CO_2 EMISSION FROM SOIL AND TERMITE MOUND IN DRY EVERGREEN FOREST AT SAKAERAT ENVIRONMENTAL RESEARCH STATION

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การปลดปล่อยคาร์บอนไดออกไซด์จากดินและรังปลวกในป่าดิบแล้ง ณ สถานีวิจัยสิ่งแวดล้อมสะแกราช

นายวารินทร์ บุญเรียม

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
สาขาวิชาชีววิทยาสิ่งแวดล้อม
มหาวิทยาลัยเทคโนโลยีสุรนารี
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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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วารินทร์ บุญเรียม : การปลดปล่อยคาร์บอนไดออกไซด์จากดินและรังปลวกในป่าดิบแล้ง ณ สถานีวิจัยสิ่งแวดล้อมสะแกราช (CO_2 EMISSION FROM SOIL AND TERMITE MOUND IN DRY EVERGREEN FOREST AT SAKAERAT ENVIRONMENTAL RESEARCH STATION) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร.พงศ์เทพ สุวรรณวารี, 149 หน้า

การหายใจของดินในป่าเขตร้อนเป็นตัวแปรสำคัญในการพิจารณาสถานการณ์ปัจจุบันและอนาคตของก๊าซคาร์บอนไดออกไซด์ (CO_2) ในบรรยากาศ ปัจจัยที่ควบคุมความแปรปรวนเชิงพื้นที่ของการหายใจของดินยังคงไม่ชัดเจนต่อการประเมินการหายใจของดินได้อย่างถูกต้องในระดับระบบนิเวศ การศึกษาครั้งนี้มีวัตถุประสงค์เพื่อหาปริมาณผลกระทบของรังปลวกต่อการหายใจของดินในป่าดิบแล้งในภาคตะวันออกเฉียงเหนือของประเทศไทย

ดำเนินการเก็บข้อมูลการปลดปล่อย CO_2 จากดิน อุณหภูมิดิน และความชื้นในดิน ใน 100 แปลงย่อย ของ 5 แปลงทดลองหลัก (ขนาด 1 เฮกแตร์ ในแต่ละแปลง) จำนวน 4 ครั้ง จากเดือนพฤศจิกายน พ.ศ. 2557 ถึงเดือนสิงหาคม พ.ศ. 2559 ในสถานีวิจัยสิ่งแวดล้อมสะแกราช จังหวัดนครราชสีมา ศึกษาการกระจายของรังปลวกและต้นไม้ในพื้นที่ทั้งหมดของ 5 แปลงหลัก วัดการปลดปล่อย CO_2 จากรังปลวกชนิดผนังรังหนา 1 ชนิด (n = 6) จำนวน 2 ครั้ง จากเดือนธันวาคม พ.ศ. 2557 ถึงเดือนสิงหาคม พ.ศ. 2559 และรังปลวกชนิดผนังรังบางอีก 5 ชนิด (n = 5) ในเดือนตุลาคม พ.ศ. 2558 และเดือนมกราคม พ.ศ. 2559 นอกจากนี้ ยังทำการประเมินอิทธิพลของวรรณะปลวก fungus comb และส่วนของตัวรังต่อการปลดปล่อย CO_2 จากรังปลวก

ผลการศึกษาพบว่า ค่าเฉลี่ยอัตราการหายใจของดินเท่ากับ 6.57 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ อยู่ในช่วงระหว่าง 2.66 ถึง 11.72 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ ซึ่งอัตราการหายใจของดินในฤดูฝน (8.81 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$) มีค่าเฉลี่ยสูงมากกว่าฤดูแล้ง (4.33 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$) เป็นสองเท่า ถึงแม้ว่าอัตราการหายใจของดินจะเพิ่มขึ้นเมื่ออุณหภูมิดินและความชื้นในดินสูงขึ้นด้วยก็ตาม แต่จะลดลงเมื่ออุณหภูมิดินและความชื้นในดินมีค่ามากกว่า 27°C และร้อยละ 21 ตามลำดับ

ค่าเฉลี่ยของการปลดปล่อย CO_2 จากรังปลวกบริเวณชนิดผนังรังหนา *Macrotermes. Carbonarius* มีค่าเท่ากับ 7.66 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ ในส่วนของกลุ่มปลวกชนิดผนังรังบาง ปลวกชนิด *Globitermes sulphureus* มีการปลดปล่อย CO_2 สูงสุด (37.71 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$) ดังนั้นเมื่อเพิ่มปัจจัย

ของรังปลวกในการหายใจของดินพบว่า ตัวรังกับช่องทางเดินใต้ดินของ *M. Carbonarius* มีส่วนร่วมในการปลดปล่อย CO_2 เท่ากับร้อยละ 0.26 และ 2.67 ของการหายใจของดินทั้งหมดของป่า ขณะที่น้อยกว่าร้อยละ 0.5 ได้จากการปลดปล่อยจากรังปลวกชนิดผนังรังบาง เนื่องจากมีขนาดพื้นที่โครงสร้างของรัง และความหนาแน่นของรังสูงกว่า อย่างไรก็ตาม การวัดการปลดปล่อย CO_2 ของพื้นดินอย่างเดียวมีความใกล้เคียงกับดินที่มีค่าการปลดปล่อย CO_2 ของรังปลวกรวมเข้าไปด้วย โดยมีความคลาดเคลื่อนน้อยกว่าร้อยละ 0.6 เท่านั้น

สาขาวิชาชีววิทยา
ปีการศึกษา 2559

ลายมือชื่อนักศึกษา วรินทร์ บุญเรือง
ลายมือชื่ออาจารย์ที่ปรึกษา
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม Atchariya Yuwadu

WARIN BOONRIAM : CO_2 EMISSION FROM SOIL AND TERMITE MOUND IN DRY EVERGREEN FOREST AT SAKAERAT ENVIRONMENTAL RESEARCH STATION. THESIS ADVISOR : ASST. PROF. PONGTHEP SUWANWAREE, Ph.D. 149 PP.

SOIL RESPIRATION/ TERMITE MOUND/ TERMITARIA/ SPATIAL VARIATION/ DRY EVERGREEN FOREST/ SAKAERAT ENVIRONMENTAL RESEARCH STATION

Soil respiration in tropical forest is an important source of current and future carbon dioxide in the atmosphere. Factors regulating spatial soil respiration are still unclear and they may lead to an inaccurate estimation of soil respiration at the ecosystem level. The aim of this study was to quantify the effects of epigeal termite mounds on soil respiration in dry evergreen forest of Northeast Thailand.

Soil respiration, temperature and moisture were measured in 100 subplots of five 1-ha main plots for four times from November 2014 to August 2016 in Sakaerat Environmental Research Station, Nakhon Ratchasima province. Distribution of termite mound and tree were also investigated. CO_2 efflux from one thick – wall mound termite species (n=6) were evaluated two times from December 2014 to November 2015 and 5 thin – wall mound termite species (n=5) were measured in October 2015 and January 2016. Furthermore, the influences of termite caste, fungus comb and nest materials of on the termitaria CO_2 efflux were investigated.

The mean rate of the annual aboveground soil respiration was 6.57 μmol CO_2 m^{-2} s^{-1}, ranged from 2.66 to 11.72 μmol CO_2 m^{-2} s^{-1}. Wet season soil respiration rate

(8.81 μmol CO_2 m^{-2} s^{-1}) was two times higher than in dry season (4.33 μmol CO_2 m^{-2} s^{-1}). Although, the soil respiration rates increase with increasing soil temperature and moisture content, but they start to drop at 27°C soil temperature and 21% soil moisture.

The mean CO_2 efflux from the termitaria of thick – wall mound termite (*Macrotermes carbonarius*) was 7.66 μmol CO_2 m^{-2} s^{-1}. Among the thin – wall mound termites, *Globitermes sulphureus* had the highest respiration rate (37.71 μmol CO_2 m^{-2} s^{-1}). When added epigeal termite mounds in soil respiration, the termitarium were to contribute 3.36% to soil respiration. Mound and underground passage of *M. carbonarius* contributed 0.26% and 2.67% of the total soil respiration, respectively. While thin –wall mound termites emitted less than 0.5%, due to the higher nest structure area and nest density of thick – wall mound termite. However, CO_2 efflux measured from soil alone was similar to the soil – termite combined measure with only less than 0.6% error.

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LIST OF ABBREVIATIONS

µmol	=	micromoles (1 mol = 10^6 µmol)
AAL	=	annual aboveground litterfall
asl.	=	above sea level
ca	=	circa (Latin word) which meaning “about”
DBH	=	diameter at breast height
DDF	=	Dry Dipterocarp Forest
DEF	=	Dry Evergreen Forest
DM	=	*Dicuspiditermes makhamensis*
e.g.	=	example
GBH	=	ground at breast height
GS	=	*Globitermes sulphureus*
ha	=	hectare
i.e.	=	id est (Latin word) which meaning “that is”
IPCC	=	Intergovernmental Panel on Climate Change
IRGA	=	infrared gas analyzer
MA	=	*Macrotermes annandalei*
MC	=	*Macrotermes carbonarius*
Mcc	=	*Microcerotermes crassus*
Mt	=	Metric Tons (or Tonnes) (1 ton = 1000 kg)
NM	=	number of mound/nest

LIST OF ABBREVIATIONS (Continued)

Pg	=	petagram (1 Pg = 10^{15} g)
ppm	=	parts per million weight
SD	=	Standard deviation
SE	=	Standard error
SERS	=	Sakarat Enviromental Research Station
tBA	=	tree’s basal areas
TC	=	*Termes comis*
TISTR	=	Thailand Institute of Scientific and Technological Research
TP	=	*Termes propinguus*

CHAPTER I

INTRODUCTION

1.1 Background and Problems

Tropical forests cover only 7% of the Earth's land surface but store 25% of global terrestrial carbon and account for 50% of net primary productivity (IPCC, 2001; Bonan, 2008). Tropical forests are important contributors to global carbon cycling (IPCC, 2001), and have been previously estimated to represent a carbon sink of 1 – 3 PgC y^{-1} (1 Pg = 10^{15} g) (Malhi and Grace, 2000). Carbon exchanges through tropical forests are expressed by the balance between carbon uptake through photosynthesis and loss through respiration. In terms of both source and sink of carbon dioxide (CO_2), tropical forests potentially constitute an importance, whereas it is widely emphasized that tropical forests are functioning as a global CO_2 sink.

An important component of the global CO_2 balance has been recognized as CO_2 efflux from the soil (soil respiration) while the environmental factors affecting not only amounts of soil respiration, but also temporal and spatial variation of soil respiration still remain unclear. In fact, soil respiration has been shown to change and fluctuate at an unexpectedly large scale (10% to 90%) (Hanson et al., 2000). Soil respiration comes from CO_2 production of all living organisms in the soil, including plant roots, soil microbes and animals (Lavelle et al., 2001; Luo and Zhou, 2006). Although soil microorganisms and roots dominantly constitute soil respiration, a

potential importance of soil animals, especially termites, has been proposed by Yamada et al. (2005; 2007). In fact, Ohashi et al. (2007) reported that an extremely higher rate of soil respiration (i.e. hot spot of soil respiration) was observed in a Malysian – tropical forest, which was quite difficult to be explained by known environmental factors, such as water contents and temperature. As the hot spots showed temporal and spatial variations, the phenomena was proposed to be attributed to un-revealed activities of soil animals, especially social insects (e.g. termites,) because it is well known that termites are superabundant soil animals in tropical forests (Yamada et al., 2003, 2005).

Termites have a significant impact on carbon cycling, ecological functioning, and carbon trace gas emissions in tropical savannas by processing large quantities of plant material (Yamada, 2005, 2006; Konate´ et al., 2003; Khalil et al., 1990). According to Sanderson (1996), the global emissions of methane and carbon dioxide are 19.7 ± 1.5 and 3500 ± 700 Mt yr^{-1}, respectively (1 Mt = 10^{12} g). These emissions contribute approximately 4% and 2%, respectively, to the total global fluxes of these gases. However, judging from accumulated studies after Sanderson (1996), it is most likely that Sanderson underestimated the importance of termites.

So far, there is no convincing demonstration showing an effect of termites on soil respiration in seasonal tropical forests. Here, this study focus on an effect of termites in soil respiration by considering their distribution and nesting pattern. Many termite nests have underground passages expanding from the nest center to up to several tens meters, not only nest themselves but also the surrounding areas are also affected by the activities of termites of the nest. Thus, the observation was conducted in termitaria (the area around termite nests) as well as non-termitaria in order to depict

effects of termites on soil respiration at a large scale, and the results can be applied for tropical forest ecosystems.

1.2 Research Objectives

1.2.1 To investigate spatial and seasonal variation of soil respiration in a dry evergreen forest (DEF) at Sakearat Environmental Research Station (SERS).

1.2.2 To quantify species, density and distribution of termite mounds in DEF at SERS.

1.2.3 To measure seasonal CO_2 efflux from termite mounds in DEF at SERS.

1.2.4 To estimate the effects of termites and environmental factors on soil respiration.

1.3 Scopes and Limitation of the Study

1.3.1 The study evaluated soil respiration on spatial variation in DEF at SERS from November 2014 to August 2016.

1.3.2 The study observed species, densities and distributions of termite mounds in DEF at SERS.

1.3.3 CO_2 efflux was quantified with a consideration of effects of the termites by measuring annual ground soil respiration as well as CO_2 termitaria emission (CO_2 efflux from termite mounds and their surroundings) in DEF at SERS from November 2014 to August 2016.

1.3.4 CO_2 efflux was also quantified with a consideration of effects of the termites by measuring CO_2 efflux from the termite individuals and nest materials in the laboratory.

CHAPTER II

LITERATURE REVIEW

2.1 Terrestrial Carbon Cycling and Climate Change

The carbon balance of the world's terrestrial ecosystems is still uncertain. Photosynthetic uptake of carbon from the atmosphere and oceans provide the fuel for most biotic processes, which reduces carbon, makes up about half of the mass of Earth's organic matter. Biological system releases carbon through respiration including respiration of plants, animals, and microbes when they use organic carbon for growth and metabolism. The controls over the carbon cycle depend on the time scale, ranging from the years, by which photosynthetic rate and surface air exchange (Houghton, 2007; Gorte, 2009).

As repeatedly pointed out, our world is currently facing one of the climatic global warming problems, which is probably caused by elevated concentrations of CO_2 in the air. CO_2 is one of the principle greenhouse gases and keeps the heat from the sun in the stratosphere by capturing an infrared ray. IPCC (2007) reported that the global atmospheric concentration of CO_2 has increased from a pre-industrial value of approximately 280 ppm to a much higher value of 379 ppm by 2005. The atmospheric concentration of CO_2 in 2005 exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from analyses of CO_2 ice cores. In addition, the annual CO_2 concentration growth rate was higher during the last 10 years (1995 -

2005 average: 1.9 ppm per year) than that during the last 45 years (1960 - 2005 average: 1.4 ppm per year), though there was year-to-year variability in growth rates.

Globally, soil respiration on ecosystem carbon cycling amounts to approximately 80-100 PgC y^{-1} (Houghton, 2007; Boden et al., 2009). Tropical and subtropical evergreen broadleaved forests contribute the largest parts of about 22 PgC y^{-1} and about 7 PgC y^{-1} from human activities, especially burning of fossil fuel and deforestation where enter to atmosphere (Raich et al., 2003). Reichstein and Beer (2008) indicated that about 10% of atmospheric CO_2 cycles through as a large pool as the annual soil respiration. However, as long as it still remains unclear how carbon stores and how spatial variability of contribution on carbon fluxes react to this rise of the temperatures, it also remains unclear how the global carbon cycle will be altered by climate change in the long term.

The assessment of consequences of climate change requires a thorough understanding of functional relations controlling turnover of greenhouse gas forming elements like carbon. Carbon accounts for approximately 0.27% of the mass of elements in the Earth's crust (Kempe, 1979), yet accounts for about 50% of dry organic matter (Houghton, 2007). Jobbágy and Jackson (2000) combined that a terrestrial vegetation contains approximately 550 ± 100 Pg of carbon and 800 Pg is on the atmosphere. An importance of soil and organic layers are sequester twice as much (1580 Pg) carbon as the atmosphere. However, the release of carbon from tropical forests may exacerbate future climate change (Cox et al., 2000), but the magnitude of the effect in climate models remains uncertain (Malhi et al., 2008). Coupled climate-carbon cycle models generally agree that carbon storage on land will increase as a result of the simultaneous enhancement of plant photosynthesis and water use

efficiency under higher atmospheric CO_2 concentrations, but will decrease owing to higher soil and plant respiration rates associated with warming temperatures (Cox et al., 2013). Consequently, even small changes of the soil respiration may largely impact atmospheric CO_2 concentrations and climate, feedback mechanisms between soil and atmosphere have to be considered. The effect of climate change may influence net carbon balance of ecosystems, it is essential to know the variability of decomposer as well as carbon fluxes in carry out decomposition processes on net primary productivity.

2.2 Variability in Soil Respiration

Soil respiration refers to an ecosystem process that fluxes on CO_2 from the soil to atmosphere via root, microbial, and soil animal respiration (Luo and Zhou, 2006). Also, the definition of soil respiration rate is the amount of CO_2 release per soil surface and time has long been considered as an authentic index of the abundance and the activity of all the soil inhabiting organisms (Basu et al., 1991; Bentham et al., 1992). Soil respiration is one of the most important pathways of carbon in forests. Indeed, soil respiration is second largest terrestrial carbon flux, following photosynthesis, by activities of soil fauna on decomposition processes. Consequently, determination of soil respiration is one of the best approaches to evaluate soil biological activities in relation to carbon and energy flow in terrestrial ecosystems. However, there are several studies in soil respiration that still do not result much insight into the contribution of each component to the carbon cycle. For examples, soil respiration that contributing 50 - 95% of total ecosystem respiration (e.g., Law et al., 1999; Janssens et al., 2001). The main sources of CO_2 are considered to be root

and soil microbial respiration (Hanson et al., 2000; Kuzyakov, 2006). The proportion of soil respiration from autotrophic and heterotrophic contributions may vary seasonally and among ecosystems (Hanson et al., 2000). Across a range of studies, the heterotrophic contribution varied from 10 to 95% and averaged 54% annually and 40% during the growing season (Hanson et al., 2000). Ohashi et al. (2007) indicated that the range of variation of soil CO_2 efflux varied widely to average of 17.4 µmol CO_2 m^{-2} s^{-1} while ground CO_2 flux rates were under 10 µmol CO_2 m^{-2} s^{-1} in tropical rain forest, whose impact was 10% of total carbon efflux from soil. Mean rates of the soil respiration vary widely within and among major vegetation biomes (Table 2.1). The lowest rates of soil respiration occur in the coldest (tundra and northern bogs) and driest (deserts) biomes, and the highest rates occur in tropical moist forest where both temperature and moisture availability are high year – round.

Table 2.1 Mean rates of soil respiration in different types of vegetation.

Vegetation	Soil respiration rate (g C/m^2/year) (mean ± SE)	n	
Tundra	60±6	11	e
Boreal forests and wood land	322±31	16	cde
Temperate grassland	442±78	9	bcd
Temperate coniferous forests	681±95	23	b
Mediterranean woodlands	713±88	13	b
Croplands, fields	544±80	26	bc
Desert scrub	224±38	3	de
Tropical savannas and grasslands	629±53	9	bc
Tropical dry forests	673±134	4	b
Tropical seasonal forests	1260±57	10	a

Source: Luo and Zhou (2006). Significant differences are indicated by Different letters

As the results, soil CO_2 efflux fluctuates widely in space and time according to changes in various factors, such as temperature, moisture, carbon content, root biomass, pH, cation exchange capacity and soil air porosity (Fang et al., 1998; Davidson et al., 2000; Kiese and Butterbach, 2002; La Scala et al., 2000; Lou et al., 2004). It is difficult to gain accurate determination of the multiplicity of sources on soil respiration because of its temporal and spatial variability.

2.2.1 Temporal Variation of Soil Respiration

Temporal variation of soil respiration is mostly driven by changes in soil temperature and moisture. Generally, soil respiration is more sensitive to variation in soil temperature at low temperatures, while it is more sensitive to changes in soil moisture at higher soil temperatures (Lloyd and Taylor, 1994; Qi et al., 2002; Reichstein et al., 2002). In the seasonal forest, biotic variables, such as microbial, root and litter biomass and quality may also strongly influence the seasonal variability of soil respiration. Most previous studies have been carried out to investigate temporal variation in microclimatic areas, which both soil temperature and water content exist all year round in the tropical seasonal forests. In tropical forests, the most influential factor affecting temporal variation of the soil respiration rate is not so much the soil temperature as the soil water content or rainfall, because the soil temperature is relatively constant (Kursar, 1989; Davidson et al., 2000). Thus, the temporal pattern study is difficult to distinguish on variability of soil respiration and cannot completely account for the spatial variability of soil respiration.

2.2.2 Spatial Variation of Soil Respiration

Spatial variation of soil respiration is important not only for understanding CO_2 dynamics but also for suitable sampling design for estimating the mean soil respiration and the response to environmental changes (Ohashi et al., 2007). Spatial variability in soil respiration occurs on various scales, from small scale to large scale which is related to either the biotic factors, such as plant root density, microbial biomass, litter amount, soil fauna, or abiotic factors such as soil temperature, soil moisture, soil organic carbon, soil total nitrogen, soil bulk density, soil porosity, soil pH (Hanson et al., 1993; Epron et al., 2004). The dimension of spatial variation in soil respiration could be large in tropical forest (Sotta et al., 2004). Soil CO_2 efflux rate is high in tropical areas (Raich and Potter, 1995; Houghton, 2007), because there are high diversity and abundance of litter production and decomposer. Recent studies found out that hot spots of soil CO_2 efflux carbon which cannot identity accuracy carbon source from soil (Stoyan et al., 2000; Risch et al., 2005; Ohashi et al., 2007). However, neither soil temperature nor water content can explain for soil respiration with time and space. Soil respiration exhibits high levels of spatial heterogeneity, especially across small spatial scales in forest ecosystem at different time scales (Xu and Qi, 2001; Franklin and Mills, 2003; Maestre and Cortina, 2003). In order to accurately estimate soil respiration in the targeted ecosystem, it is important to acquire information on spatial and temporal distribution of soil respiration on the basis of overlapping distribution of substrates, soil physical conditions, soil organisms, and temperature and moisture conditions (Maestre and Cortina, 2003; Adachi et al., 2005). Therefore, it is essential to have information on

spatial and temporal variability for estimating average rate of soil respiration at regional scales.

2.3 The Potential Contribution of Termites to Soil Respiration in Tropical Forest

Termites (Isoptera) are important structural component of soil partition and they are major importance to driving the carbon cycle and plant nutrients on litter decomposition within the forest ecosystem (Coleman et al., 2004). Termites are essential to many habitats and ecosystems especially in the tropics. Termite dispersal over broad spatial scale is supposed to development of their pattern in phenotype, or in behavior according to varying environmental conditions (Bardgett, 2002; De Deyn and Van der Putten, 2005). The presence of soil animals greatly accelerates litter decomposition and carbon release in tropical forests worldwide (Meyer et al., 2011; Schädler and Brandl, 2005). Especially, termites (invertebrates >2 mm in size) are considered ecosystem engineers and species that modify the soil or litter in ways that either promote or constrain the activities of soil microbes and other soil animals (Jones et al., 1994; Chapin et al., 2002; Groffman et al., 2004; Eisenhauer et al., 2007).

Termites possess symbiotic bacteria in their absence for assimilated wood. It's widely recognized that the physical break down of the litter by soil insects involves mechanical disintegration while the biological breakdown includes degradation by microbes. In many ecosystems of soil insects have special importance in leaf consumption, sometime are abundance, concentrated in relatively small areas, and active during great part of the year.

Table 2.2 Density (Mean ± SD) of soil macro invertebrates in tropical forest.

	Density (number m^{-2})
Saprophage	
Gastropoda	0
Oligochaeta	5±7
Isopoda	31±34
Diplopoda	6±7
Blattodea	31±20
Isoptera	824±871
Orthoptera	14±15
Lepidoptera	0
Diptera	8±11
Elateridae	5±6
Other Coleoptera	3±5
Zoophage	
Araneida	83±43
Chilopoda	34±29
Staphylinidae	23±25
Formicidae	727±628

Source: Tsukamoto and Sabang (2004).

Above is the list of soil animals found abundant in a tropical forest and amongst them, termites and ants are the core group (Table 2.2). Termites make up to 824 N/m^2 (Tsukamoto and Sabang, 2004). On the other hand, biomass of termite account to 95% of the soil animal biomass in tropical rainforests (Donovan et al., 2007). For instants, they are consumed 1.4 $ton/ha/yr^{-1}$ of litter as well as 90% of dead wood in the tropical rain forest, Malaysia (Yamada et al., 2003). Recent studies have shown the importance of soil animal diversity to function such as carbon flux being linked to

termite and nematode diversity and a positive relationship between ant species richness and nutrient redistribution (Lawton et al., 1996). Soil animals only account for about 5% of soil respiration as their major effect on decomposition has been presumed to be enhancement of microbial activity (Wall et al., 2001). According to Yamada et al. (2005) termites were responsible for mineralizing carbon. Seventy-seven kg of organic carbon per hectare from a total input of 5,780 tons C/ha/year, which means a modest 1.3%. Nevertheless, these estimates are not representative of the entire forest. As mentioned above, the gap between the ranges of variation in soil respiration varied widely (50% - 95% of total ecosystem respiration) as well as the impact of CO_2 hot spot (10% of total soil respiration) which may contribute by soil animal activities in their own nest/mound patterns and spatial distribution at different time scales. Recent studies suggested that the point sources of CO_2 hot spot caused by nests of soil animal such as termites, ants, and earthworms which may increase spatial variation of soil respiration (Risch et al., 2005; Ohashi et al., 2007).

Table 2.3 The carbon mineralization of termite populations and fungus combs in tropical forest.

Natural ecosystem site	Annual rainfall (mm)	Biomass ($g\ m^{-2}$)		Total C mineralization/litter annual aboveground (%)
		Termite population	Fungus comb	
Tropical forest				
Sakaerat, Thailand	1,144	16.7	40.1	11.2
Mbalmayo, Cameroon	1,520	75.5	14.3	8.3
Pasoh, Malaysia	2,000	9.4	42.3	7.5
Manaus, Brazil	2,500	6.8	0.0	1.3
Sabah, Malaysia	2,700	3.5	6.1	1.1
Sarawak, Malaysia	5,000	2.4	0.4	0.6
Savanna				
Mokwa, Nigeria	1,175	10.6	98.5	38.7
Lamto, Ivory Coast	1,297	1.7	24.1	10.2
Fete Ole, Senergal	435	1.0	3.4	5.3

Source: Yamada et al. (2005).

Termites contributed only 1 – 2% of carbon mineralization from individuals in Africa rain forests which their relative contribution to ecosystem decomposition is relatively low (see; Bignell and Eggleton, 2000). Yamada et al. (2005) indicated that the fungus-growing termites were abundant in Asia's highly seasonal dry forests at the dry evergreen forest, Sakaerat Environmental Research Station. They mineralized about 11.2% of annual aboveground litterfall (AAL) by respiration from their

populations and fungus combs while the fungus combs were responsible for a major part (7.2% of the AAL).

Previous measurements of epigeal termite mounds (termitaria), ubiquitous in many savannas, have shown that they are considerable point sources of soil carbon dioxide (CO_2) (Table 2). Estimates of carbon mineralization by savanna termites (Interface feeder) as a proposition of all CO_2 production is up to 20% by using soda lime in Australia savannas (Holt, 1987).

Table 2.4 Previous field studies on soil CO_2 emissions from termite mounds in the tropical savannas.

Tropical savannas and site	Respiration (g CO_2 m^{-2} h^{-1})		Method	Studies
	Termites mound	Ground soil		
South Africa	1.8	-	covering the entire mound with large chambers	Seiler et al. (1984)
Australia	1.6 (n = 52)	-	air samples from inside the mounds	Kahlil et al. (1990)
West Africa	1.4 and 3.0 termite mounds without and with fungi-combs, respectively.	0.8 in woody savannas and 1.4 in grassy and shrubby savannas.	chamber-based measurements	Konate´ et al. (2003)
West Africa	1.64 (n = 5)	-	chamber-based measurements	Brümmer et al. (2009)
Serengeti National Park, Tanzanian	1.91	lower fluxes in the surrounding savanna	chamber-based measurements	Risch et al. (2012)

Several field studies conducted in African savannas have shown that termite mounds are considerable point sources of soil CO_2 emissions (Seiler et al., 1984; Kahlil et al., 1990; Konate´ et al., 2003; Brümmer et al., 2009). For example, Brümmer et al. (2009) measured on average 322 mg CO_2 – C m^{-2} termitaria/hr compared to only 100-157 mg CO_2 – C m^{-2} non – termite influenced soil, while Konate´ et al. (2003) reported roughly 16 µmol CO_2 m^{-2} s^{-1} was released from termitaria with fungus combs compared to 9 µmol CO_2 m^{-2} s^{-1} from non – termite influenced grassy savanna. On the other hand, CO_2 fluxes from the termite mound determined by seasonal dynamic and changes in biomass in mounds of *Microcerotermes nervosus*, a common species in Australian tropical savannas. There was significantly between mean CO_2 flux per unit termite biomass in the wet season (3.7 ± 0.8 mg CO_2 – C g $termite^{-1}$ day^{-1}) greater than the flux in the dry season (2.7 ± 0.2 mg CO_2 – C g $termite^{-1}$ day^{-1} (Jamali et al., 2011) (Table 2.5).

Table 2.5 Seasonal dynamics in CO_2 flux (per unit termite biomass) and termite biomass in mound samples of *M. nervosus* as measured in the laboratory (mean ± SD).

	Wet season	Dry season
Termite flux		
CO_2 (mg CO_2-C g $termite^{-1}$ day^{-1})	3.7 ± 0.8	2.7 ± 0.2
Biomass		
Mean biomass (g termite kg $mound^{-1}$)	35.0 ± 3.8	3.6 ± 0.9
Mean mass of a worker (mg)	1.34 ± 0.04	1.41 ± 0.07
Mean mass of a soldier (mg)	1.87 ± 0.02	1.91 ± 0.11

Source: Jamali et al. (2011)

Konate et al. (2003) computed that the CO_2 fluxes produced by fungus-comb chambers of *Odontotermes* and *Ancistrotermes* at the scale of each savanna type and at the landscape-scale in the Lamto, Ivory Coast. Using field estimates of fungus-comb chamber densities, and the total respiration rates from individual chambers of these two termite species as estimated in the laboratory as show in Table 2.6.

Table 2.6 Estimated CO_2 emission rates from respiration rates per chamber estimated from laboratory measurements, and estimated field chamber densities of two termite species as A= *Odontotermes* B= *Ancistrotermes*.

Scale	Total area (%)*	Density of A (m^{-2})	CO_2 emission rate (A) (µmol CO_2 m^{-2} s^{-1})	Density of B (m^{-2})	CO_2 emission rate (B) (µmol CO_2 $m^{-2}s^{-1}$)	CO_2 emission rate from the two species (µmol CO_2 m^{-2} s^{-1})
Grassy savanna	25.2	0.7	0.028	0.4	0.006	0.034
Shrubby savanna	70.9	1.5	0.059	1.6	0.025	0.084
Woody savanna	3.9	0.7	0.028	3.9	0.060	0.088
Lamto landscape	100	1.3	0.050	1.4	0.022	0.072

*According to Gauthier (1989) cited by Konate et al. (2003)

As above mentioned, previous measurement the pattern of CO_2 efflux from epigeal termite mounds (termitaria) was in many savannas, most results suggest that high soil CO_2 emission from the mound center would be compensated by lower emissions from the surrounding.

However, CO_2 emissions originate from nesting and foraging activity of termites and it is very common to find underground passages of termites in the region of Asian

tropical forest, and the quantitative data regarding the direct contribution of termites to carbon release via respiration are not intact and rare as well.

2.4 Termite Nest/Mound

All termites live in highly organized and integrated societies or colonies within the confine of excavations within wood-aboveground or in subterranean and epigeal nest systems. Termites can be categorized under two major groups which is wood/litter feeders (which comprise fungus-growers and non-fungus) and soil-feeders.

Wood/litter-feeders are involved in the decomposition of aboveground organic matter, while soil-feeders contribute to the decomposition of below ground organic matter (soil organic matter). Termites are excavate soil aiming to build nesting and foraging structures especially the epigeous nests (mounds) which are the most conspicuous termite products that were a reason for the inclusion termites in ecosystem engineering ranks. Termite mound can reach very high densities where more than 100 mounds ha^{-1} (Korb and Linsenmair, 2001). In Africa and Asia the most prominent mound builder are the fungus-grower termites, Macrotermitinae (Termitidae) (Korb, 2003). The following nesting groups were recognized for 4 groups by Eggleton et al. (1996);

1) Wood nesting

Termites in this group live in or around standing trees or dead logs. The dead wood may or may not be gradually replaced with carton material.

2) Hypogeal or Subterranean nesting

Termites whose colony centers are below the ground without any indication of their presence. They use their feces and mineral soil in nest construction become a complex underground nests. This enables the foragers to forage on above ground vegetation.

3) Epigeal Mound Building

Termites whose colony centers associated with living or dead vegetation aboveground are commonly known as mound builders. The mound are usually well defined and highly complex species-specific structures. Material used for construction are of three main types: subsoil with relatively low organic content added with salivary secretion (*Macrotermes*), wood carton (a mixture of faeces and macerated wood with a high lignin content), or mixture of faeces and organic-rich topsoil (many soil feeders). Epigeal mound structure can differ widely within genera and also between regions within in widely distributed species.

