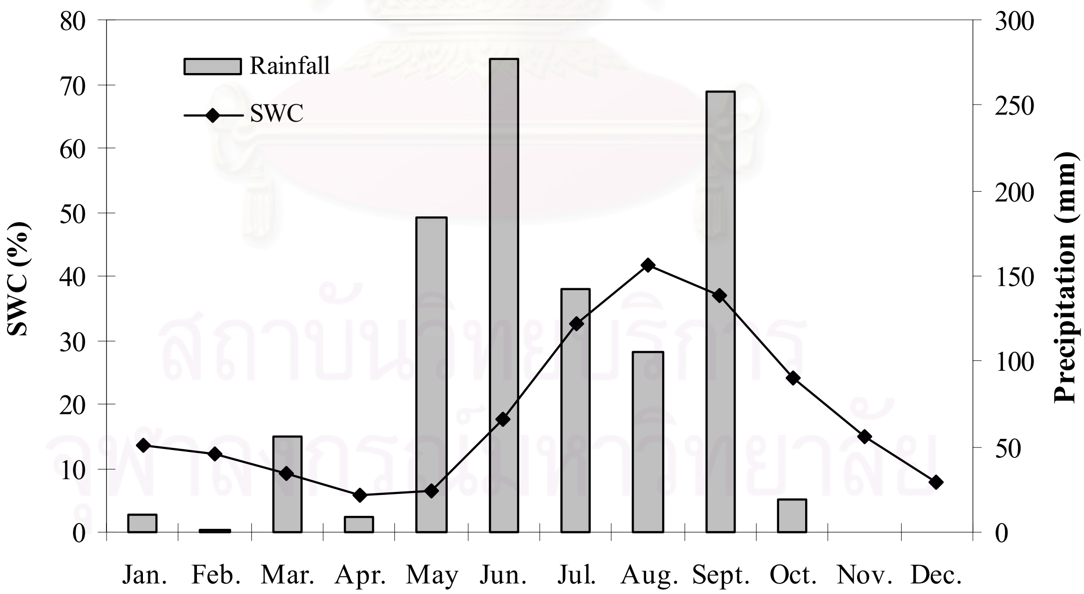

Figure 4.3 Comparison of averaged soil water content and total monthly precipitation in 2003 at Sukhothai.

Source: Precipitation, Thai Meteological Department (2003)

4.3 Soil Respiration rates

4.3.1 Diurnal variation of Soil Respiration rates

SR rates were measured on clear days without rainfall from January to December in 2003. The diurnal patterns of SR at both periods were similar to the diurnal patterns of soil surface temperature throughout the year, with low rates in early morning and midnight. The SR rates peaked at around 14:30 (13.00 ± 15.00 hours) local time, after that dropped rapidly to its minimum at midnight associating with daily Ta and Ts (Figure 4.4). The diurnal range was normally less than about 30% of its mean value. SR followed the increasing trend of Ts in the morning, but then leveled off with slight fluctuations while Ts kept increasing in the afternoon and then slow down in the evening. In the afternoon of March 16th 2003 (030316), SR rates showed a similar pattern as others day, but peak was higher and the fluctuations were much smaller. It might be occurring from the beginning of rainy period. Diurnal SR was significantly higher in dry period than in wet period.

According to temperatures above the soil surface also showed a significant diurnal variability. Daily changes of Ts were more remarkable in the upper soil layers. At 5 cm depth, Ts were showed the same pronounced period trend of air temperature above ground surface. Therefore, SR was significantly related to the temperature at 5 cm below ground, in which generally increased from sunset and decreased gradually after sunrise.

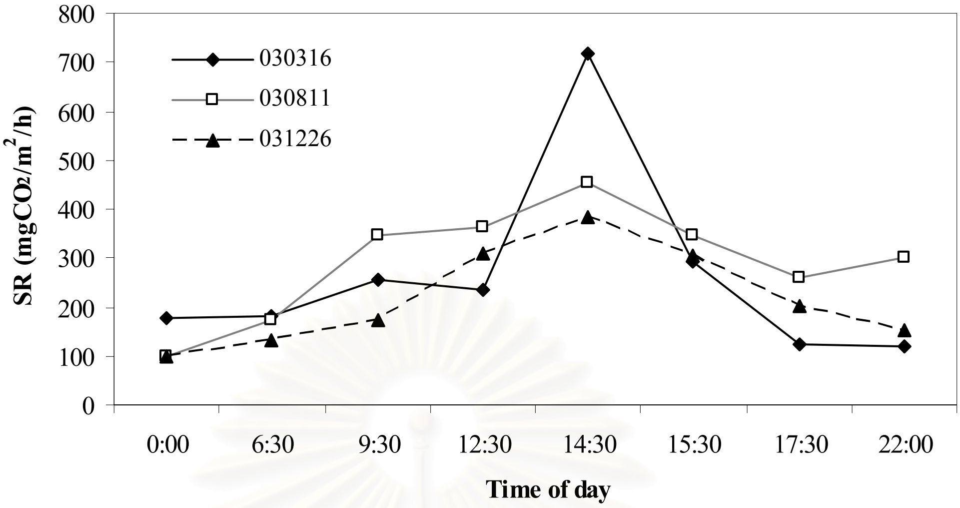

Figure 4.4 Diurnal variations of soil respiration in March (030316), August (030811) and December (031226).

4.3.2 Interannual variation of Soil Respiration rates

SR rates measured at Paddy field exhibited interannual variations with maximum value of 821.2 mg CO_2 m^{-2} h^{-1} in January 2003 and a minimum value of 0.0 mg CO_2 m^{-2} h^{-1} after submerged condition in October of the same year (Figure 4.5). SR rates varied from a high at the beginning of January and then slowly decreased to nearly mean (342.4 mg CO_2 m^{-2} h^{-1}) from March until September, after that went to the lowest in October (0.0 mg CO_2 m^{-2} h^{-1}) and returned to moderate value again in November to December.

Figure 4.6 shows average daily SR measured by the closed chamber technique in the paddy field in 2003. During the dry period, it could be noticed that respiration rate gradually decreased from January to March (from dry period to wet period) and the standard deviation of each day was not over 268.60 mg CO_2 m^{-2} h^{-1}. Mostly, daily fluxes were not greater than 1,200 mg CO_2 m^{-2} h^{-1} with low fluctuation. However, during the changing period from February to March, respiration slightly decreased. Considering the trend of SR and Ts shown in Figure 4.7, no the effect of seasonal change in this period as discussed above. In contrast, respiration rates declined as Ts decreased and as SWC decreased in the dry period in November to December. The variation of SR followed soil moisture during the dry period when volumetric soil moisture was low. This result suggested that there could be a relation between SR, Ts and SWC; this aspect will be discussed for more details later on.

In wet period, when SWC was relatively high, the SR rate appeared to be almost constant, excluding July. The exception was the extremely high respiration rates in July, which was taken immediately after rain because limiting of time in that month. It might be related to the release of CO_2 dissolved in rain, the displacement of soil air by rainwater, or degassing due to the decrease in pressure with time in soil air pore. The recorded average rates were large and higher than the other month's rates, which were taken on clear day without rainfall. In contrast, significant changes in SR rated were detected on the raining day. When rainfall occurred continuous from middle of June; the SR increased from 397.4 to 2,320.6 mg CO_2 m^{-2} h^{-1} soon after the onset of rainfall.

The averaged daily SR could be noticed that respiration rate rapidly decreased from March to April and the standard deviation of each day was not over 139.48 mg CO_2 m^{-2} h^{-1}. Mostly, daily fluxes were not greater than 680 mg CO_2 m^{-2} h^{-1} with high fluctuation. However, during the submerged period in October, respiration decreased to zero. Considering the trend of SR and Ts shown in Figure 4.1.8, also accepted that no effect of season change in this period as in the dry period.

In conclusion, the interannual variation in SR obtained from the two periods might be affected by many parameters. In Section 4.7 will be discuss the effects of these parameters.

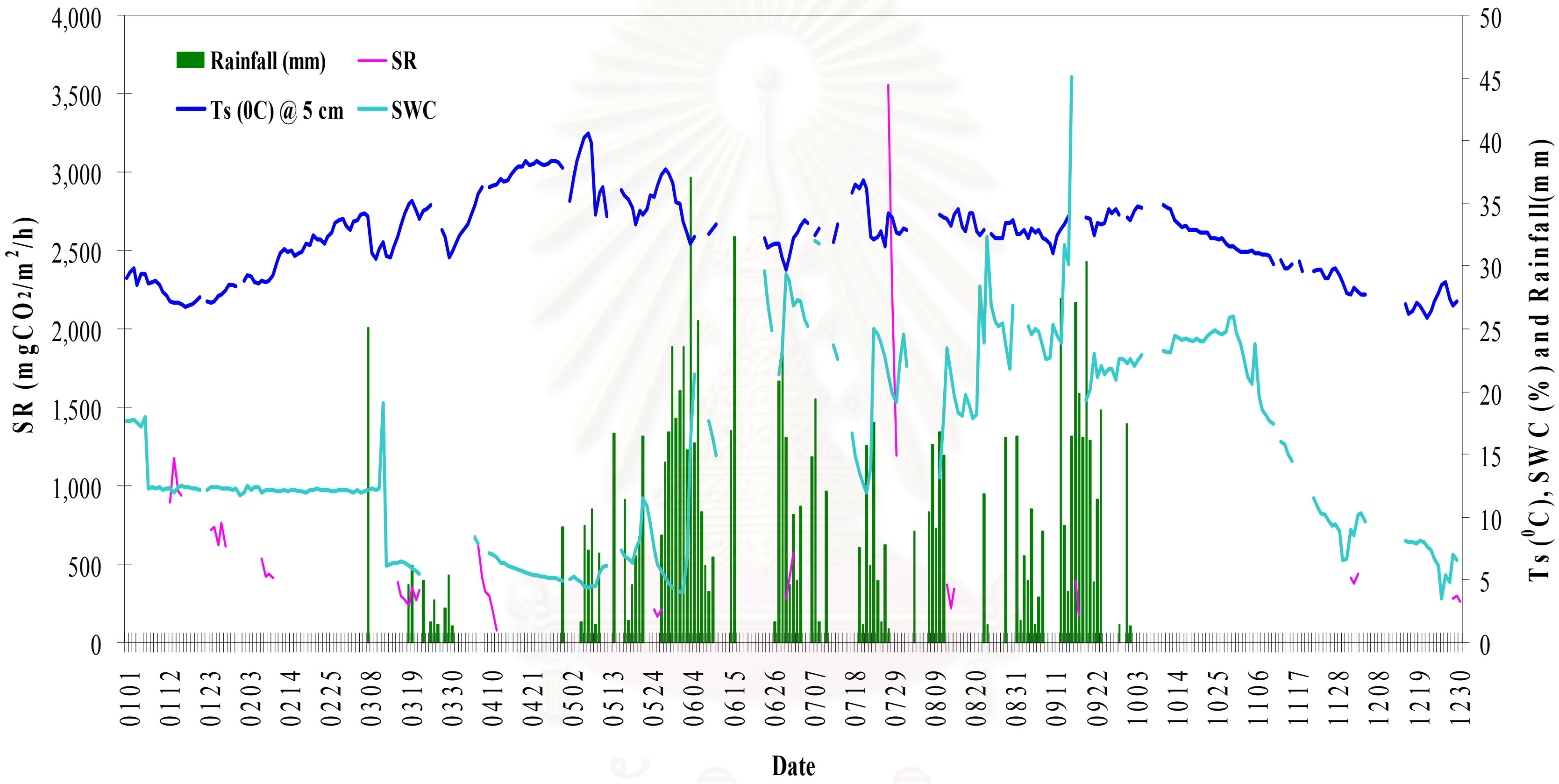

Figure 4.5 Daily averaged of soil respiration (SR), soil temperature (Ts), soil moisture (SWC) and rainfall amount in 2003.

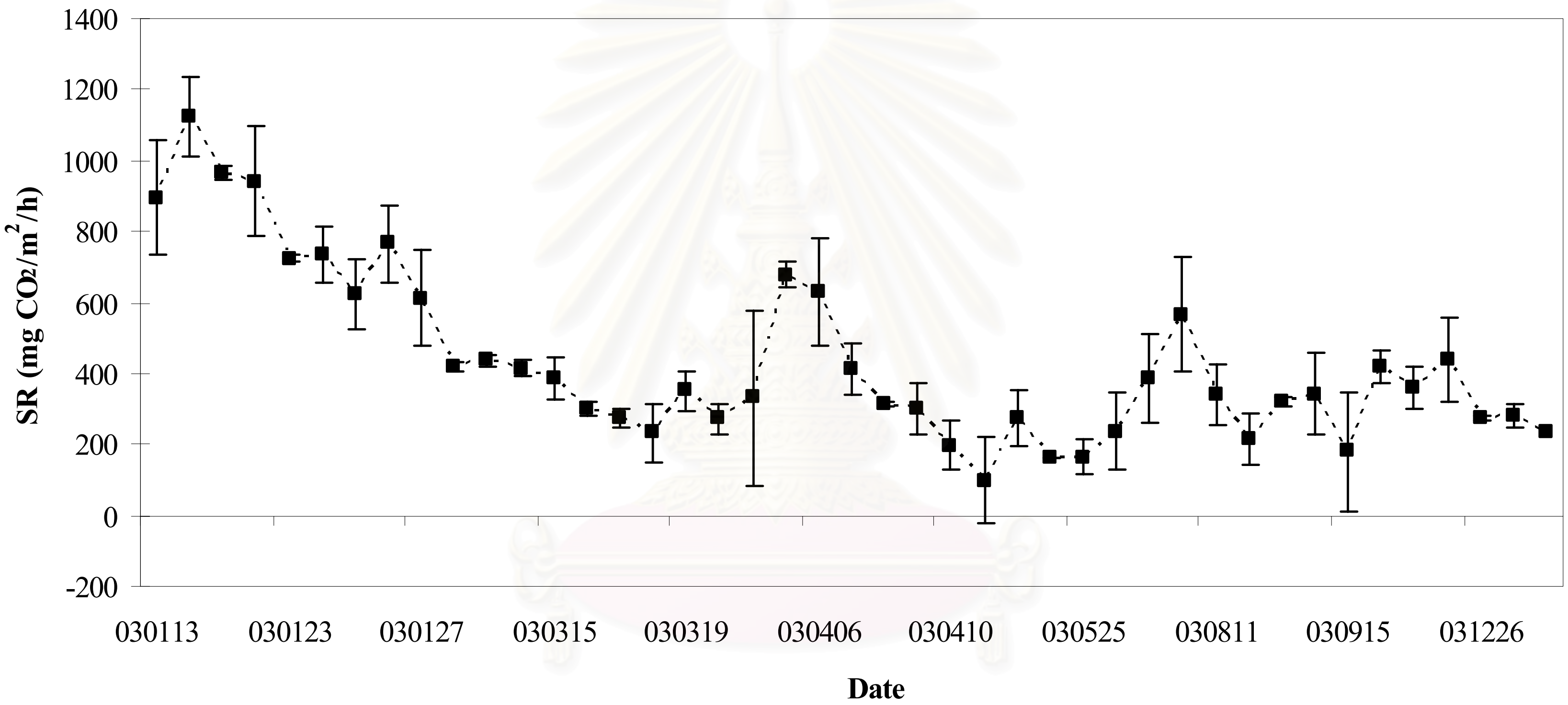

Figure 4.6 Daily average of soil respiration rate (SR) on the days have measured in 2003.