4) Arboreal nesting

Nest is on the trees at different heights. These nests are normally made of wood carton. In most case, the nests are connected to the ground by cover runways.

In the tropical region, nests of *Macrotermes* (fungus-growing termites) are widely distributed on various kinds of soil (e.g. Hesse, 1955). Although appearing on everywhere among social insects, the nests of termites in particular exhibit a wild diversity of structure. This diversity is not only related to differences in social complexity, but also to adaptations evolved in response to the needs of the colony: defense, food storage, and a homeostatic environment necessary for survival and growth of offspring (Emerson, 1938; Noirot and Darlington, 2000). In a dry evergreen

forest of Sakaerat, Thailand, Takematsu et al. (2003) reported that the density of nests of *Microcerotermes crassus* were 165 nests/ha and the relative abundance was very much higher than in the other Southeast Asian forests.

The main function of termite mounds certainly is to provide a home for a large colony. The epigeal nests are more exposed to ambient fluctuations as the protective layer between the nest and the environmental factors then subterranean nests. It's provide homeostatic conditions within the nest. There are difference of the mound building due to soil particles in the case of termites and plant material for thatched ant mounds. (Korb, 2011).

The function of termite mound architecture is mainly serves as a ventilation or as a thermoregulation device. The different between the function of the mound architecture and the mechanism of mound function, they are not mutually independent. There are several mechanisms of the mound with varying importance in different areas. Even within an area the mechanisms might vary depending on season and also on short-term fluctuations over a day. Thus, functional significance of mound shape depends on species and especially their environment (Korb, 2011).

In particularly, the mound building, fungus growing termites reach high densities in soils of tropical forests. While not adequate information on how to calculate nutrient fluxes through termites, the data available support the argument that termites contribute significantly to atmospheric fluxes of CO_2. Also, the structure and shape of epigeal termite mounds in the tropical seasonal forest are quite different from savannas. Thus, the pattern and value of CO_2 emissions in tropical seasonal forests could be also different.

CHAPTER III

METHODS

3.1 Study Site Description

3.1.1 Location and History

The Sakaerat Environmental Research Station (SERS) is one of the four UNESCO designated biosphere reserves in Thailand. The Sakaerat Biosphere Reserve was established in September 1967 by the Applied Scientific Research Corporation of Thailand to use as a national forest reserve for scientific research by the Royal Forest Department, Ministry of Agriculture and Cooperative. The study area of this research is located in the Sakaerat Environmental Research Station (SERS) (Figure 3.1), the biosphere reserve areas in Man and Biosphere Program of UNESCO. This station has been being dedicated as an ecological reserve for scientific purposes. It is administered by the Thailand Institute of Scientific and Technological Research (TISTR) as a facility for ecological and environmental research. SERS is located in Nakhon Ratchasima Province. It spans Phu Luang Subdistrict, and Udomsap Subdistrict in the Pakthongchai District and Wang Nam Khieo District. It is located at approximately 14° 30' N and 101° 55' E, about 300 km northeast from Bangkok and 60 km from Nakhon Ratchasima (Korat) on highway 304. The station ground cover an area of 78 km^2 (approximately 48,750 rai).

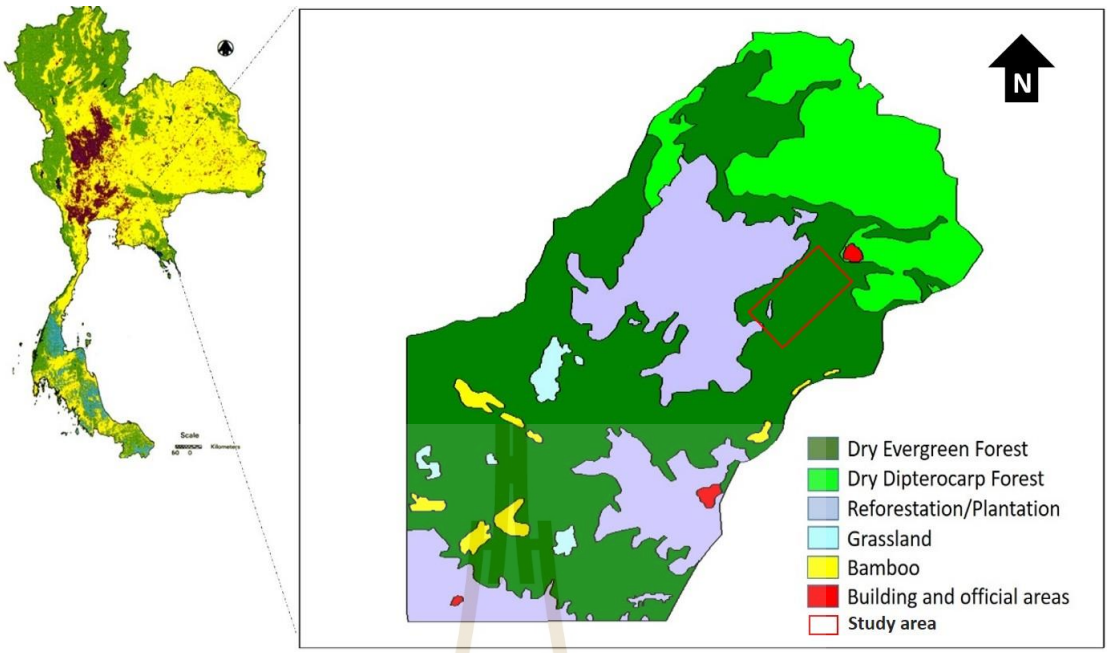

Figure 3.1 Sakaerat Environmental Research Station (TISTR, 2016a)

3.1.2 Topography and Geography

Sakaerat Environmental Research Station is situated in mountainous terrain at an altitude of 280-762 m above sea level (asl.). Important mountains on the station grounds are Khao Phiat (762 m asl), Khao Khieo (790 m asl), and Khao Sung (682 m asl) (Suriyapong, 2003). The station office is at 390 m asl.

The entire area of SERS appears to be underlain by sandstone of the Phra Wihan formation of the Khorat group to a maximum thickness of 1.025 m. It lies comformably on the purplish siltstone, micaceous sandstone, and conglomerate on the Phu Kradung formation on the same group. The sedimentary rock is sandstone; upper soil texture is characterized as clay loam, sandy loam, and sandy clay loam (Bunyavejchewin, 1997).

3.1.3 Climate

Average annual temperature at Sakaerat is 26°C and average annual rainfall is 1,260 mm with monthly rainfall less than 40 mm during the dry season from November to March and wet season started from May to October (TISTR, 2016a). The mean relative humidity at the SERS meteorological station was 88.3% from 2000 to 2009 (Hasin et al., 2014). The relative humidity increases after April until October, and decreases after February (TISTR, 2016a).

3.1.4 Vegetation and Forest Types.

SERS has two major natural vegetation types that consists of 29.5 km^2 of dry evergreen forest (DEF) and dry dipterocarp forest (DDF) occurs of 12.2 km^2 (Wacharakitti et al., 1980). The dominant tree species is *Hopea ferrea* and canopy trees attain 30 to 40 m (Kanzaki et al., 1995). Both are primary forest. The majority of the vegetation is dense DEF. Several small areas of bamboo are found in the DEF at higher elevations. The boundary between the two types of forest is sharp; though between them narrow strips of transitional mixed deciduous vegetation can be found. The DEF is considered an intermediate between tropical rainforest and mixed deciduous. At SERS, the DEF has a dense, four-story canopy. This forest dominates the southwest section of the station, extending northeast to cover 60% of the station. It includes species such as *Hopea ferrea*, *Hopea odorata* and *Hydnocarpus ilicifolia*. However many lianas and vines often climb to the mid-story from the ground. The DDF occupies the rolling hills in the northeast of the station; here sandstone boulders and laterite are common. It covers 18% of the station area. DDF are open, generally consisting of uniformly spaced trees, with sparse foliage allowing the sun's ray to reach the ground. Vegetation in this forest is more seasonal, but common trees are *Shorea obtusa, Dipterocarpus intricatus*,

Shorea siamensis and *Gardenia sootepensis* with a thick understory of bamboo grasses (*Bamboo vietnamensis*). The remaining area is composed of reforested land (18%), grassland (1%), bamboo (1%), and the office and operational buildings (2%) (TISTR, 2016b).

3.1.5 Soil Characteristics

The dominant great soil group of the SERS, occurring in all topographic positions is Red-Yellow Podzolic soils on materials derived from both sandstone and shale (Suriyapong, 2003). Series are Khao Yai for the deep members, Tha Yang for the shallow stony members, and Muak Lek for the deeper soils on shale-derived material. The depth of soil is about 40-120 cm. Soil texture is mainly coarse sandy clay loam to sandy loam and clay loam. The scarps mostly consist of rock outcrop and some stony screen materials (Suriyapong, 2003).

3.2 Aboveground Soil Respiration and Environmental Factors

Five main plots (each size is 100 m × 100 m) were set up in the dry evergreen forest as a map shown in Figure 3.2. Each plot was divided into 100 subplots (each size is 10 m × 10 m). PVC collars (10 cm in diameter and ca. 3 cm in height) were placed in the center of each subplot. These PVC collars were the points where soil respiration was measured. The five main plots were established at the different places in DEF that according to the vegetation, elevation, soil characteristic (Figure 3.3).

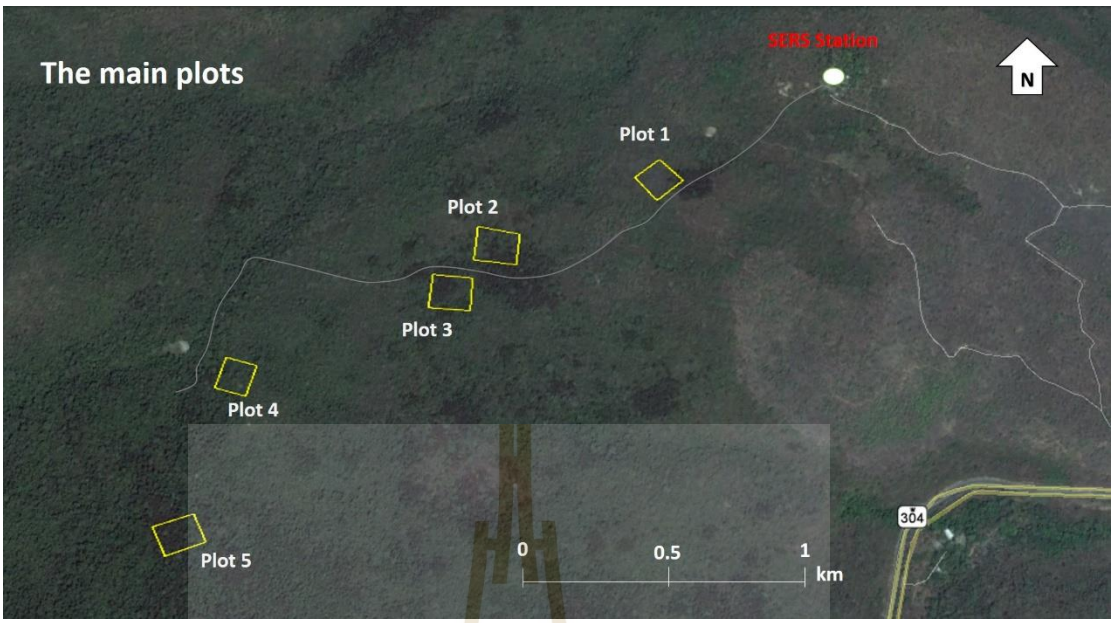

Figure 3.2 Map of the five main plots in the DEF at SERS.

Figure 3.3 Characteristic of the main plots in the DEF.

Each main plot were separated into 100 subplots. PVC collars were placed at each center of the subplots (Figure 3.4). The rates of soil respiration were measured by using a portable infrared gas analyzer (IRGA, EGM-4, PP Systems) with a closed soil CO_2 efflux chamber (SRC-1, PP Systems) (diameter 10 cm) on every PVC collars (Figure

3.5) 2 times per each season in dry and wet seasons from November 2014 to August 2016 (Table 3.1). After measurement in each subplot, the soil temperatures and soil moisture contents were measured immediately by portable probes.

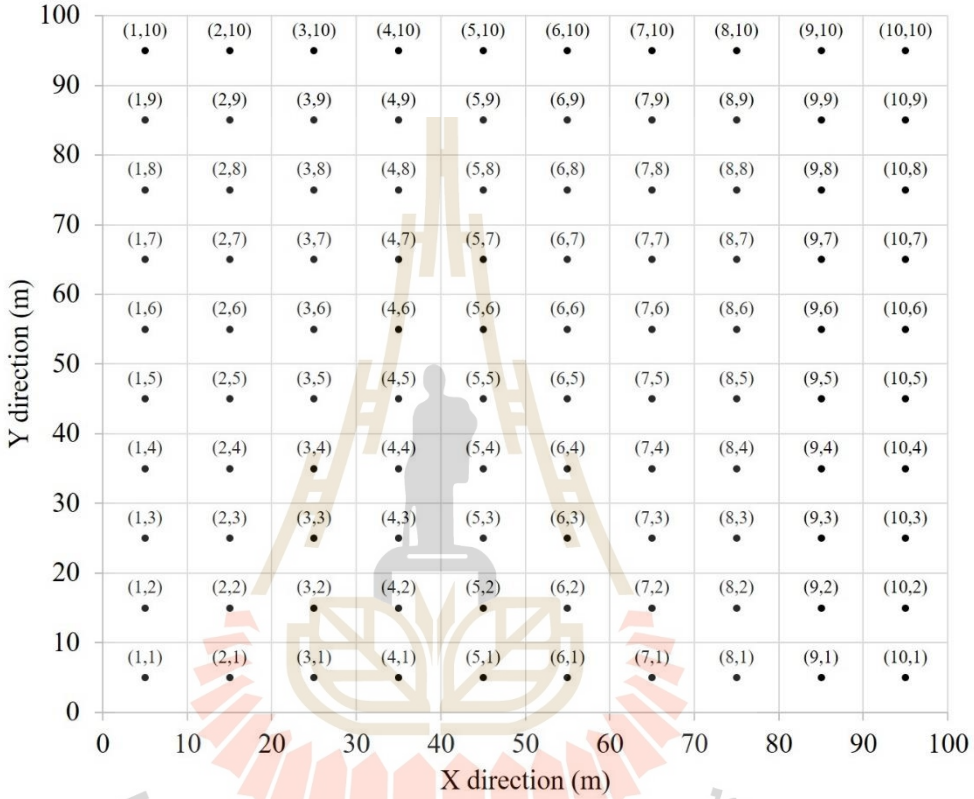

Figure 3.4 Example of the main plot with the measurement points at the center of every subplots (100 points) for determinant of soil respiration in each main plot (1 ha), Subplots were numbered as in the parentheses.

Table 3.1 Sampling times of annual ground soil respiration from October 2014 to August 2016 (started measurement from 9:00 am until 6:00 pm).

Main plots	Sampling times			
	1st time	2nd time	3rd time	4th time
Plot 1	17/Nov/2014	11/Oct/2015	28/Mar/2016	17/Jul/2016
Plot 2	28/Nov/2014	17/Oct/2015	26/Mar/2016	18/Jul/2016
Plot 3	21/Dec/2014	19/Oct/2015	23/Mar/2016	19/Jul/2016
Plot 4	22/Nov/2014	10/Oct/2015	27/Mar/2016	23/Jul/2016
Plot 5	20/Dec/2014	18/Oct/2015	29/Mar/2016	15/Aug/2016

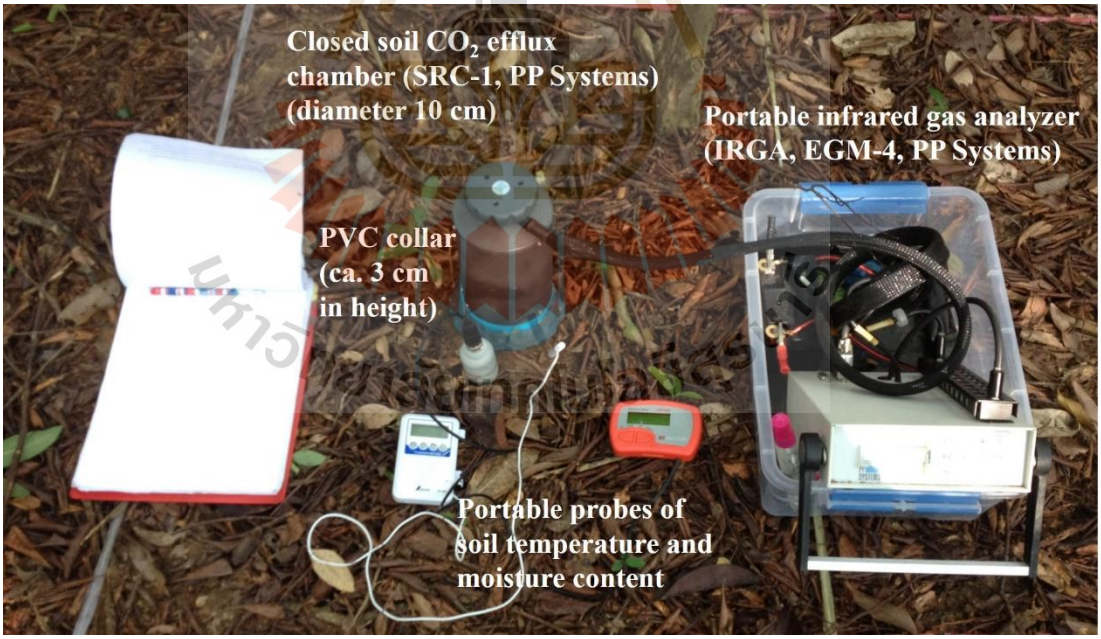

Figure 3.5 Portable instruments for measurements of CO_2, soil temperature and soil moisture content in the field.

In addition, the 5 main plots were not only used for measurement for soil respiration, but also for observations of environmental factors (Figure 3.6) as follows;

1) Soil temperature and soil moisture content

As mentioned above, Soil temperatures and soil moisture contents at depth of 10 cm were collected in every PVC collar points at the main plots and nearby termite mounds after measurement of CO_2 efflux soon by using an electric thermometer connected to a probe and an electric device that can measure soil moisture content by two probes.

2) Dominant tree species and forest structure

Living trees with the DBH (diameter at breast height) being larger than 20 cm were considered by directly measurement of GBH (girth at breast height) ≥ 60 cm (GBH = Pi × DBH) in this study. Positions of all the trees were put onto the map of the main plots, and stand structural parameters were calculated, such as tree density, total basal area, mean and range of DBH of trees.

3) Species, density, and distribution of 7 living mounds/nests (*Macrotarmes carbonarius*, *Macrotermes annandalei*, *Microcerotermes crassus*, *Dicuspiditermes makhamensis*, *Globitermes sulphureus*, *Termes comis*, and *Termes propinguus*) were observed within the 5 main plots. The positions of mounds were measured and put onto the map of the main plots. Then, a list of termite species were made by separating of mound structure types (thin - and thick - wall) with the density, which was calculated based on numbers of mounds found in the main plots. Distribution of termite mounds are expressed by maps where the positions of each mounds were shown. The identification of termite species were based on morphological characters of soldiers and the shape of mounds.

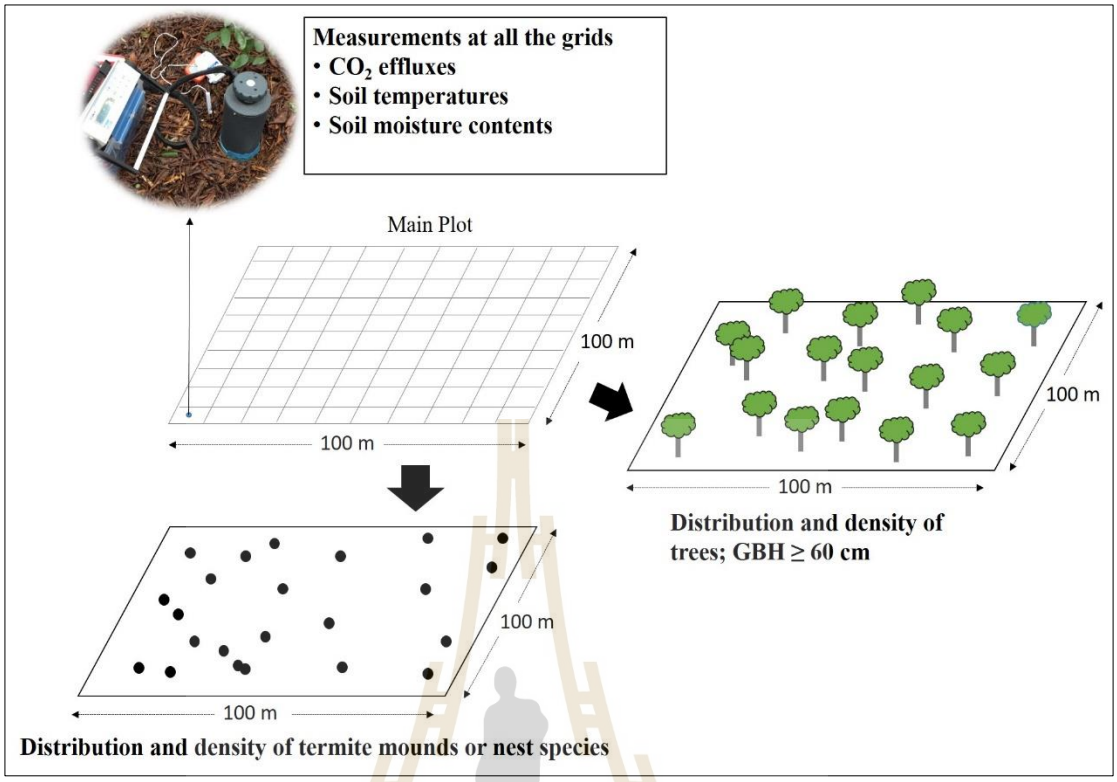

Figure 3.6 Experimental design for determination of annual ground soil respiration and environmental factors from the main plots.

3.3 CO_2 Efflux from Termitaria

According to Yamada (2003) reported that there are dominant 7 species of mound building termites which can be further categorized in two different groups, thick - wall mound (fungus growing termite) (Figure 3.7) and thin - wall mound (non-fungus growing termite) (Figure 3.8) groups based on mound structure (i.e. thickness of mound wall) as well as gas exchange.

Figure 3.7 Appearance of the thick - wall mounds: (A) *M. carbonarius* and (B) *M. annandalei*.

Figure 3.8 Appearance of the thin - wall mounds: (A) *D. makhamensis*, (B) *M. crassus*, (C) *G. sulphureus*, (D) *T. propinguus*, and (E) *T. comis*.

3.3.1 CO_2 efflux from the Termitaria of Thick-Wall Mound

The thick - wall group consists of *Macrotarmes carbonarius* (Figure 3.9) and *Macrotermes annandalei* (Yamada, 2003). These mound are visible on the ground without camouflaging to its surroundings. However, CO_2 efflux from termitaria of *M. annandalei* was not measured in this field, because it is not occurring very often and the mounds are mostly flat to the soil surface, there is a distinct mound in this reserve.

Figure 3.9 Cross section of a mound of *Macrotermes carbonarius* (thick-wall mound ground).

The extra plots were set up for measuring CO_2 efflux rates around the mounds of *M. carbonarius* in the DEF (Figure 3.10). There were determined from the information and structure of their mounds, by considering the distance of passage traversing through entire nest at an ambient of the mound. The size of mounds were measured of height from the mounds base with North-South direction and circuit mounds. The extra plots were either 8 m × 8 m for the small mound size, and 10 m × 10 m for big and medium mound sizes. An extra plot was divided into 100 grids (1 m × 1 m ×100 m for big and medium mounds and 80 cm × 80 cm × 100 m for the small mounds). Then, the PVC collars were placed on the center of the grids for measurement of soil respiration (Figure 3.11).

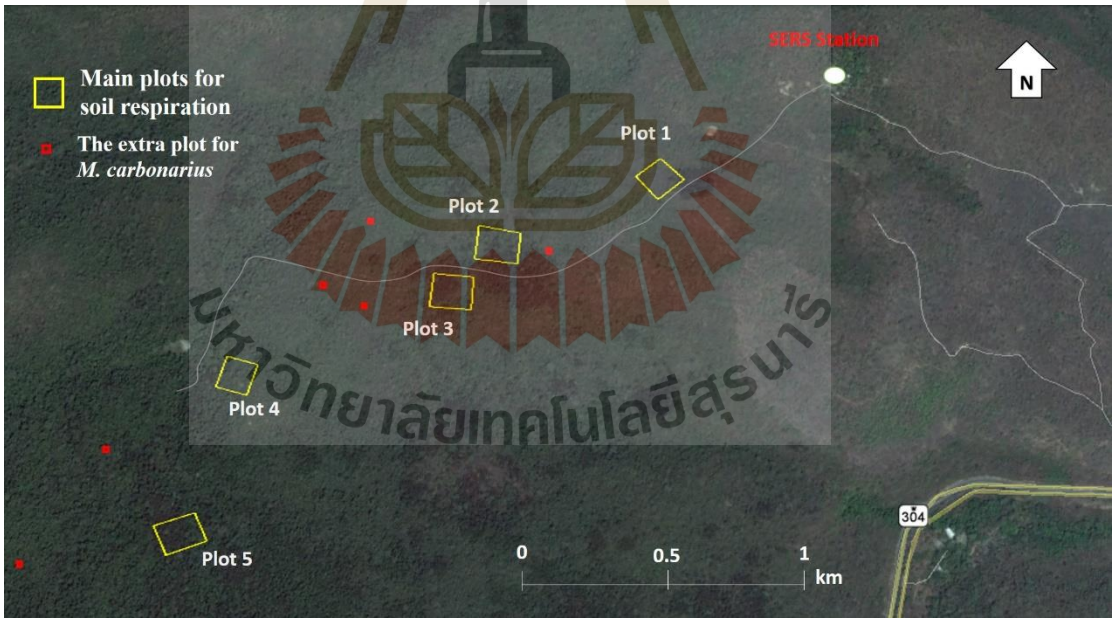

Figure 3.10 Position of the 6 extra plots (red points) in the DEF.

Figure 3.11 An example of extra plot for the thick - wall mounds built by of fungus - grower termites.

The thick - wall mound species were measured of CO_2 efflux on the mound for 6 measurement points and 100 measurement points for the surrounding soil for 2 times (during wet and dry season) (Table 3.2). Also, the soil temperatures and soil moisture contents were measured immediately by portable probes. The distribution of trees and neighbor mounds were observed with DBH and volume, respectively. Plot experimental design for the termiteria of thick - wall mounds shown in Figure 3.12.

High CO_2 efflux rates were found on the measurement points (PVC collars at the center grids), these points were examined for active or inactive by excavating. In the case of active mound, such excavated underground passages will be soon repaired about 1 hr. by termites. The depth and diameter of underground passages were measured. Distribution of the high rate flux points were put on to the map of thick - wall mound plots.

Table 3.2 Sampling times of CO2 efflux from termitaria of the thick - wall mound (*M. carbonarius*) during from October 2014 to July 2016 (started measurement from 9:00 am until 6:00 pm).

Plot	Sampling times	
	1st time	2nd time
Small mound 1	19/Jan/2015	22/Oct/2015
Small mound 2	24/Jan/2015	20/Oct/2015
Medium mound 1	28/Dec/2014	21/Oct/2015
Medium mound 2	28/Mar/2015	02/Nov/2015
Big mound 1	31/Jan/2015	24/Oct/2015
Big mound 2	21/May/2015	01/Nov/2015

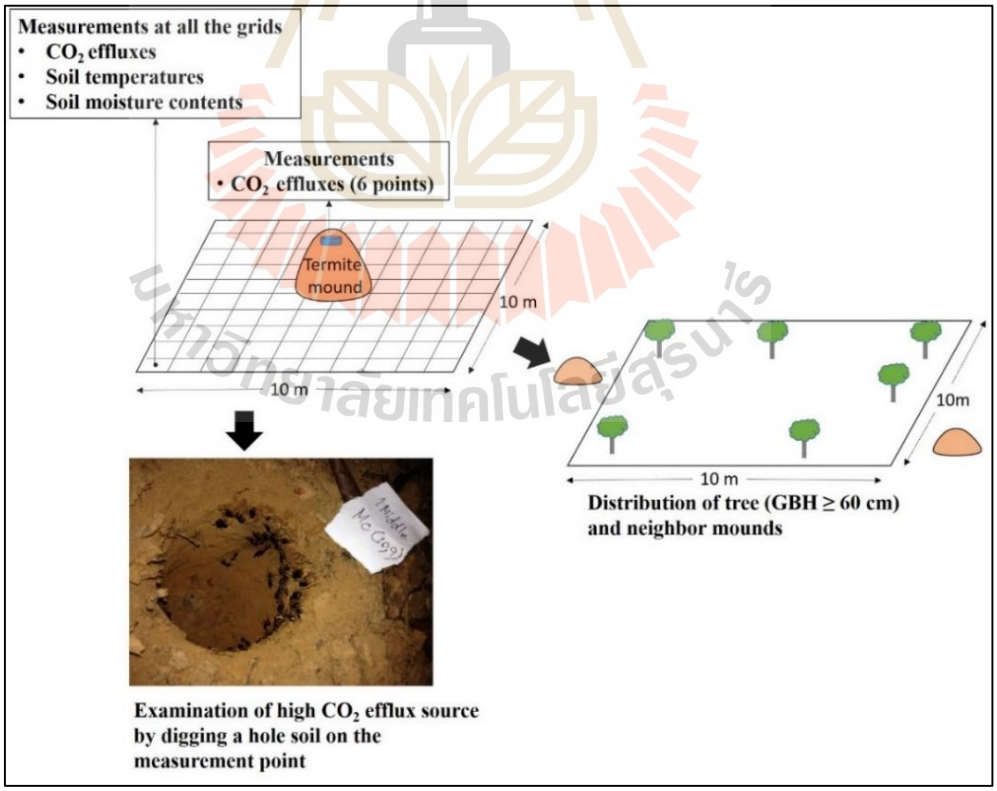

Figure 3.12 Experimental design for determine CO_2 efflux and relative factors from the thick – wall mound.

3.3.2 CO_2 efflux from the Thin – Wall Mound

Mainly, five species of thin - wall mound builders are distributed in the study site, *Microcerotermes crassus* (Figure 3.13), *Dicuspiditermes makhamensis, Globitermes sulphureus, Termes comis,* and *Termes propinguus*.

Figure 3.13 An example of the thin-wall mound (*Microcerotermes crassus*).

Five thin-wall mounds of each 5 species were measured of height by height from the bottom to the top (highest position) at four directions, north, south, east and west, with circular length of the bottom.

The CO_2 efflux from the thin - mounds were measured by using EGM-4 connected with collars to mound and soil surface. Also, the surrounding the mound (reference points) for 3 – 5 points were measured (Figure 3.14). There was observed for 2 times in wet and dry season (Table 3.3).

Figure 3.14 Experimental design for determine CO_2 efflux from the thin – wall mound.

Table 3.3 Sampling times of CO2 efflux from termitaria of the thin - wall mound in dry and wet season.

Species	n	Sampling times	
		Dry season	Wet season
D. makhamensis	5	29 –31 January 2016	24 –31 October 2015
G. sulphureus	5	29 –31 January 2016	25 – 31 October 2015
M. crassus	5	29 –30 January 2016	24 –27 October 2015
T. propinguus	5	29 – 31 January 2016	25 – 27 October 2015
T. comis	5	29 – 30 January 2016	26 –31 October 2015

3.4 CO_2 Efflux from Termites, Fungus Combs, and Nest Materials

This study estimated the fraction of the termitaria CO_2 efflux rates by respiration from termite population, fungus comb, and their nest materials in July 2016.

Two species of fungus growing termites (*Macrotarmes carbonarius* and *Macrotermes annandalei*) were conducted. Cast of the termite individuals (by separate small workers, big workers, small soldiers, and big soldiers), fungus combs and their nest materials (Figure 3.15) were collected from 2 species of randomly selected mounds for 3 mounds per each species from the DEF. Respiration rates were measured by using LI-820 CO_2 Gas Analyzer. After measurements, counting and weighing of each cast of termites and also fungus-comb and nest material were weighed.

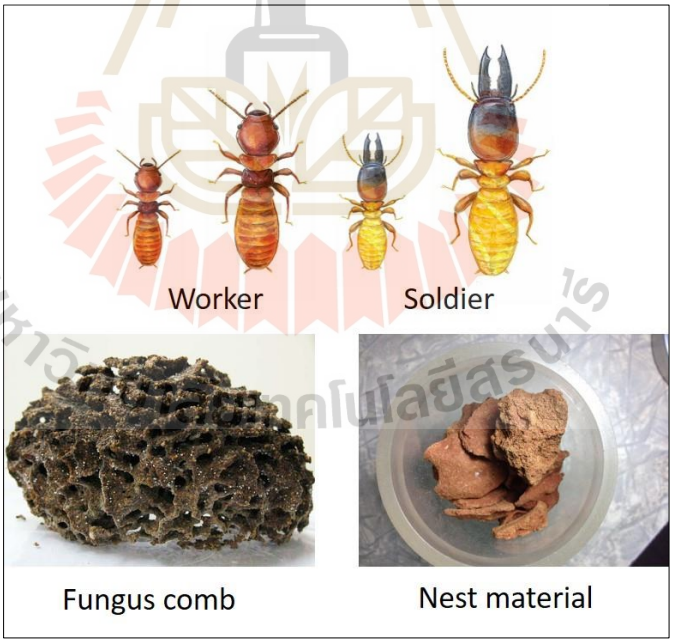

Figure 3.15 An example of termite cast, fungus comb and nest material in the thick - wall mound (fungus growing termite).

Predominantly, five species (as mentioned above) of randomly selected mound for 3 mounds per each species from the DEF. The nest was separated all individuals from the mound (by separate workers and soldiers) and nest material (Figure 3.16). Respiration rates were measured from both nest without termites (carton nest) and termite individuals by using LI-820 CO_2 Gas Analyzer. Then the number of individuals were counted and weighed as well as nets materials were also weighed.

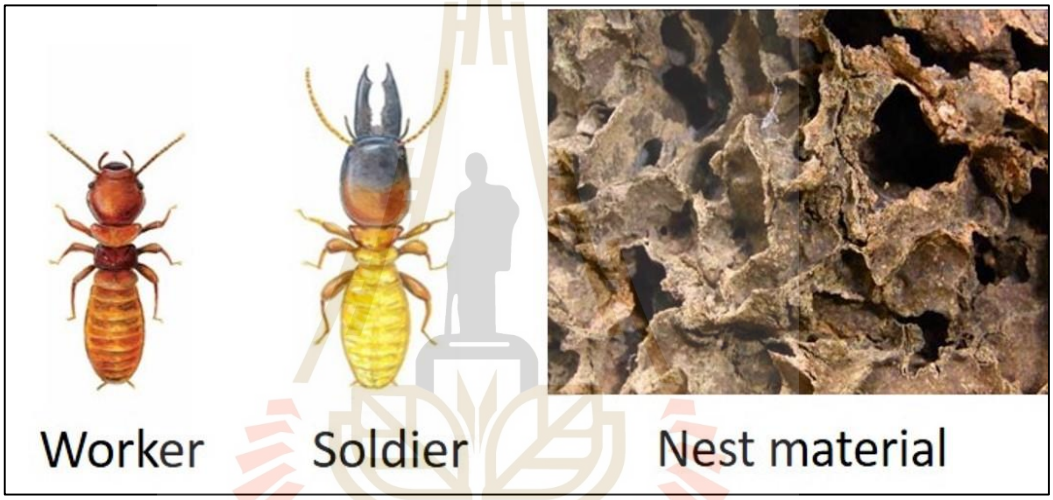

Figure 3.16 An example of termites and nest materials in the thin-wall mound (non-fungus growing termite).

The summary of collecting and preparing the samples of thin and thick – wall mounds for measurement of respiration rates was showed in Figure 3.17.

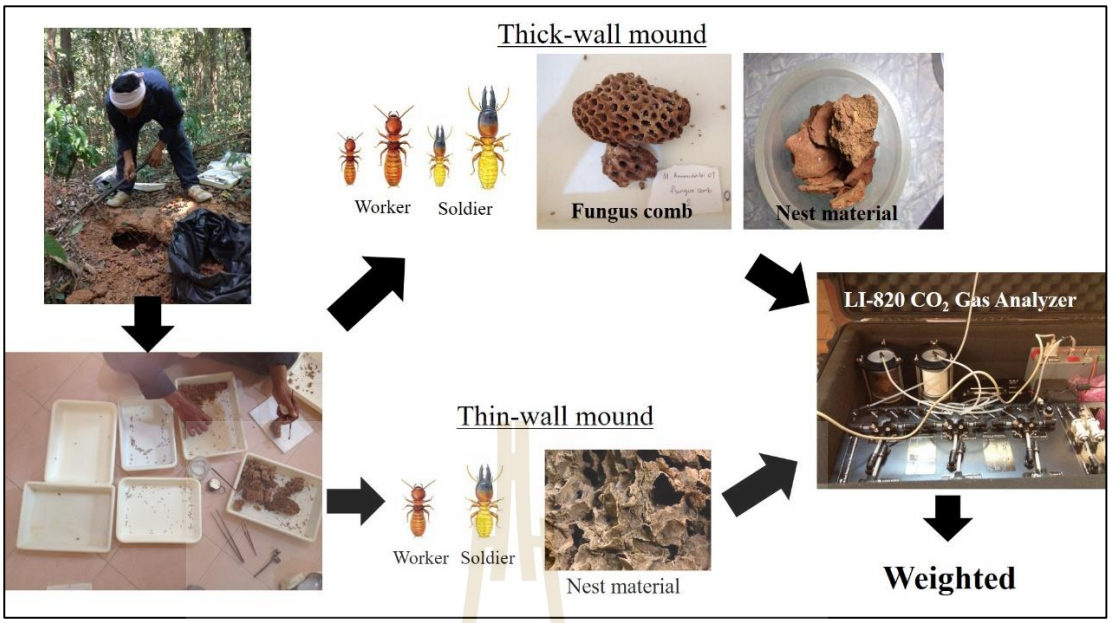

Figure 3.17 Flow chart of the collecting and preparing samples for CO_2 measurement from the thick and thin – wall mounds.

3.5 Data Analysis

The density of termite mound and trees in the main plot will be calculated by using the equation as follows:

$$Di = Xi/ai$$

Where, Di = the density of termite mound and trees; Xi = the total number of species of termite mounds and trees (i); ai = the study area of the termite mound species and tree (i).

Estimation of epigeal termites 'mounds dimensions were calculated from measurements of the base perimeter (V = volume, H = height and R the circle radius). The formula used is as follows:

$$V = 1/3\,\pi R^2H$$

Distribution of termite mounds and the trees are expressed by maps where the positions of each mounds will be shown.

Soil respiration rates from the 5 main plots, significant of difference between the plots were tested by ANOVA with Tukey HSD's post hoc test. The significantly different between the seasons in each year that was tested by paired T- test. To compare the relationship between CO_2 efflux and environmental factors (i.e., soil temperature and soil moisture content), linear regression analyses was used for the termite nest and the control data separately.

The ANOVA with Tukey HSD's post hoc test was used for analysis of CO_2 efflux rate for detecting significant differences in among the different thick-wall mounds and was used for analysis the significant differences of CO_2 efflux rate in each seasonal variation times of the thin – wall mound.

To compare the relationship between CO_2 efflux and environmental factors (i.e., soil temperature and soil moisture content), linear regression analyses was used for the termite nest and the control data separately.

This study was calculated the increment of soil respiration due to activity of soil animals to reveal the effect. Data distribution and density of nests of termites: quantitative assessment of the impact on the soil respiration of whole forest.

Also this study building a new model to evaluate and predict variation pattern of soil respiration contributed by soil animals, like termites, on the basis of various ecological data of which is the number of individuals in the nest, the nest structure, and individual body weight as well as interaction of environmental factors where operated by climate change.

CHAPTER IV

RESULTS AND DISCUSSIONS

The results of this study were analyzed with statistical tests assessing the extent to which the contribution and control/comparison groups participated on the soil respiration rates were different. The results of this study are divided into 7 parts as follows;

4.1 Climatic Data of SERS

Sakaerat area is a seasonal tropical climate as dry season and wet season (Rainy season) with the minimum temperature of approximately 9 – 12° C and maximum temperature of approximately 40 – 45° C in dry winters and hot humid summers, respectively. The average weekly climate data of October 2014 to August 2016 was collected from the information of meteorological observation by SERS – weather station 4 because there are in DEF that covers this study sites (TISTR, 2016c; Figure 4.1).

During the incubation period, the total rainfall was 1751.2 mm, there was highest in September 2015 with the value of 277.8 mm and the major droughts were recorded in December 2015, February 2016, and March 2016. The average percent of relative humidity was 74.06 (range 69.8 – 83.5) and the average of evaporation was 1.19 mm (range 0.62 – 1.80). The average annual temperature was 26.7°C (range 7.9 - 40.6).

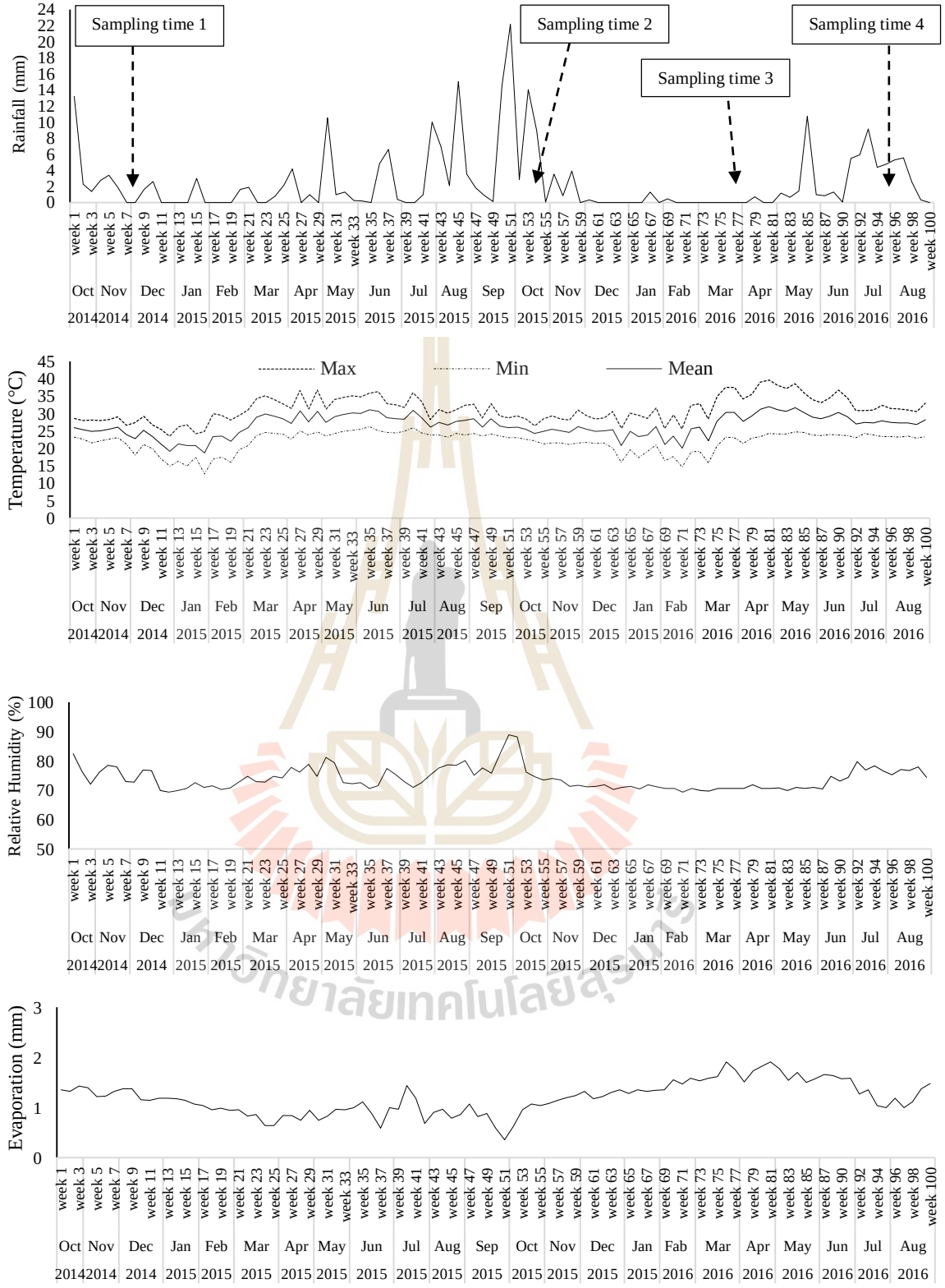

Figure 4.1 The weekly rainfalls, temperature, humidity, and evaporation, and sampling times of main plots for 4 times from October 2014 to August 2016 in the DEF at SERS.

4.2 Soil Respiration from the Main Plots

There were five main plots for determinant of annual ground soil respiration for 4 sampling times from November 2014 to August 2016. Mean of soil respiration rates for the main plots were significantly different ($P< 0.001$) between the plots. The box plot indicates the median as a horizontal line is drawn at the box between the distributions of data set (above and below), and "whiskers" below and above the box show the locations of the minimum and maximum, respectively. (Figure 4.2).

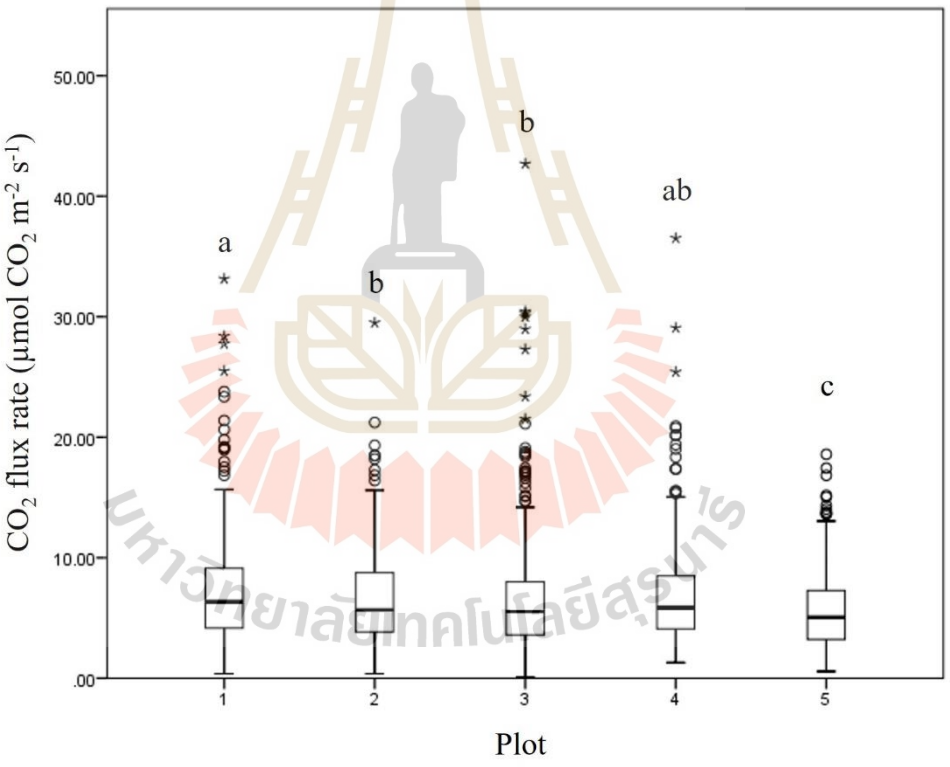

Figure 4.2 Box plot of soil respiration rates from the five main plots. Different letters indicates significant difference among the plots from one-way ANOVA with Tukey's HSD post hoc test ($P< 0.001$).

Table 4.1 Mean of soil respiration rate in each main plot for 4 seasons.

Main plot	Soil respiration rates (µmol CO_2 m^{-2} s^{-1}; mean ± SD)				
	Nov – Dec, 2014 (dry season)	Oct, 2015 (wet season)	Mar, 2016 (dry season)	Jul – Aug, 2016 (wet season)	Average
Main plot 1	6.20 ± 1.99	7.64 ± 3.24	3.35 ± 2.20	11.72 ± 5.38	7.23 ± 4.59 [a]
Main plot 2	5.64 ± 2.30	6.61 ± 2.48	2.66 ± 1.49	11.08 ±3.57	6.50 ± 3.96 [b]
Main plot 3	4.98 ± 2.43	7.65 ± 3.33	2.88 ± 3.49	10.78 ± 6.40	6.57 ± 5.12 [b]
Main plot 4	5.30 ± 1.61	7.70 ± 4.62	4.15 ±2.10	10.72 ± 4.26	6.97 ± 4.23[ab]
Main plot 5	4.91 ± 1.96	7.52 ± 2.47	3.21 ±2.14	6.69 ±3.70	5.58 ± 2.14 [c]
Seasonal mean	5.41 ± 2.12	7.42 ± 3.33	3.24 ± 2.42	10.20 ± 5.09	6.57 ± 4.29

Different letters indicates significant difference among the main plots from one-way ANOVA with Tukey's HSD post hoc test ($P< 0.001$)

Mean of respiration rates which were highest in the main plot 1 and main plot 4 that were ranged of 0.37 – 33.14 µmol CO_2 m^{-2} s^{-1} and ranged of 1.29 – 36.52 µmol CO_2 m^{-2} s^{-1}, respectively. While, main plot 3 and main plot 2 were not significantly different from main plot 4 which was ranged 0.08 – 42.68 µmol CO_2 m^{-2} s^{-1} and range of 0.38 – 29.50 µmol CO_2 m^{-2} s^{-1}, respectively. Main plot 5 was the lowest rate that the rate was ranged of 0.57 – 18.58 µmol CO_2 m^{-2} s^{-1}. The mean of soil respiration rate in each main plot for 4 times were shown in Table 4.1.

The temporal distributions of soil respiration, soil temperature, and soil moisture content of the main plot 1 to 5 for 4 sampling times from October 2014 to August 2016 were shown in Figures 4.3, 4.6, 4.9, 4.12, and 4.15., and also its the distribution maps of the main plot 1 to 5 were shown in Figures 4.4 – 4.5, 4.7 – 4.8, 4.10 – 4.11, 4.13 – 4.14, and 4.16 – 4.17, respectively.

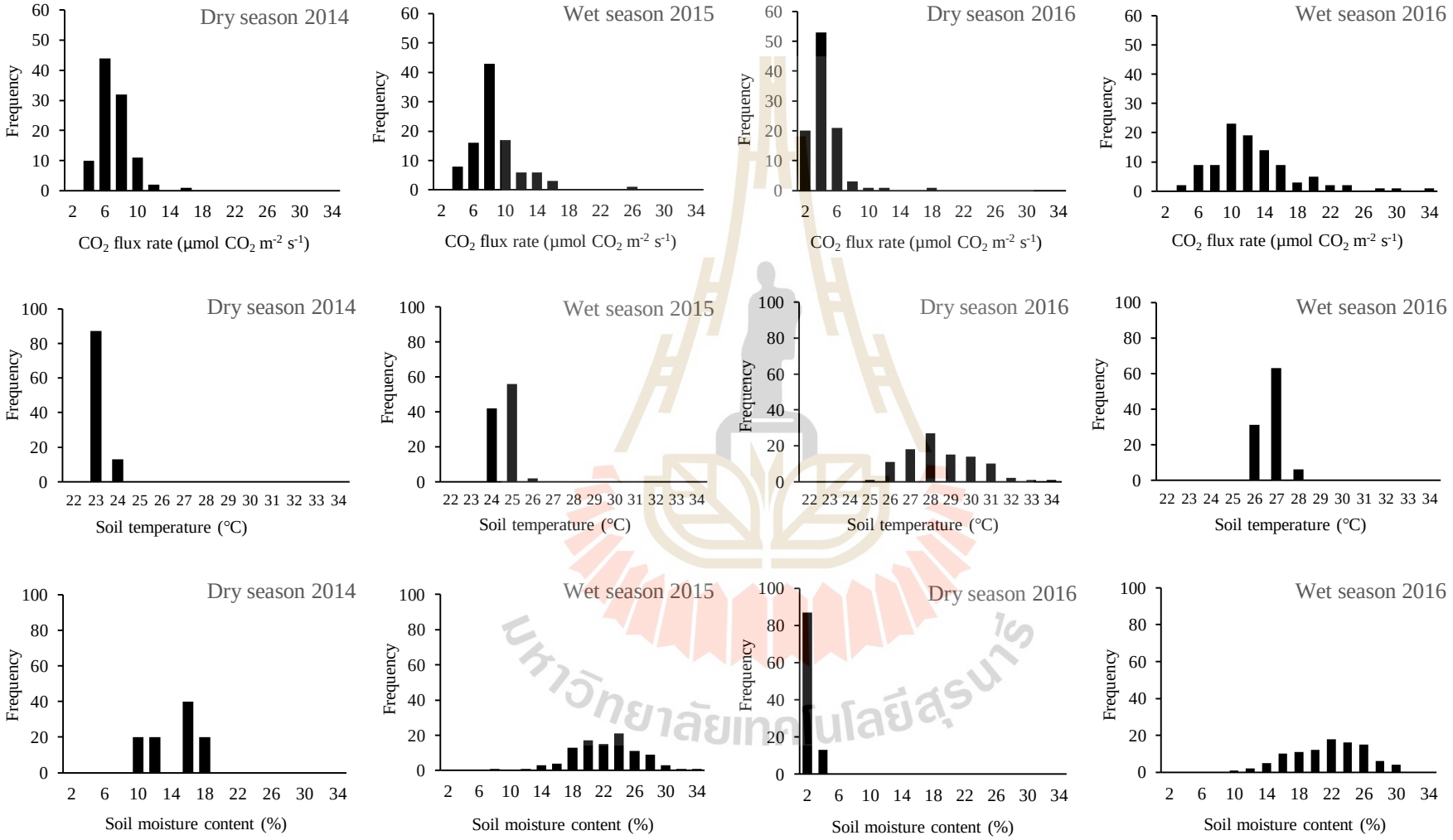

Figure 4.3 Frequency distribution of soil respiration, soil temperature, and soil moisture content in a main plot 1 for 4 times.

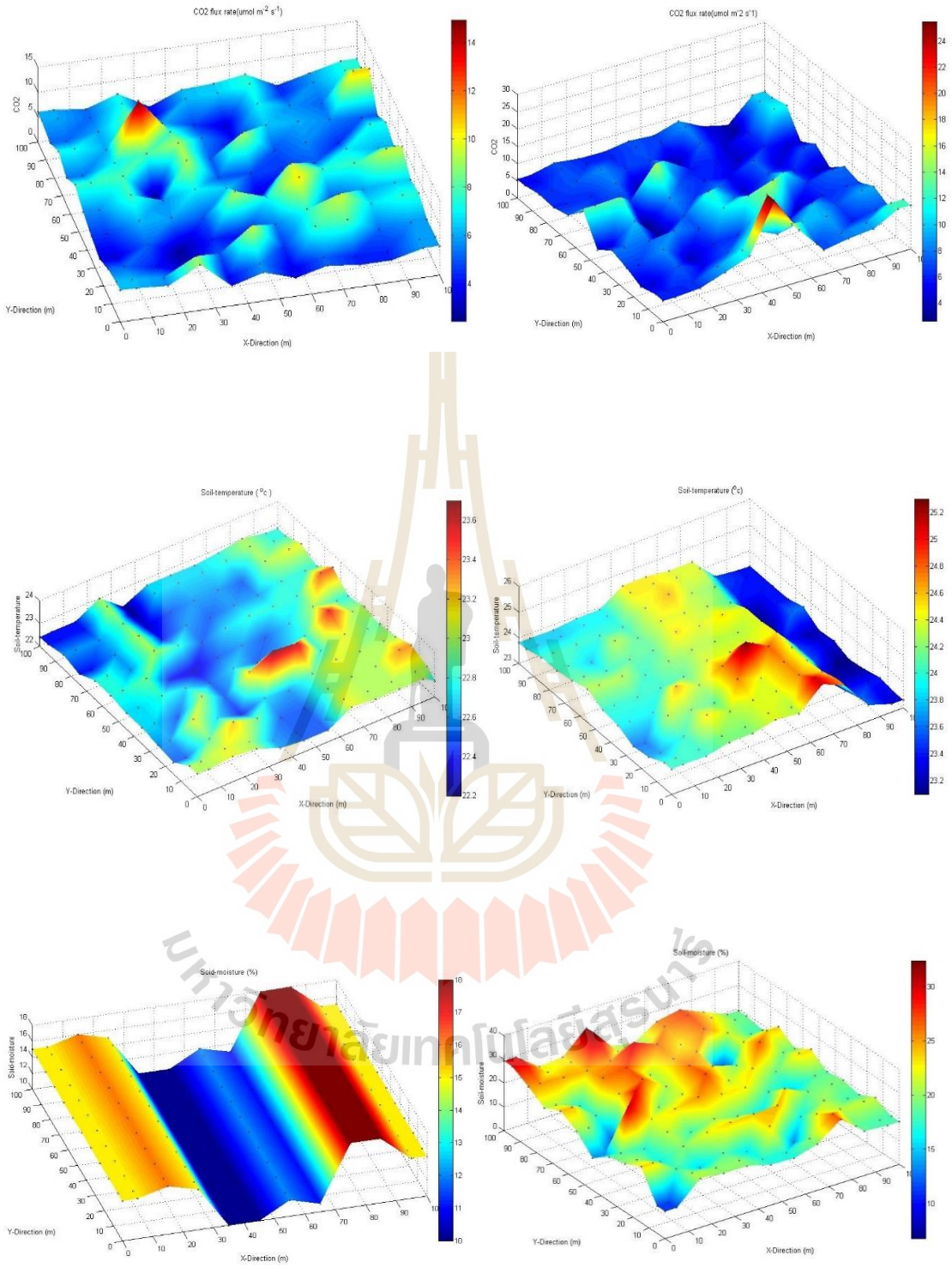

Figure 4.4 Distribution maps of soil respiration (μmol CO_2 m^{-2} s^{-1}) (Top), soil temperature (°C) (Center), and soil moisture content (%) (Bottom) in dry season 2014 (Left) and wet season 2015 (Right) from the main plot 1.

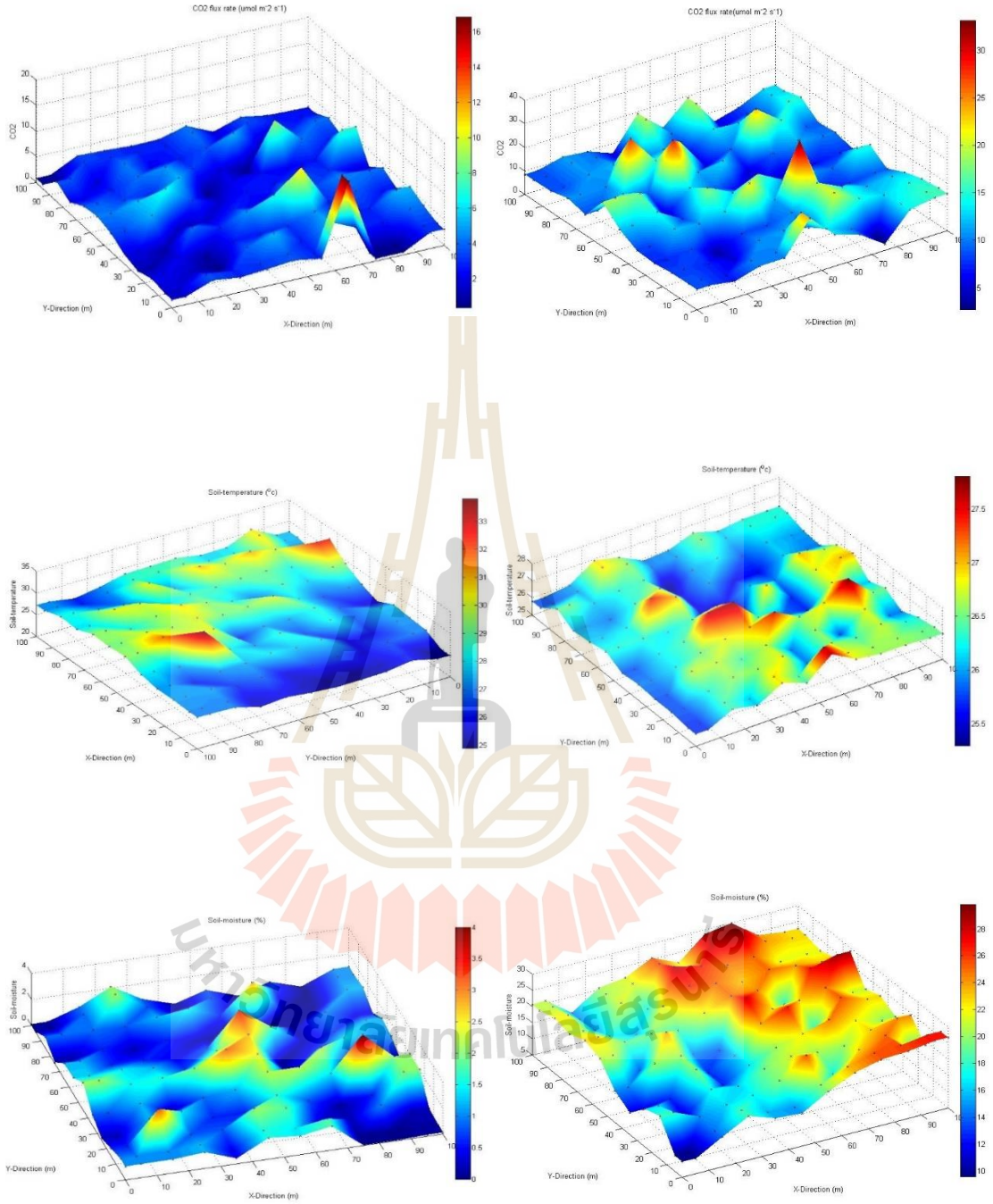

Figure 4.5 Distribution maps of soil respiration (µmol CO_2 m^{-2} s^{-1}) (Top), soil temperature (°C) (Center), and soil moisture content (%) (Bottom) in dry season (2016) (Left) and wet season 2016 (Right) from the main plot 1.

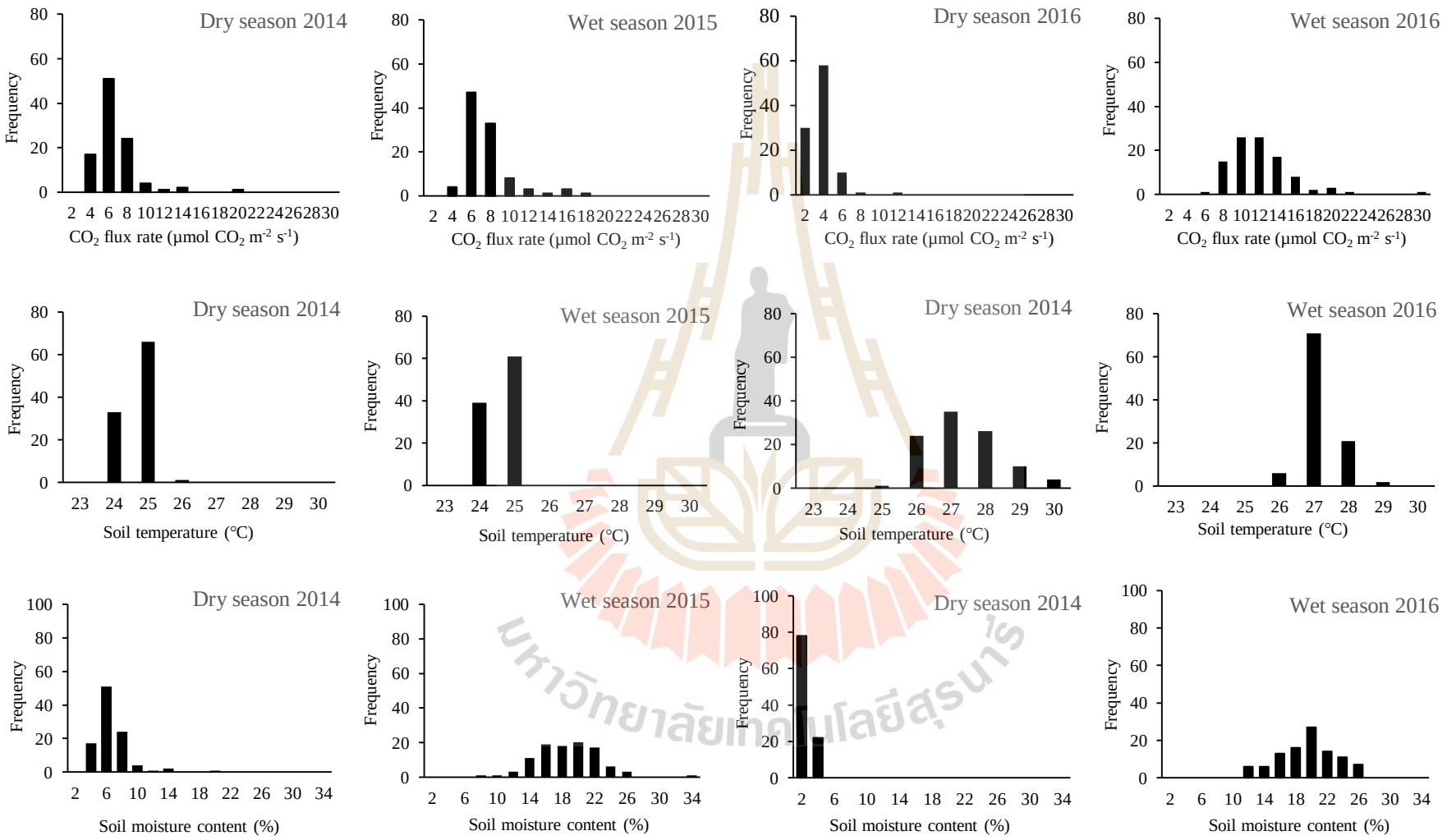

Figure 4.6 Frequency distribution of soil respiration, soil temperature, and soil moisture content in a main plot 2 for 4 times.