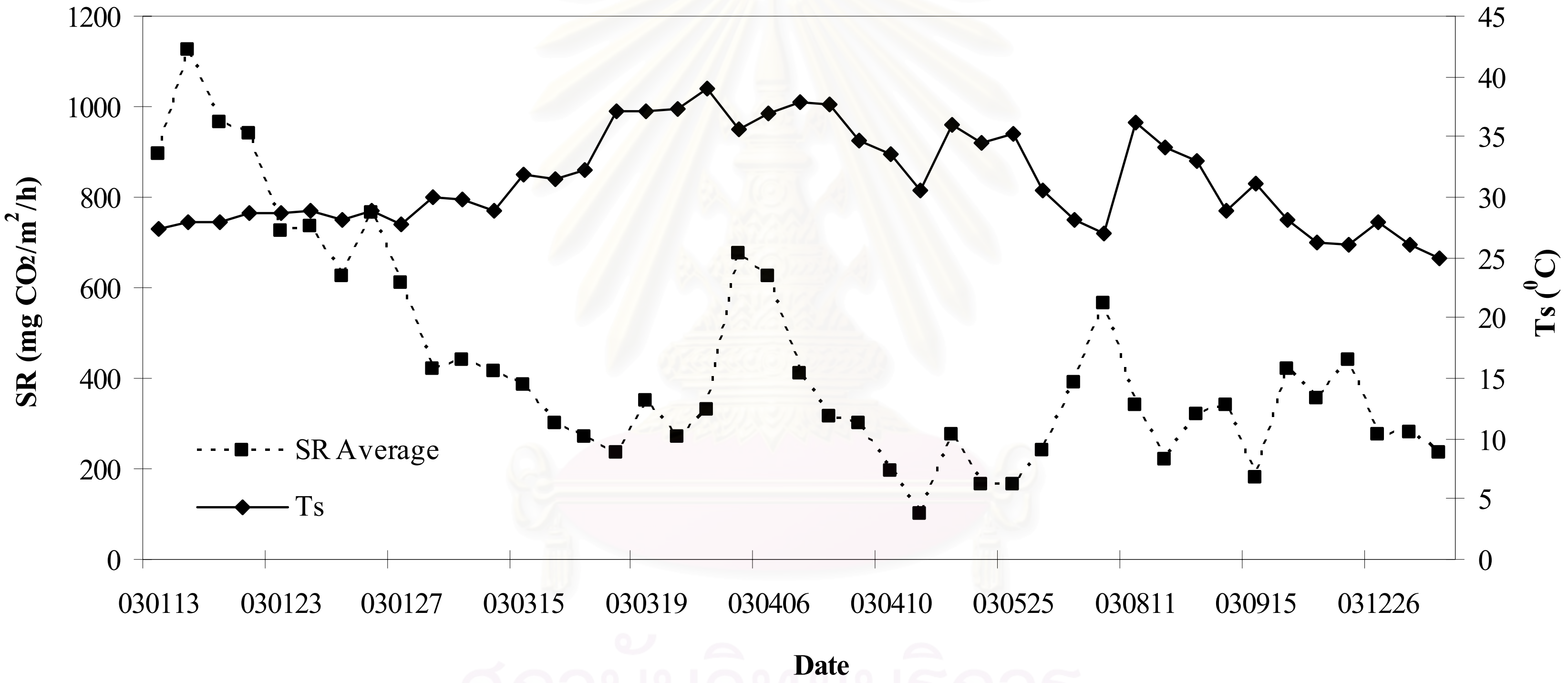

Figure 4.7 Daily average of soil respiration rate (SR) and soil temperature (Ts) on the days have measured in 2003.

4.4 Effect of Soil Temperature and Soil Water Content on Soil Respiration

4.4.1 Dry period

Under field condition, Ts and SWC exhibited amplitude with respective influences on SR. SR rates seemed to increase nonlinearly with soil and air temperatures. For the dry period, the correlation between respiration rate and Ts was also found to be nonlinear (Figure 4.8). Averaged respiration rate in January was high (1,124.80 mg CO_2 m^{-2} h^{-1}) might be caused by residual of fresh organic matter after harvesting in the end of December 2002. Considering the trend of SR as shown in Figure 4.5, respiration rates in January exhibited high and then decreased to moderate rate in February, the exact reason for this peak is still unknown but it is possible that this was might be the fresh organic matter left out by decomposition process with time. In this period, however, the relation between respiration rates and temperature could still be represented by a nonlinear equation with great scattering. This finding was attributed to the simple relation between temperature and reaction rate, e.g. Arrhenius law. As the temperature increased, the decomposition rate of organic constituents in soil took place at a higher rate resulting in a higher emission rate of CO_2 which is one of the end products from the decomposition process. These results were confirmed with the plotting SR rate against SWC as illustrated in Figure 4.9. SR also exhibited increasing with SWC and gave higher correlation than Ts. This meant that temperature was not the major factor that influenced respiration rates. At this point, it is quite obvious that both soil moisture and temperature controlled and SWC might be the major influencing parameter on the SR rate in dry period.

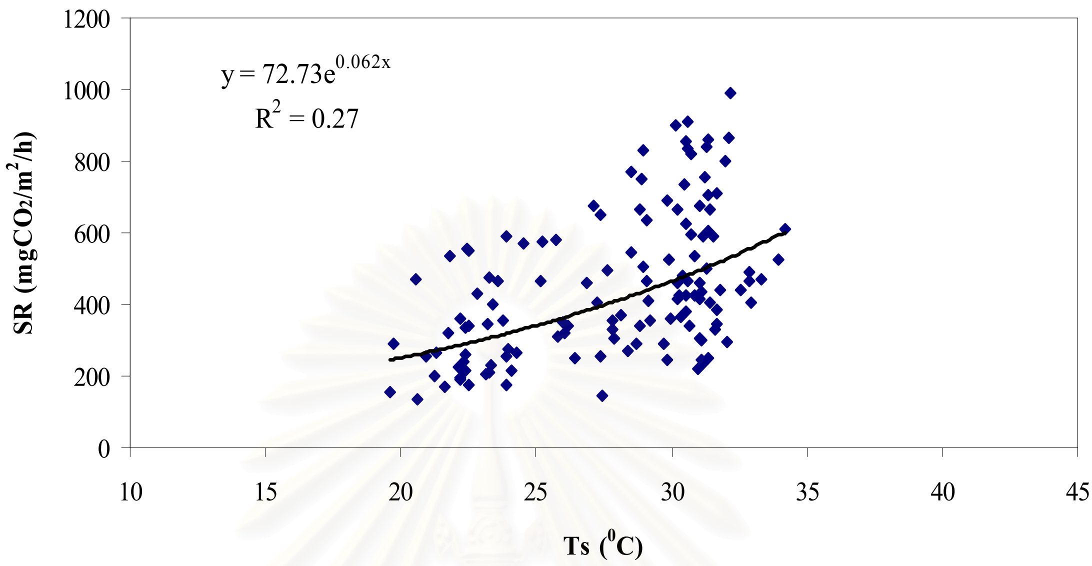

Figure 4.8 Relationship between soil respiration rate (SR) and soil temperature at 5 cm depth (Ts) in the dry period.

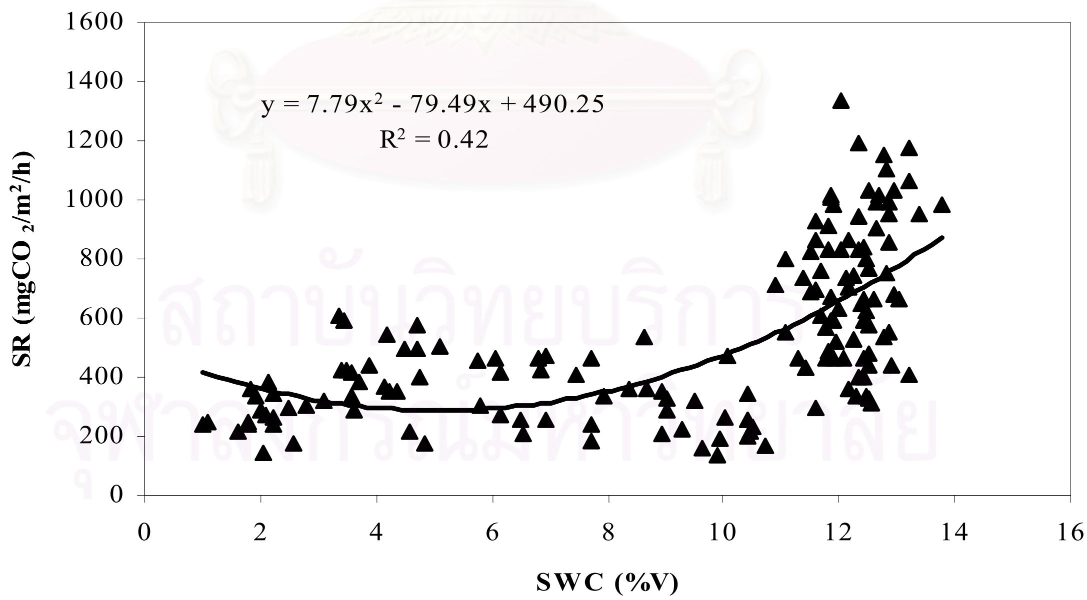

Figure 4.9 Relationship between soil respiration rate (SR) and soil water content at depth of 5 cm (SWC) in the dry period.

4.4.2 Wet period

SR rates appeared to increase nonlinearly with Ts as exponential function. Figure 4.10, excluded respiration rates in July, the correlation between respiration rate and temperature was also found to be nonlinear with slightly lower R^2 (0.25) than in dry period (0.27). For example, the data from March to April indicate that respiration rates were increased associated with increasing of Ts and declined after April accompanied by decreasing Ts in May until September (Figure 4.7). Whereas, SR rate was a much poorly correlated with SWC, and no significant of linear and nonlinear relationship was observed as illustrated in Figure 4.11. That seemed to indicate that SWC was provided and fluctuated by rainfall throughout the period. Therefore, during the wet period SWC was high with range 20% to 60% by supply of rainfall water. That might be the major factor that influenced SR rate in the wet period is Ts and SWC acted as minor factor.

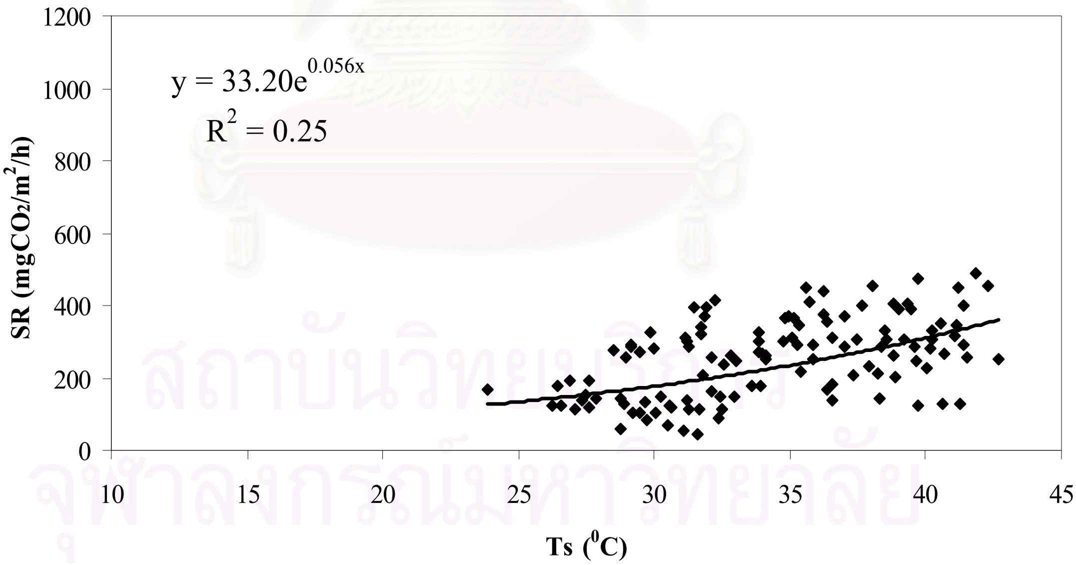

Figure 4.10 Relationship between soil respiration rate (SR) and soil temperature at 5 cm depth (Ts) in the wet period.

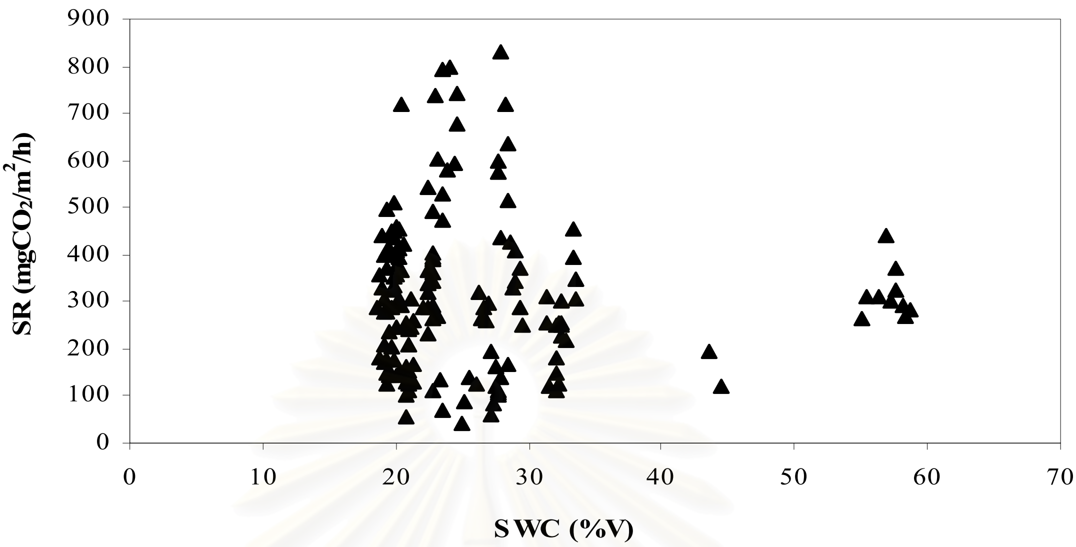

Figure 4.11 Relationship between soil respiration rate (SR) and soil water content at depth of 5 cm (SWC) in the wet period.

4.5 Regression analysis

Linear and nonlinear regression analysis was used to model the influence of soil moisture and Ts on SR rates. A data set of 194 observations from the four points, located near metrological measurement tower was used. Correlations between SR and environmental variables explained a considerable amount the variations. Due to the scatter plots of both Ts and SWC versus SR were high distribution and low R^2. Therefore, residual analysis was used to test the equation.

4.5.1 Dry period

Ts accounted for 27% of the variation in SR. SWC was also significant and explained an additional 42% of the variation ($p < 0.001$). Overall regression model had a total R^2 of 0.49 (Table 4.2). There was a poor correlation between SR and Ts even though SR displayed a typical relationship with Ts. Fitting exponential function, power function or Arrhenus equation (equation (2.3)) on SR against Ts data gave R^2 values of 0.27. In contrast, there was a better correlation between SR and SWC (Fig. 4.9). Five empirical models were selected and fitted against SR, Ts and SWC data (Table 4.2). Anyhow, the models are poorly fitted and unexplained variation. Residual examination which is time sequence plot was necessary use for testing that variation has not been able to explain by that equation. Residuals that obtained by use of Eq.(D5) were evenly distributed and gave horizontal band when plotted against time (Fig. 4.12). That is indicative that time effect is not influencing the data. And when plotted against Ts, their variance was a bit not constant. But for SWC plotting, predicted SR using Eq.(D5) tended to slightly underestimate respiration at low SWC in the paddy field and at high SWC there were sometimes rather large differences between measured and predicted values.

The R^2 for bivariate models were very similar (0.46-0.49). However, multiple nonlinear regressions with Ts and SWC (D5) gave better results than simple regression with Ts or SWC as the only one independent variable. Eq.(D5) likely predicted most accurate and most unbiased values of SR more than another equation in the dry period. In particular, bivariate models including Ts and SWC functions can explain variation of SR better than univariate models with Ts or SWC. For example, combining Eq. (D2) with a quadratic function of SWC (Eq. (D3), Table 4.3 slightly improved the R^2, even through the RMSE values were higher but the residuals plot gave unbiased more than Eq. (D5). Therefore, Eq. (D5) which included Ts as a second variable would be necessarily complicated. There was statistical significant influence of Ts and SWC on SR during the dry period.