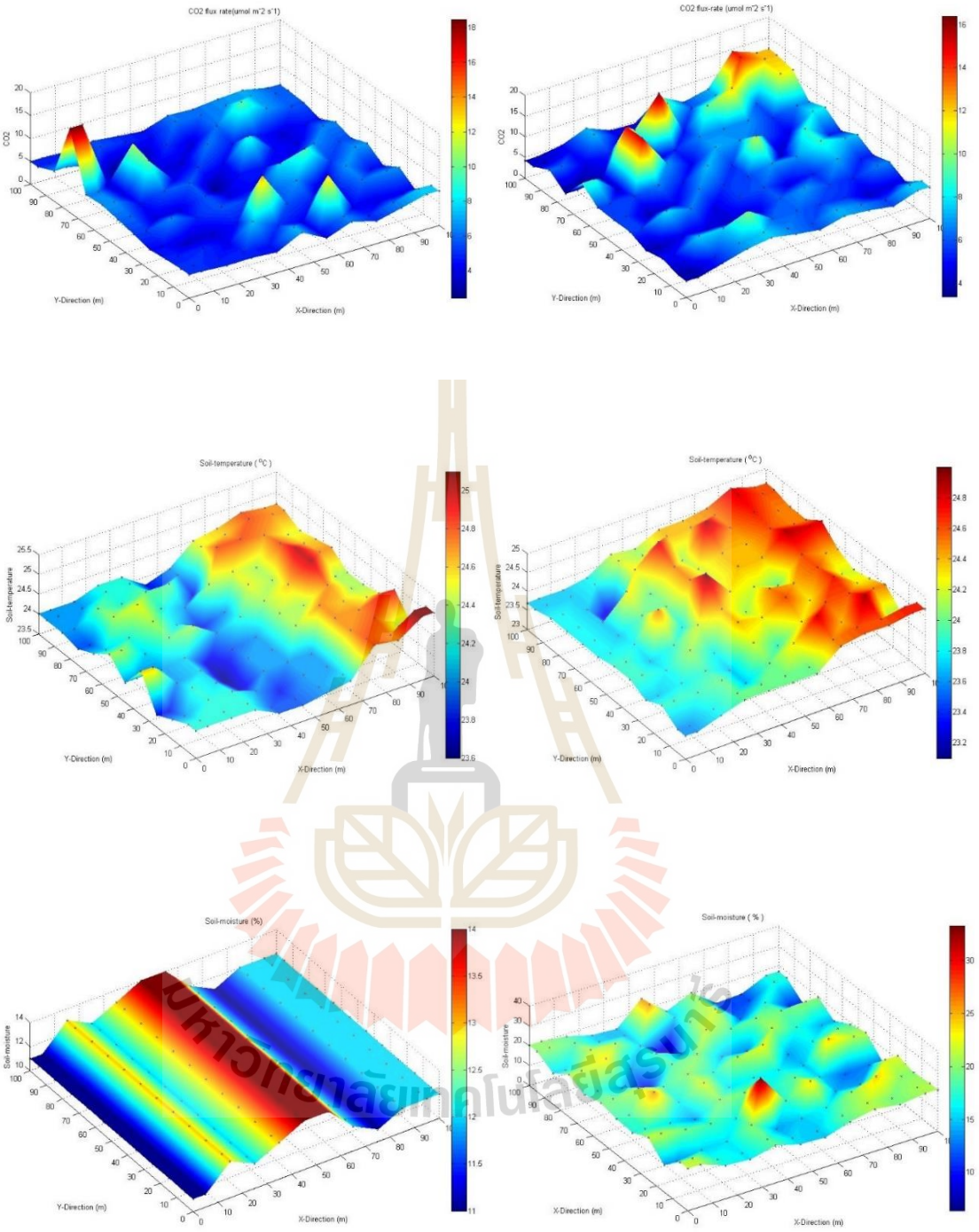

Figure 4.7 Distribution maps of soil respiration (µmol CO_2 m^{-2} s^{-1}) (Top), soil temperature (°C) (Center), and soil moisture content (%) (Bottom) in dry season 2014 (Left) and wet season 2015 (Right) from the main plot 2.

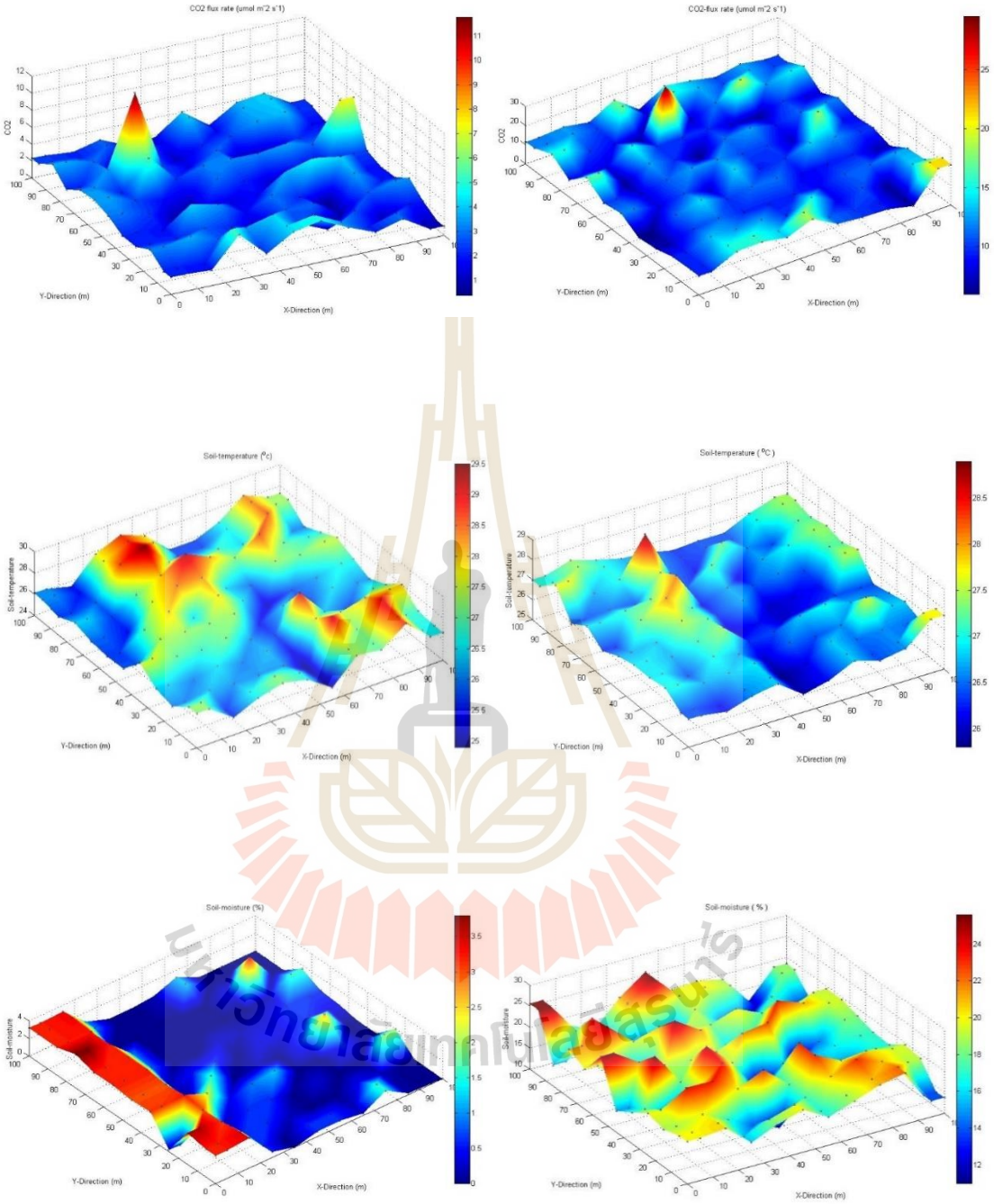

Figure 4.8 Distribution maps of soil respiration (μmol CO_2 m^{-2} s^{-1}) (Top), soil temperature (°C) (Center), and soil moisture content (%) (Bottom) in dry season 2016 (Left) and wet season 2016 (Right) from the main plot 2.

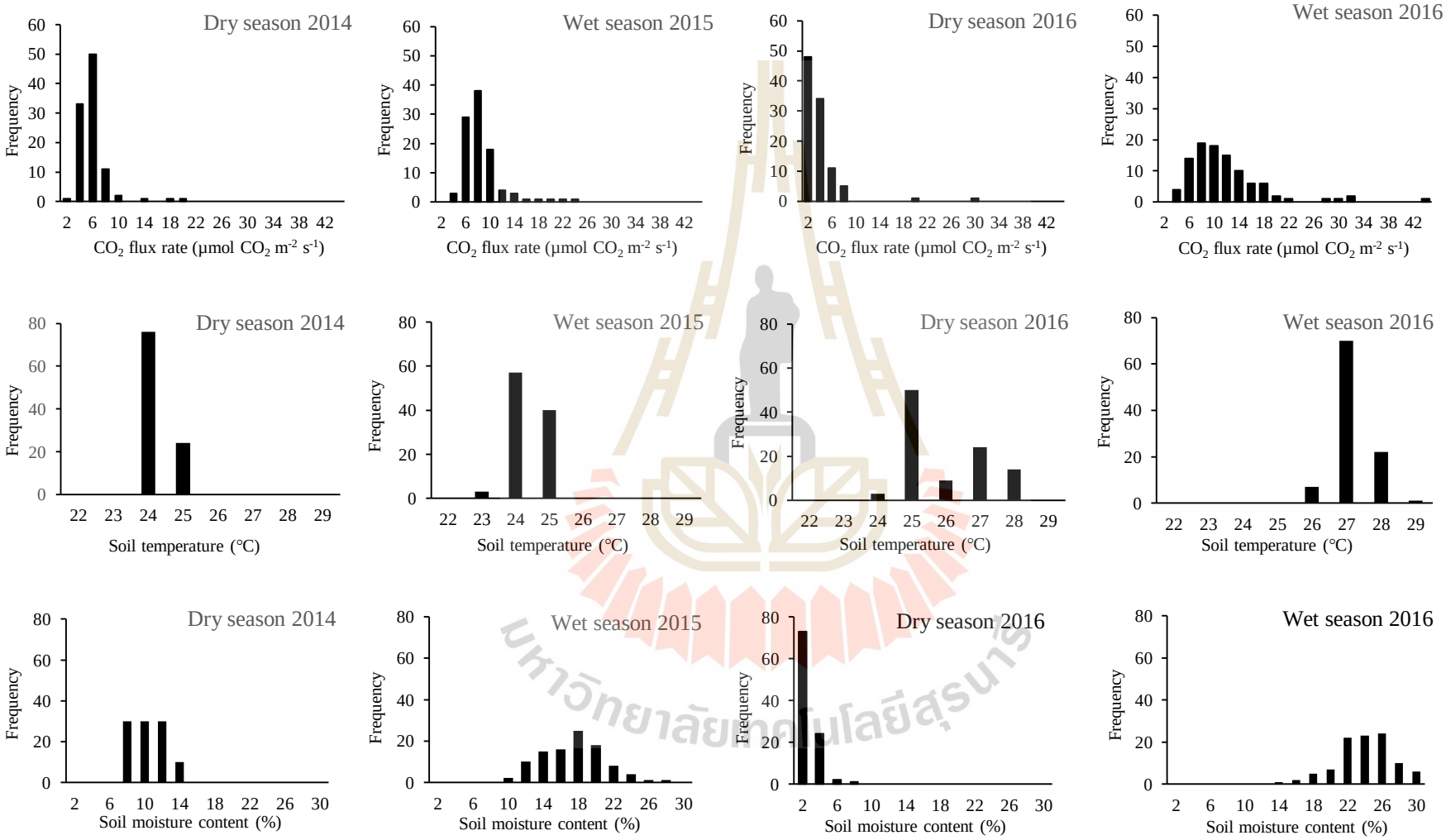

Figure 4.9 Frequency distribution of soil respiration, soil temperature, and soil moisture content in a main plot 3 for 4 times.

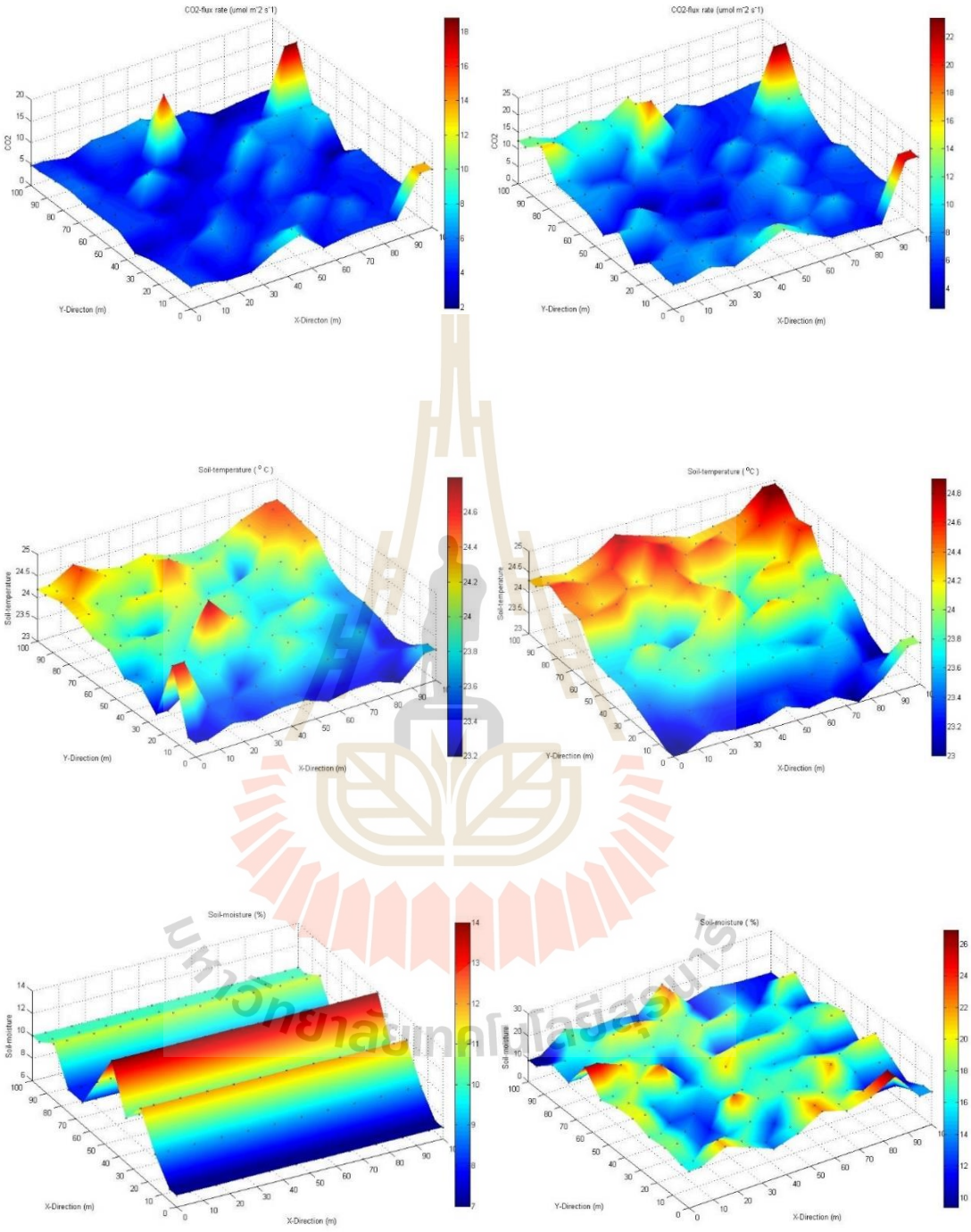

Figure 4.10 Distribution maps of soil respiration (μmol CO_2 m^{-2} s^{-1}) (Top), soil temperature (°C) (Center), and soil moisture content (%) (Bottom) in dry season 2014 (Left) and wet season 2015 (Right) from the main plot 3.

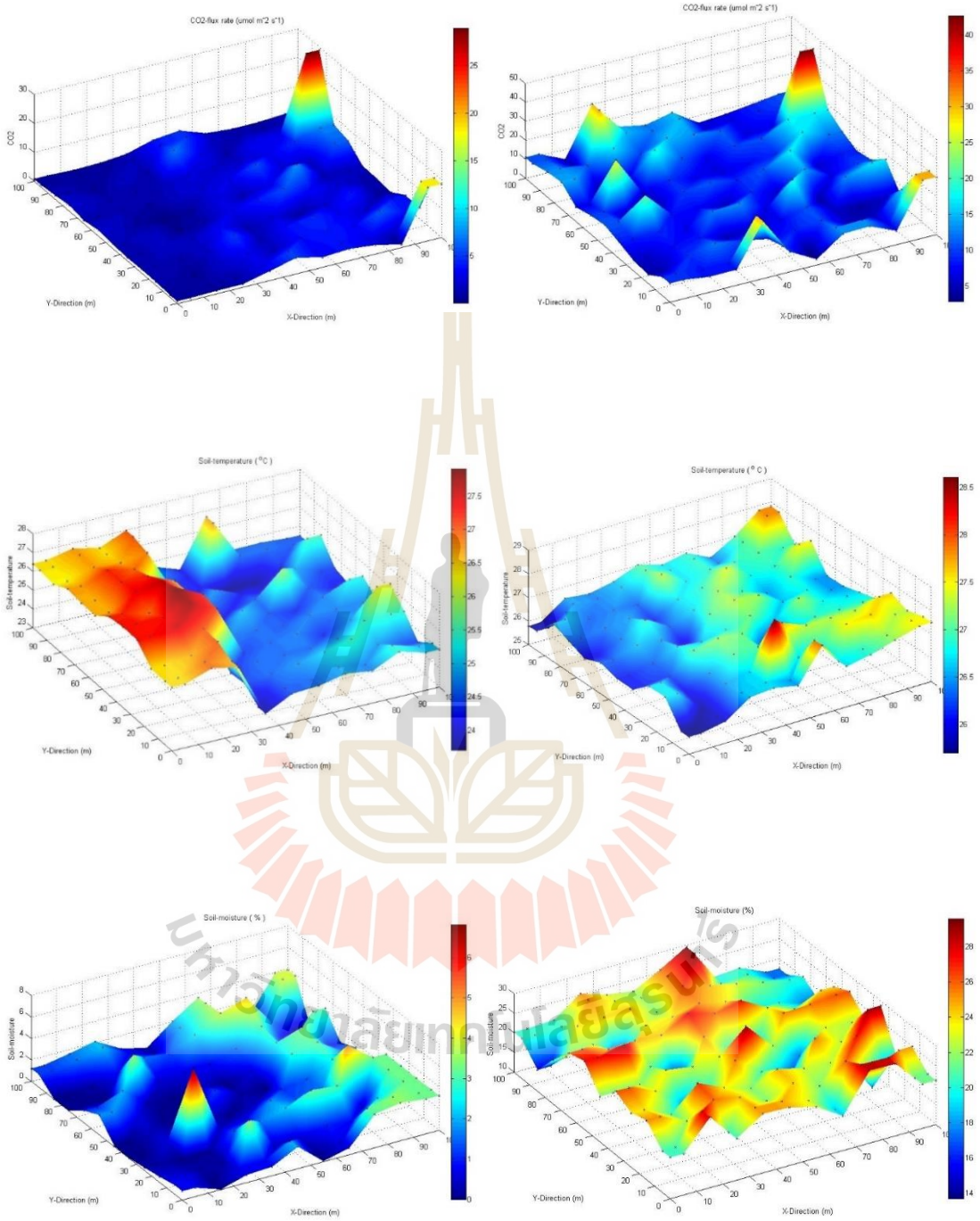

Figure 4.11 Distribution maps of soil respiration (µmol CO_2 m^{-2} s^{-1}) (Top), soil temperature (°C) (Center), and soil moisture content (%) (Bottom) in dry season 2016 (Left) and wet season 2016 (Right) from the main plot 3.

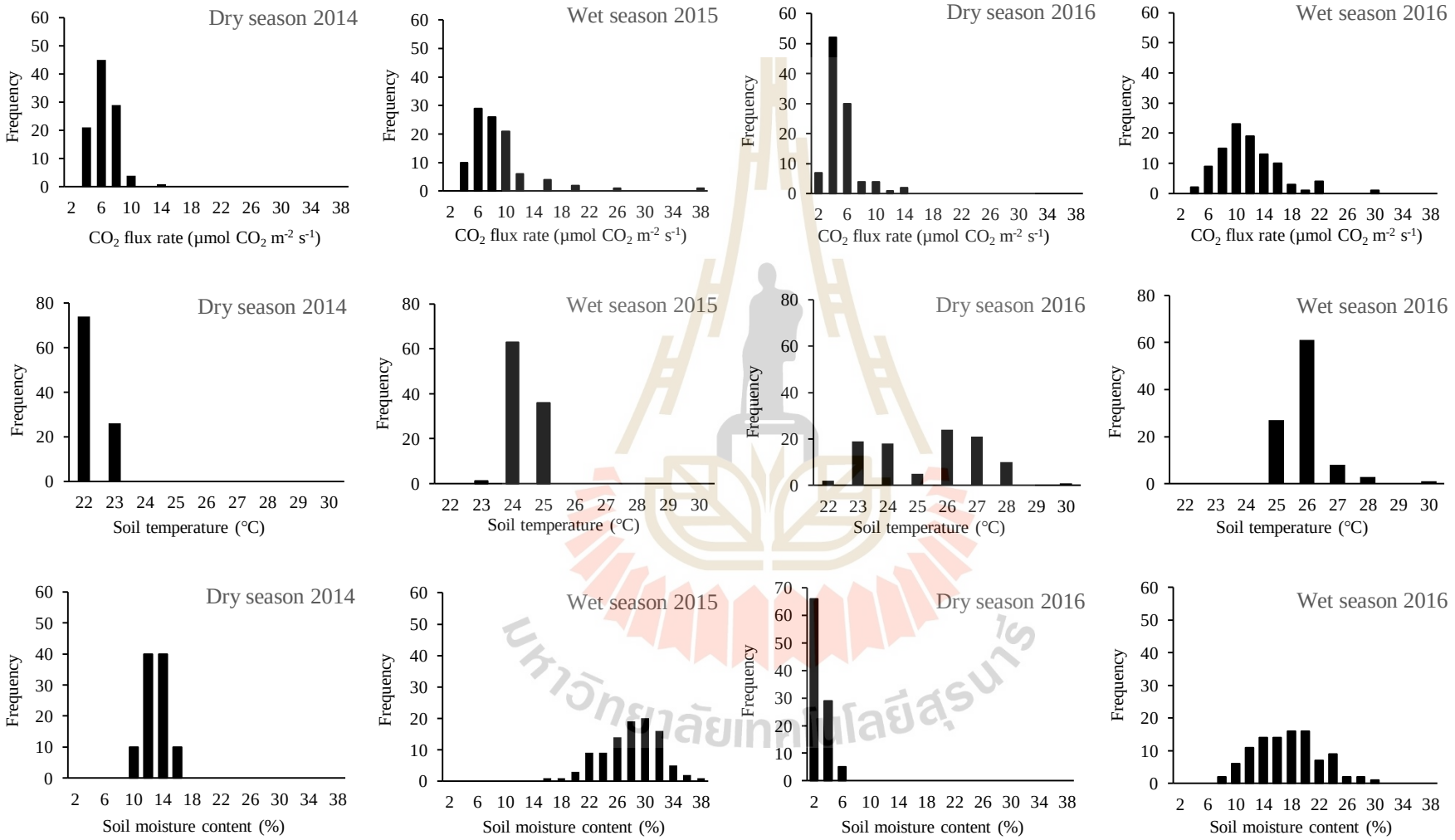

Figure 4.12 Frequency distribution of soil respiration, soil temperature, and soil moisture content in a main plot 4 for 4 times.

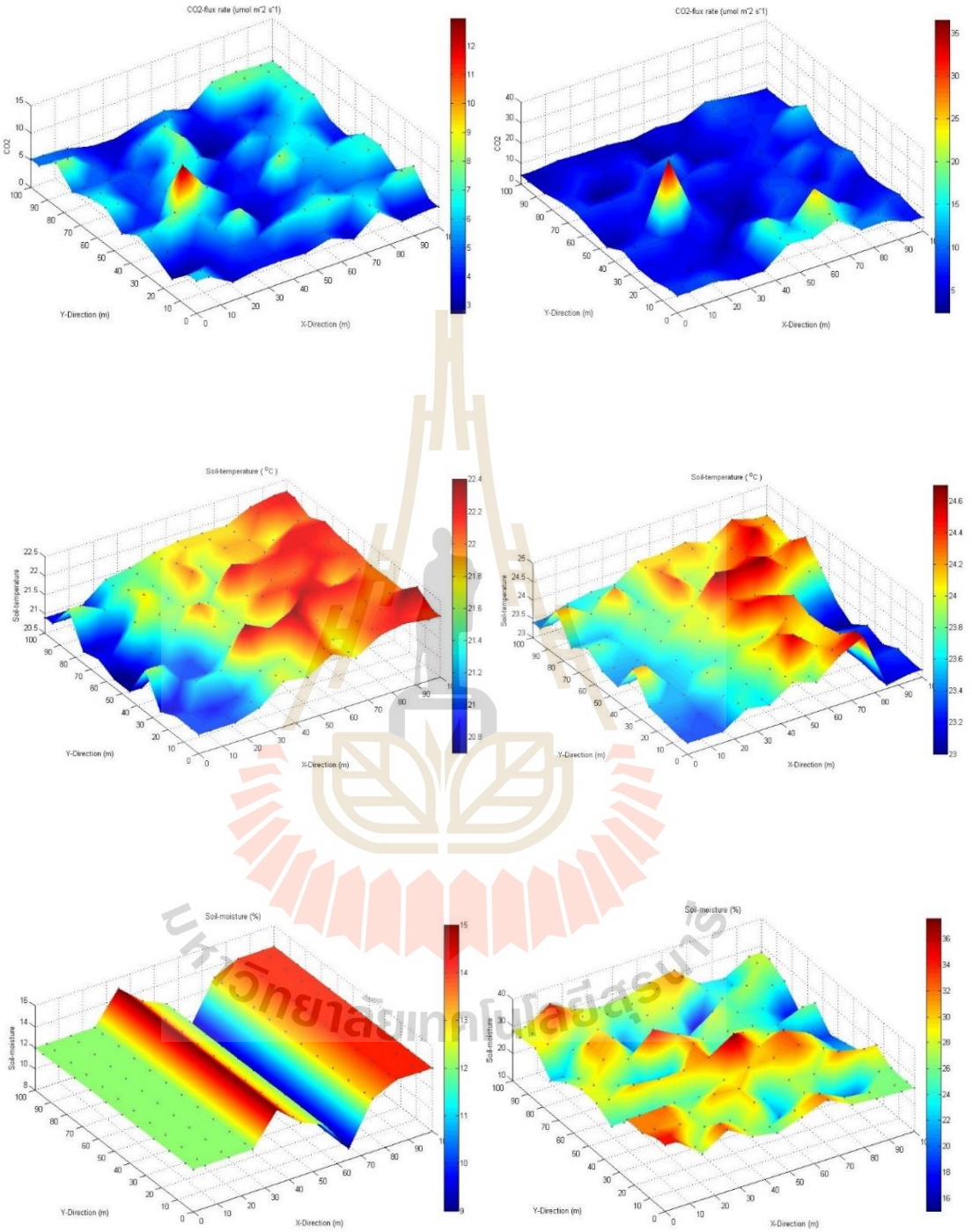

Figure 4.13 Distribution maps of soil respiration (µmol CO_2 m^{-2} s^{-1}) (Top), soil temperature (°C) (Center), and soil moisture content (%) (Bottom) in dry season 2014 (Left) and wet season 2015 (Right) from the main plot 4.

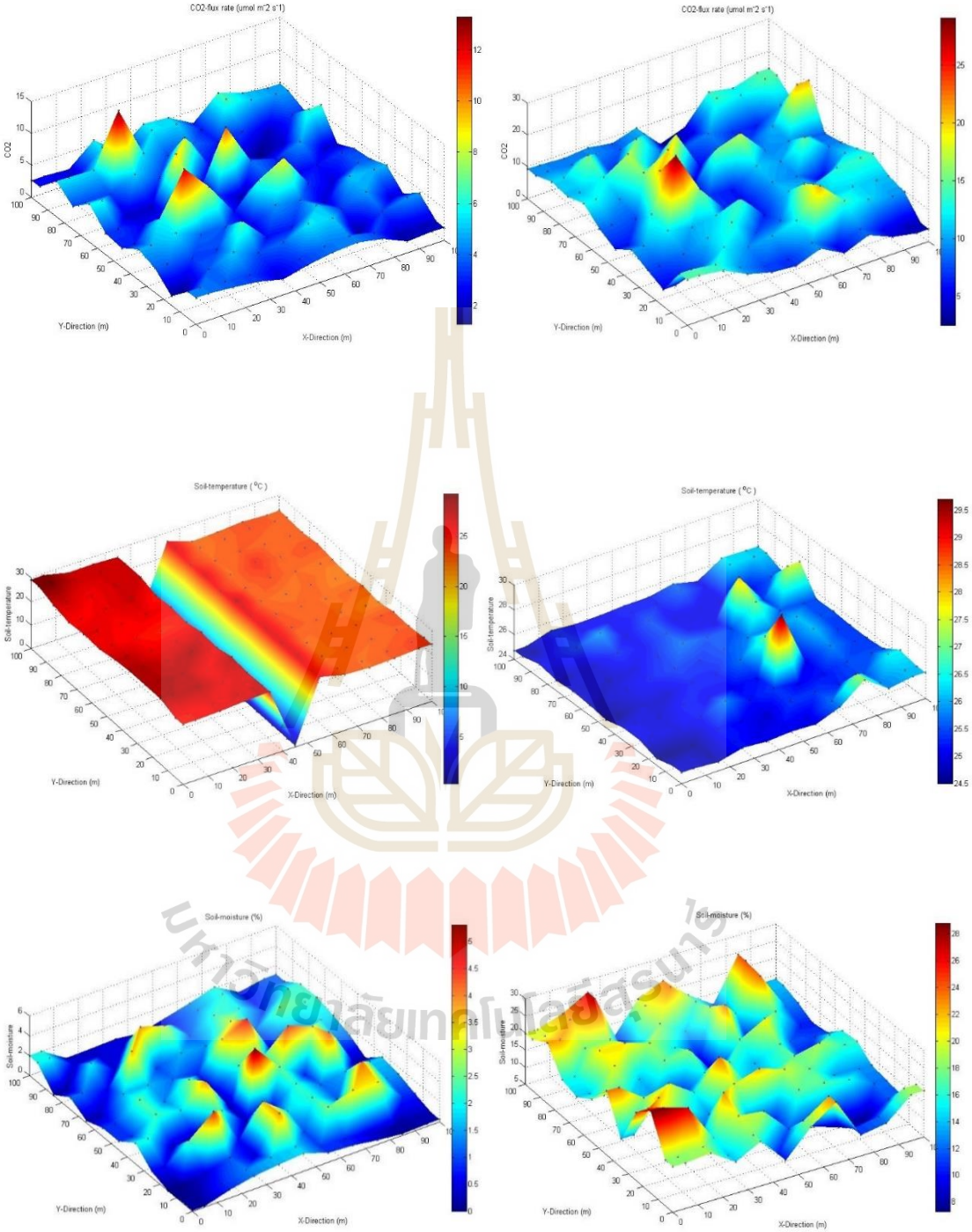

Figure 4.14 Distribution maps of soil respiration (μmol CO_2 m^{-2} s^{-1}) (Top), soil temperature (°C) (Center), and soil moisture content (%) (Bottom) in dry season 2016 (Left) and wet season 2016 (Right) from the main plot 4.