Table 4.2 Estimated parameters (a, b, c, d, e), coefficients of determination (R^2) and root mean square error (RMSE) for three univariate and two bivariate empirical models describing the relationship between soil respiration (SR) and soil water content (SWC) in dry period

Fitted function	Equation no.	Fitted and derived parameters					R^2	RMSE
		a	b	c	d	e		
$SR = c+b \times Ts$	D1		24.82	-241.98			0.23	174.45
$SR = a \times e^{(b)Ts}$	D2	72.72	0.062				0.27	0.39
$SR = c-d \times SWC+e \times SWC^2$	D3			410.29	-41.47	4.45	0.42	164.81
$SR = b \times Ts+d \times SWC+c$	D4		25.02	-469.37	26.09		0.46	141.28
$SR = a \times e^{bTs}+c+d \times SWC+e \times SWC^2$	D5	72.72	0.062	-185.06	24.28	0.09	0.49	143.42

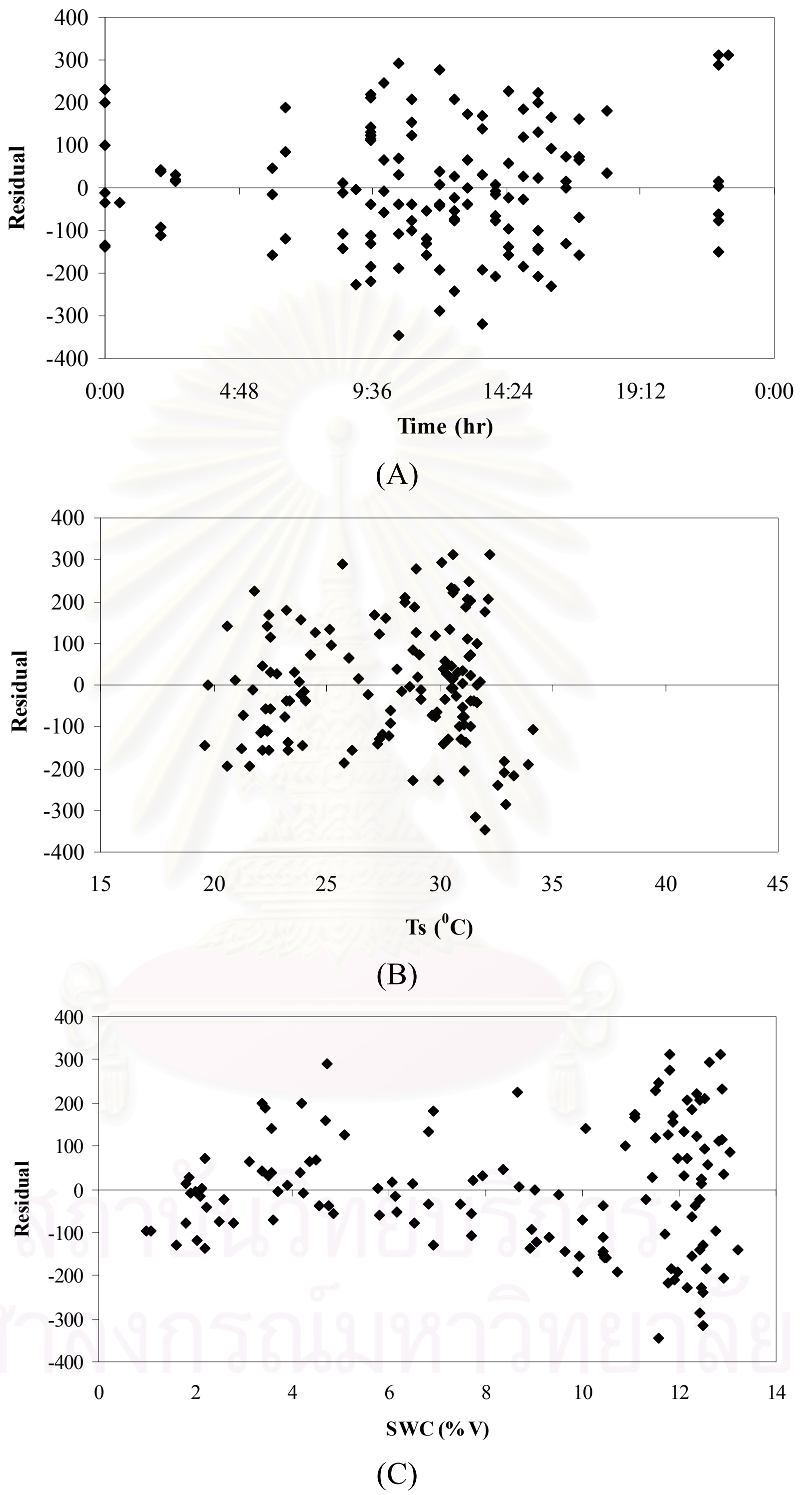

Figure 4.12 Residual error term of predicted soil respiration as a function of (A) time, (B) soil temperature (Ts) at a depth of 5 cm and (C) soil water content (SWC) in the top 5 cm. Soil respiration was predicted using Eq.(D5) in the dry period.

4.5.2 Wet period

Ts accounted for 25% of the variation in SR. SWC was shown no significant (R^2 = 0.04) and can not explain the variation (Figure 4.11). Most of regression models had an averaged R^2 of 0.20. Also, five empirical models that predicted an equation were selected and fitted against Ts, SWC and SR data (Table 4.3). The models are also poorly fitted and unexplained variation well. Residual examination still was necessary use for testing that variation has not been able to explain by that equation. The R^2 for W5 models were highest (0.31). Residuals that obtained by use of Eq.(D5) were quite distributed along the axis when plotted against time and Ts that indicated no time effect and no abnormality (Fig. 4.13). But for SWC plotting, predicted SR using Eq.(W5) tended to relatively overestimate respiration at high SWC and at low SWC there also were high tendency and sometimes largely different between measured and predicted values.

However, Eq. (W5) likely predicted most accurate and unbiased values of SR more than another equation in the wet period. Bivariate models including Ts and SWC functions can explain variation of SR better than univariate models with Ts or SWC. For example, combining Eq. (W2) with a quadratic function of SWC (Eq. (W3), Table 4.3 marginally improved the R^2, even through the RMSE values were higher but the residuals plot gave more unbiased than Eq. (W5). Therefore, Eq. (W5) which included SWC as a second variable would be necessarily complicated. There was statistical significant influence of Ts and SWC on SR during the wet period.

In conclusion, during the dry period, the nonlinear relationship was found as the best-fit regression equation (Eq. (D5)) in term of Ts as exponential and SWC as quadratic. Similar, in wet period, the best-fit equation was exponential in term of Ts and SWC as quadratic (Eq. (W5)). The measured and predicted SR rates as a function of time are shown in Fig. 4.14. Although, the variation patterns of the predicted values were quite constant, the amplitude was underestimated in the dry and the wet period when Ts are constant or decreased and SWC are increased.

Table 4.3 Estimated parameters (a, b, c, d, e), coefficients of determination (R^2) and root mean square error (RMSE) for three univariate and two bivariate empirical models describing the relationship between soil respiration (SR) and soil water content (SWC) in wet period.

Fitted function	Equation no.	Fitted and derived parameters						
		a	b	c	d	e	R^2	RMSE
SR = c+b×Ts	W1		12.16	-163.95			0.26	94.02
SR = a × e $^{(b)Ts}$	W2	33.19	0.056				0.25	0.45
SR = c-d×SWC+e×SWC^2	W3			410.55	-10.63	0.16	0.04	107.37
SR = b×Ts+d×SWC+c	W4		12.34	-244.78	1.98		0.29	92.18
SR = a × e ^{bTs}+c+d×SWC+e×SWC^2	W5	33.19	0.056	150.20	-9.74	0.16	0.31	91.16

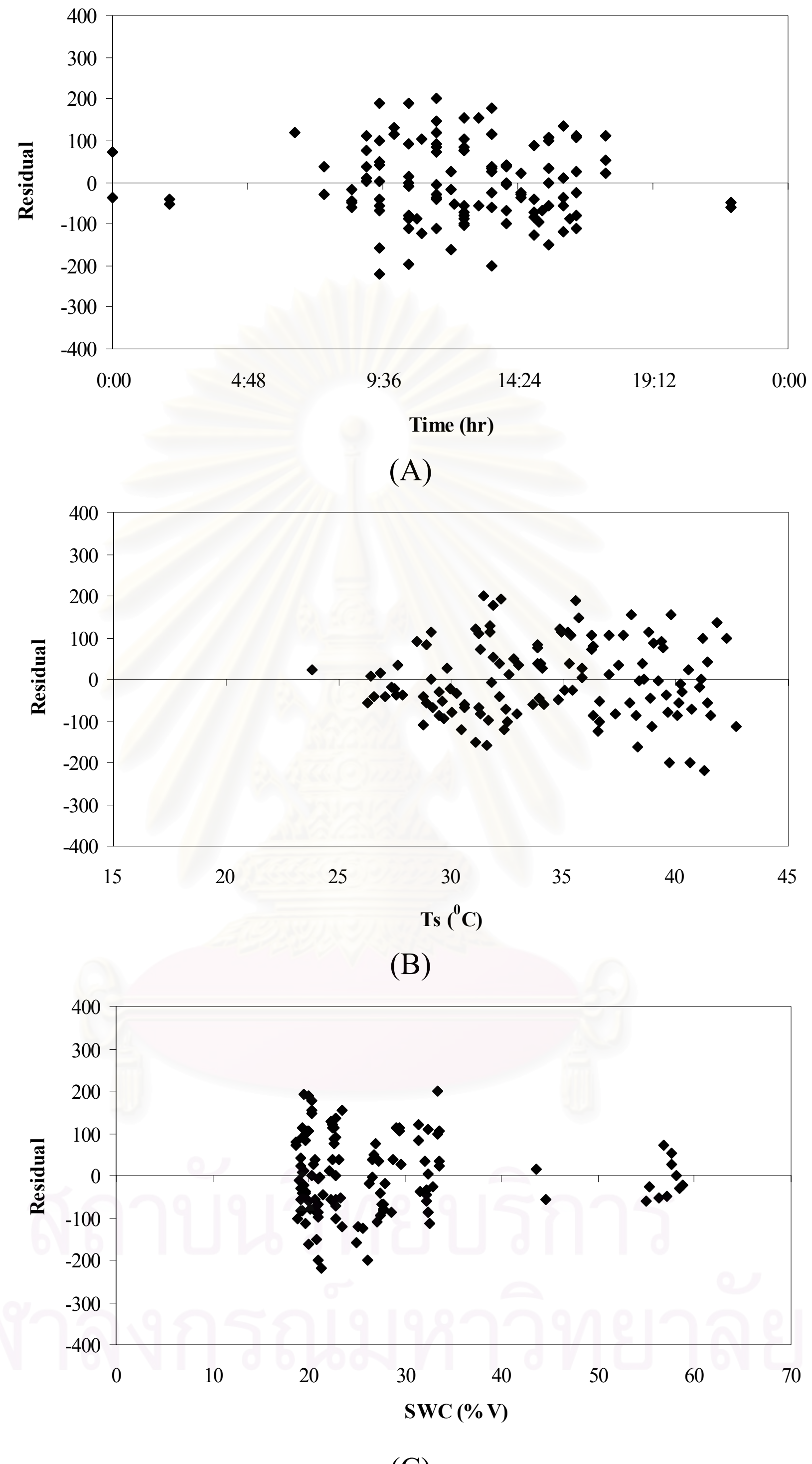

Figure 4.13 Residual error term of predicted soil respiration as a function of (A) time, (B) soil temperature (Ts) at a depth of 5 cm and (C) soil water content (SWC) in the top 5 cm. Soil respiration was predicted using Eq.(W5) in the wet period.

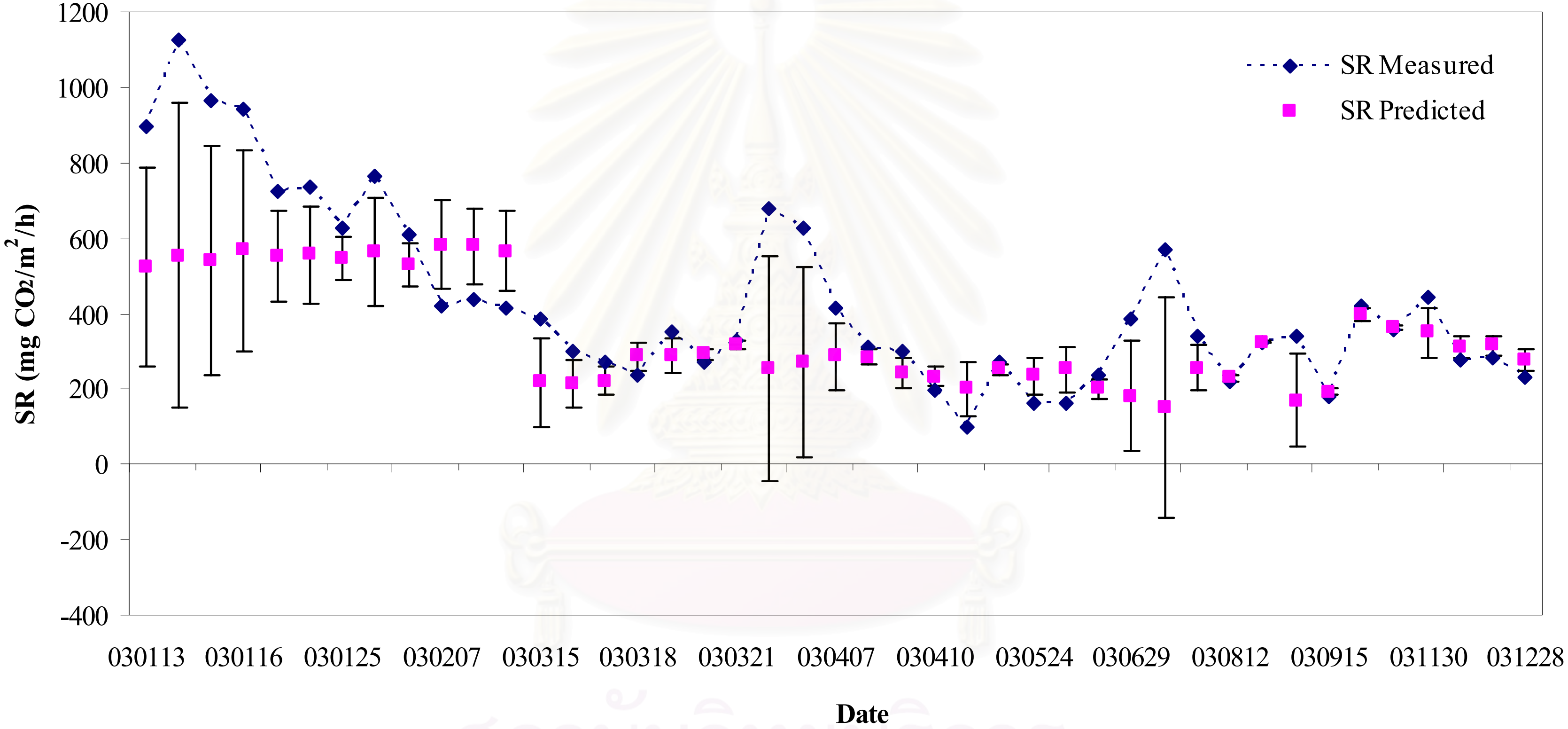

Figure 4.14 Comparison the daily averaged of soil respiration between measured and predicted.

4.6 Total annual of Soil Respiration

Based on the total annual variation of SR from paddy field, Sukhothai province (Figure 4.15 and Table 4.4), in which the dry period, total SR rates with value of 1.38 kg CO_2 m^{-1} $y^{-1}$and 1.53 kg CO_2 m^{-1} y^{-1} for measured and predicted value, respectively. For the wet period, total SR rates to be 1.61 kg CO_2 m^{-1} $y^{-1}$and 1.36 kg CO_2 m^{-1} y^{-1} for measured and predicted value, respectively. We estimated the annual total SR rates at the paddy site to be 2.99 kg CO_2 m^{-2} y^{-1} by measured data during the measured period from January to December 2003. And we estimated by calculated from across equation in part of the dry and the wet period to be 2.89 kg CO_2 m^{-1} y^{-1} for the same period (Table 4.4). The predicted annual value was slightly lower value than measured value approximately 3.4% that caused by underestimate of nonlinear equation during the wet period and slightly overestimated in the dry period.

The temperature dependence of SR, commonly referred to as the Q_{10} value, has been the focus of many studies. The value of Q_{10} is the factor by which the respiration rate differs for a temperature interval of 10^0C. The nonlinear equations give Q_{10} value to be 1.86 and 1.75 in the dry and wet period, respectively (Table 4.4). That indicated sensitivity responsible with temperature in difference period and environment. In the dry period, there was stronger response of SR rate to Ts more than in the wet period. This responsibility was associated with stronger correlations of SR with both Ts and SWC in the dry period, whereas strong correlation of Ts but a bit correlation of SWC in the wet period.

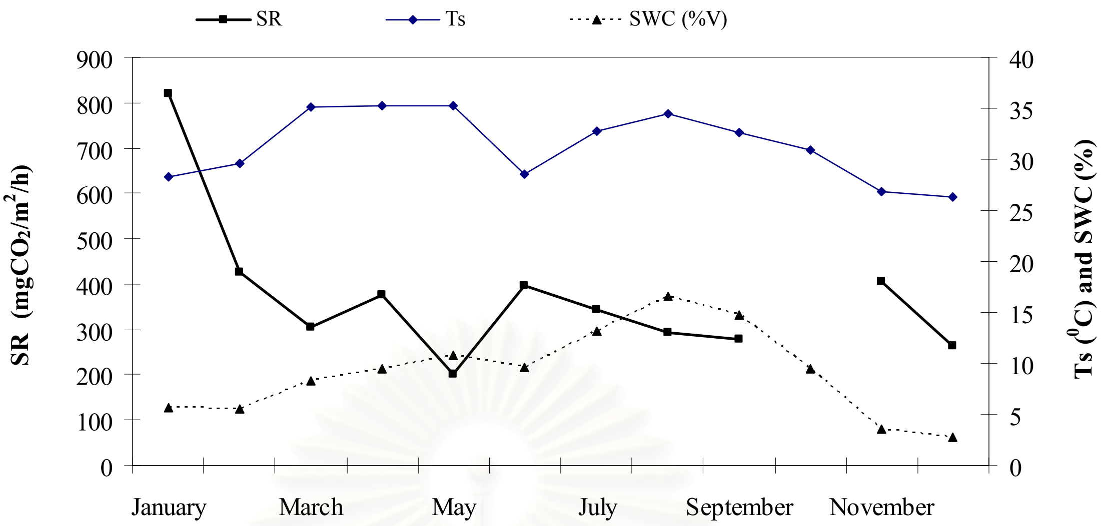

Figure 4.15 Soil respiration (SR), soil temperature (Ts) at 5 cm depth and soil moisture (SWC) in top 5 cm

Table 4.4 Comparison between total annual of Soil Respirations and Q_{10} values derived from measurement (Measured) and multiple nonlinear equations (Predicted) in which the dry period (D5) and the wet period (W5).

	Total annual ($kg\ CO_2\ m^{-2}\ y^{-1}$)	Total of Dry period ($kg\ CO_2\ m^{-2}\ y^{-1}$)	Total of Wet period ($kg\ CO_2\ m^{-2}\ y^{-1}$)
Measured	2.99	1.38	1.61
Predicted	2.89	1.53	1.36
Q_{10}		1.86	1.75

4.7 Rewetting and post-rainfall effect on Soil respiration

The abnormally high value of SR rates (1,500-4,300 mg $CO_2\ m^{-2}\ h^{-1}$) on 26th to 28th July, the exact reason for this peak is still unknown but it is possible that this was an influence of rainfall occurrences which rewetting soil where a major change in Ts took place. After analyzing Figure 4.16, the interesting points are following:

(1) The increase in respiration rate during that time associated to soil rewetting after pre-rainfall, soil was hot and dry for short time (10 days without rain). Underground depth still remained some SWC, although the surface appears very dry. To support this reason as a comparison between SWC that measured by TDR at 5 cm and 15 cm in July are shown in Figure 4.17. Therefore, the rewetting event on 26th July by the rainfall occurrence and rainfall could infiltrate through the shallow depth but could not move deeper because the deeper layer still remained some SWC. The infiltrating water was replaced of CO_2 gaseous in the soil porosity of the shallow layer. Almost of soil CO_2 emitted and confound with increased microbial activity and population because of the increasing respiration rates also associated with Ts (Figure 4.18). The result as the over high respiration rate, in the morning of 26th July 2003. On the contrary, in the afternoon of 26th July 2003 after SWC reached 23 % by volume, respiration rates declined while SWC was increasing. Later on the decrease in respiration rates might have resulted from the restriction of the soil porosity by rainfall filtration, reducing soil air-filled pore space and respiration and increasing anaerobic activity of soil microorganism (Figure 4.19).

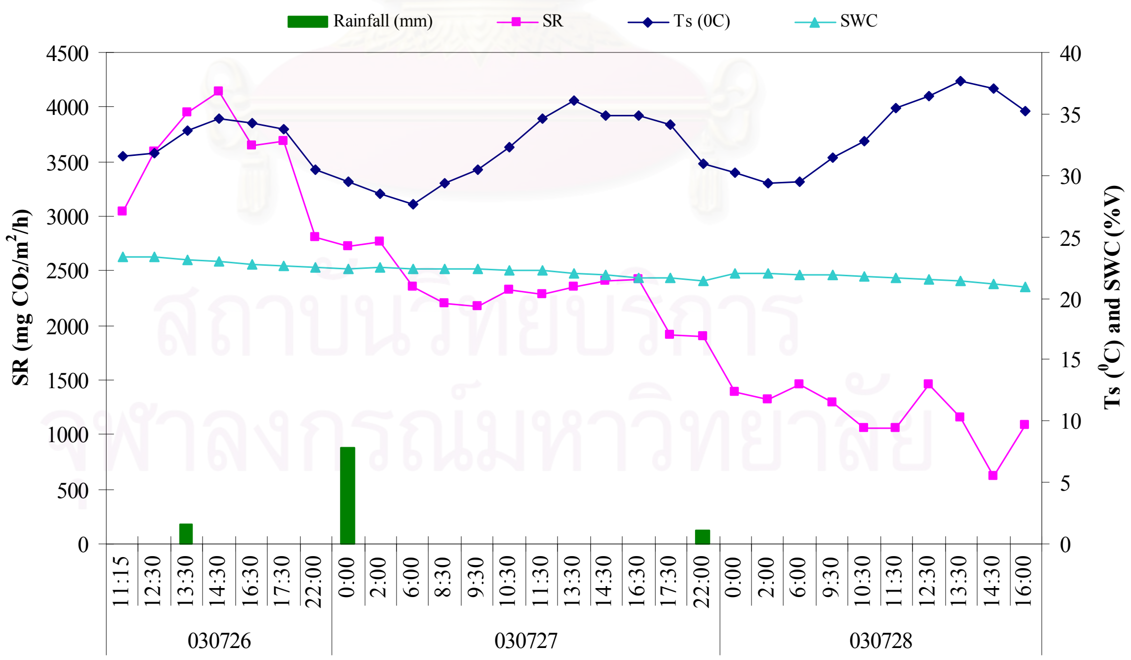

Figure 4.16 Diurnal variations of soil respiration (SR), soil temperature (Ts) at 5 cm depth and soil moisture (SWC) in top 5 cm on 26th – 28th July 2003.

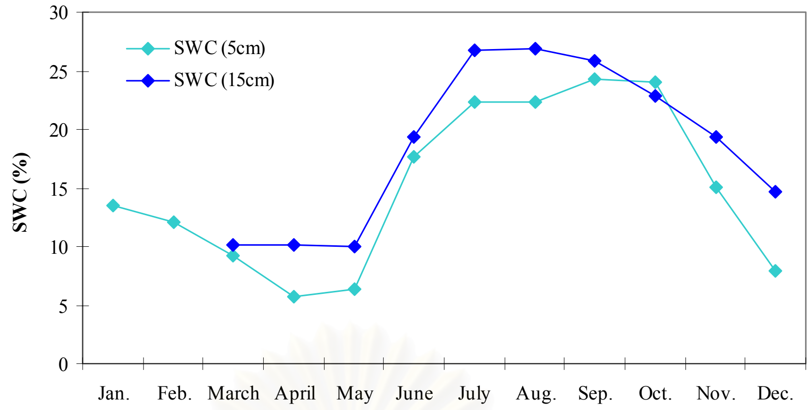

Figure 4.17 A comparison between soil water content (SWC) at depth of 5 cm and 15 cm in the soil by TDR in 2003.

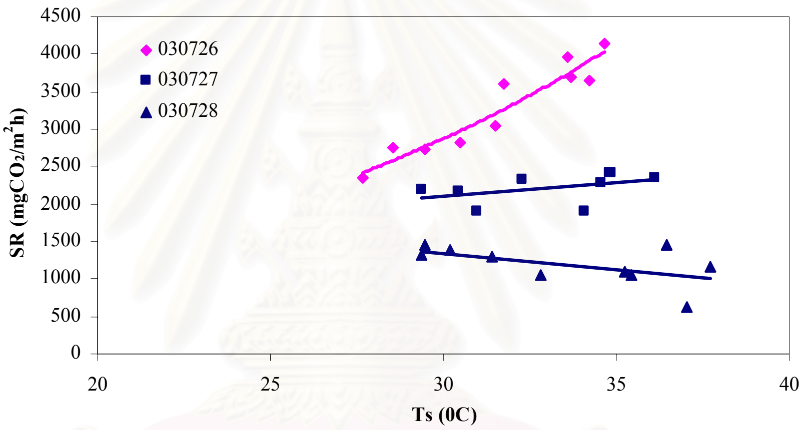

Figure 4.18 Relationship between soil respiration (SR) and soil temperature (Ts) in each day of 26th – 28th July 2003

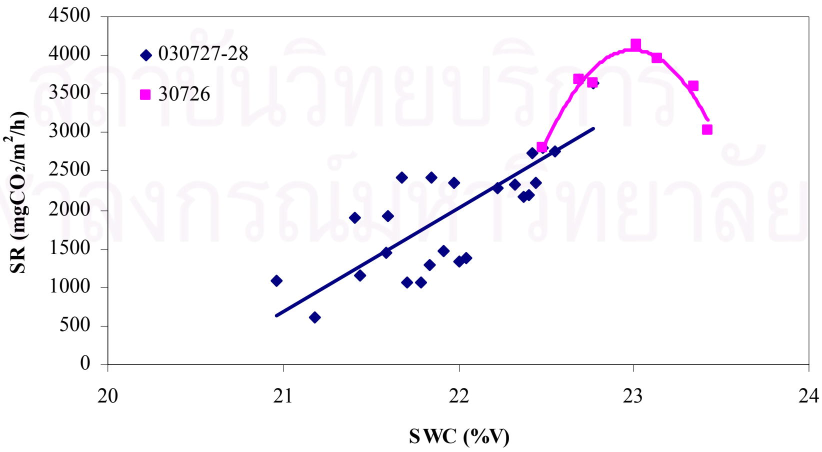

Figure 4.19 Relationship between soil respiration (SR) and soil water content (SWC) on 26th July showed linear relation and on 27th – 28th July 2003 showed quadratic relation.

(2) The decreasing of respiration rate on 27th and 28th July 2003 might have caused as the reason earlier. After soil condition saturated respiration rates were declined due to low pore space in soil, the microorganism in soil could not supply O_2 from pore space to generate more CO_2 which the same rate as first date, although Ts gradually increased but respiration rate showed low response on 27th July 2003 and negative response on 28th July 2003 (Figure 4.16). It should also be noted that attributed to re-wetting of soil which might also have affected SR.

(3) The relationship between Ts and SWC is shown in Figure 4.20. Ts exhibited inversely linear correlation with SWC during 21% to 23% by volume. However, SWC is more than 23%, there were showed quadratic relation. That meant the assumption as earlier that SWC at 23% is the restriction of the soil porosity for respiration process by SWC at surface layer 5 cm.

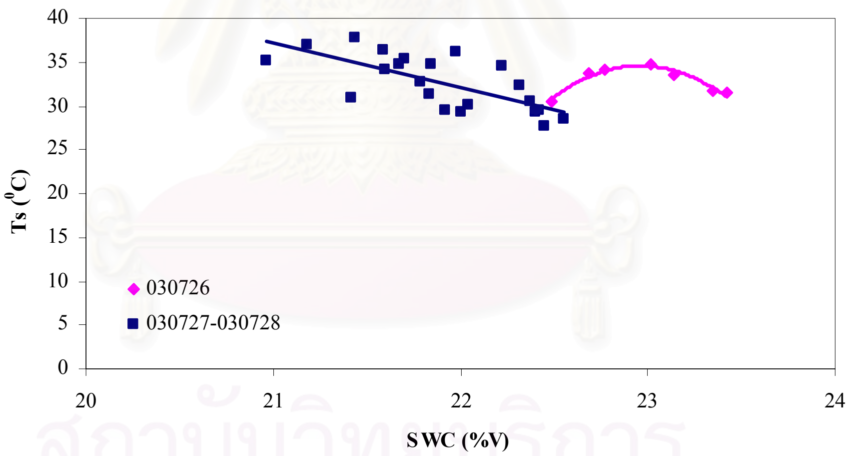

Figure 4.20 Relationship between soil temperature (Ts) and soil water content (SWC) on 26th July showed linear relation and on 27th – 28th July showed quadratic relation

4.8 DISCUSSION

4.8.1 Soil temperature, Soil Water Content and other factor influence on Soil Respiration

The SR rates measured monthly over one year period, particular dry period (528.58 mg CO_2 m^{-2} h^{-1} overall mean) and wet period (299.12 mg CO_2 m^{-2} h^{-1} average mean). Soil respiration was comparatively high from January to February, and was steadily stable rates between March to December. The rates of soil respiration were relatively high in the dry period and low in the wet period. Unlike Shoji *et al.* (2004) who found that the rate of SR in evergreen forest, north of Thailand were high in the rainy period and low in the dry period.

In many research studies, Ts was noted to be a strong and positive predictor of SR. This study found both Ts and SWC varied markedly with period and SR rates varied on both Ts and SWC. There were high SWC limit the response of SR to Ts. SR of both microbial activities and plant roots is sensitive to changes in Ts. We detected differences in the sensitivity of the different respiration at two periods. The results revealed that Ts explained 27% and 25% in the dry and the wet period, respectively of the total SR rates in Arrhenius equation. The lower R^2 in our regression model could be explained by the relatively short duration of the studying and the lack of other factors. However, this strong relationship between SR and temperature is not unexpected since SR rates reflect microorganism activities that were highly temperature dependent of tropical soil (Bekku *et al.,* 2003).

In the other hand, Shoji *et al.* (2004) reported that the rate of SR in evergreen forest, north of Thailand is determined predominantly by soil moisture, not by Ts. Conant *et al.* (2000) found that soil moisture was the main factor influencing soil CO_2 flux in three semiarid ecosystems in Arizona. Unlike other results reported in some review articles, soil moisture showed a less limiting effect on the variability in SR rates. The influence of moisture content on SR is complicated through its effect on respiratory activity of roots and microbes on transport through the soil. The inhibition of SWC on SR is significant only at its low in the dry period (SWC less than 20%), SWC appears to dominate factor as SR rates increasing relatively high response to temperature associated with SWC increasing. SR exhibited slowly response to temperature and SWC has no clear effect on respiration rates over that SWC range in the wet period. This is agreement with that reported by Fang and Moncrieff (2001) and Rey *et al*. (2002). Moreover, SWC may limit SR in two ways, either by limiting aeration, and thus the diffusivity of air, when it is high or by stressing soil micro communities and root respiration when it is low. At this site, SWC strongly limited SR during the dry period when SWC dropped below a value of 13% over 0-5 cm depth. The small range of moisture values that accounted for the low percentage of the overall variability in SR rates in our study was explained by moisture 32% and 4% in the dry and the wet period, respectively of the total SR rates in quadratic equation.