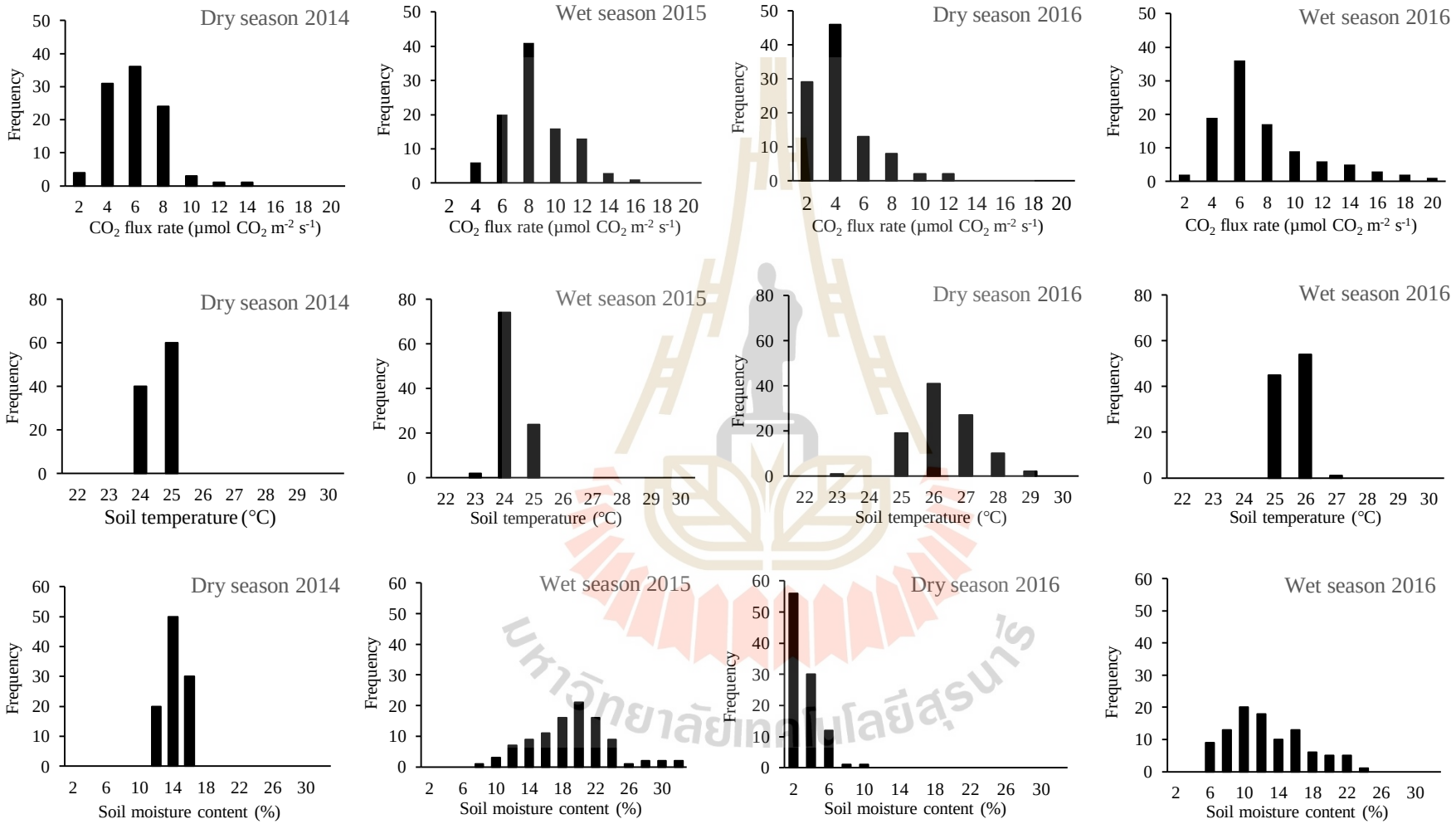

Figure 4.15 Frequency distribution of soil respiration, soil temperature, and soil moisture content in a main plot 5 of 4 times.

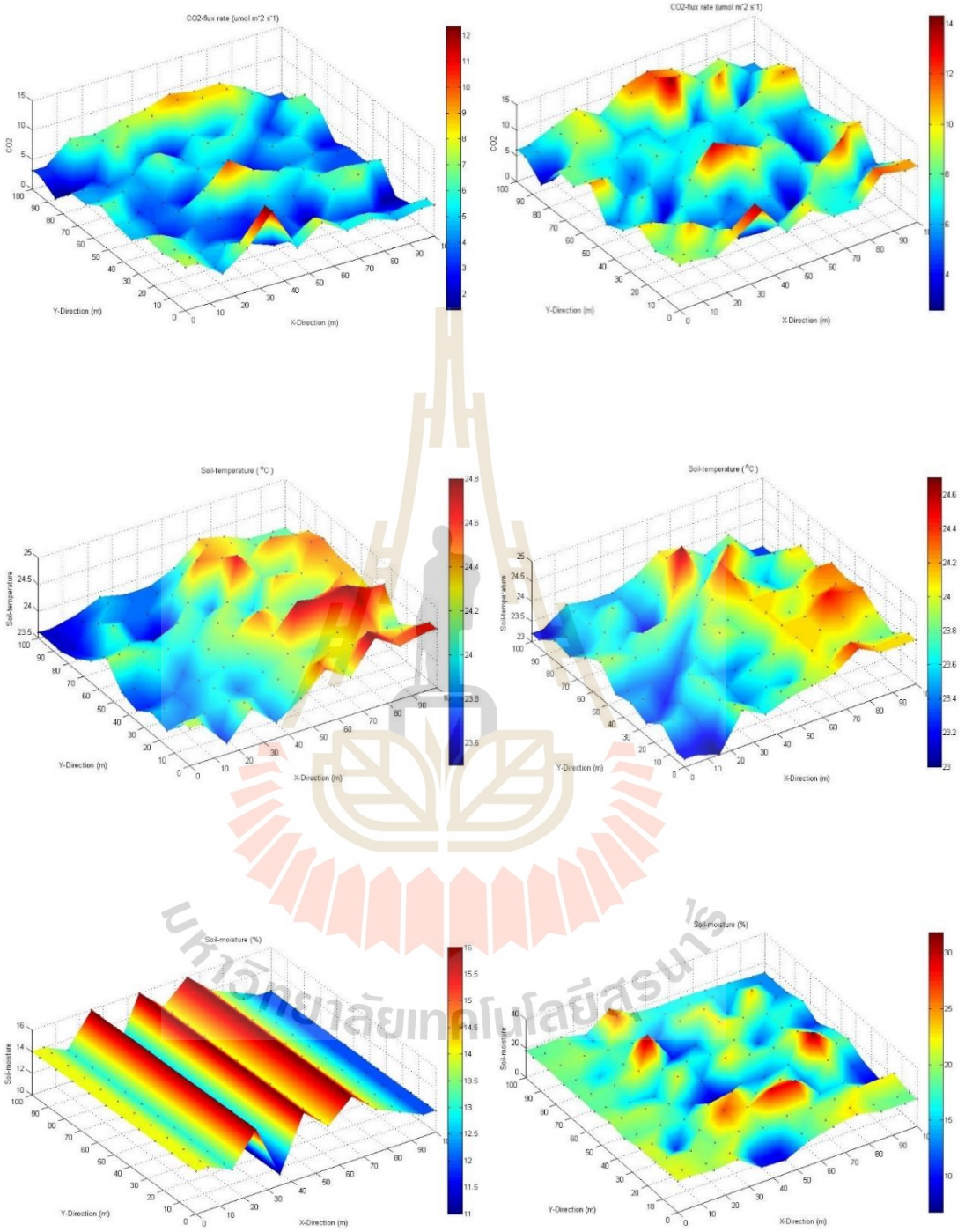

Figure 4.16 Distribution maps of soil respiration (μmol CO_2 m^{-2} s^{-1}) (Top), soil temperature (°C) (Center), and soil moisture content (%) (Bottom) in dry season 2014 (Left) and wet season 2015 (Right) from the main plot 5.

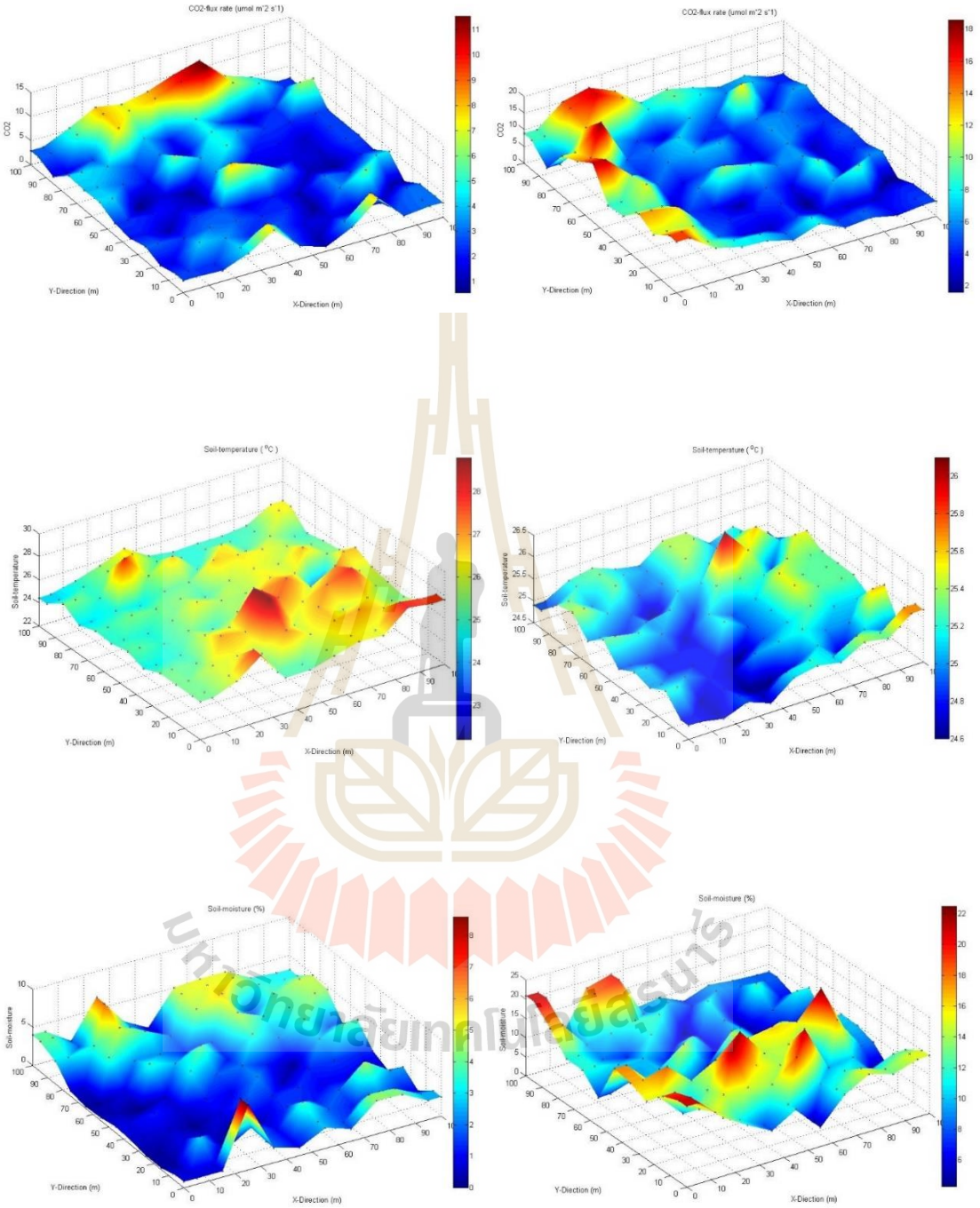

Figure 4.17 Distribution maps of soil respiration (µmol CO_2 m^{-2} s^{-1}) (Top), soil temperature (°C) (Center), and soil moisture content (%) (Bottom) in dry season 2016 (Left) and wet season 2016 (Right) from the main plot 5.

The overall mean of soil respiration rate was 6.57 ± 4.29 µmol CO_2 m^{-2} s^{-1}, with the mean of variation ranged from 2.66 to 11.72 µmol CO_2 m^{-2} s^{-1} from the main plots. The distribution estimates of soil respiration rates displayed a positive skewed frequency distribution with a skewness of 2.065 ± 0.05 (Figure 4.18). It was a maximum range of 42.68 µmol CO_2 m^{-2} s^{-1}. The temporal pattern of soil respiration rate was changed by seasonality in the fluctuation range of the soil temperature and soil moisture (Figure 4.19).

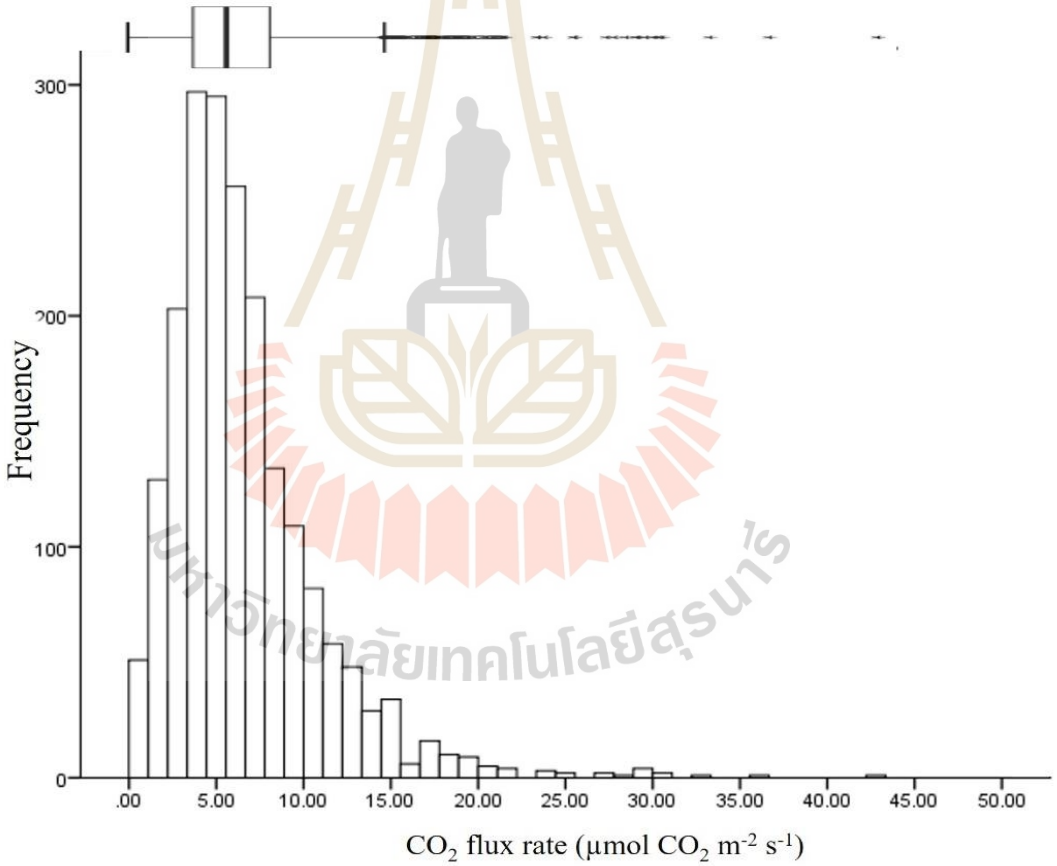

Figure 4.18 Frequency distribution of the soil respiration rate from the five main plots in DEF. The box plot indicates the median as a vertical line is drawn at the box between the distributions of data set, and "whiskers" left and right the box show the locations of the minimum and maximum, respectively.

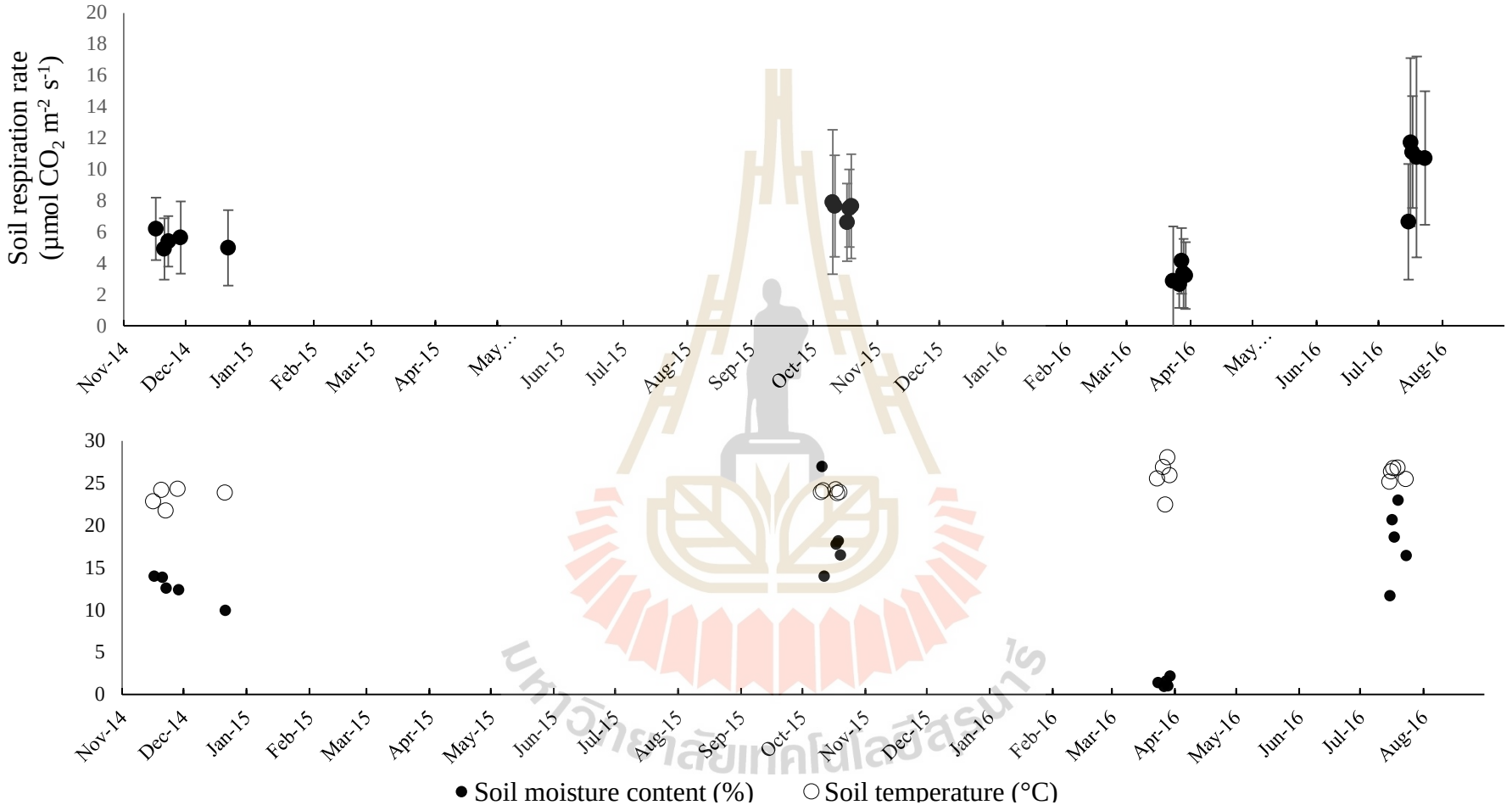

Figure 4.19 Seasonal change in contribution to the means of soil respiration, soil temperature, and soil moisture content during November 2014 to August 2016.

Soil respiration rates from the main plots were significantly different between dry season and wet season among the years (Table 4.2). The mean of the annual ground soil respiration rate was significantly higher twice in the wet season (8.81 ± 4.5 µmol CO_2 m^{-2} s^{-1}) than dry season (4.33 ± 2.5 µmol CO_2 m^{-2} s^{-1}). With the average of soil temperature and soil moisture were 24.54 ± 0.71°C and 7.02 ± 0.78% in the dry season, respectively, and which were 25.02 ± 0.42% and 18.40 ± 0.42 in the wet season, respectively. The distribution of data set display as a box plot as show in Figure 4.20.

Table 4.2 Comparison of soil respiration rate between plot, season, and year.

Source of variation	Soil respiration rate (µmol CO_2 m^{-2} s^{-1})		
	df	*F*	*P*
Plot	4	14.239	**0.000**
Season	1	916.044	**0.000**
Year	1	4.383	**0.036**
Plot * Season	4	6.701	**0.000**
Plot * Year	4	7.242	**0.000**
Season * Year	1	277.163	**0.000**
Plot * Season * Year	4	15.672	**0.000**

Statistically significant *P* – value are in bold. The comparison test was determined by ANOVA.

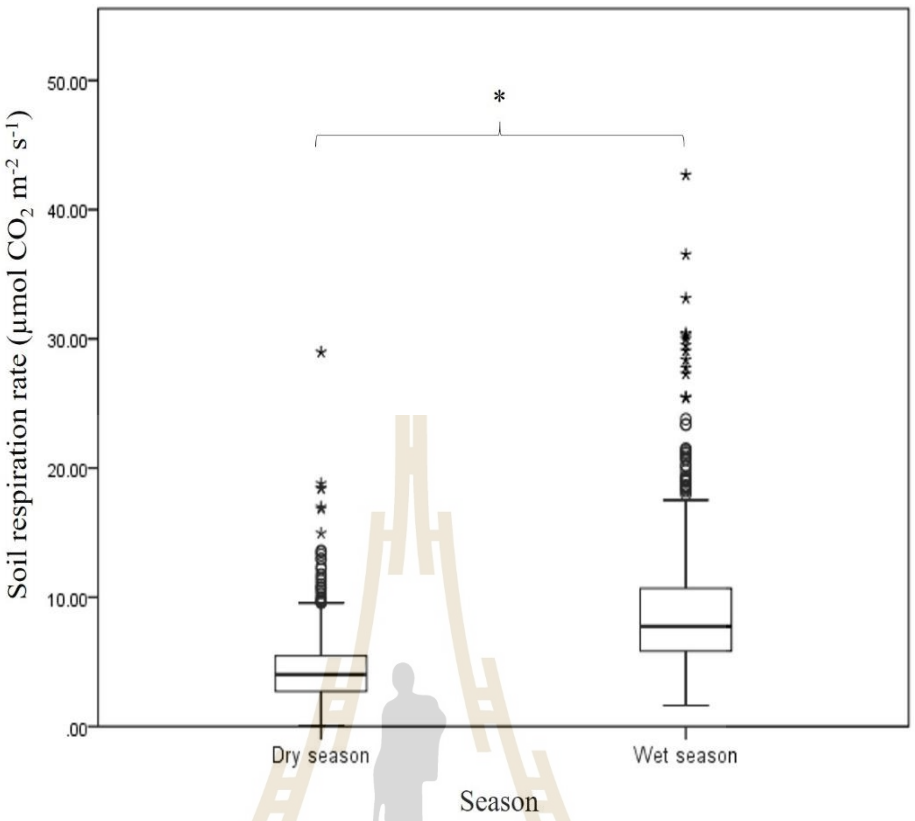

Figure 4.20 Box plot showed the simulated variability of soil respiration rates in dry and wet season. Significant difference between dry and wet seasons using t – test (P< 0.001) is indicated by asterisk.

Seasonal and yearly variation of soil respiration showed significantly different between the seasons and years (P< 0.001) (Figure 4.21). In the first year, the means of soil respiration rates were 5.41 ± 2.1 and 7.42 ± 3.3 5 µmol CO_2 m^{-2} s^{-1} in dry and wet seasons, respectively. For the second year, the soil respiration rates were mean of 3.25 ± 2.4 and 10.20 ± 5.1 5 µmol CO_2 m^{-2} s^{-1} in dry and wet seasons, respectively.

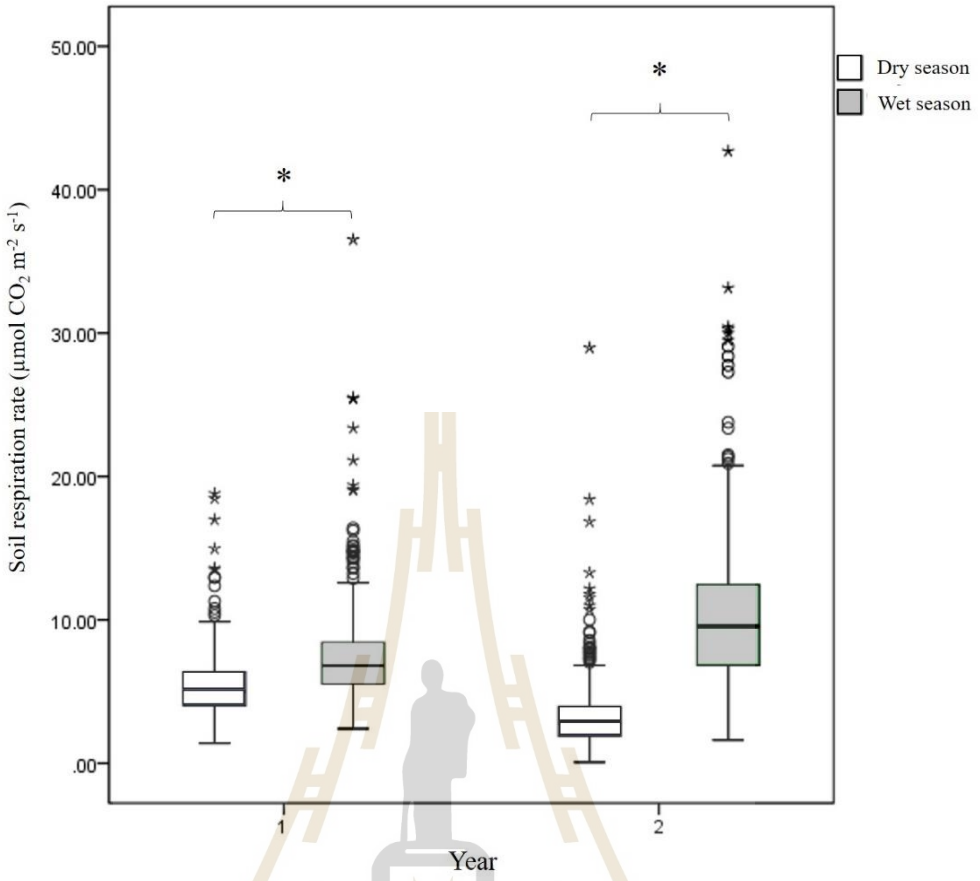

Figure 4.21 Box plot of soil respiration rates at the different seasons and years. Asterisks indicate significant difference between dry and wet season in each year by using paired t – test ($P< 0.001$).

Soil respiration rates of the main plots were significantly different between the seasons in each year that was tested by paired t – test ($P< 0.01$) as shown in Figure 4.22. The soil respiration rates were significant difference between the seasons in a year from each main plot as well as the high rates with high percentage of soil moisture contents caused by peak rain and rainy season.

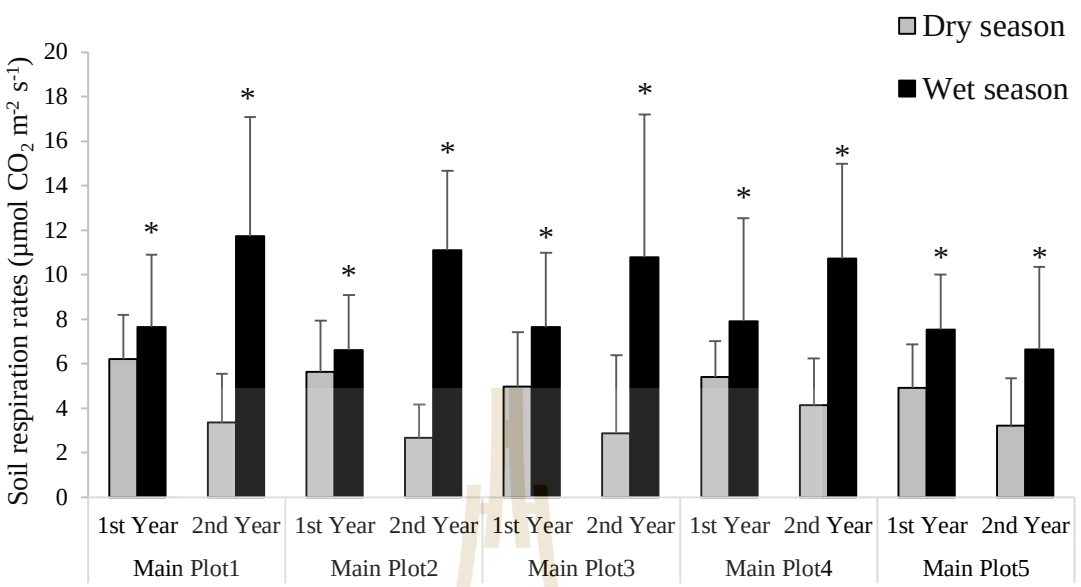

Figure 4.22 Comparison of seasonal soil respiration from the main plots in dry and wet seasons in each year. Asterisks indicate significant difference between dry and wet season in each year by using paired t – test ($P< 0.01$).

4.3 Relationship of Soil Respiration and Soil Temperature and Soil Moisture Content

Soil respiration, together with soil temperature and soil moisture, showed strong seasonal variations with higher rates in the hot humid seasons and lower values in the cool dry seasons. Soil respiration rates were significantly positive correlated with both soil temperatures (R = 0.053, $P< 0.05$) and soil moisture contents (R = 0.452, $P< 0.001$) from the main plots that were shown in Figures 4.23 and 4.24, respectively.

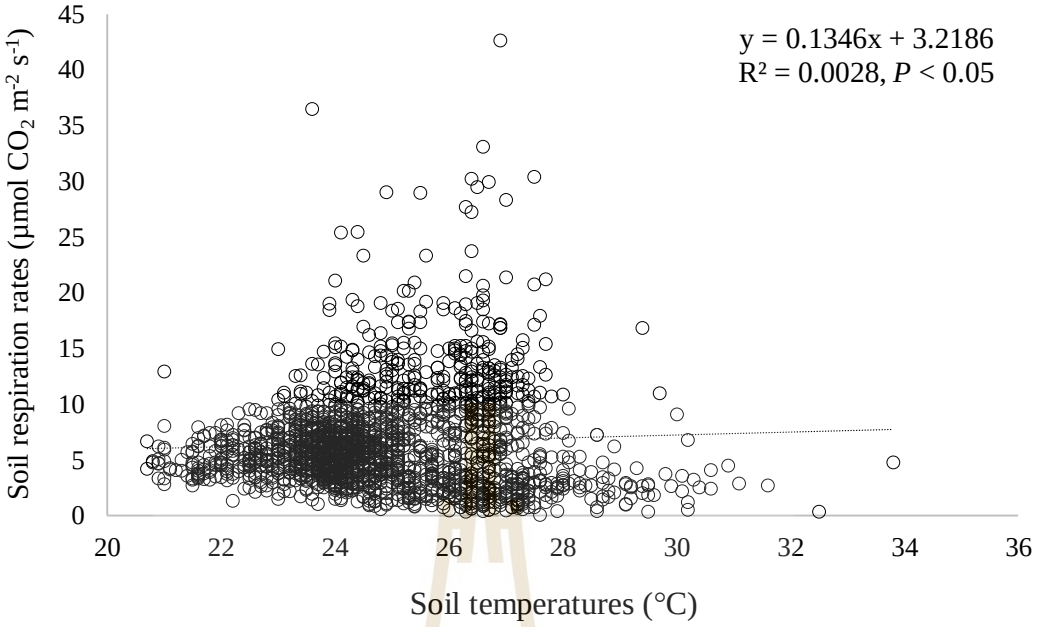

Figure 4.23 Relationship between soil respiration rates and soil temperatures from the main plots.

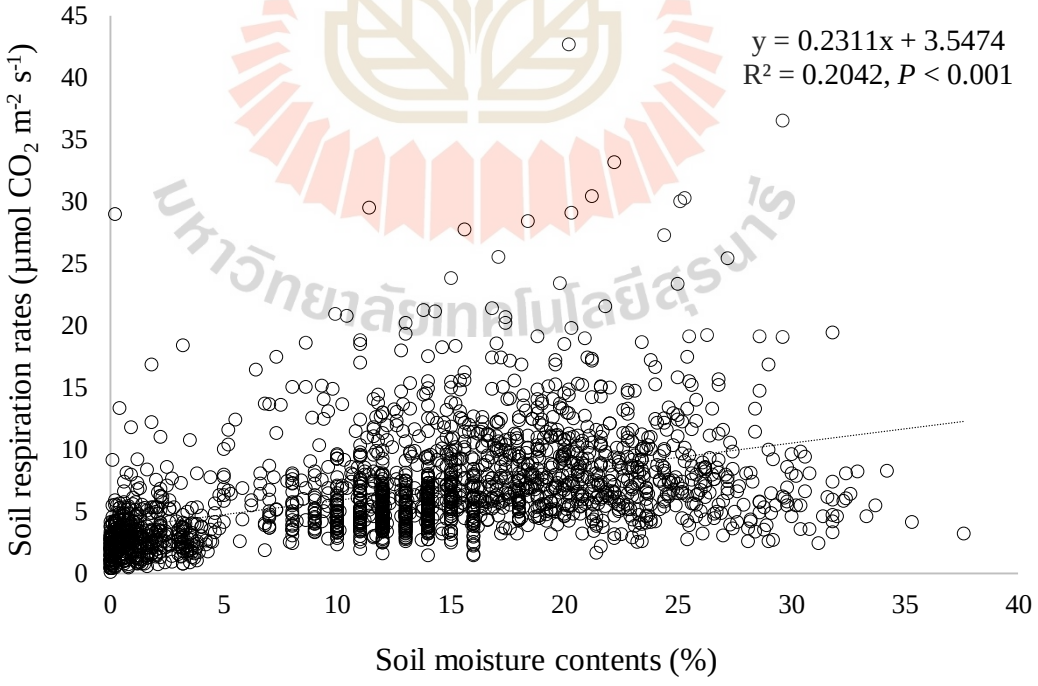

Figure 4.24 Relationship between soil respiration rates and soil moisture contents from the main plots.

Generally, soil respiration rate increased with increasing soil temperature and soil moisture content (e.g., Lloyd and Taylor, 1994; Xu and Qi, 2001; Qi et al., 2002; Reichstein et al., 2002). Furthermore, soil respiration rates were negatively correlated with soil temperatures and soil moisture contents, it was decreased in conditions where soil temperatures were higher than 27°C in dry season (Figure 4.25), and soil moisture contents were greater than 21% in wet season (Figure 4.26). According to Adachi et al (2009), the soil respiration rate was also decreased with increasing of soil moisture content at more than 21% in diurnal variation, and soil respiration rates increased with decreasing soil temperature in dry season that were not water available for the microbial activity. On the other hand, the relationship between soil respiration rate and soil moisture content that showed significant positive with the soil moisture content was less than 18% and showed significant negative when soil moisture content was more than 18% (Hasin et al., 2014). This variability in the timing and magnitude of precipitation events can effect soil respiration. High soil moisture content creates a barrier at the soil atmosphere surface, which could inhibit the diffusion of CO_2 out of the soil (Sotta et al., 2004).