SR rates were comparatively high during January. It was surprising how this respiration rate was shown in our study at beginning study and then relatively decreased, giving that the measurements were taken after harvesting and tillage in December 2002. We reasoned that mainly affected by the increased microbial activities and population. Due to after harvesting and tillage, residual of rice was abandoned in the field and there were still remain high SWC. Assume that the amount of microbial biomass carbon and carbon substrates available for decomposition are included in total soil carbon. The amount of substrate and water available was high, in addition of changing soil biophysical environment from anaerobic to aerobic condition. The exhibition of residual organic matter and aerobic condition quickly made the physical environment favorable to the microbes, results an instant higher SR rates in January. After that SR rates decreased, the variation is most likely to result from either substrate limitation or from changes in population size, particular the latter as Ts increases over that time. The soil organic matter substrates were still remained in soil in which lower than first that gave the result as decreasing SR rates. An instant response was also reported by Lee *et al*. (2002) and Lee *et al*. (2004), although some of these authors may have observed and ignored the short-term response.

4.8.2 Soil Respiration models and Q_{10} value

The response of SR to Ts is commonly expressed using different types of equations such as exponential (Davidson *et al*., 1998; Rey *et a*l., 2002; Lee *et al*., 2002; Cao *et al*., 2004), or Arrhenius as equation (2.3) (Fang, 2001), or linear (Fang, 2001 and Shoji *et al.*, 2004). Each of these models has been success in fitting data under specific circumstances. According to our result nonlinear relationships between SR rates and Ts were found for both the dry and the wet period. Similar with Mielnick and Dugas (2000) who also established nonlinear equation from tall grass prairie data set. Our equation results based on only Ts and SWC which accounted 49% and 31% of SR variation in the dry and the wet period. There were seemed the maximum limiting that both of Ts and SWC can pay attention on SR in Sukhothai Paddy soil. That gave the predicted value output from our established equation as higher in dry period and lower in wet period than the measured value. Over that can be account by additional other factors.

As expected, there was greater scatter in the relationship between Ts, SWC and SR in both dry and wet period. This might be the cause of factors other than soil temperature that may also affect the activity of soil microorganisms and plant roots. Denote in January exhibited high SR rates while Ts and SWC was lower than other months. Popescu (2001) constructed linear regression model by addition species of plant, temperature on position and carbon content in the model. The model can account SR variation in mixed hardwood 75 %.

The Q_{10} value in which defines the temperature dependence or sensitive to SR variation on the exponential function (equation 2.4). Ts accounted 1.86 and 1.75 of Q_{10} value in the dry and the wet period, respectively. The Q_{10} value in the dry period which is relatively higher shows a bit stronger response SR to Ts with narrow Ts range. It is known that respiration of both plant root systems and microbial communities is sensitive to changes in Ts (Rey *et al.*, 2004). In particular, the narrow range of temperature changes, results as high temperature response (high Q_{10}). Similar with Davidson (1998) who found that high Q_{10} (3.9) in temperate mixed hardwood forest with Ts ranged 2^0 – 17^0 C. And Cao *et al*. (2004) measured in grazing field at Alpine meadow, also noted Q_{10} to be 3.22 and 2.75 in light grazing and heavy grazing by -10^0 to 15^0 Ts range.

In contrast, our result in the wet period shows low response temperature remark with wider Ts range than in the dry period. This agrees with Gulledge and Schimel (2000) who reported that 1.3 – 1.9 range of Q_{10} in flood plain exhibited by 5^0 – 30^0 C of Ts range.

4.8.3 Total annual of Soil Respiration

The mean SR rate measured at our study site for twelve months measurement period was 2.99 kg CO_2 m^{-2} y^{-1}. Similar values were reported by Shoji *et al.* (2004) that were 2.56 kg C m^{-2} $year^{-1}$ in the north of Thailand and Cao *et al.* (2004) estimated 2.04 kg C m^{-2} $year^{-1}$ in China light grazing. Our site generated a moderate annual respiration rate, comparing with other kind of land use (Table 2.2). Minimum total annual of 0.73 kg C m^{-2} $year^{-1}$ reported by Fank *et al.*, 2002, which measured in Semi arid grassland. In addition, maximum value measured at pine forest. That was 3.3 kg C m^{-2} $year^{-1}$, was reported by Pumpanen *et al* (2003). It is known that both of Ts and SWC are the basically effects driving SR in the present. Moreover, site location and land use also influenced to SR. Because site environment pay attention to control microclimatic. And the difference in CO_2 release between land uses must be due to microclimatic and soil environment difference.

Therefore, how much soil can CO_2 was limited by Ts and SWC in particular influenced the chemical process of while how the amount of soil CO_2 that can get off through the atmosphere was limited by soil physical properties. Because of paddy soil was low water and air permeability, soil emitted CO_2 to the atmosphere in lower rates than another soil that was higher permeability (e.g. Pumpanen J. *et al*, 2003).

4.8.4 Rewetting and post-rain effect on Soil Respiration

The extremely high value of SR rates (1,500-4,300 mg CO_2 m^{-2} h^{-1}) on 26th to 28th July, it is still not clear due to lack of replication. Usually measurements will taken in the sunny day without rain, in this case measurements were taken with exception of 1 hr after rain occurrence because of limit of time. One possible explanation is that post-rainfall increases in SR are caused by suddenly replacing of gaseous in soil pore by rain water and drive almost soil CO_2 released to atmosphere. The following that sharp decrease in SR occurrence might be caused by the limiting of the soil air-filled pore space and the dissolution of soil air CO_2 into the filtrating rain water. Overall the reduction of SR post-rainfall seems constrained by the property of soil (e.g. texture, structure, component, compactness).

In agreement with Rochette *et al*. (1991), Lee M-S (2002) and Lee X. (2004) studied effects of rainfall even on SR. They also concluded the abnormally high SR after rain and later sharply decrease caused by quickly rain water take place and instead of CO_2 gaseous and after that soil was restricted on soil air-filled pore. Result as decreased SR on the following day. However, more research is needed to clarify the mechanisms of the post-rain increases in SR.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Monitoring the variation of CO_2 emission from the soil surface and evaluation the Ts and SWC factors that effect in its magnitude are fundamental to the understanding to evolution of carbon circulation in the paddy field. The conclusions of this work are following:

1) Interannual variation on SR exhibited highest in January, the later month quite steady except for the extremely high respiration rates in July. In particular dry period mean averaged of 528.58 mg CO_2 m^{-2} h^{-1} and wet period mean average of 299.12 mg CO_2 m^{-2} h^{-1}. This variability was associated with correlations of SR with both Ts and SWC.

2) Ts was high in the wet period and low in the dry period. During the 8 months wet period, Ts slightly changed but SWC large change corresponding with rainfall pattern. In the dry period, SR rates were dominated to limit by SWC. Ts is minor factor influence. Whereas, in the wet period, SR rates were poorly correlated with both Ts and SWC, however Ts also is the most likely affecter and SWC still be minor factor even though shows a bit correlation.

3) The comparison of annually SR between 2.99 kg CO_2 m^{-2} y^{-1} by measured data and 2.89 kg CO_2 m^{-1} y^{-1} by calculated from equation in part of the dry (1.53 kg CO_2 m^{-1} y^{-1}) and wet period (1.36 kg CO_2 m^{-1} y^{-1}). There were slightly overestimated in the dry period equation and underestimated in the wet period equation.

4) The predictive equation

$$\text{Dry period: } SR = 72.72 \times e^{0.062\, Ts} - 185.06 + 24.28 \times SWC + 0.09 \times SWC^2$$

$$\text{Wet period: } SR = 33.19 \times e^{0.056\, Ts} + 150.20 - 9.74 \times SWC + 0.16 \times SWC^2$$

5.2 Recommendations

SR is a major source of CO_2 in terrestrial ecosystems. Paddy field has been unconcerned in CO_2 emission. However, from this work showed the fact that SR is generated in a significant annual quantity.

This work focused on the soil emission rates of CO_2 from paddy areas which dependent on several factors such as temperature and moisture. This knowledge is important in the future planning for agricultural strategy as there is a potential that these emissions could be controlled through the adjustment of plantation techniques.

In addition, experimental data from this work will be useful as an extension to the existing database on the soil CO_2 emission rates from agricultural areas. The completion of this kind of database is essential for the development of reliable mathematical models in the soil CO_2 emission which are required to estimate the exact amount to contribute CO_2 concentration in the atmosphere in set of the global cycle.

The available experimental data in this work was subject to many constraints particularly the limitations of measurement duration, instruments, and techniques. It is recommended that the followings be carried out to overcome these constraints:

1. The period of measurement should be done more frequency and long term measurement such as every two week-interval continuously 3 years to obtain the rice growth stage, the repeat environmental variation, land management activities and get high accuracy of measuring data.

2. The number of factors should be sufficient for account more significantly in variation, within organic matter, diffusion potential, pH, etc.

3. The several land use should be concern more significantly. Due to the meteological towers under GAME-T project are also located in Thailand at Nakornratchasima, Lampang and Chiangmai.

4. A better measuring instrument should be developed to omit the loss of data due to the unavoidable error from measurement.

There is still a need for a further collection of data on the soil CO_2 emission flux from other kind of land use to complete the data set regarding the contribution of agriculture to the global environmental problems. Various other types of green house gases such as Methane, Nitrous oxide, etc. also should be taken into the data set. This opens up a wide area of research for the future.

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APPENDICES

Appendix A

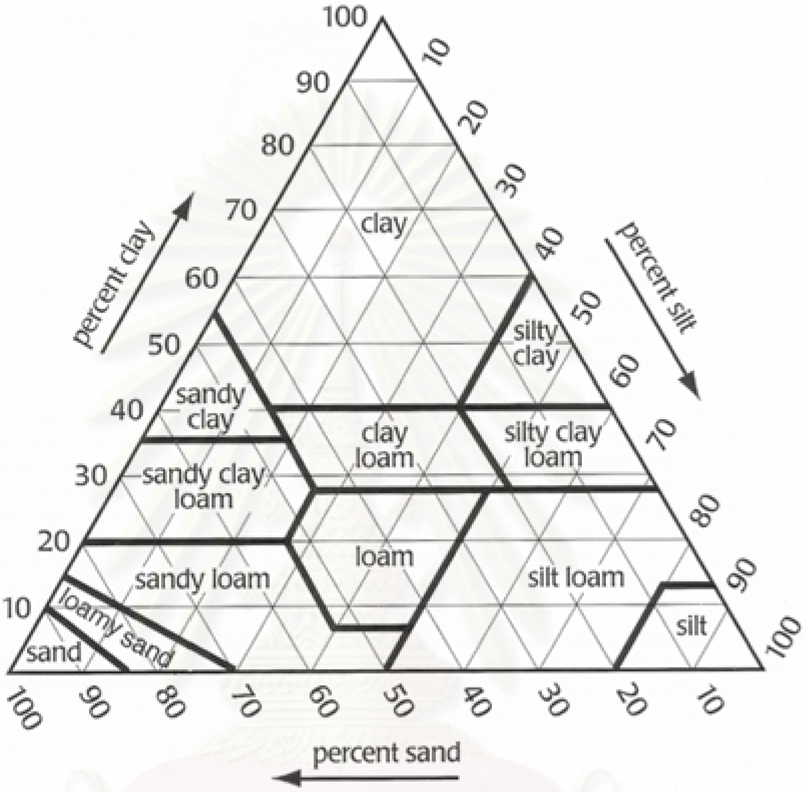
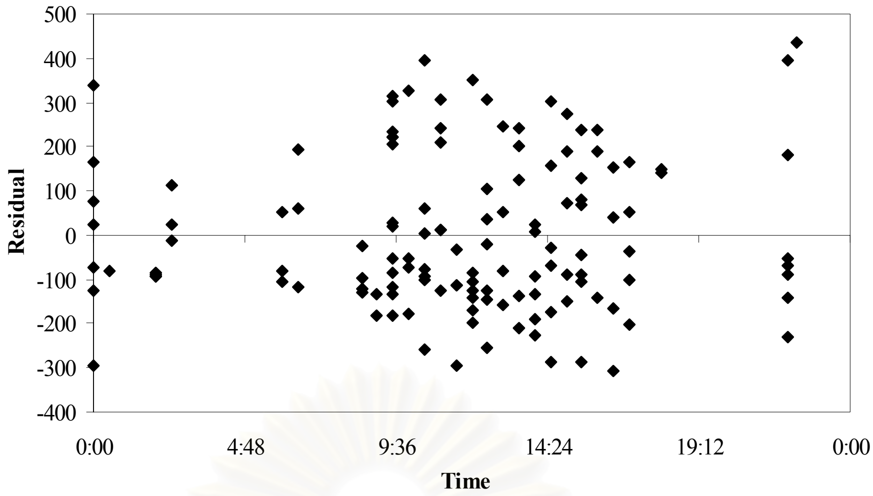
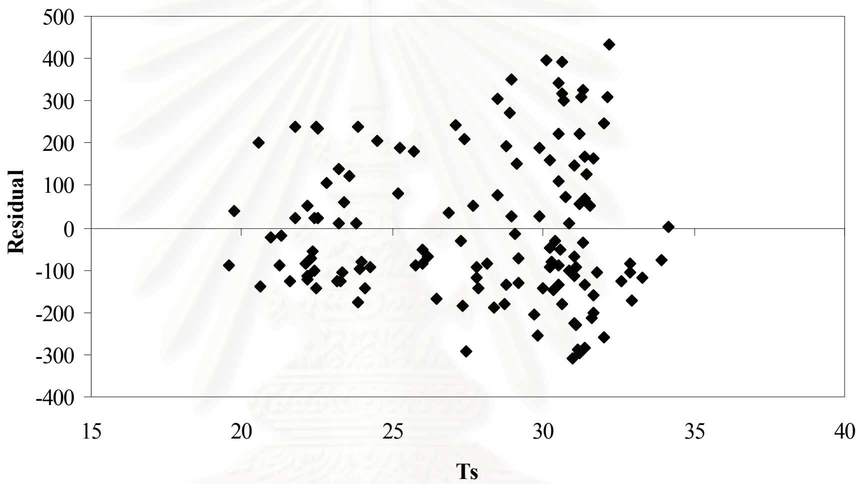


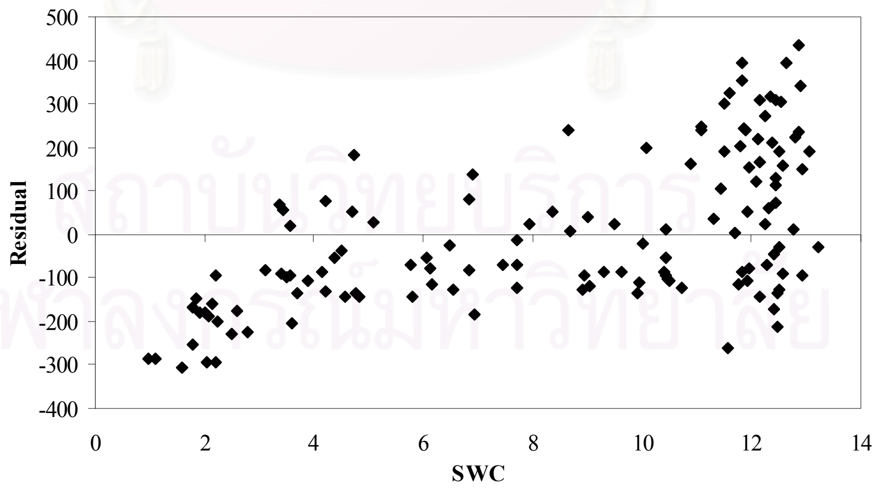
Figure A.1 The USDA textural triangle showing the percentages of sand, silt, and clay in each of the textural classes.
Source: Thomas (2002)



(A)



(B)



(C)

Figure A.2 Residual error term of predicted soil respiration as a function of (A) time, (B) soil temperature (Ts) at a depth of 5 cm and (C) soil water content (SWC) in the top 5 cm. Soil respiration was predicted using Eq.(D1) in the dry season.