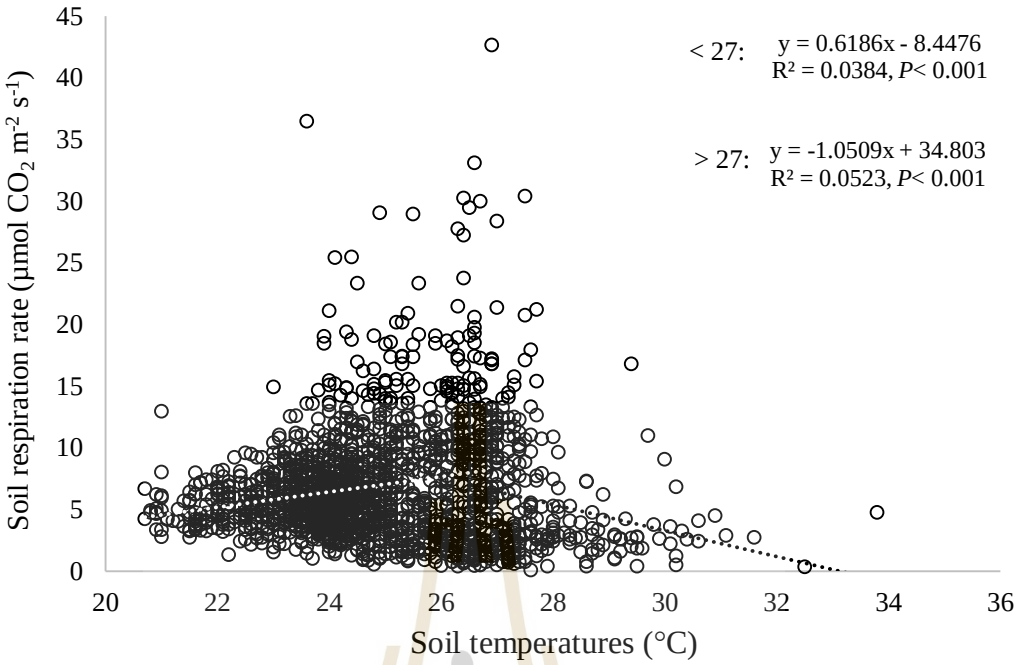

Figure 4.25 Changes in soil respiration with the soil temperature. The regression was run separately for soil temperature (< 27°C and > 27°C).

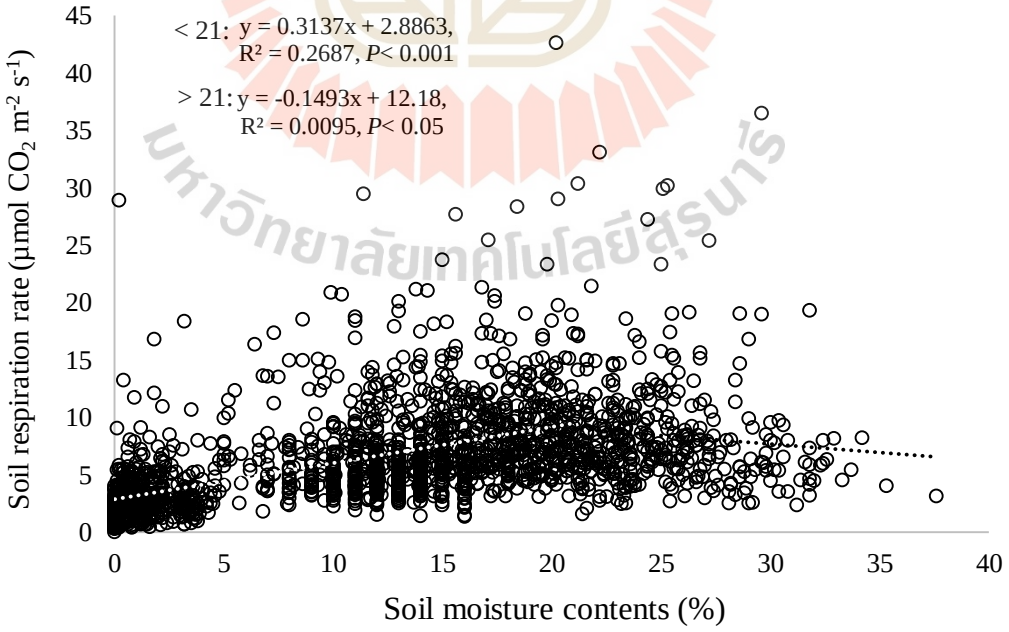

Figure 4.26 Changes in soil respiration with the soil moisture content. The regression was run separately for soil moisture content (< 21% and > 21%).

4.4 CO_2 Efflux from Termite Mounds

CO_2 efflux from both termiteria groups, thick – wall and thin – wall mounds were measured in dry season and wet season. For the thick – wall mound group, CO_2 efflux rates were only measured from termiteria of *M. carbonarius* because the mound of *M. annandalei* is not occurring very often and their mounds are mostly flat to the soil surface, there is a distinct mound in this reserve.

4.4.1 CO_2 efflux from termitaria of the thick – wall mound (*M. carbonarius*)

The frequency distribution of CO_2 efflux rates from the termitaria of *M. carbonarius* with very sizes in each seasons shown in Figure 4.27.

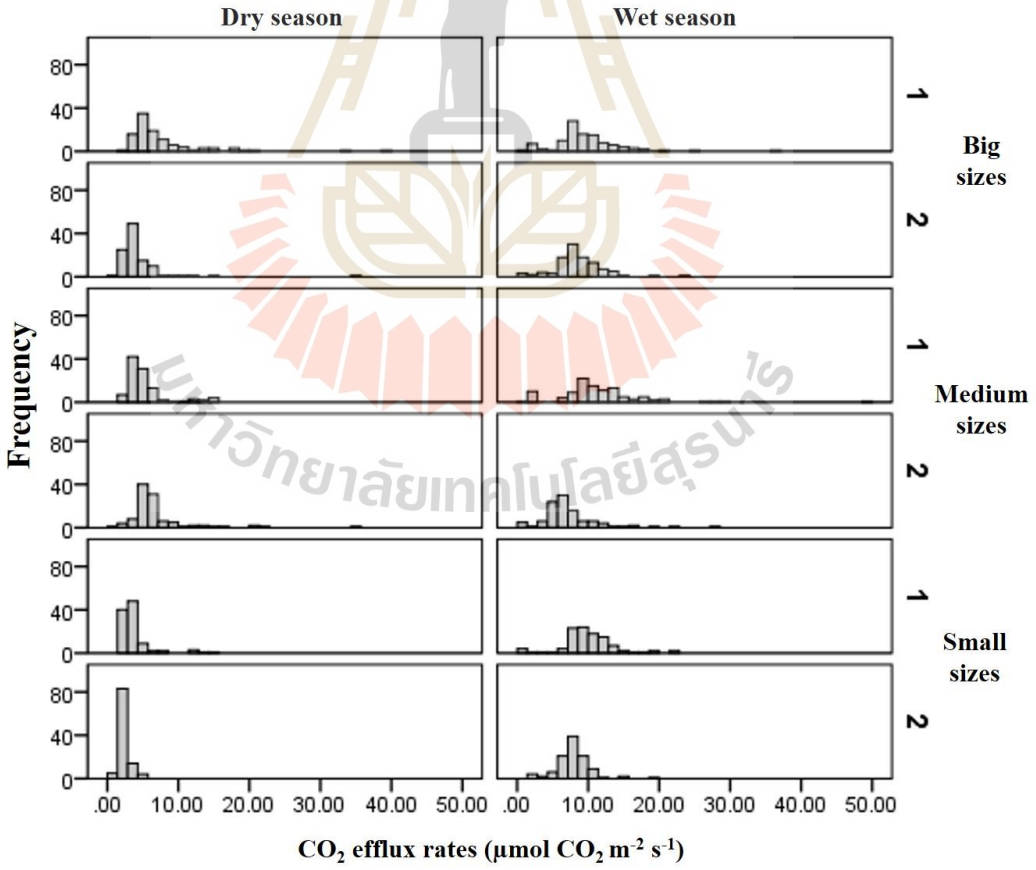

Figure 4.27 The frequency distribution of CO_2 efflux rates from the termitaria of *M. carbonarius* with very sizes in dry and wet season.

The total mean of CO_2 efflux rate from 6 termitaria of *M. carbonarius* and surrounding soils in each 2 mounds of small, medium, and big sizes were 7.10 ± 4.74 µmol CO_2 m^{-2} s^{-1} which of 5.03 ± 4.03 µmol CO_2 m^{-2} s^{-1} in dry season and 9.17 ± 4.49 µmol CO_2 m^{-2} s^{-1} in wet season. CO_2 efflux rates from 6 mounds of *M. carbonarius* from its mounds and surrounding soils of each size in dry and wet seasons shown in Table 4.3. The distribution estimates of CO_2 efflux rates from the mounds and surrounding soils in each termitaria's size plot that showed in Figure 4.28. Mean of CO_2 efflux rates from the surrounding soil was 7.35 ± 4.72 µmol CO_2 m^{-2} s^{-1} with the large fluctuations of 0.91- 39.66 and 1.52 – 49.37 µmol CO_2 m^{-2} s^{-1}, in dry and wet season, respectively. The mean of CO_2 efflux rates from the mound was 2.94 ± 2.73 µmol CO_2 m^{-2} s^{-1} that showed the range in dry season larger than the wet season with the range of 0.15 – 18.53 and 0.51 – 7.78 µmol CO_2 m^{-2} s^{-1} in dry and wet season, respectively.

CO_2 efflux rates from the mounds and surrounding soils were significantly different from seasonal variation (Table 4.4). The mean of CO_2 efflux rates from the surrounding soils were significantly higher than those the mounds in dry (F = 3.760, P = 0.05) and wet season (F = 141.87, P< 0.001).

CO_2 efflux from soil surrounding soils were higher in wet season than the dry season (F = 436.38, P< 0.001). While CO_2 efflux rates from the mounds were higher in dry season than wet season (F = 4.22, P = 0.04). The distribution of seasonal variation in CO_2 efflux rate data display as a box plot as shown in Figure 4.29. Also, the map of CO_2 efflux rates, and its soil temperatures and soil moisture contents from the termitaria of *M. carbonarius* plots in each size of both of season was shown in Figures 4.30, 4.31, 4.32, 4.33, 4.34, and 4.35.

Table 4.3 CO_2 efflux rates (µmol CO_2 m^{-2} s^{-1}; mean ± SD) from the 6 plots of *M. carbonarius* (MC) (mound and surrounding soil) with very of sizes in dry and wet seasons.

Plot	Volume of mound (m^3)	Dry season		Wet season		
		Mound	Surrounding soil	Mound	Surrounding soil	Total mean
Small MC1	0.09	5.34	3.69	1.44	10.54	6.90
Small MC2	0.02	3.07	2.32	3.94	8.20	5.16
Medium MC1	0.40	2.48	5.43	1.67	12.24	8.42
Medium MC2	0.37	1.90	7.11	1.06	9.85	7.05
Big MC1	1.52	6.97	7.66	2.03	10.14	8.65
Big MC2	0.75	3.41	4.39	2.20	8.87	6.41
Seasonal mean		3.86±3.35	5.10±4.06	2.06+1.52	9.97±4.24	
Overall mean		5.03 ± 4.03		9.17 ± 4.49*		7.10±4.74

* Significant difference between dry season and wet season of termitaria.

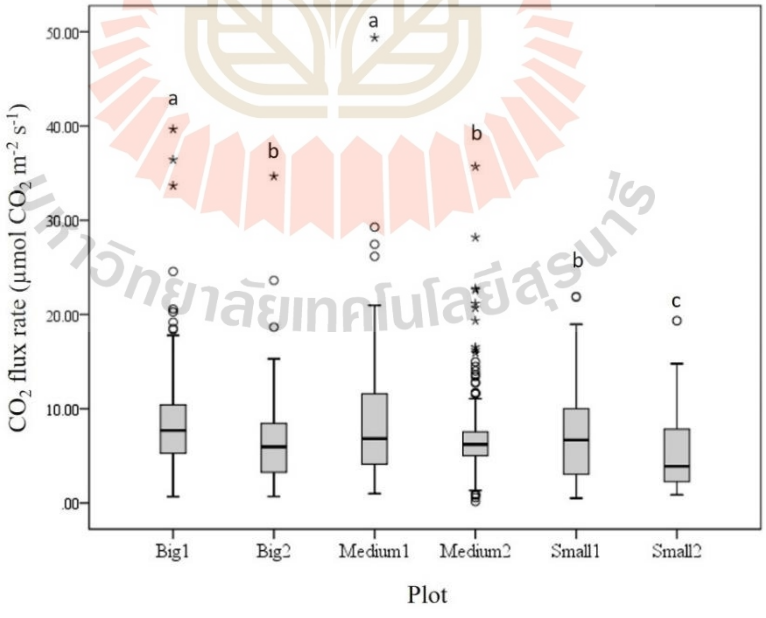

Figure 4.28 Box plot of distribution of CO_2 efflux rates from the termitaria of *M. carbonarius* in each size. Different letters indicates a significant difference among the plots at $P = 0.031$ by one – way ANOVA test.

Table 4.4 Comparison of CO_2 efflux between plot, location (mound and surrounding soil), and season.

Source of variation	CO_2 efflux rates (µmol CO_2 m^{-2} s^{-1})		
	df	*F*	*P*
Plot	5	2.464	**0.031**
Season	1	9.027	**0.003**
Location	1	95.130	**0.001**
Plot * Season	5	2.595	**0.024**
Plot * Location	5	2.593	**0.024**
Season* Location	1	48.94	**0.001**
Plot * Season * Location	5	1.984	0.078

Statistically significant *P* – value are in bold.

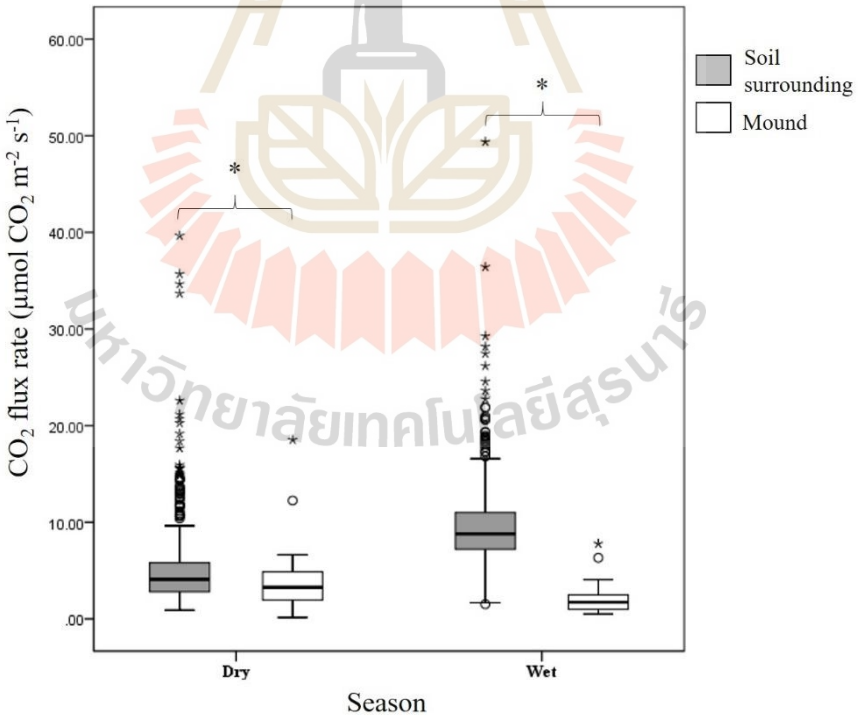

Figure 4.29 Box plot of distribution of seasonal variation in CO_2 efflux rates from termitaria of *M. carbonarius* in dry and wet season. Significant differences are indicated by asterisk (*P* = 0.001).

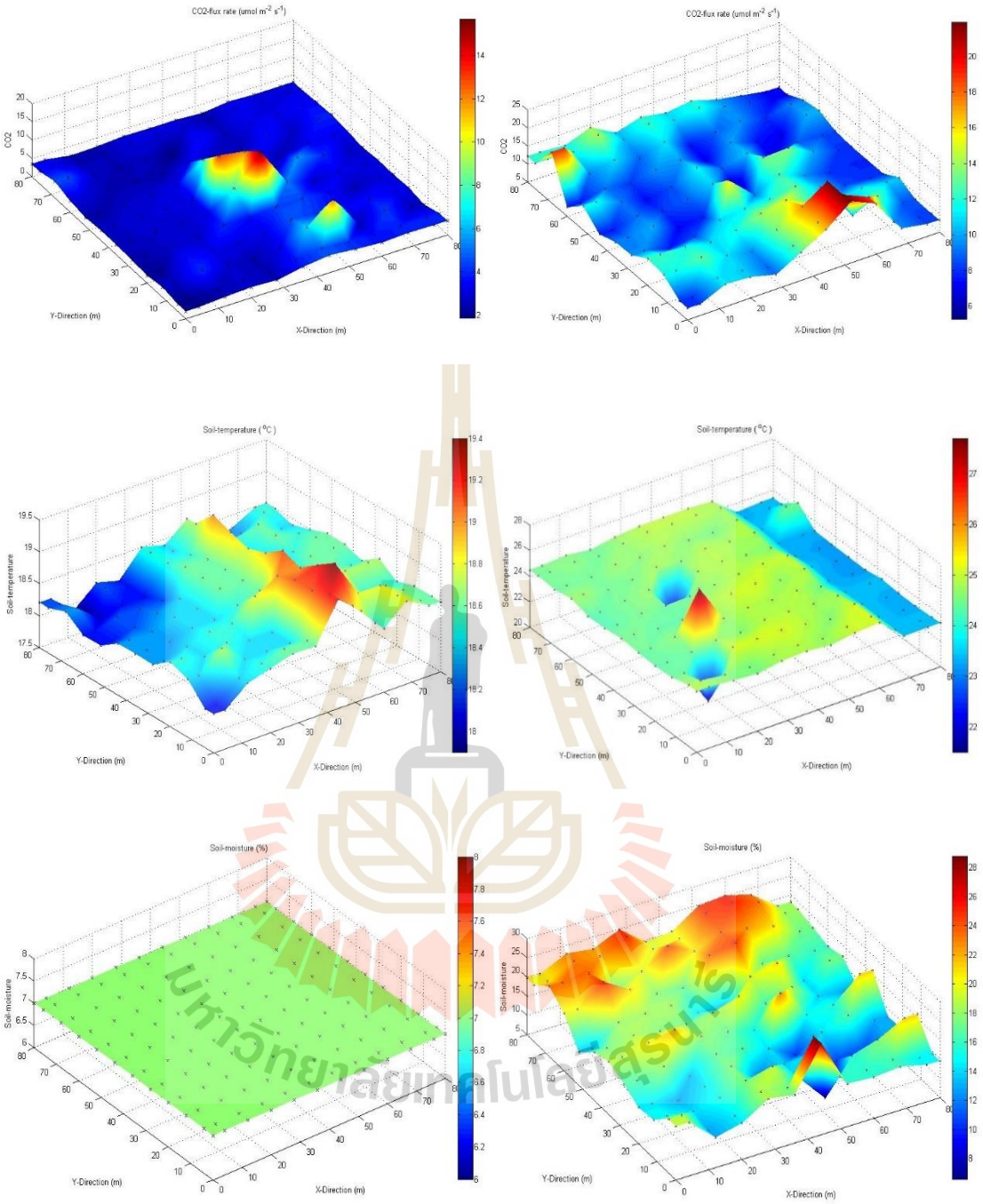

Figure 4.30 The maps of CO_2 efflux rates (µmol CO_2 m^{-2} s^{-1}) (Top), and its soil temperatures (°C) (Center) and soil moisture contents (%) (Bottom) from the termitaria of *M. carbonarius* (Small size 1) in dry (Left) and wet (Right) season. No data for soil temperature and soil moisture content on the mound.

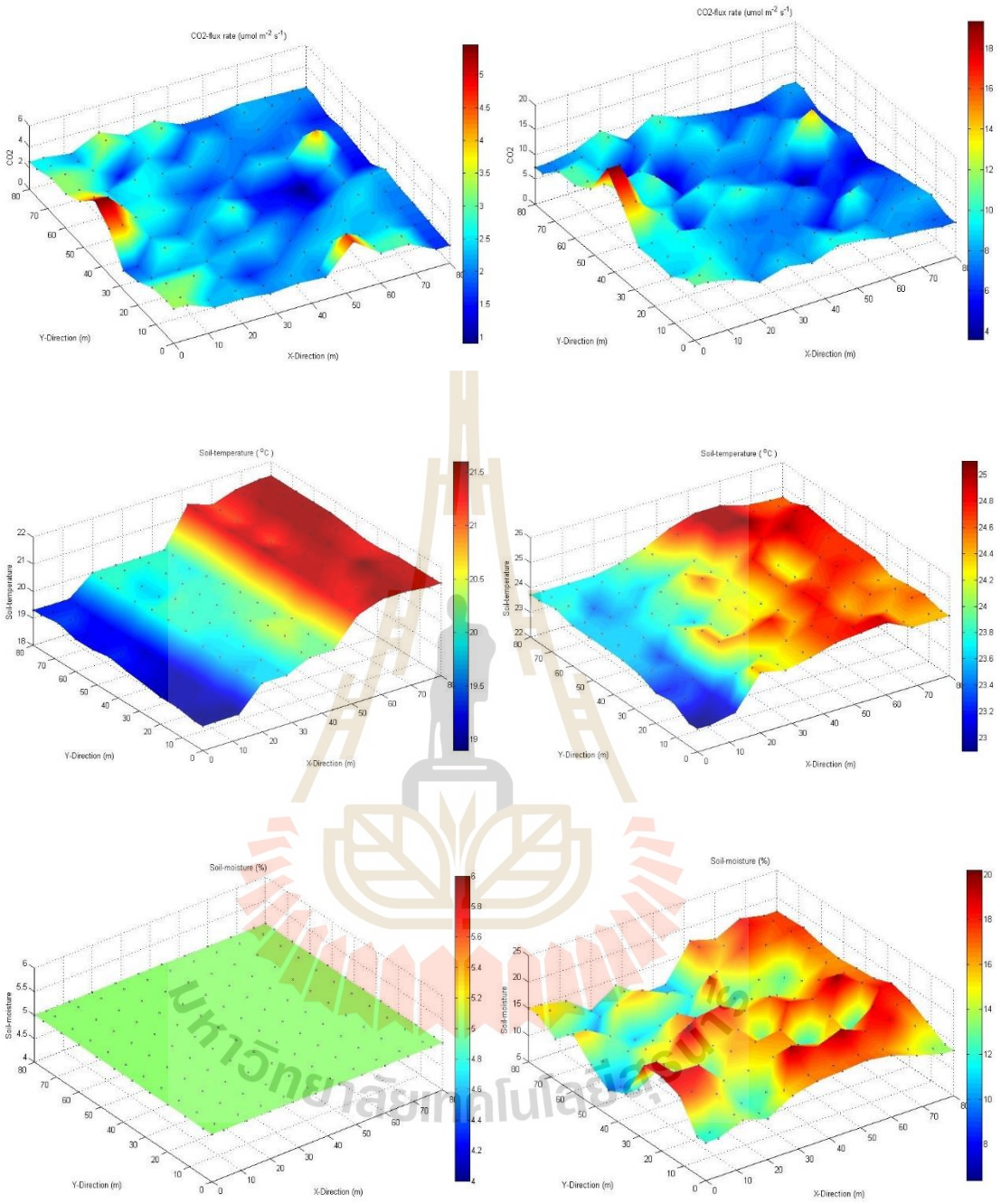

Figure 4.31 The maps of CO_2 efflux rates (µmol CO_2 m^{-2} s^{-1}) (Top), and its soil temperatures (°C) (Center) and soil moisture contents (%) (Bottom) from the termitaria of *M. carbonarius* (Small size 2) in dry (Left) and wet (Right) season. No data for soil temperature and soil moisture content on the mound.

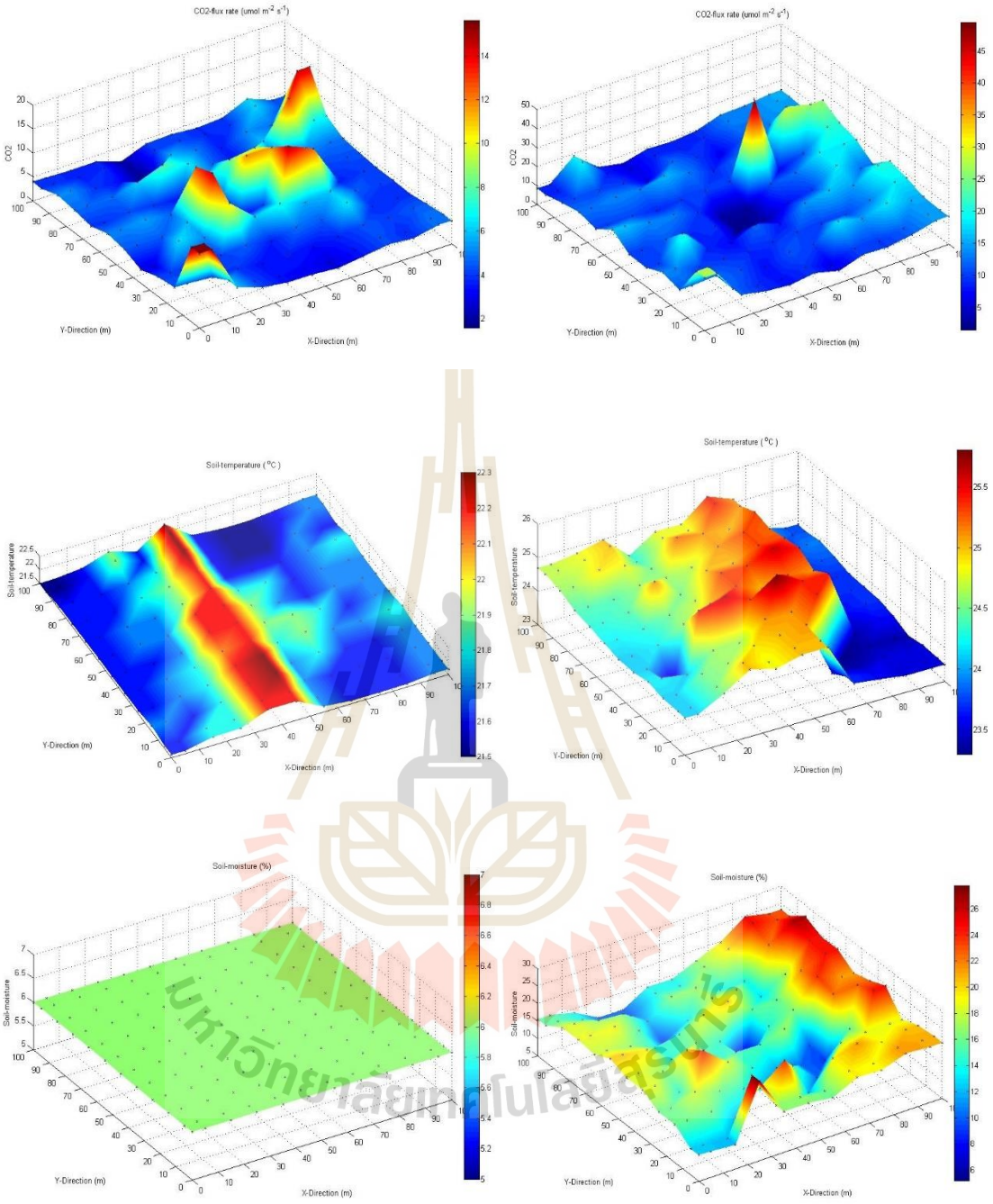

Figure 4.32 The maps of CO_2 efflux rates (μmol CO_2 m^{-2} s^{-1}) (Top), and its soil temperatures (°C) (Center) and soil moisture contents (%) (Bottom) from the termitaria of *M. carbonarius* (Medium size 1) in dry (Left) and wet (Right) season. No data for soil temperature and soil moisture content on the mound.

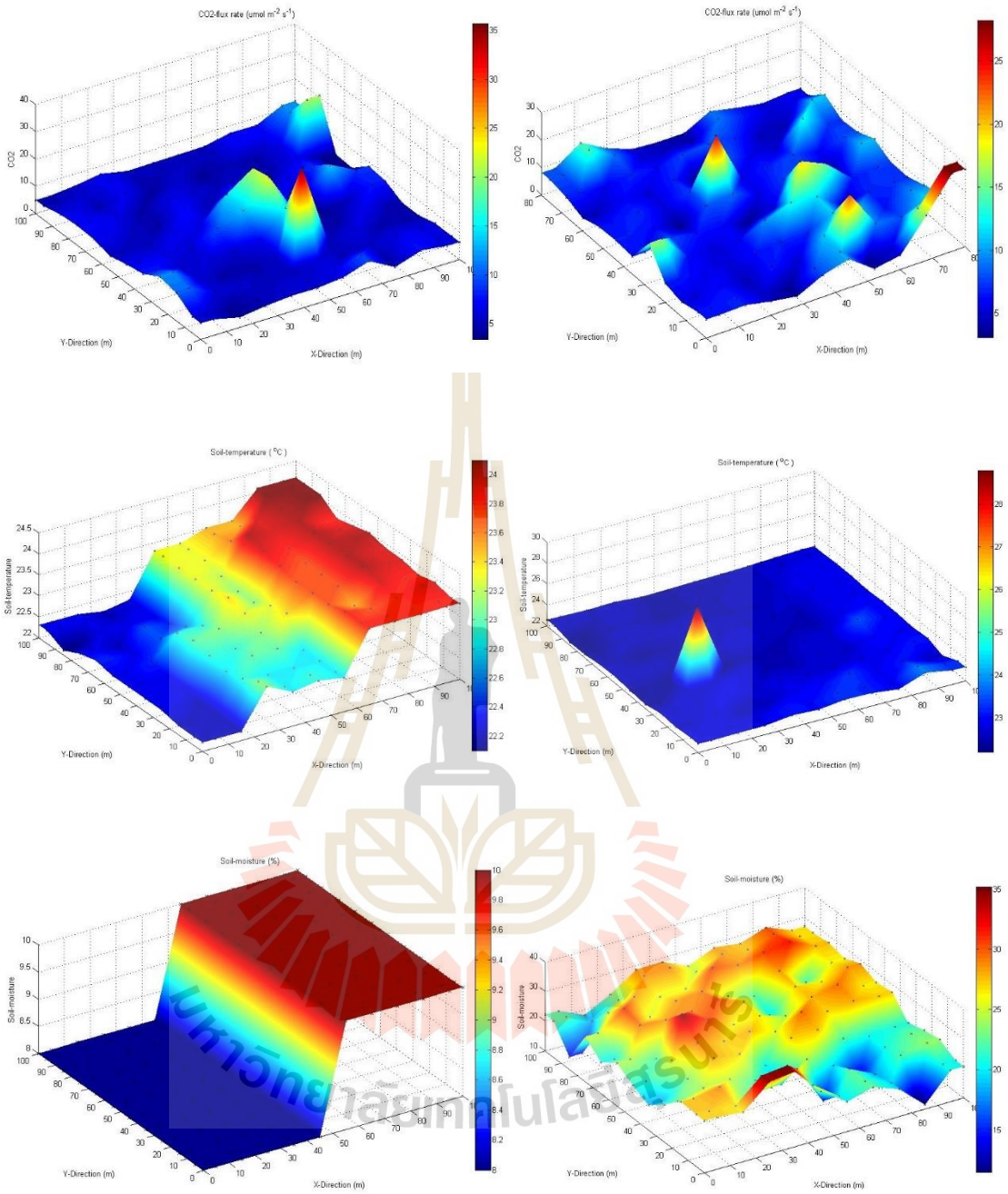

Figure 4.33 The maps of CO_2 efflux rates (μmol CO_2 m^{-2} s^{-1}) (Top), and its soil temperatures (°C) (Center) and soil moisture contents (%) (Bottom) from the termitaria of *M. carbonarius* (Medium size 2) in dry (Left) and wet (Right) season. No data for soil temperature and soil moisture content on the mound.

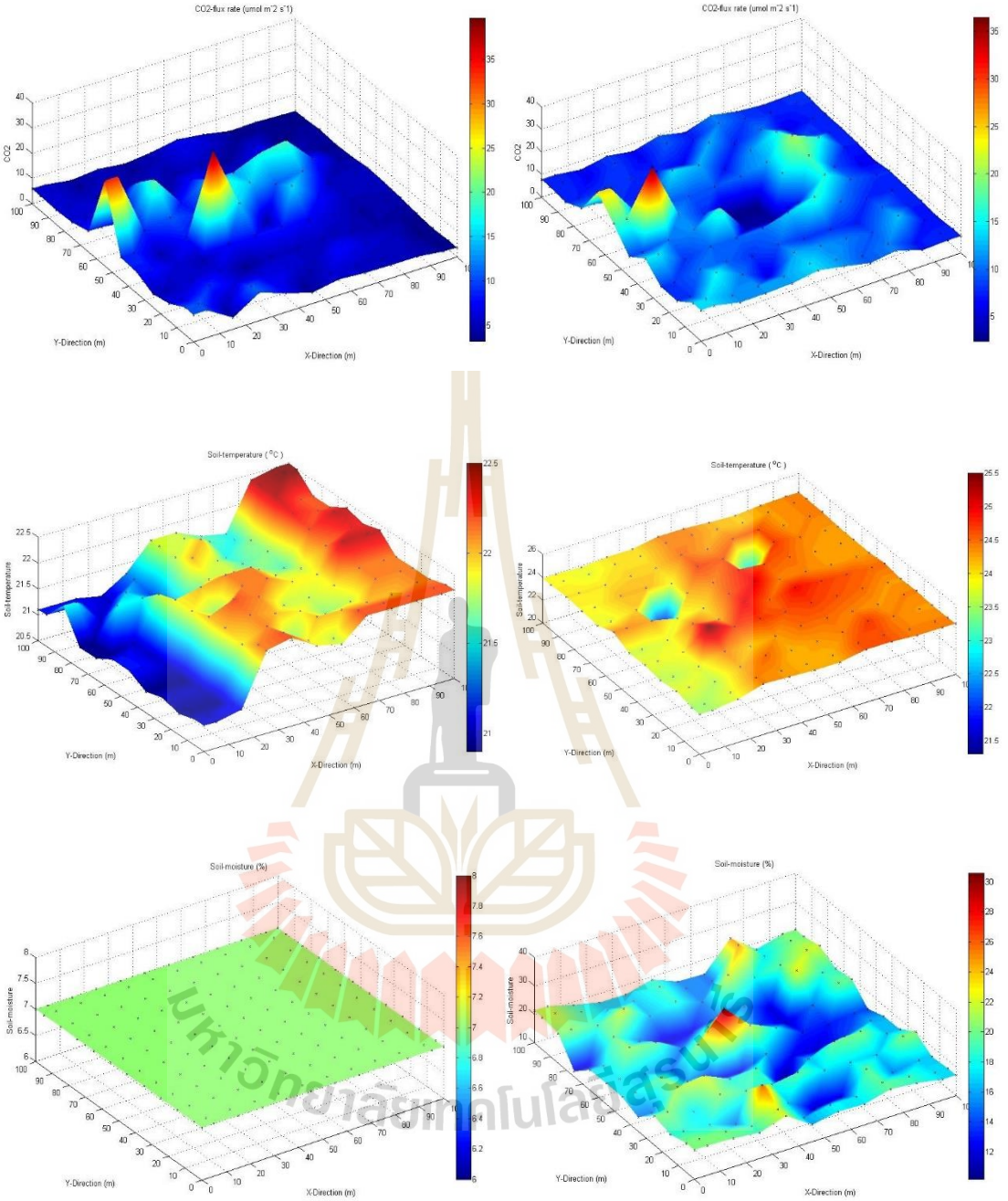

Figure 4.34 The maps of CO_2 efflux rates (µmol CO_2 m^{-2} s^{-1}) (Top), and its soil temperatures (°C) (Center) and soil moisture contents (%) (Bottom) from the termitaria of *M. carbonarius* (Big size 1) in dry (Left) and wet (Right) season. No data for soil temperature and soil moisture content on the mound.

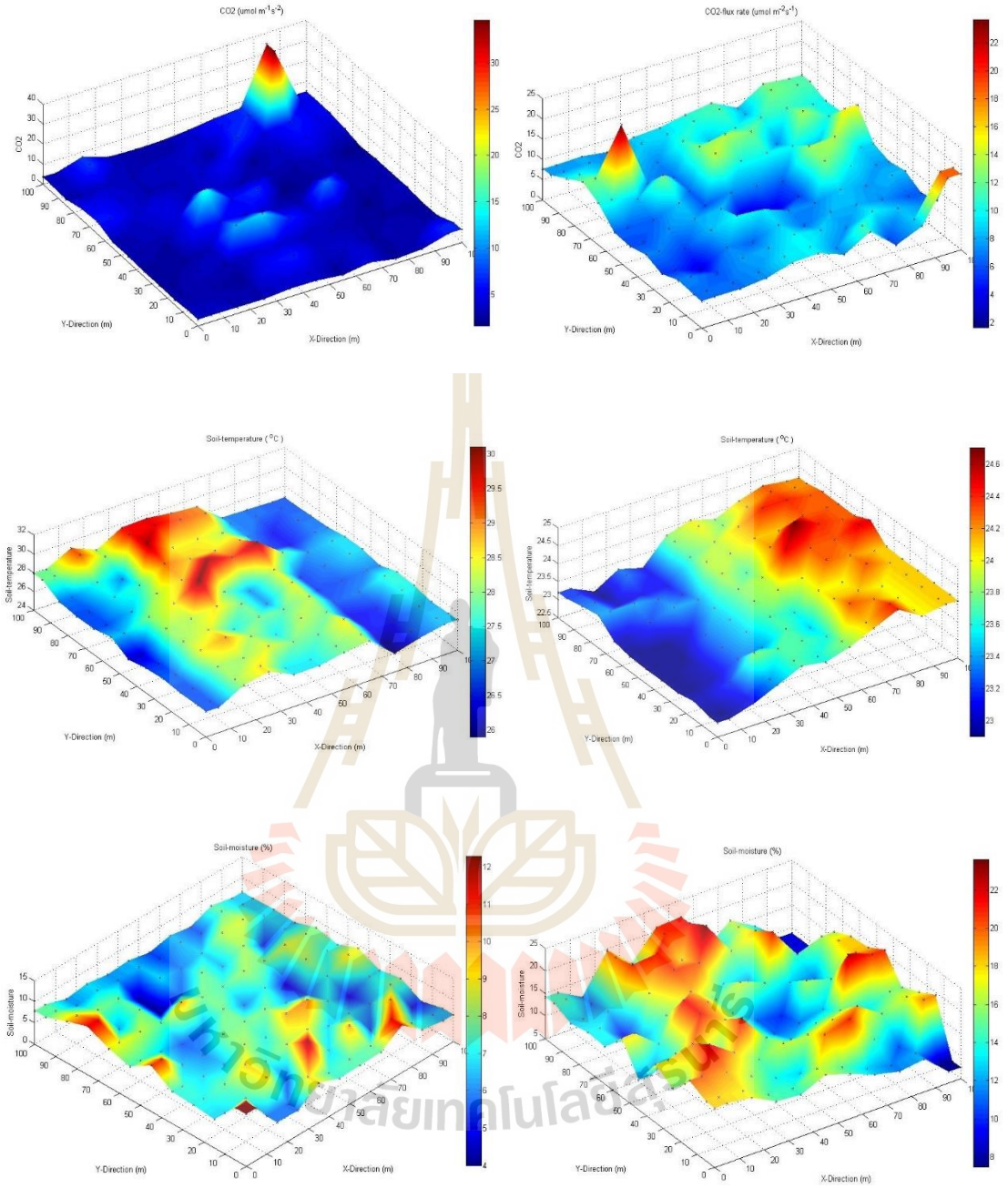

Figure 4.35 The maps of CO_2 efflux rates (µmol CO_2 m^{-2} s^{-1}) (Top), and its soil temperatures (°C) (Center) and soil moisture contents (%) (Bottom) from the termitaria of *M. carbonarius* (Big size 2) in dry (Left) and wet (Right) season. No data for soil temperature and soil moisture content on the mound.

4.4.2 CO_2 efflux from termitaria of the thin – wall mound

CO_2 efflux rates (µmol CO_2 m^{-2} s^{-1} ± SD) of the thin wall mounds were measured from 5 dominant species. The averages of CO2 efflux rates from *Globitermes sulphureus* (GS) (37.71 ± 14.68) and *Microcerotermes crassus* (Mcc) (15.50 ± 7.84) were significant difference from among the thin – wall species, while CO_2 efflux rates from *Termes comis* (TC) (6.45 ± 2.35), *Termes propinguus* (TP) (1.98 ± 1.78), and *Dicuspiditermes makhamensis* (DM) (1.79 ± 0.99) were not significant difference (Figure 4.36). Comparison of CO2 efflux between species, location (mound and surrounding soil), and season was tested by ANOVA that showed in Table 4.45.

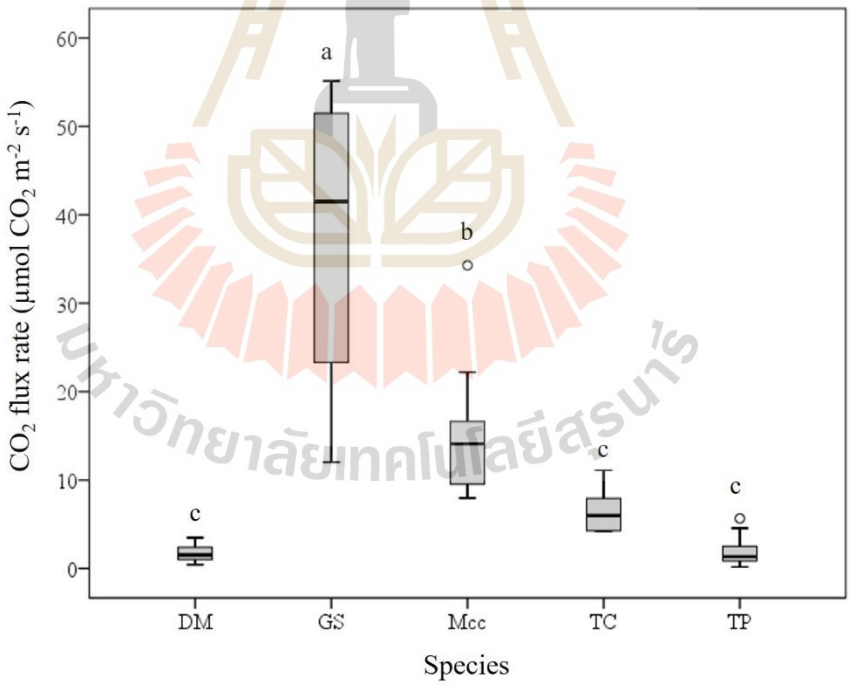

Figure 4.36 Box plot of CO_2 efflux rates from the thin – wall mound in each species, DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus*. Different letters indicate significant of difference among the species was tested by ANOVA with Tukey's HSD post hoc test ($P< 0.05$).

In both of seasons, the mean annual CO_2 efflux rate from the mounds were significant difference between dry and wet seasons for each species nest (P = 0.05) (Figure 4.37) that ranged between 8.98 ± 11.42 – 16.39 ± 18.06 µmol CO_2 m^{-2} s^{-1}, while from the surrounding soils ranged of 2.29 ± 0.89 – 7.84 ± 2.33 µmol CO_2 m^{-2} s^{-1}. There was significantly different between CO_2 efflux from the nests and surrounding soils (control) (Figure 4.38).

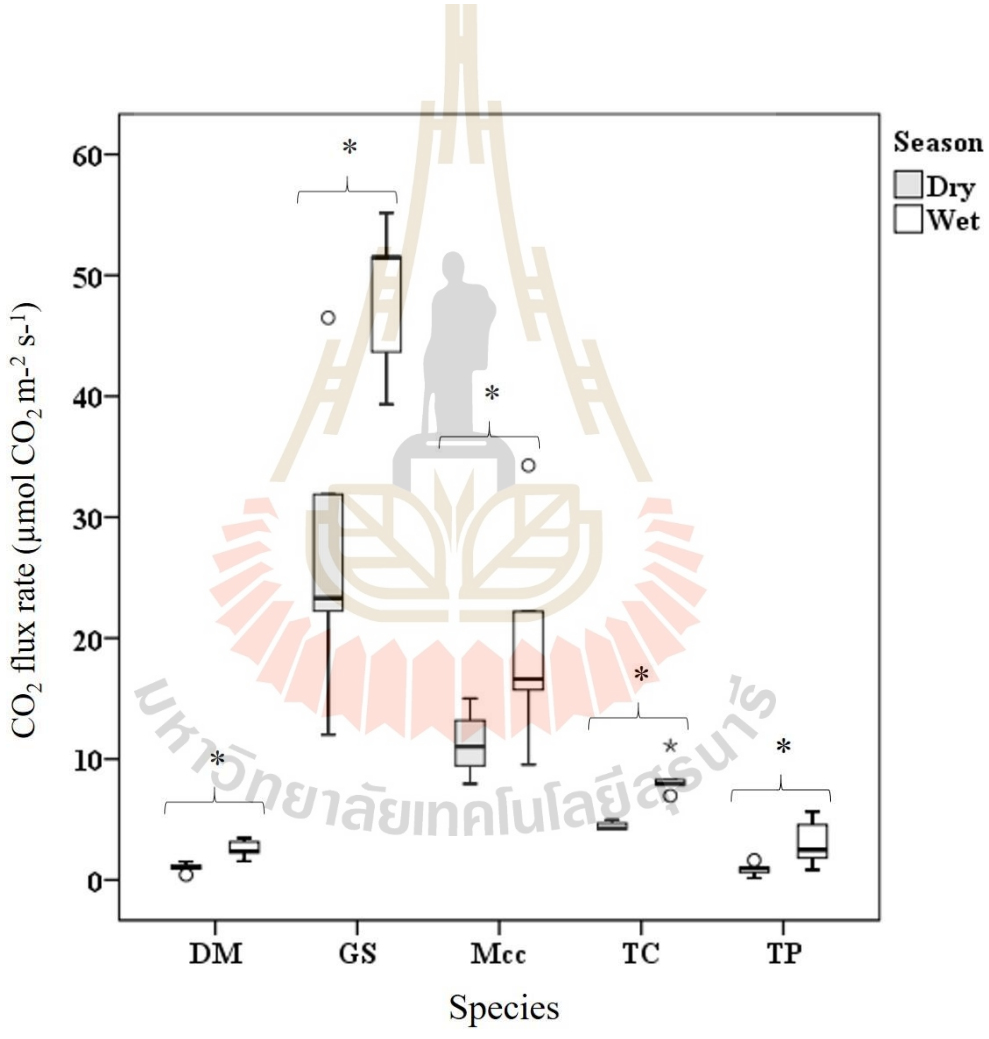

Figure 4.37 Mean of CO_2 efflux rate from the thin wall mounds in dry and wet seasons, DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus*. Asterisk indicates significant difference between dry and wet season in each species at P< 0.05.

Table 4.5 Comparison of CO_2 efflux between species, location (nest and surrounding soil), and season.

Source of variation	CO_2 efflux rates (µmol CO_2 m^{-2} s^{-1})		
	df	*F*	*P*
Species	4	190.662	**0.001**
Season	1	180.740	**0.001**
Location	1	252.380	**0.001**
Species * Season	4	104.937	**0.001**
Species * Location	4	1778.22	**0.001**
Season* Location	1	34.330	**0.049**
Species * Season * Location	4	147.357	**0.001**

Statistically significant *P*-value are in bold.

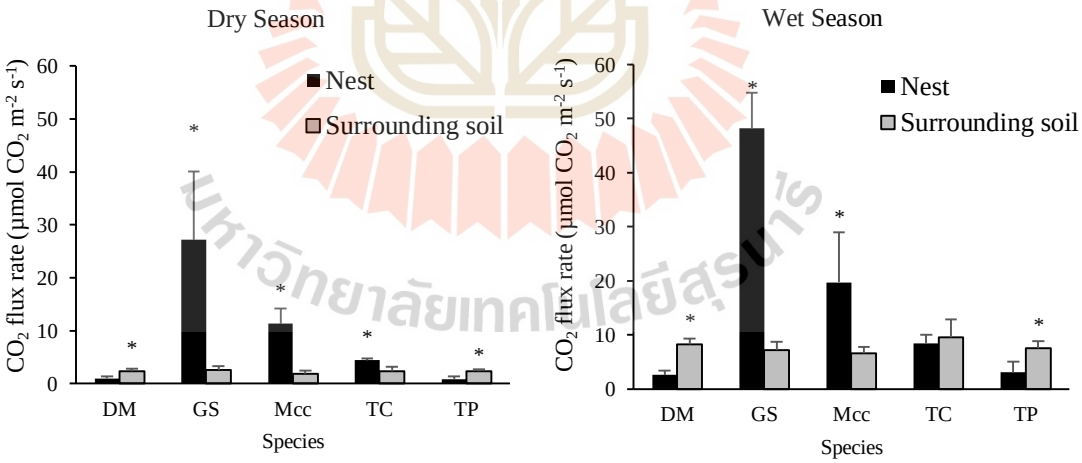

Figure 4.38 CO_2 efflux rates from the thin – wall mounds in each species during dry and wet season, DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus*. Asterisks indicate significant of difference between the nest and surrounding soil in each species which was tested by t - test ($P< 0.001$).

4.4.3 CO_2 efflux from Termite Casts, Fungus Comb and Nest Materials

The fractions of the termitaria CO_2 efflux rates were estimated in the laboratory by respiration from termite populations (divided into castes as small workers, big workers, small soldiers, and big soldiers), fungus combs, and their nest materials. Mean respiration rate of thick and thin – wall termites were showed in Table 4.9.

4.4.3.1 Thick – Wall Mound

Respiration rates of *M. carbonarius* (n = 3) from termite individuals ranged from 8.62 – 16.14 µmol CO_2 g^{-1} h^{-1}, while fungus comb and nest material were 12.08 ± 1.22 µmol CO_2 g^{-1} h^{-1} and 0.128 ± 0.004 µmol CO_2 g^{-1} h^{-1}, respectively. The respiration rates of *M. carbonarius* were significantly highest in small workers (16.15 ± 1.14 µmol CO_2 g^{-1} h^{-1}) (Figure 4.39).

Respiration rates of *M. annandalei* (n = 3) from termite individuals ranged from 7.27 – 47.14 µmol CO_2 g^{-1} h^{-1} while fungus comb and nest material were 7.46 ± 0.83 µmol CO_2 g^{-1} h^{-1} and 0.08 ± 0.03 µmol CO_2 g^{-1} h^{-1}, respectively. The respiration rate of *M. annandalei* was significantly highest in small soldiers (47.14 ± 4.02 µmol CO_2 g^{-1} h^{-1}) (Figure 4.40).

From all the mound proportion, total mean of respiration rates were significantly higher in *M. annandalei* (16.84 µmol CO_2 g^{-1} h^{-1}) than *M. carbonarius* (10.21 µmol CO_2 g^{-1} h^{-1}) ($P< 0.001$).

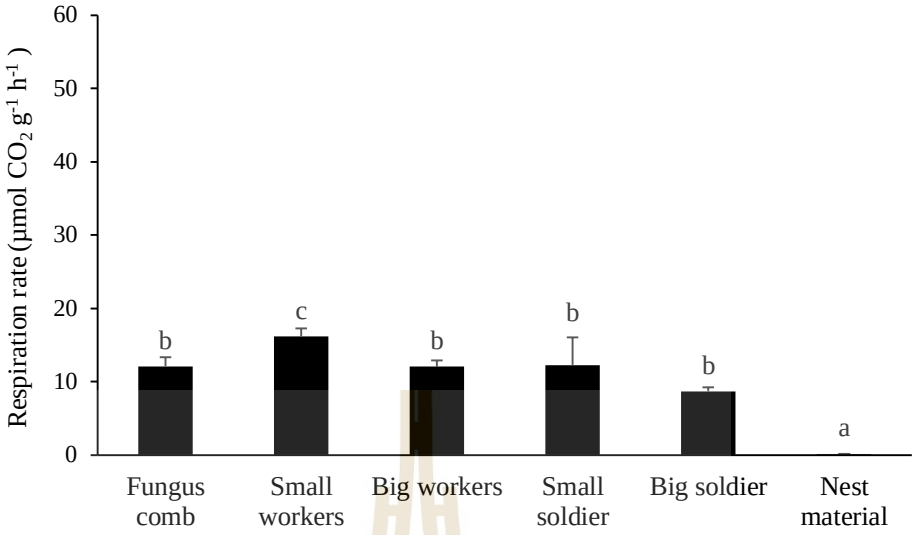

Figure 4.39 Respiration rates and percentages of contribution from *M. carbonarius* represented by termite castes, fungus combs, and their nest materials. Significant differences are indicated by the different letters (P = 0.05, n = 3).

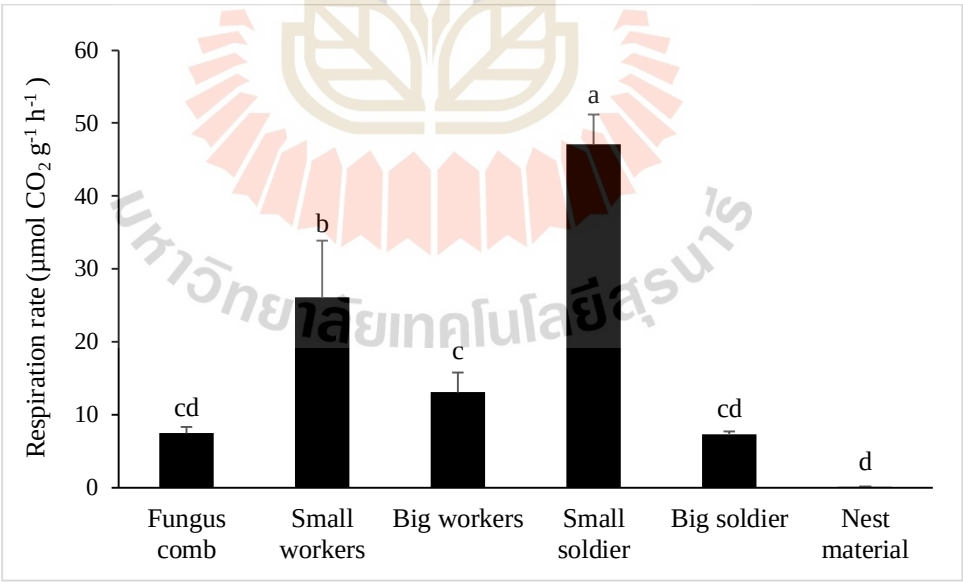

Figure 4.40 Respiration rates and percentages of contribution from *M. annandalei* represented by termite castes, fungus combs, and their nest materials. Significant differences are indicated by the different letters (P = 0.05, n = 3).

4.3.3.2 Thin – Wall Mound

For thin – wall mound, termite individuals (workers and soldiers) and their nest materials were separated for the measurement of respiration rates. The rates of respirations were significantly different between worker, soldier, and nest materials in each species (P = 0.05) (Figure 4.41). However, the total mean of respiration rates from each species were not significantly different at 0.05% which of 13.99 ±11.18, 14.10 ± 12.58, 18.57 ± 16.79, 18.90 ± 17.20, and 19.66 ± 17.84 µmol CO_2 g^{-1} h^{-1} ± SD from *G. sulphureus*, *D. makhamensis*, *T. comis*, *T. propinguus*, and *M. crassus*, respectively.

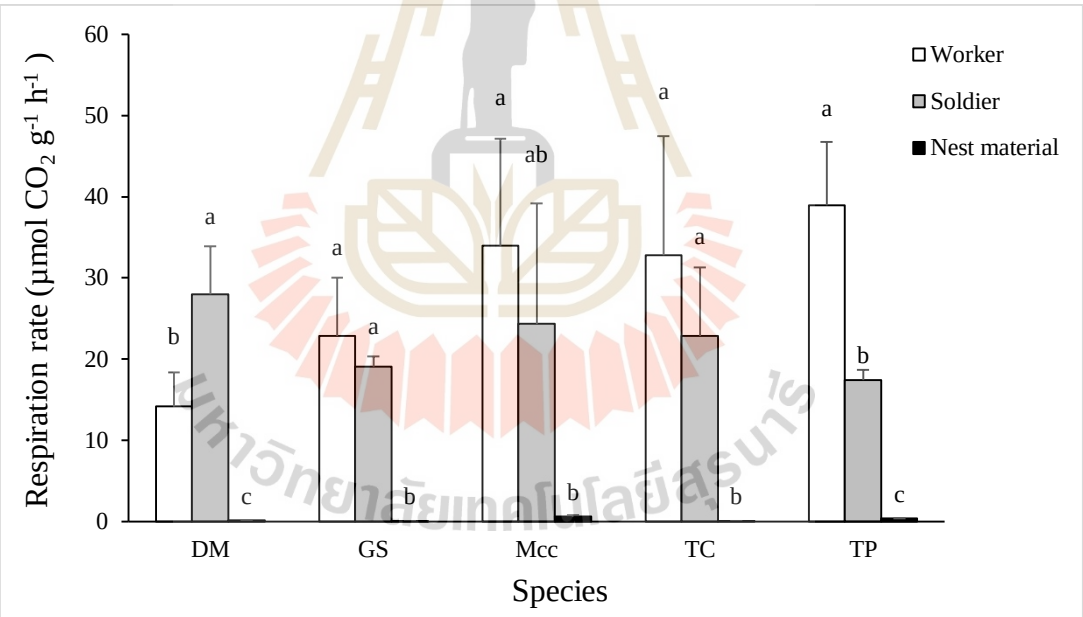

Figure 4.41 Respiration rates from the thin – wall mounds in each castes and nest materials. DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus*. Different letters indicate significant of difference between worker, soldier, and nest material from each species, which was tested by ANOVA with Tukey's HSD post hoc test (P = 0.05).

As the result, there were great in the individual's respiratory rate from smaller body weight termites (Table 4.7). In case of thick – wall mound, the high rates of respiration were estimated by castes of small workers of *M. carbonarius* and small soldiers and small workers of *M. annandalei*. While, the thin – wall mounds were found the high rates of respiration in both caste of workers and soldiers that those ratio of body weight and the individuals number were no significant difference between workers and the soldiers in each species (Table 4.6). According to Jeeva et al. (1999) the gas flux of termites was varied conversely with body weight as lower metabolic rate have shown in termites with the greater weight because the gas consumption of termites in smaller body weight have efficiency to arising the greater variation in the metabolic rate.

Table 4.6 Comparison of the mean weight of workers and soldiers from the thin – wall species.

Species	Castes	Mean weight (g/100 individuals) (n = 3)	*F*	*P*
DM	Worker	0.388	1.591	0.222
	Soldier	0.350		
GS	Worker	0.276	1.263	0.274
	Soldier	0.310		
Mcc	Worker	0.252	0.349	0.561
	Soldier	0.234		
TC	Worker	0.256	1.027	0.323
	Soldier	0.287		
TP	Worker	0.138	0.021	0.888
	Soldier	0.133		

DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus*

Table 4.7 Mean respiration rate of thick and thin – wall termites and their nest compositions.

Family/species	Respiration rates (μmol CO_2 g^{-1} h^{-1})						Total mean
	Fungus comb	Worker		Soldier		Nest material	
		small	big	small	big		
Macrotermitinae							
M. carbonarius	12.08b	16.15a	12.05b	12.26b	8.62b	0.13c	10.21
M. annandalei	7.46cd	26.08b	13.07c	47.14a	7.27cd	0.08d	16.84
Termitinae							
D. makhamensis	-	14.17b		27.99a		0.15c	14.10
G. sulphureus	-	22.84a		19.08a		0.06b	13.99
M. crassus	-	33.98a		24.38ab		0.64b	19.66
T. comis	-	32.76a		22.86a		0.09b	18.57
T. propinguus	-	38.95a		17.41b		0.36c	18.90
Yamada et al. (2005)*							
M. carbonarius	7.8	16.7	18.9	23.6	18.6	-	17.12
M. annandalei	14.7	23.7	25.0	18.9	13.6	-	19.18
D. makhamensis	-	14.2		14.2		-	14.2
G. sulphureus	-	9.9		8.5		-	9.2
M. crassus	-	10.5		10.8		-	10.65
T. comis	-	7.2		-		-	7.2
T. propinguus	-	19.2		19.2		-	19.2

Different letters indicate significant of difference between worker, soldier, and nest material from each species. * Respiration rates of termite and fungus comb were estimated in the DEF at SERS.

4.5 Distribution and Density of Termite Mounds and Trees

4.5.1 Termite mounds

Numbers of living 7 mound/nest species (epigeal nests) were counted from 5 main plots (Table 4.8). The different types of termite mounds are represented to variable densities (Table 4.11). The density of *M. crassus* was higher than those species, while the lowest of density was *M. annandalei* ($P < 0.001$). Also, Yamada et al., 2003 reported that *M. crassus* was predominated 46 and 36% of the abundance and biomass of the termites in DEF, Sakaerat, respectively. Besides, the mound density of Macrotermitinae (Thick-wall) and Termitinae (Thin – wall) in DEF was given by assumed to be the overall mean nest populations of these mound – building termites in Malaysia by Matsumato (1976) (Yamada et al., 2003) (Table 4.9).

Table 4.8 Number of termite mounds/nests from the main plots in the DEF.

Type of nest structure	Species	Main plot1	Main plot2	Main plot 3	Main plot 4	Main plot 5	Total
Thick wall	*M. carbonarius*	41	21	41	38	25	166
	M. annandalei	1	na	na	1	4	6
Thin wall	*D. makhamensis*	32	71	103	29	31	266
	G. sulphureus	6	9	7	5	6	33
	M. crassus	66	84	53	38	61	302
	T. comis	3	92	43	11	15	164
	T. propinguus	12	81	67	51	39	250

The density of living 7 mound/nest species from each main plot showed in Figure 4.42. The map of termites mound distribution showed that the highest of *M. crassus* (41.0%), *T. comis* (25.6%), *D. makhamensis* (33.0%), *T. propinguus* (29.7%), and *M. crassus* (33.5%) in main plot 1, main plot 2 (Figure 4.43), main plot 3, main plot 4 (Figure 4.44), and main plot 5 (Figure 4.45), respectively.

For the density of *M. carbonarius*, there was contributed exceeds 29 mound/ha in the Malaysia (Matsumato, 1979) as well as *M. carbonarius* is widely distributed in the tropical Asia forest such as Cambodia, Borneo, and Thailand (Inoue et al., 2001b). On the other hand, the density of *Macrotermes* was only less than 5 mound/ha in Africa grass (Collins, 1981; Darlington, 1984).

Table 4.9 Density of termite mounds/nests from the main plots in the DEF.

Type of nest structure	Species	Density (ha) Present study	Relative Density: RD (%)	Density (ha) (Yamada et al., 2003)
Thick wall	*M. carbonarius*	33.2±9.86	13.98	8
	M. annandalei	1.2±1.73	0.51	21
Thin wall	*D. makhamensis*	53.2±32.88	22.41	17
	G. sulphureus	6.6±1.52	2.78	7
	M. crassus	60.4±16.92	25.44	165
	T. comis	32.8±36.36	13.82	18
	T. propinguus	50±26.53	21.06	47

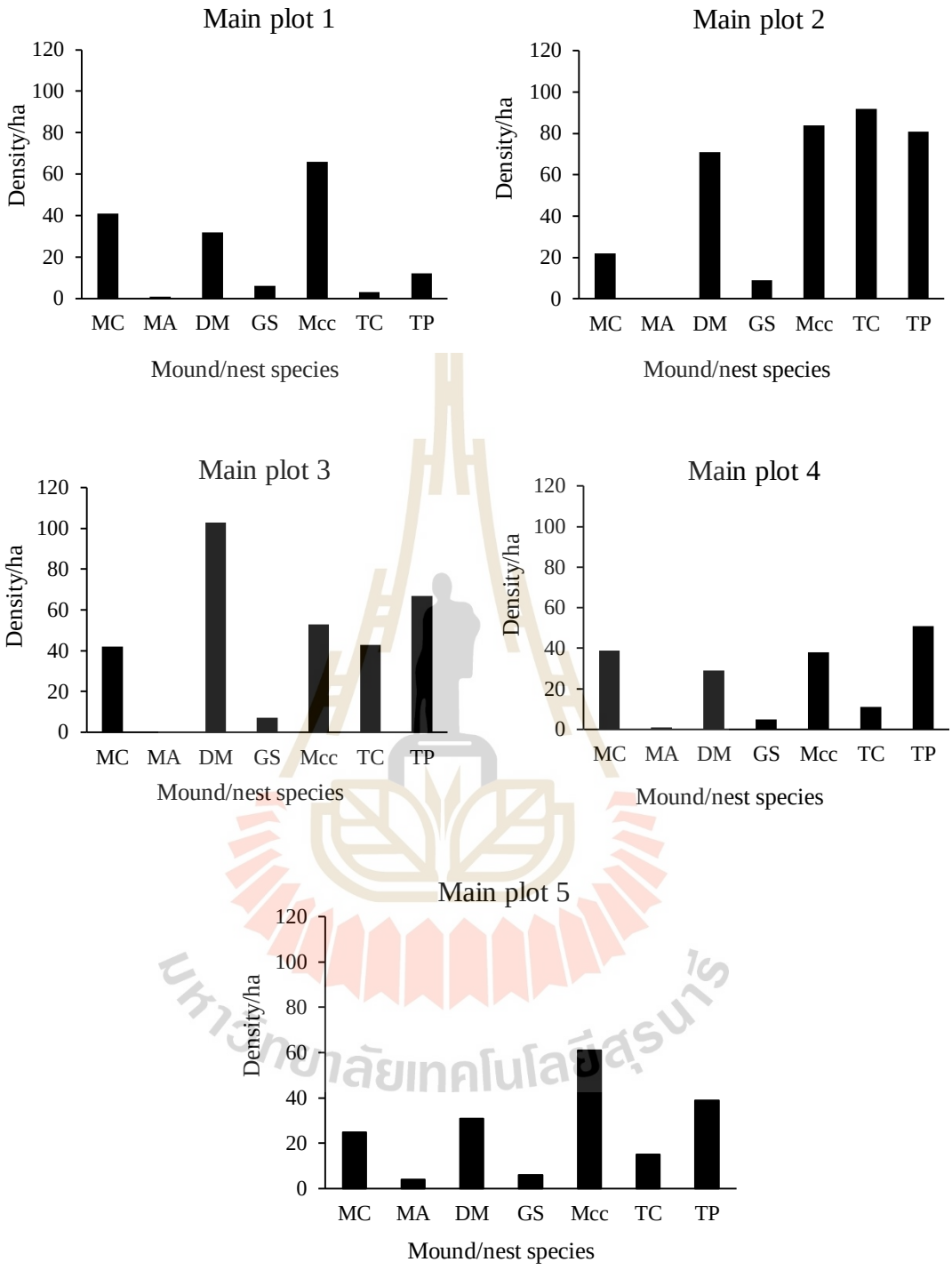

Figure 4.42 Density of termite mound/nest species in each main plot, MC: *M. carbonarius*, MA: *M. annandalei*, DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus*.