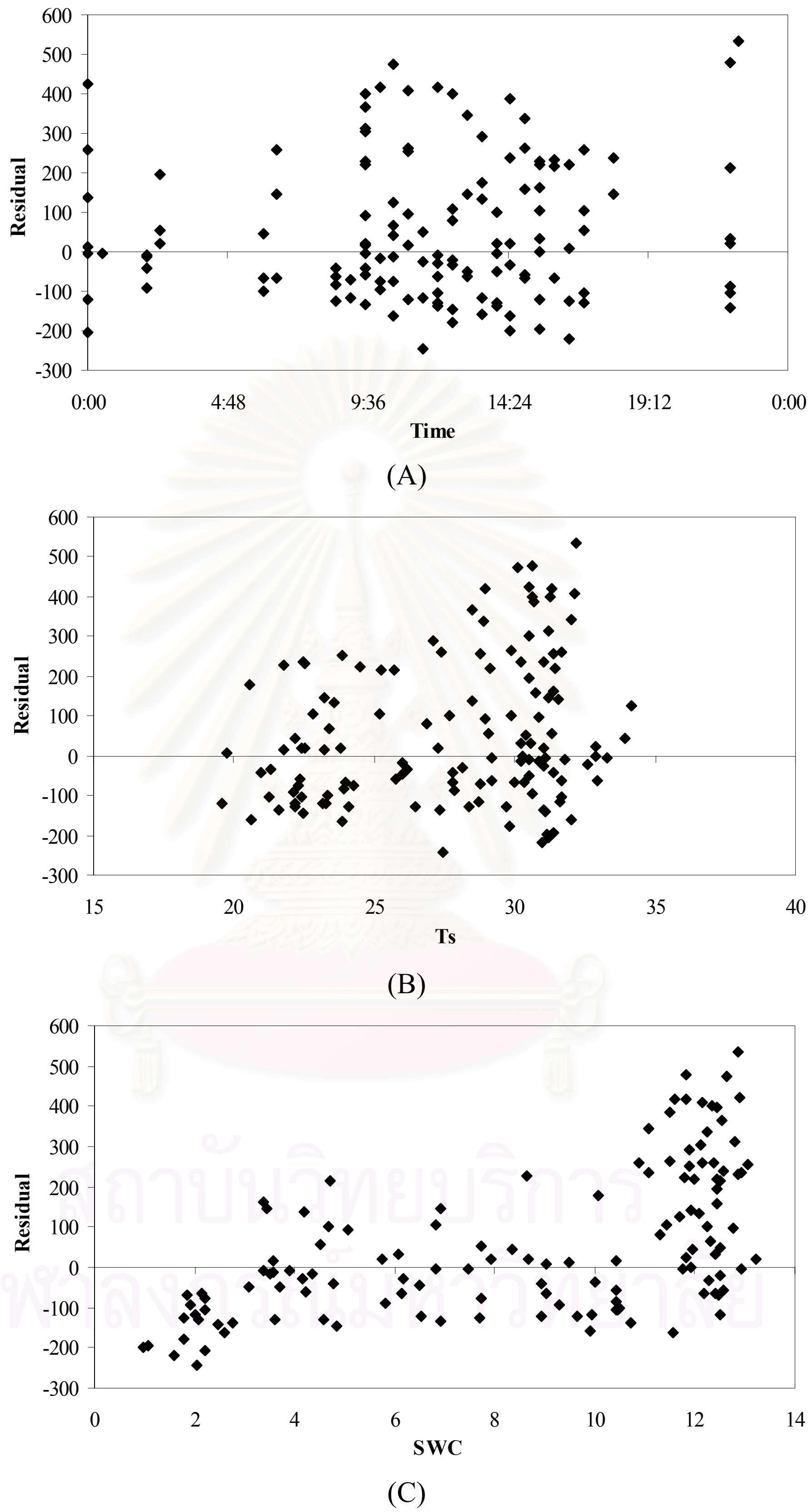
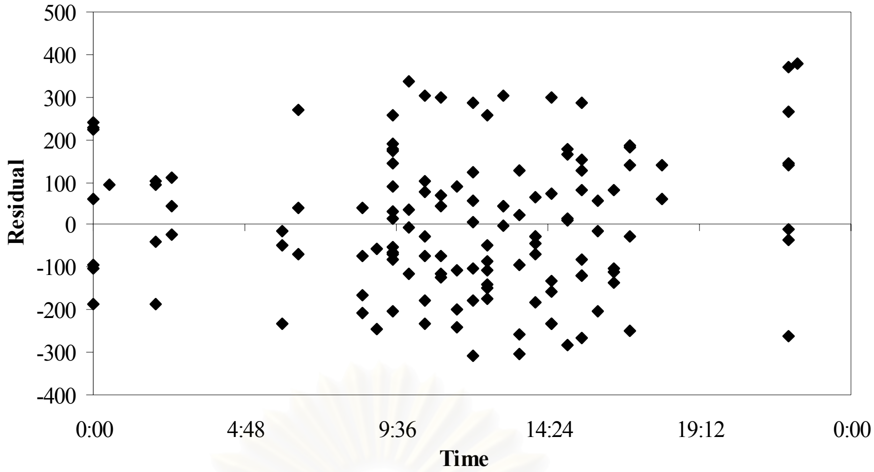
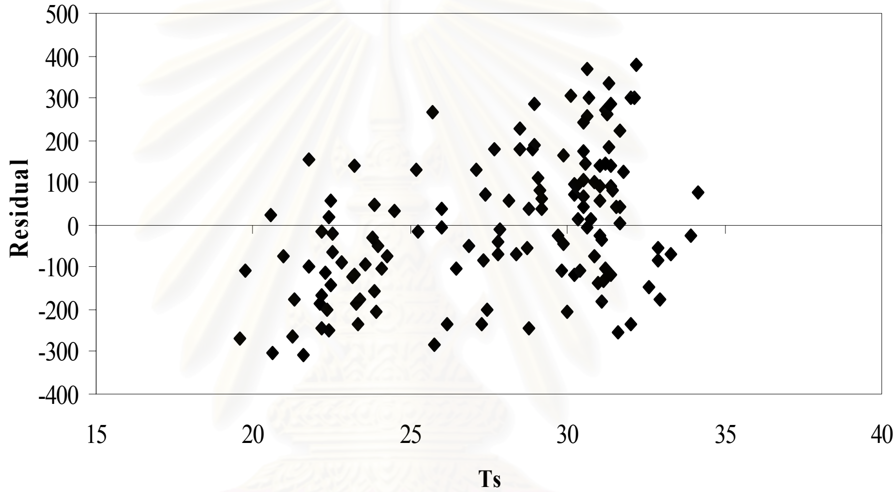


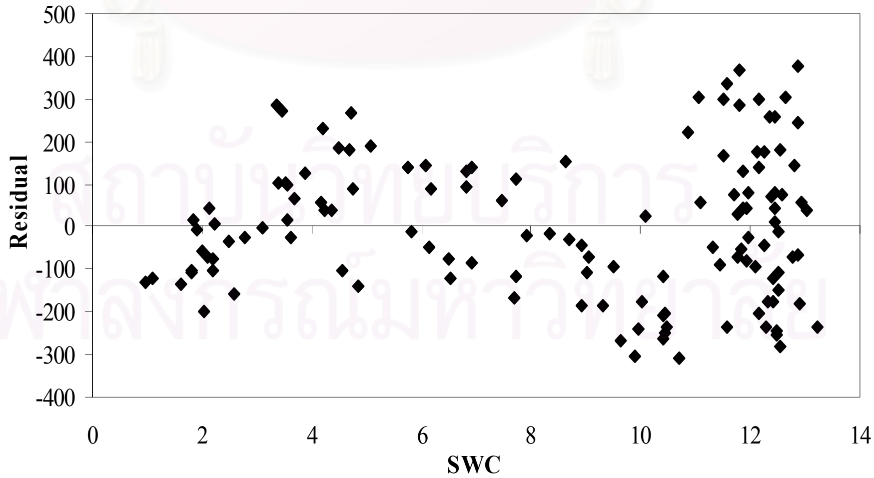
Figure A.3 Residual error term of predicted soil respiration as a function of (A) time, (B) soil temperature (Ts) at a depth of 5 cm and (C) soil water content (SWC) in the top 5 cm. Soil respiration was predicted using Eq.(D2) in the dry season.



(A)

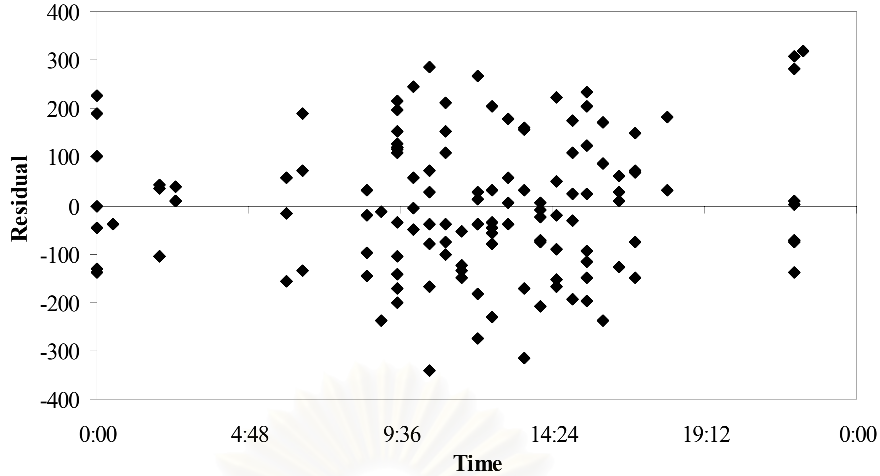


(B)

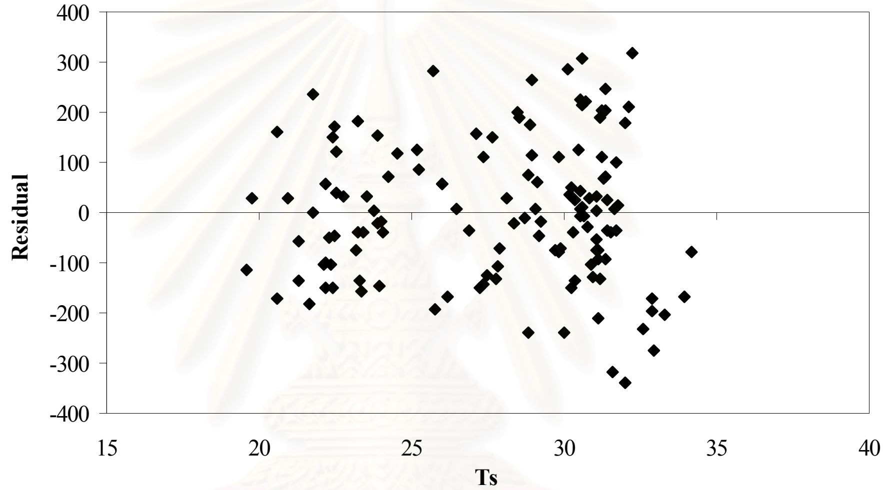


(C)

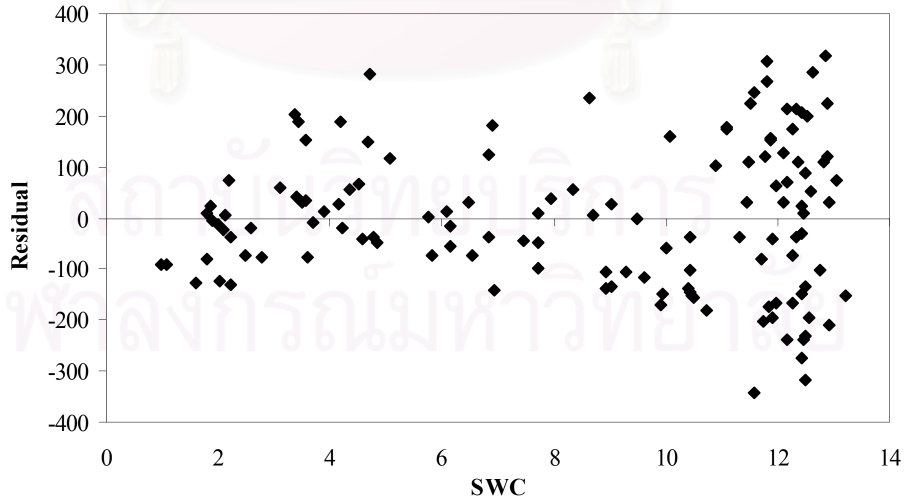
Figure A.4 Residual error term of predicted soil respiration as a function of (A) time, (B) soil temperature (Ts) at a depth of 5 cm and (C) soil water content (SWC) in the top 5 cm. Soil respiration was predicted using Eq.(D3) in the dry season.



(A)

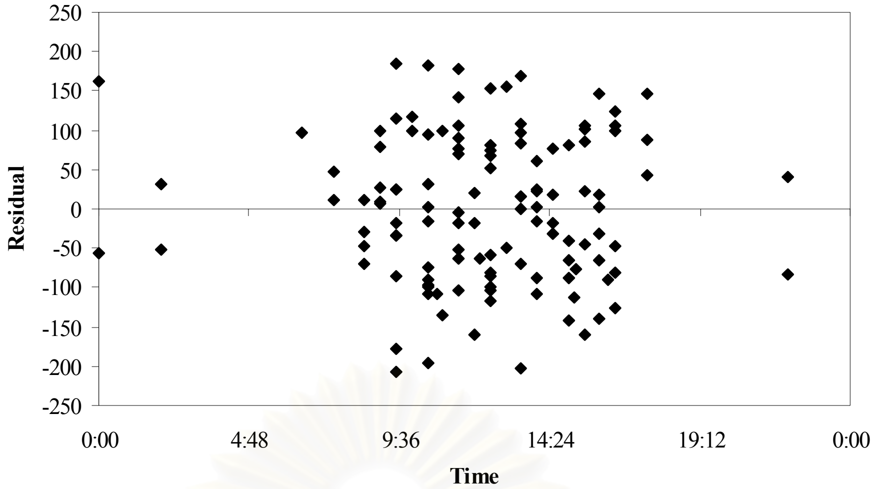


(B)

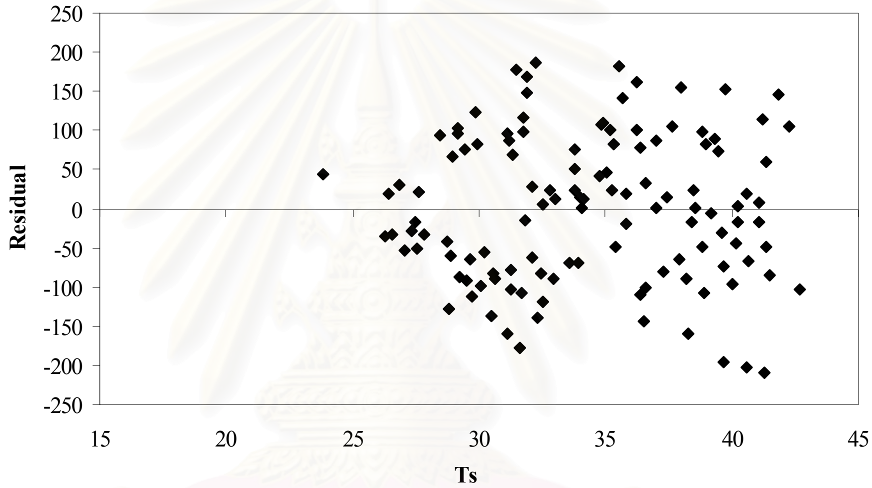


(C)

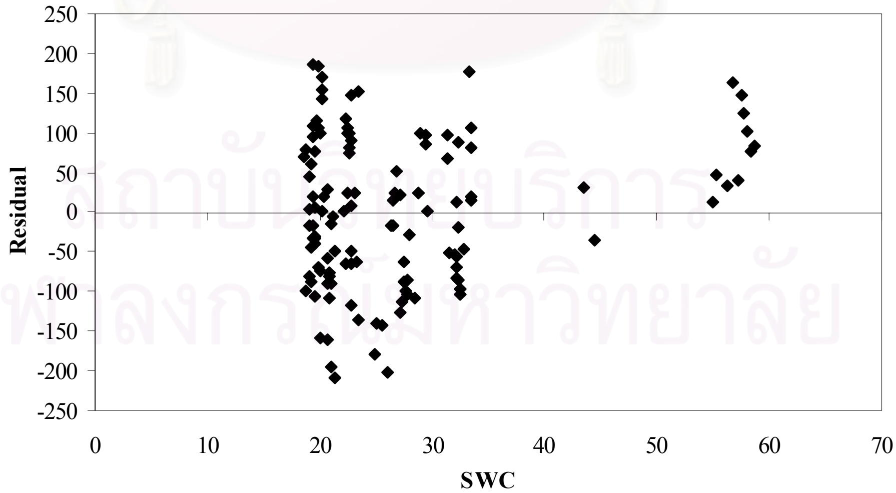
Figure A.5 Residual error term of predicted soil respiration as a function of (A) time, (B) soil temperature (Ts) at a depth of 5 cm and (C) soil water content (SWC) in the top 5 cm. Soil respiration was predicted using Eq.(D4) in the dry season.



(A)

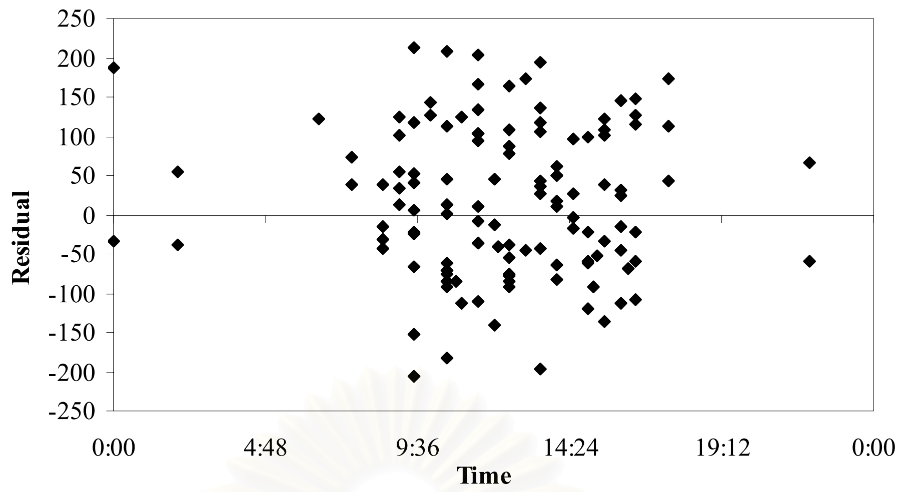


(B)

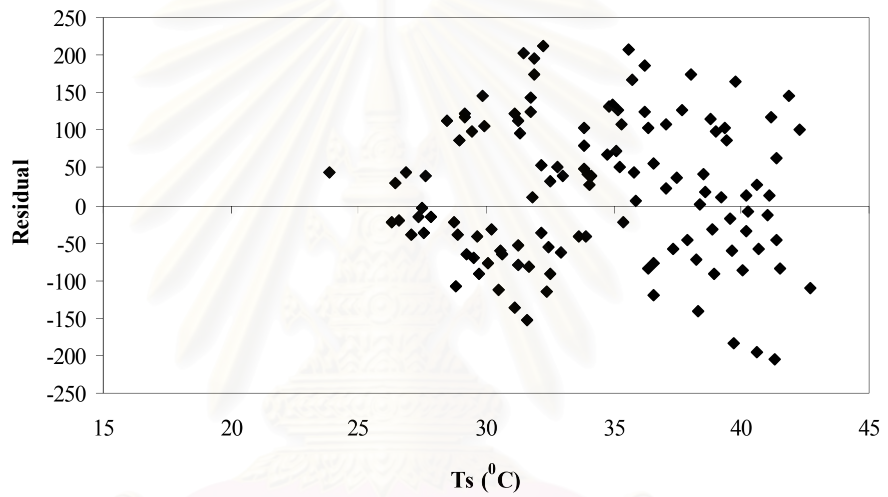


(C)

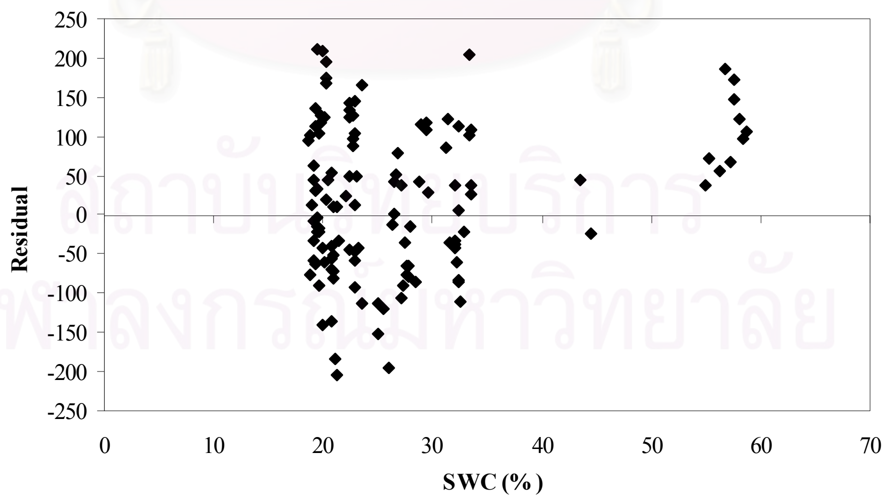
Figure A.6 Residual error term of predicted soil respiration as a function of (A) time, (B) soil temperature (Ts) at a depth of 5 cm and (C) soil water content (SWC) in the top 5 cm. Soil respiration was predicted using Eq.(W1) in the wet season.



(A)

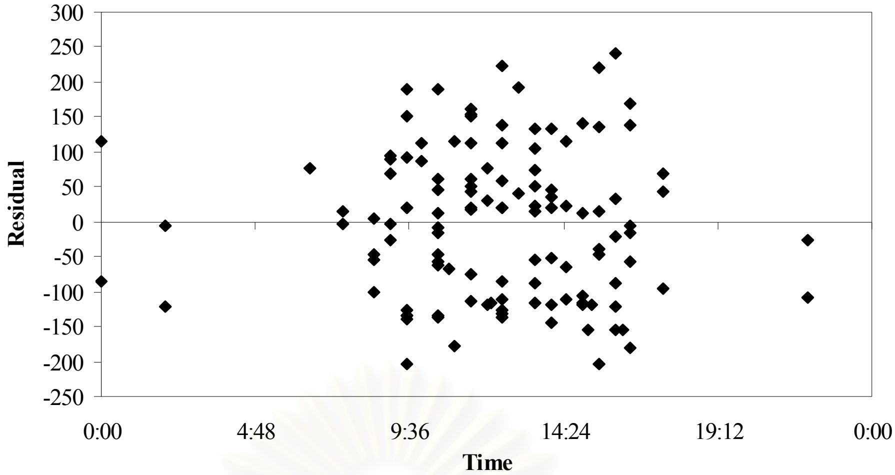


(B)

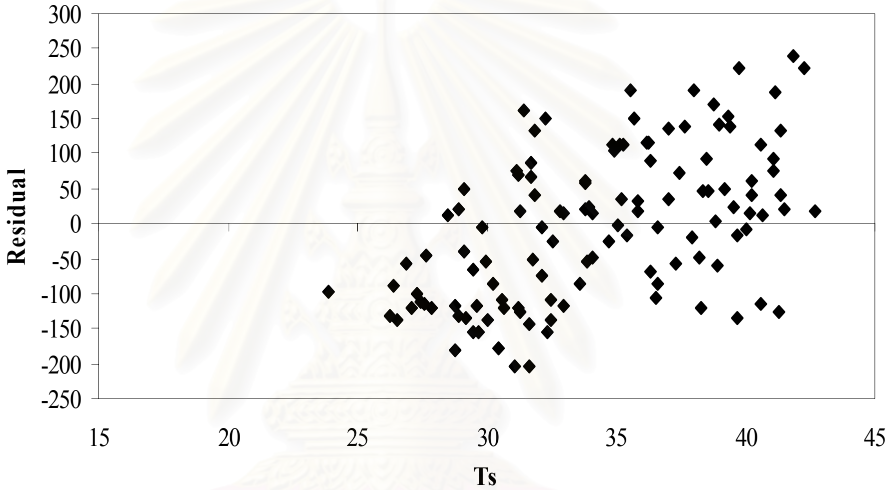


(C)

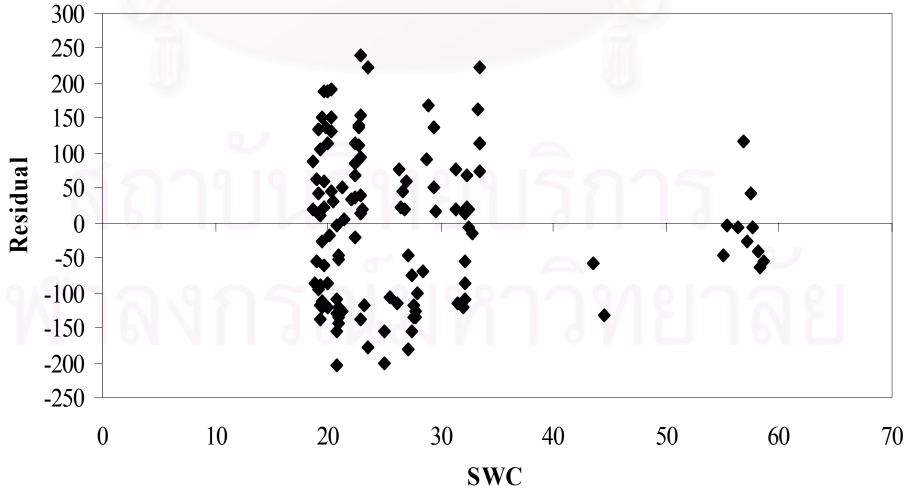
Figure A.7 Residual error term of predicted soil respiration as a function of (A) time, (B) soil temperature (Ts) at a depth of 5 cm and (C) soil water content (SWC) in the top 5 cm. Soil respiration was predicted using Eq.(W2) in the wet season.



(A)

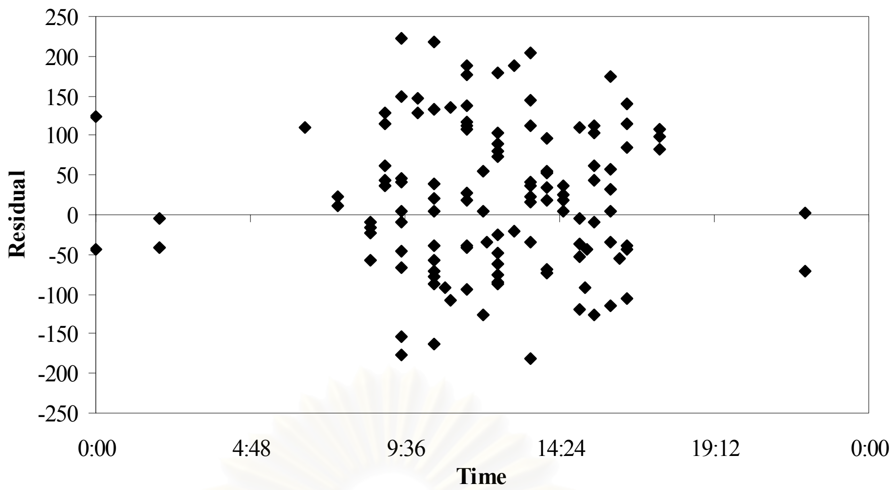


(B)

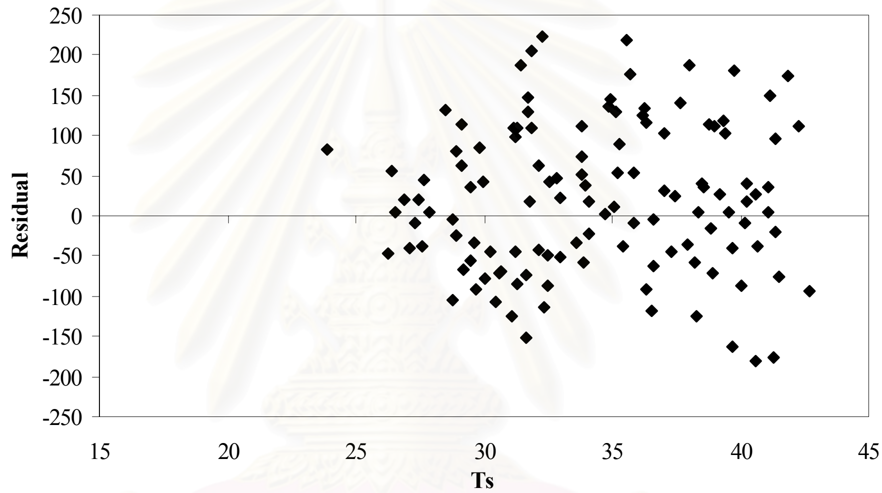


(C)

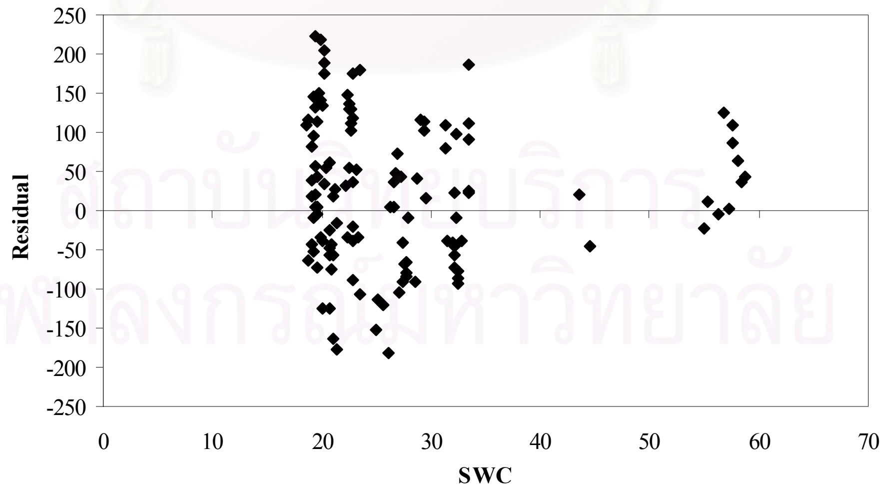
Figure A.8 Residual error term of predicted soil respiration as a function of (A) time, (B) soil temperature (Ts) at a depth of 5 cm and (C) soil water content (SWC) in the top 5 cm. Soil respiration was predicted using Eq.(W3) in the wet season.



(A)



(B)



(C)

Figure A.9 Residual error term of predicted soil respiration as a function of (A) time, (B) soil temperature (Ts) at a depth of 5 cm and (C) soil water content (SWC) in the top 5 cm. Soil respiration was predicted using Eq.(W4) in the wet season.

Appendix B

Table B.1 Measured data in January, 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
030113	9:30	987.14	22.13	11.89
	10:30	1006.95	24.87	11.86
	11:30	1035.16	28.26	12.93
	13:30	833.50	30.61	12.35
	14:30	900.48	30.13	12.63
	16:00	828.76	28.95	11.81
	17:30	674.37	27.11	11.87
030114	9:00	1151.23	21.94	12.79
	11:00	1031.48	26.56	12.52
	12:00	1174.86	29.28	13.23
	13:30	1337.88	30.23	12.02
	15:00	1103.81	30.67	12.81
	16:00	949.50	29.28	13.37
030115	9:30	950.60	22.13	12.84
	10:30	924.63	24.64	11.58
	11:30	1012.49	27.90	12.71
	13:00	991.52	30.68	12.63
	14:00	1195.82	30.79	12.33
	15:00	946.94	30.32	12.32
	16:30	747.69	28.89	12.25
030116	10:30	982.08	25.46	13.77
	12:00	1014.48	28.34	11.86
	13:30	911.35	30.61	11.82
	14:30	856.49	30.54	12.88
030123	9:30	762.72	22.16	11.68
	10:30	739.96	25.09	11.38
	11:30	664.80	28.80	13.04
	12:30	754.96	31.22	12.81
	14:00	863.81	32.14	12.16
	15:30	591.06	31.54	11.92
	16:30	687.68	29.84	11.49
030124	9:00	692.15	22.13	11.58
	10:30	832.43	25.06	12.05
	11:30	632.71	29.09	11.97
	12:30	676.82	31.04	12.93
	14:00	991.12	32.21	12.87
	15:00	708.66	31.69	10.88
	16:00	627.27	30.53	12.45

Table B.1 (Cont.) Measured data in January, 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
030125	9:00	549.97	22.51	12.88
	10:00	591.00	23.88	11.88
	11:30	405.70	27.26	13.21
	12:30	461.26	30.21	12.42
	13:00	862.46	31.33	11.59
	15:00	842.23	31.26	12.44
	16:00	666.62	30.24	12.59
030126	9:00	798.03	22.26	12.48
	10:00	574.42	25.23	12.51
	11:30	768.89	28.48	12.53
	12:30	534.38	30.88	12.77
	14:00	1061.70	32.36	13.23
	15:15	798.04	31.99	11.07
	16:15	821.63	30.71	11.50
030127	9:00	553.48	22.44	11.08
	10:30	569.95	24.50	11.78
	11:30	648.83	27.38	12.38
	12:30	525.28	29.88	12.26
	14:00	665.19	31.41	12.44
	15:30	703.29	31.38	12.15
	Average	813.41	28.25	12.30
	Max.	1337.88	32.36	13.77
	Min.	405.70	21.94	10.88

Table B.2 Measured data in February, 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
030206	12:30	480.65	30.38	12.50
	13:30	330.73	31.61	12.49
	15:30	594.76	30.75	12.44
	16:30	735.69	30.49	12.11
030207	9:30	398.06	23.40	12.32
	10:50	461.51	26.86	11.30
	12:30	436.78	31.11	12.92
	14:00	466.48	32.86	11.92
	15:10	467.86	33.29	11.76
	16:30	292.80	32.02	11.58
030208	9:30	430.18	22.79	11.43
	10:30	337.81	26.16	12.27
	12:00	360.30	29.98	12.17
	13:30	488.89	32.88	11.83
	15:00	610.62	34.18	11.70
	16:00	403.99	32.94	12.42
030209	9:30	465.99	23.56	12.09
	11:00	308.50	25.77	12.56
	12:10	338.55	28.80	12.47
	14:00	523.94	33.93	11.96
	16:00	439.93	32.58	12.50
	Average	446.38	29.82	12.13
	Max.	735.69	34.18	12.92
	Min.	292.80	22.79	11.30

Table B.3 Measured data in March, 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
030315	9:30	494.13	28.29	19.25
	10:30	413.99	32.25	19.45
	12:00	451.69	35.57	19.91
	13:30	411.81	35.70	20.24
	15:00	393.03	31.89	20.24
	22:00	152.11	27.47	19.43
030316	0:00	176.52	26.43	19.34
	6:30	169.79	23.86	19.11
	9:30	409.77	28.26	19.24
	11:00	238.00	32.54	19.54
	13:00	376.31	36.24	20.04
	15:00	716.81	37.23	20.33
	16:30	291.59	35.83	20.39
	18:00	175.46	33.60	19.92
	22:20	144.73	28.76	19.64
030317	0:00	142.49	27.84	19.51
	2:30	125.77	26.57	19.39
	9:30	276.83	28.47	19.34
	11:00	323.97	33.82	19.62
	14:30	452.80	38.01	20.27
	15:30	306.30	38.57	20.28
030318	10:00	147.86	32.94	19.30
	12:30	400.09	37.65	19.83
	14:30	245.01	39.66	20.09
	16:00	142.00	38.30	20.01
030319	9:30	439.22	31.36	19.01
	11:00	369.64	34.93	19.32
	13:00	286.34	39.57	19.61
	14:30	451.67	41.19	19.73
	16:00	202.14	38.91	19.64
030320	9:30	286.68	31.30	18.62
	11:00	180.86	36.58	18.83
	14:00	399.46	41.38	19.20
	15:30	280.43	40.16	19.19
	17:00	209.52	37.31	19.08
030321	11:30	355.96	36.34	18.74
	13:30	328.42	40.22	19.02
	15:00	307.54	40.24	19.12
	Average	307.28	34.35	19.55
	Max.	716.81	41.38	20.39
	Min.	125.77	23.86	18.62

Table B.4 Measured data in April, 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
030405	9:30	578.48	29.74	23.89
	10:30	796.09	33.53	24.01
	12:30	593.32	36.89	24.46
	14:00	743.70	39.29	24.57
	15:30	675.62	39.08	24.59
030406	9:30	739.22	31.52	22.95
	10:30	600.88	35.16	23.10
	12:30	527.81	37.80	23.44
	14:30	793.83	40.11	23.53
	16:00	471.93	39.74	23.49
030407	9:30	543.93	31.79	22.35
	10:30	288.95	35.24	22.44
	12:00	392.15	38.98	22.70
	13:30	491.11	41.84	22.85
	15:00	344.52	41.11	22.86
030408	9:00	338.58	31.72	22.35
	10:30	366.18	34.84	22.44
	12:30	389.52	39.43	22.70
	14:00	290.66	41.38	22.85
	15:30	264.56	40.68	22.86
	17:00	232.23	37.91	22.35
030409	9:30	320.54	31.72	22.44
	10:30	363.50	35.16	22.70
	12:00	403.67	39.36	22.85
	22:00	113.48	32.50	22.86
030410	0:30	206.91	31.79	21.00
	2:30	138.44	31.23	20.93
	6:30	104.17	29.49	20.74
	8:30	254.59	32.13	20.71
	11:00	210.55	38.22	20.97
	17:00	307.90	39.18	21.20
	22:00	148.61	32.45	20.78
030411	0:00	113.27	31.65	20.93
	2:30	54.19	31.09	20.74
	6:00	128.52	28.89	20.71
	Average	380.90	35.50	22.47
	Max.	796.09	41.84	24.59
	Min.	54.19	28.89	20.71

Table B.5 Measured data in May, 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
030523	10:00	251.24	34.08	29.60
	12:00	372.56	37.02	29.39
	14:00	406.41	38.81	28.98
	15:30	328.69	38.51	28.77
	17:00	169.23	36.34	28.50
	22:00	112.50	31.28	27.78
030524	0:00	119.57	30.63	27.56
	2:00	84.33	29.69	27.39
	6:00	59.29	28.79	27.09
	9:30	259.67	32.80	26.74
	12:00	286.58	38.39	26.56
	13:30	318.09	41.06	26.32
	15:30	126.94	40.61	26.08
	18:00	137.34	36.54	25.58
	22:00	89.29	32.35	25.07
030525	0:00	42.24	31.62	24.94
	2:00	70.70	30.49	23.50
	6:30	132.91	29.64	23.27
	9:30	270.19	33.82	23.10
	11:30	287.50	37.03	22.11
	12:30	260.24	38.84	21.40
	14:30	129.78	41.28	21.31
	16:30	123.59	39.69	21.03
	Average	193.00	35.19	25.74
	Max.	406.41	41.28	29.60
	Min.	42.24	28.79	21.03

Table B.6 Measured data in June, 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
030628	8:30	165.80	27.59	21.25
	10:30	244.94	30.94	21.17
	11:30	151.87	31.43	21.02
	12:30	239.62	31.54	20.88
	13:30	163.92	31.50	20.75
	15:30	422.36	31.86	20.51
	16:30	364.28	31.93	20.39
	17:30	149.62	30.92	20.25
	22:00	246.11	27.43	20.04
030629	0:00	406.42	26.84	20.01
	2:00	461.39	26.53	19.97
	6:30	511.96	26.20	19.84
	8:30	334.18	27.78	19.86
	10:00	351.55	29.62	19.87
	11:30	438.06	30.36	19.83
	13:30	355.61	29.90	20.05
030630	8:30	830.24	26.54	27.90
	10:00	599.88	27.00	27.64
	11:30	425.84	27.41	28.70
	14:30	341.62	26.90	29.05
	17:30	634.35	27.03	28.52
	Average	373.31	28.92	22.26
	Max.	830.24	31.93	29.05
	Min.	149.62	26.20	19.83

Table B.7 Measured data in July, 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
030726	11:15	3037.70	31.50	23.42
	12:30	3594.37	31.74	23.34
	13:30	3952.01	33.59	23.14
	14:30	4138.17	34.65	23.02
	16:30	3650.50	34.20	22.77
	17:30	3694.12	33.71	22.69
	22:00	2812.63	30.49	22.48
030727	0:00	2728.98	29.47	22.42
	2:00	2760.84	28.55	22.55
	6:00	2350.08	27.68	22.44
	8:30	2196.24	29.37	22.40
	9:30	2180.66	30.43	22.37
	10:30	2320.13	32.29	22.32
	11:30	2280.68	34.58	22.22
	13:30	2350.00	36.11	21.97
	14:30	2413.22	34.83	21.84
	16:30	2420.53	34.83	21.67
	17:30	1914.16	34.10	21.60
	22:00	1900.47	30.95	21.41
030728	0:00	1385.44	30.18	22.05
	2:00	1325.20	29.35	22.00
	6:00	1460.37	29.46	21.92
	9:30	1294.40	31.39	21.84
	10:30	1059.39	32.81	21.79
	11:30	1056.13	35.44	21.70
	12:30	1452.42	36.44	21.59
	13:30	1156.49	37.71	21.44
	14:30	616.15	37.04	21.18
	16:00	1092.90	35.23	20.96
	Average	2227.39	32.69	22.16
	Max.	4138.17	37.71	23.42
	Min.	616.15	27.68	20.96

Table B.8 Measured data in August 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
030811	9:00	396.26	31.44	33.37
	10:00	347.42	35.30	33.47
	12:00	307.30	37.46	33.49
	13:00	348.27	40.58	33.47
	14:00	455.23	42.28	33.39
	17:00	218.62	35.39	32.87
	22:00	302.62	31.23	32.38
030812	0:00	124.52	30.58	32.22
	2:00	147.42	30.23	32.12
	6:00	112.43	27.08	31.99
	8:30	310.86	31.13	31.38
	10:00	248.63	32.99	32.09
	11:00	179.55	33.90	32.13
	12:00	253.02	35.84	32.34
	13:00	226.24	40.03	32.44
	14:00	252.19	42.68	32.50
	15:00	255.21	41.51	32.39
030812	22:00	283.25	29.95	58.70
030813	0:00	270.48	29.47	58.37
	2:00	292.58	29.15	58.06
	8:30	323.49	29.86	57.64
	9:30	370.95	31.88	57.57
	11:30	299.51	34.74	57.20
	12:30	438.71	36.21	56.80
	13:30	313.07	36.58	56.32
	15:30	309.53	35.08	55.33
	16:30	262.38	34.12	55.00
	Average	283.32	34.32	41.67
	Max.	455.23	42.68	58.70
	Min.	112.43	27.08	31.38

Table B.9 Measured data in September 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
030914	8:30	121.19	26.27	44.50
	9:30	193.78	26.88	43.57
	10:30	119.57	27.57	31.56
	11:30	254.40	28.93	31.31
	12:30	286.40	29.14	29.40
	14:30	515.88	30.76	28.36
	15:30	719.25	31.02	28.17
	16:30	437.25	30.66	27.94
	17:30	577.40	30.04	27.69
	22:00	194.04	27.63	27.18
030915	8:30	138.85	27.32	27.89
	10:30	104.64	29.21	27.76
	11:30	102.21	30.06	27.66
	12:30	164.22	32.13	27.46
	14:30	299.19	33.82	26.90
	15:30	264.31	33.96	26.52
	Average	280.79	29.71	30.24
	Max.	719.25	33.96	44.50
	Min.	102.21	26.27	26.52

Table B.10 Measured data in November 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
031128	8:30	357.09	23.78	8.69
	9:30	462.61	25.16	6.82
	10:30	494.89	27.65	4.69
	11:30	502.73	28.95	5.08
	12:30	423.07	30.83	3.51
	13:30	441.31	31.78	3.89
	14:30	459.74	31.05	5.76
	15:30	426.70	30.27	6.82
	16:30	466.52	29.05	7.72
	17:30	328.35	27.79	9.04
	22:00	255.15	23.91	10.43
031129	0:00	345.05	23.23	10.42
	2:00	213.19	22.41	10.46
	6:30	197.96	21.28	10.42
	7:30	321.76	21.76	9.50
	8:30	338.73	22.50	7.94
	9:30	274.07	23.98	6.14
	10:30	350.84	26.00	4.36
	11:30	370.83	28.14	4.16
	12:30	382.46	30.54	3.69
	13:30	606.29	31.35	3.38
	14:30	499.38	31.31	4.50
	15:30	465.31	30.59	6.07
	16:30	410.05	29.16	7.46
	17:30	353.72	27.81	8.94
	22:00	230.50	23.33	10.49
031130	0:00	259.27	22.38	10.44
	2:00	170.18	21.62	10.71
	7:30	468.42	20.58	10.07
	8:30	537.03	21.79	8.64
	9:30	474.25	23.24	6.92
	10:30	578.69	25.73	4.72
	11:30	543.58	28.51	4.20
	12:30	414.68	30.19	3.57
	13:30	590.18	31.19	3.45
	14:30	403.64	31.39	4.77
	15:30	413.82	31.04	6.16
	Average	400.87	26.79	6.87
	Max.	606.29	31.78	10.71
	Min.	170.18	20.58	3.38

Table B.11 Measured data in December 2003.

Date (YYMMDD)	Time	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
031226	8:30	172.54	22.49	4.84
	9:30	174.77	23.87	2.58
	10:30	247.97	26.44	1.80
	11:30	289.05	28.69	2.00
	12:30	339.89	30.64	1.90
	13:30	344.46	31.69	2.22
	14:30	385.17	31.66	2.13
	15:30	304.09	31.05	2.78
	16:30	291.56	29.71	3.61
	17:30	306.84	27.86	5.81
	22:00	209.12	23.28	8.92
031227	0:00	222.51	22.13	9.30
	2:00	359.13	22.19	8.36
	6:30	187.80	22.20	7.71
	7:30	240.09	22.29	7.72
	8:30	206.51	23.16	6.54
	9:30	212.57	24.09	4.56
	10:30	320.89	26.02	3.10
	11:30	272.12	28.36	2.09
	12:30	362.52	30.33	1.85
	13:30	299.96	31.11	2.48
	14:30	236.75	31.19	2.21
	15:30	424.93	30.53	3.39
	16:30	353.22	29.21	4.23
	17:30	252.81	27.35	6.92
	22:00	195.76	22.16	9.95
031228	0:00	267.19	21.29	10.02
	2:00	132.69	20.61	9.91
	6:30	156.22	19.59	9.63
	7:30	288.68	19.74	9.03
	8:30	253.82	20.96	6.48
	9:30	335.45	22.41	3.56
	10:30	267.05	24.26	2.21
	11:30	145.66	27.46	2.03
	12:30	243.98	29.83	1.80
	13:30	243.33	31.12	0.98
	14:30	250.81	31.35	1.09
	15:30	219.01	30.94	1.60
	Average	263.60	26.30	4.67
	Max.	424.93	31.69	10.02
	Min.	132.69	19.59	0.98

Table B.12 Monthly averaged data in 2003.

Monthly	SR ($mgCO_2/m^2/h$)	Ts (^0C)	SWC (%)
January	821.2	28.3	12.3
February	424.9	29.6	12.1
March	306.1	35.2	19.5
April	375.0	35.3	22.5
May	200.9	35.3	26.0
June	397.4	28.6	23.0
July	344.9	32.8	32.5
August	292.3	34.5	41.6
September	279.6	32.7	36.8
October	0.0	30.9	22.5
November	406.1	26.9	6.8
December	262.7	26.4	4.6
Average	342.6	31.3	21.7
Max.	821.2	35.3	41.6
Min.	0.0	26.4	4.6

BIOGRAPHY

Miss Parichat Wetchayont was born on 5th January, 1978 in Bangkok. She finished her secondary course from Satrinontaburi in March, 1996. After that, she studied in the major of General Science in Faculty of Science at Kasedsart University and graduated in March, 2000. She continued her further study for Master's degree in Earth Science at Chulalongkorn University. She achieved her Master's degree in April, 2005.