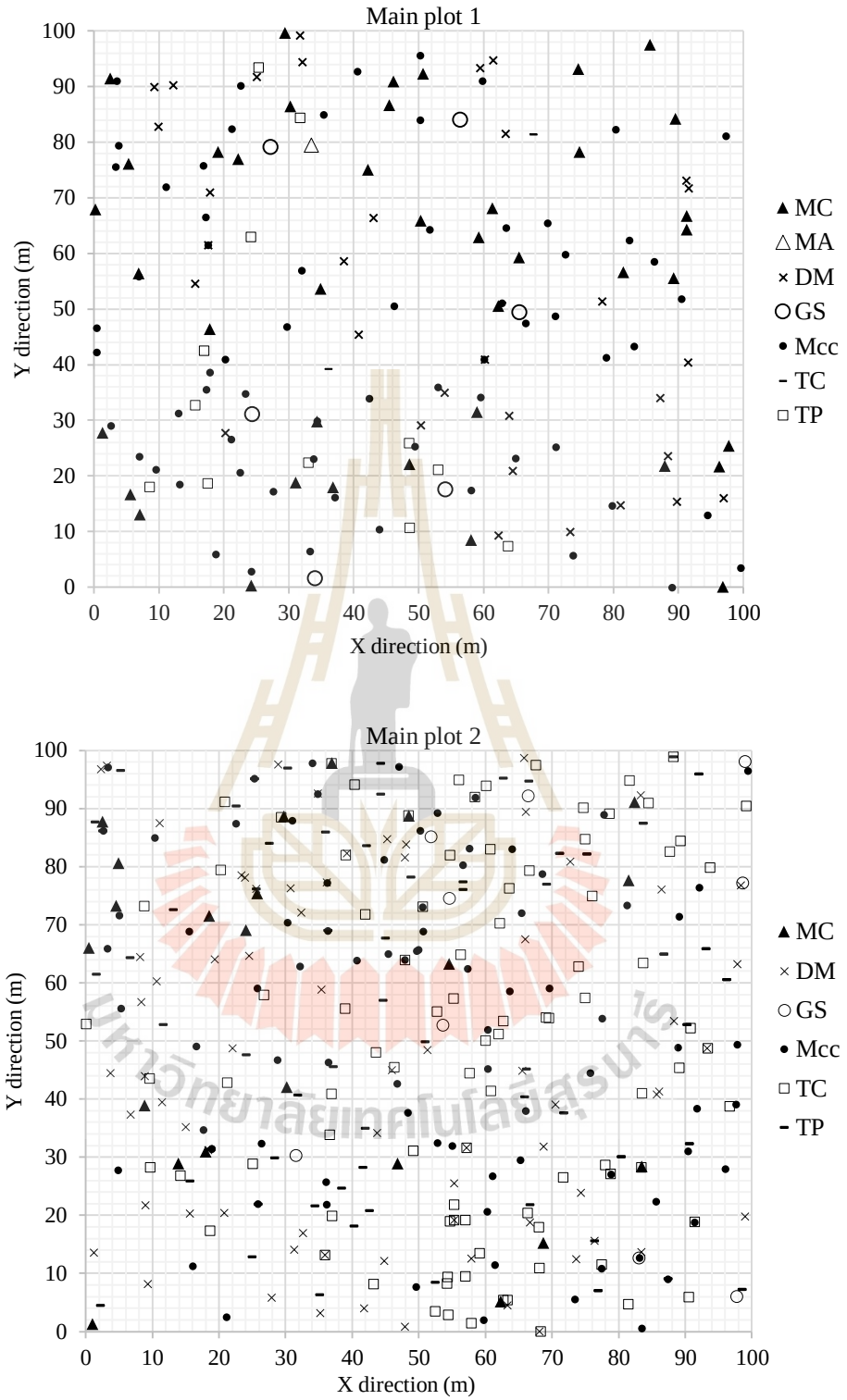

Figure 4.43 The map of termites mound distribution in main plot 1 and 2, MC: *M. carbonarius*, MA: *M. annandalei*, DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus*.

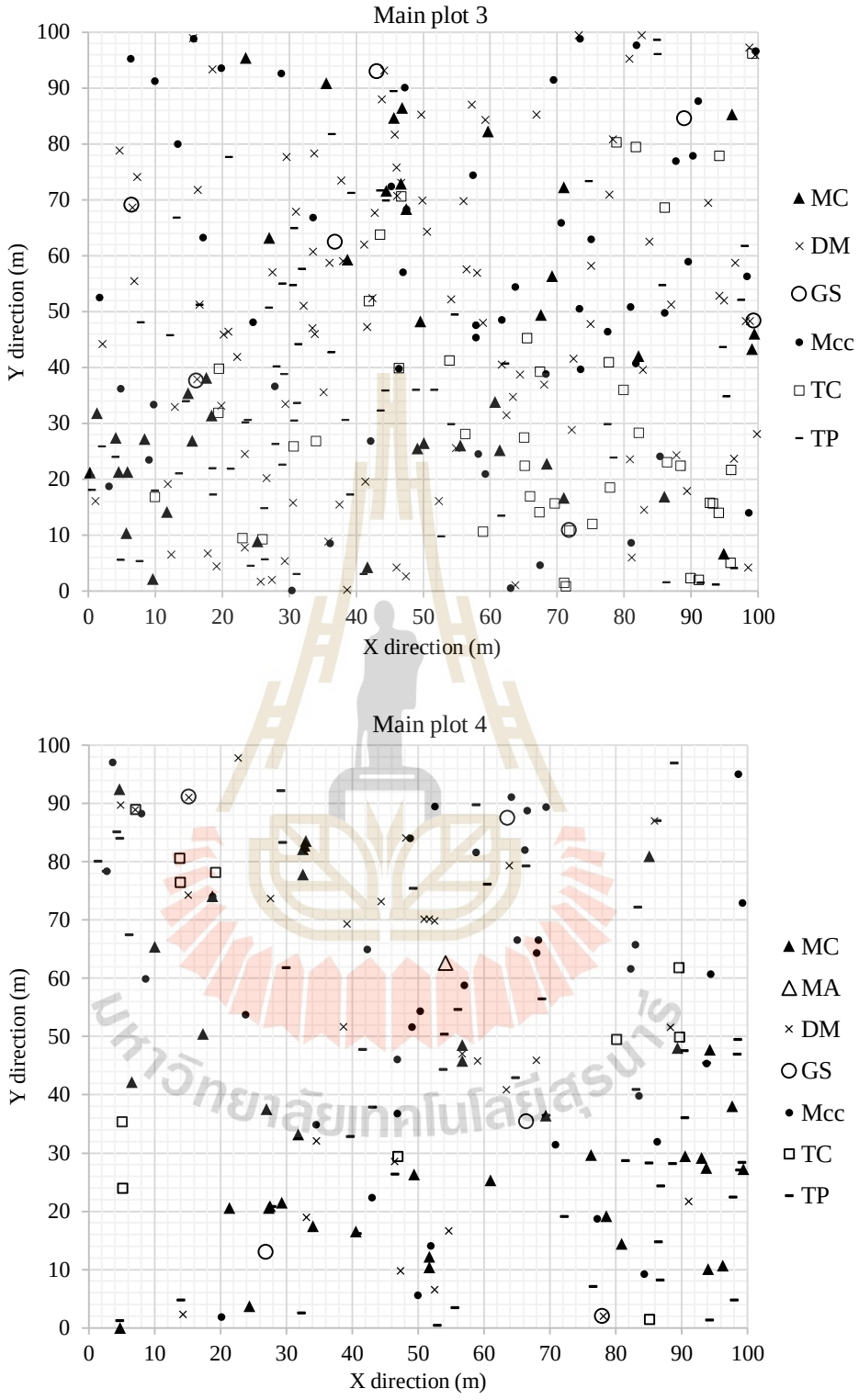

Figure 4.44 The map of termites mound distribution in main plot 3 and 4, MC: *M. carbonarius*, MA: *M. annandalei*, DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus*.

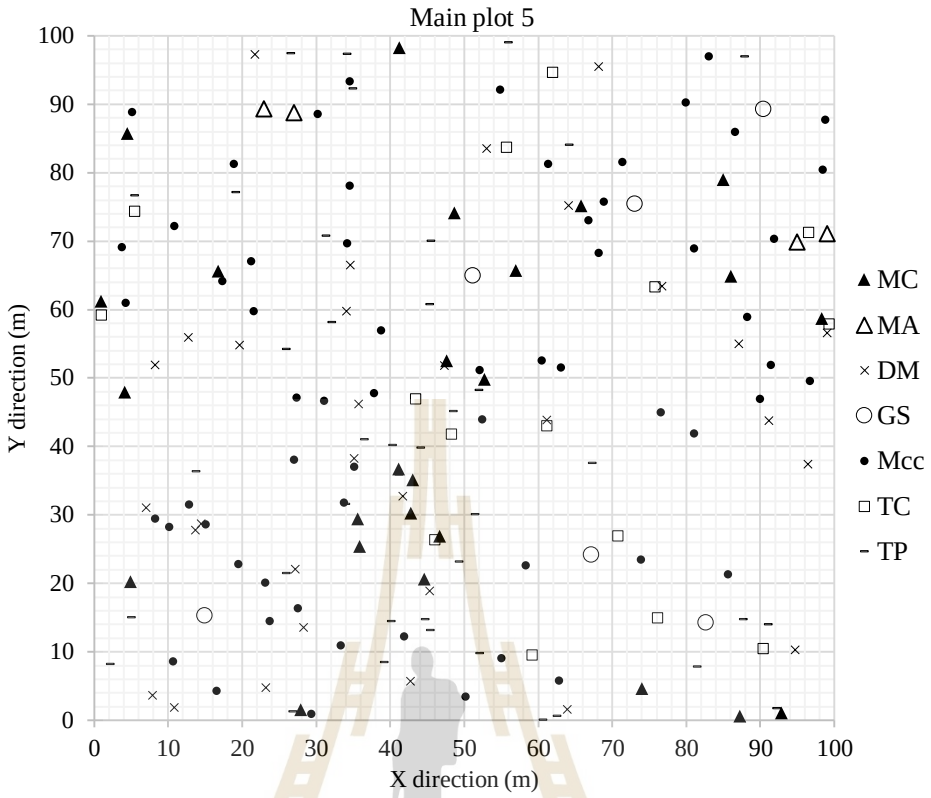

Figure 4.45 The map of termites mound distribution in main plot 5, MC: *M. carbonarius*, MA: *M. annandalei*, DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus*.

4.5.2 Trees

DBH of living trees being larger than 20 cm were considered by directly measurement of GBH ≥ 60 cm (DBH > 20 cm) from the 5 main plots (Table 4.10). Density of trees with the different ranges of DBH in each main plot showed in Figure 4.46. In each main plot, the distribution of the tree DBH was dominated by the range of 20 – 30 cm with 76.1%, 55.4%, 55.5%, 68.7% and 46.2% in main plot 1, 2, 3, 4, and 5, respectively (Figure 4.47).

Table 4.10 Number and density of the living trees with different range of DBH from the main plots.

DBH (cm)	Number of trees					Total number	Density (trees/ha)
	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5		
20 – 30	108	124	151	101	86	570	114
30 – 40	19	38	54	25	40	176	35.2
40 – 50	7	29	47	5	24	112	22.4
50 – 60	0	17	13	7	11	48	9.6
60 – 70	5	10	1	1	12	29	5.8
70 – 80	2	1	2	5	8	18	3.6
80 – 90	1	1	2	0	5	9	1.8
> 90	0	4	2	3	0	9	1.8
Total	142	224	272	147	186	971	194.2
Total basal area (m^2)	10.20	26.36	25.73	14.17	23.84	100.31	

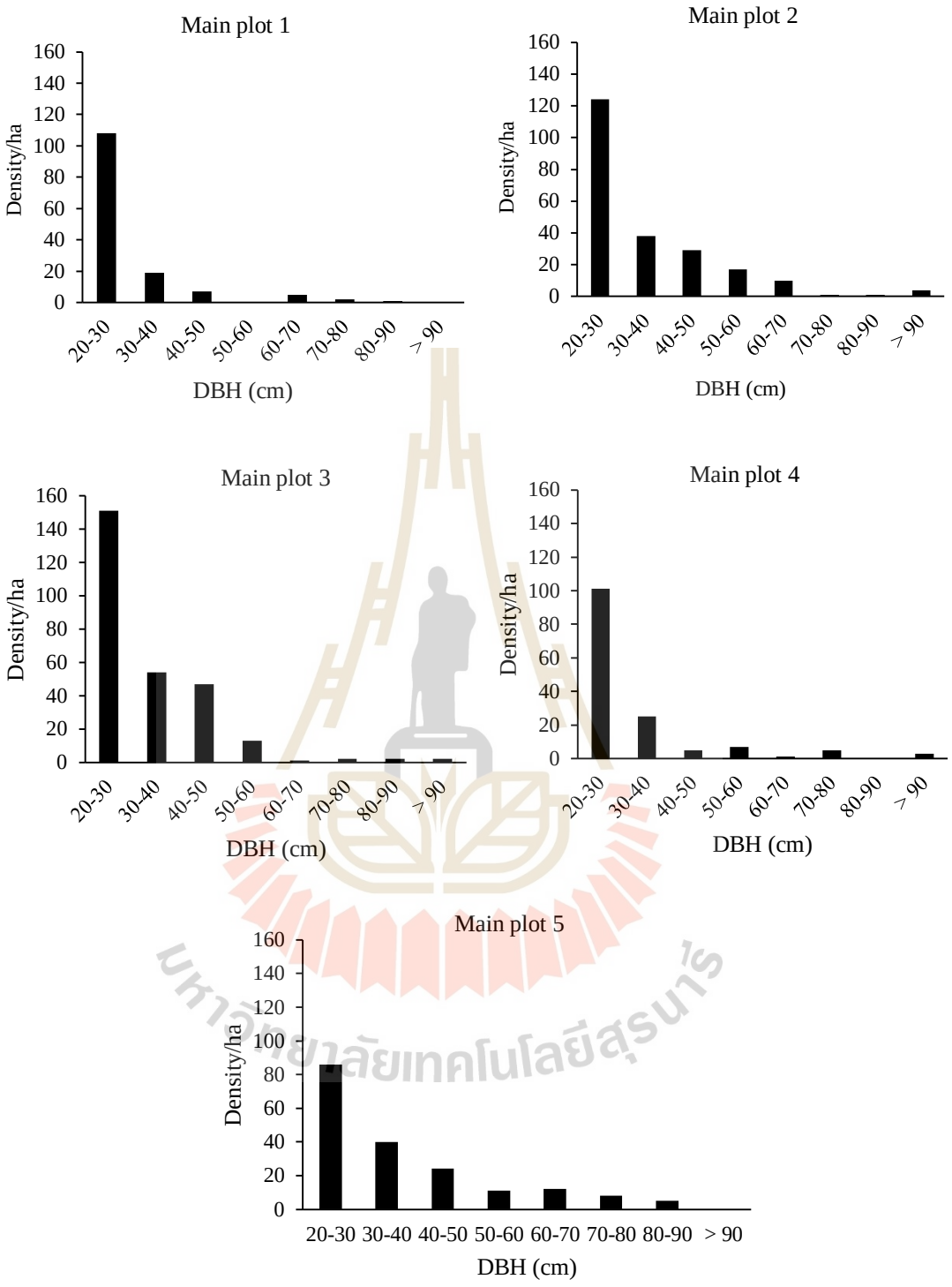

Figure 4.46 Density of living trees with different of DBH in the 5 main plots.

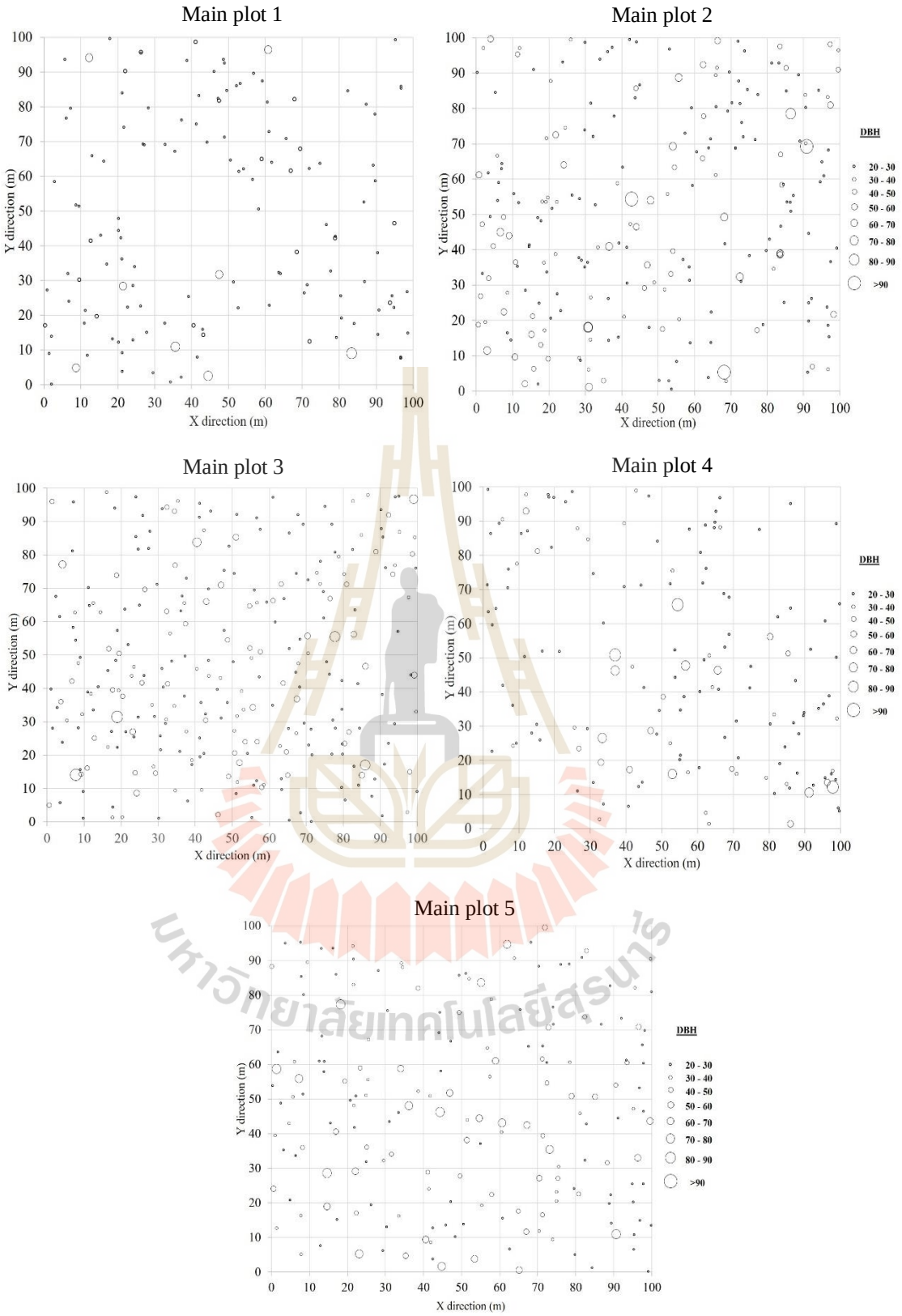

Figure 4.47 Distribution map of living trees with the different of DBH from the main plots.

4.6 Effects of Termitaria on Soil Respiration

As already mentioned, the ground soil respiration was determined from the main plots that were included CO_2 effluxes from soil microbes, roots and subterranean soil insects with variation in soil temperatures and soil moistures. In additions, this study was estimated the effects of epigeal nests, a term used for a termite mound, the above ground nest of a colony of termites (Lavelle and Spain, 2003) that were contributing to the accurate soil respiration rate. However, CO_2 effluxes from the termiteria of thick - and thin - wall mound were different because of the nest structures. The fluxes of CO_2 where directly released from the nests of the thin – wall types, but the case of thick-wall mounds, there were mostly dispersal effluxes from surrounding of the mounds (underground passages). Thus, the surrounding soil of the thick – wall mounds were investigated by dispersal of CO_2 efflux rates. Besides, the sizes and positions of trees were also considered.

4.6.1 Termitaria of thick – wall mounds (*M. carbonarius*)

Effect of the underground passages of *M. carbonarius*, the termitaria CO_2 effluxes were determined by the depth and diameter of the active holds where were found the high rates of CO_2 effluxes (hot spots) in the range of approximately 7 – 40 µmol CO_2 m^{-2} s^{-1} in dry season and 10 – 50 µmol CO_2 m^{-2} s^{-1} in the wet season. After checking of the measurement points, 69.31% of the extremely high CO_2 efflux rates were found that the underground passages with varying depth and diameter (e.g. in Figure 4.48), and the rest were found under the flat roots (close to the big trees) (26.73%), and the normal soils (3.96%) (Table 4.11).

Figure 4.48 Appearance of termites of *M. Carbonarius* from their underground passages.

Table 4.11 Source and average of high rates of CO_2 effluxes by checking underground soils in the depth of 40 cm from the termitaria of *M. carbonarius*.

Termataria of *M. carbonarius**	Number of high CO_2 efflux source		
	Underground passage	Surrounding Soil	
		Under the flat root	Normal soil
Small size	11	6	-
Medium size	23	14	3
Big size	36	7	1
Total	70	27	4
Average of CO_2 efflux rate (µmol CO_2 m^{-2} s^{-1}± SD)	15.97 ± 9.20	18.11 ± 5.9	16.99 ± 2.83

* Number of samples = 1200

The mean of CO_2 efflux rate from the underground passages of the thick wall mound was 15.97 ± 9.20 µmol CO_2 m^{-2} s^{-1}, which mean ranged from 14.27 to 19.25 µmol CO_2 m^{-2} s^{-1}. Frequency distribution of CO_2 efflux rate from soil around the mounds and underground passages of the termite mounds shown in Figure 4.49. CO_2 efflux rates from surrounding soil including the underground passages (7.36 µmol CO_2 m^{-2} s^{-1}) was significantly higher than soil alone around the mound (6.86 µmol CO_2 m^{-2} s^{-1}) ($P< 0.001$). Although, CO_2 efflux from the surrounding soil was included the high CO_2 efflux rates from under the flat roots and normal soils, which mean were 18.11 and 16.99 µmol CO_2 m^{-2} s^{-1}, respectively.

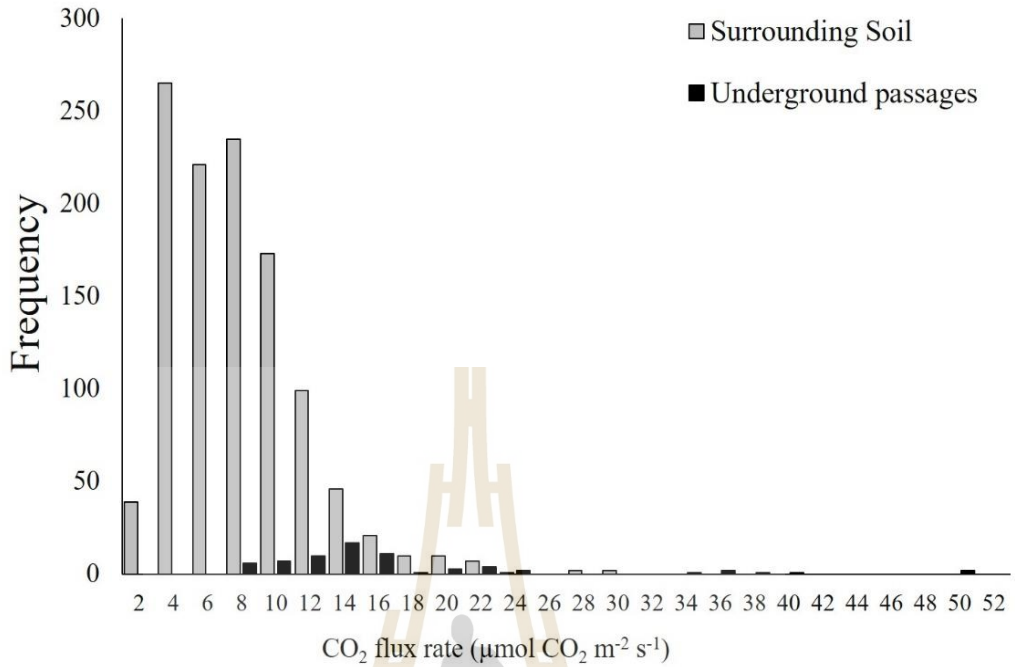

Figure 4.49 Frequency distribution of CO_2 efflux rate from surrounding soil and underground passages of the termite mounds.

In fact, the mean rate of CO_2 efflux (15.97 ± 9.2 µmol CO_2 m^{-2} s^{-1} ± SD) from the underground passages of termite mound is not only from the activities of termites but also from the microbe activities by the gas pass through the surrounding soil as well underground tunnels. Consequently, mean of CO_2 efflux rate was 9.11 µmol CO_2 m^{-2} s^{-1} from the underground passages of thick – wall mound only. Because the CO_2 efflux rate of soil alone around the mound (6.86 µmol CO_2 m^{-2} s^{-1}) was excluded. While CO_2 efflux from above the mound was only 2.94 µmol CO_2 m^{-2} s^{-1}. Thus, the average of CO_2 efflux from the termitaria (mound and underground passage) of *M. carbonarius* was 7.66 µmol CO_2 m^{-2} s^{-1}. An aspect of the effect of *M. carbonarius*'s mound and surrounding soil on soil respiration shown in 4.50.

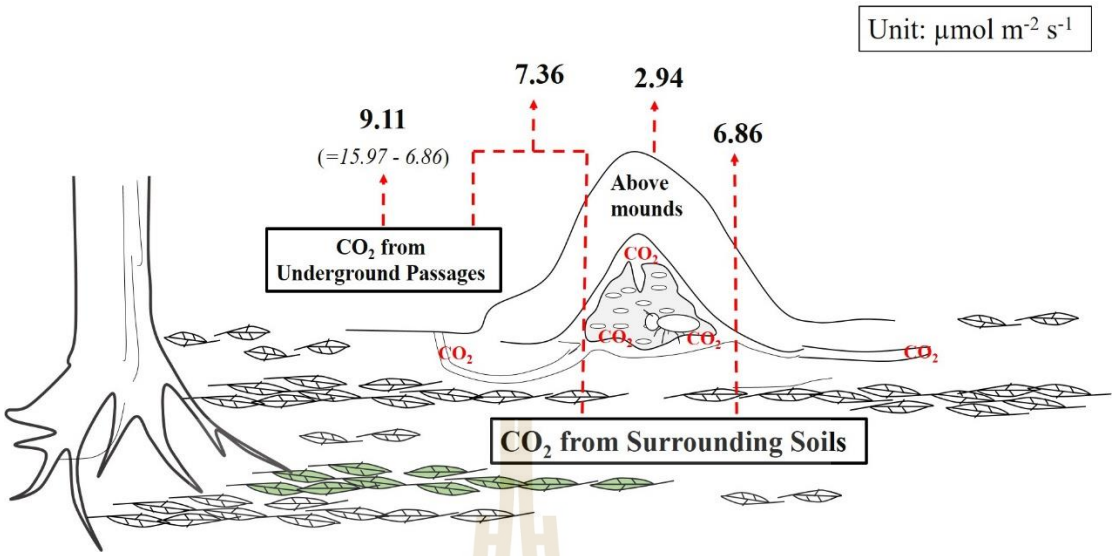

Figure 4.50 An aspect of the effect of *M. carbonarius*'s mounds and surrounding soils on soil respiration.

The result of relationship between underground passages of *M. carbonarius* and their CO_2 efflux rates showed that there were no significant difference in CO_2 efflux rates between depths and diameters of underground passages in dry and wet seasons (Figure 4.51 and 4.52). The spatial distribution maps of high rates of CO_2 effluxes, underground passages, DBH of trees (>9.5 cm), and neighbor mounds of each *M. carbonarius* plots were shown in Figures 4.53, 4.54, 4.55, 4.56, 4.57, and 4.58.

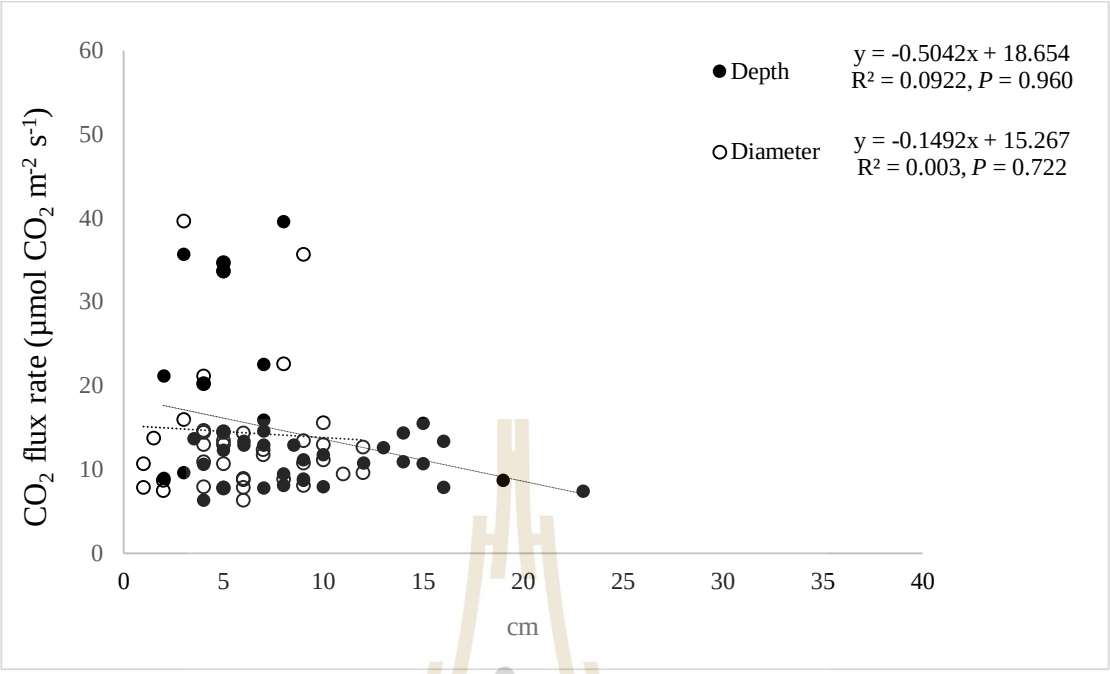

Figure 4.51 Comparison for CO_2 efflux among the hold depth and diameter of the underground passage in dry season (sampling numbers = 42).

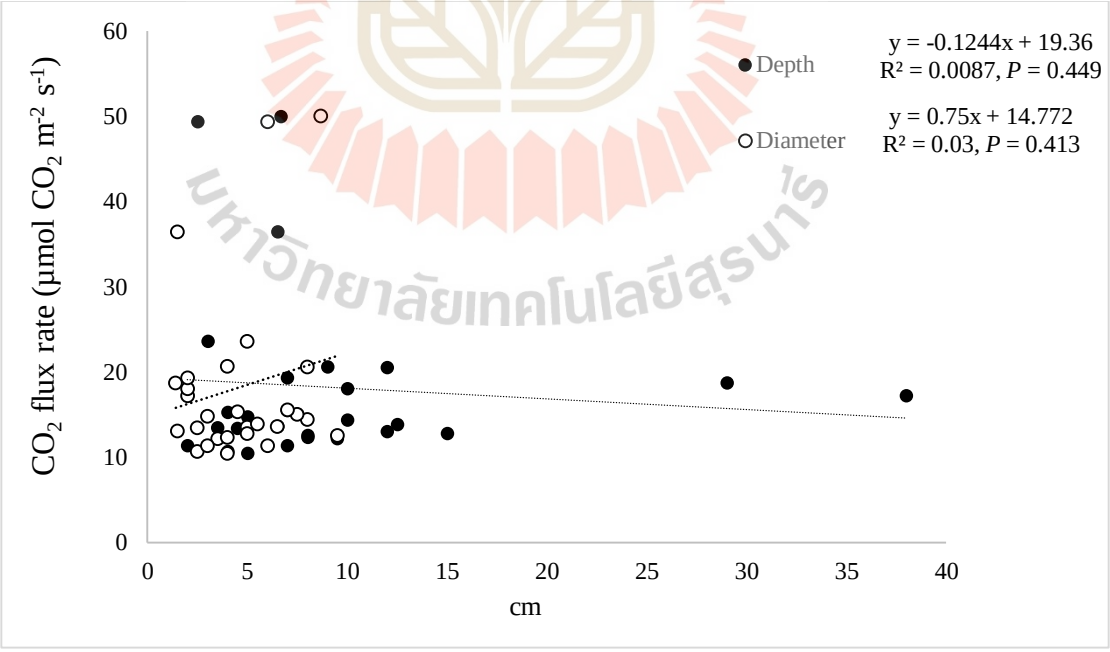

Figure 4.52 Comparison for CO_2 efflux among the hold depth and diameter of the underground passage in wet season (sampling numbers = 28).

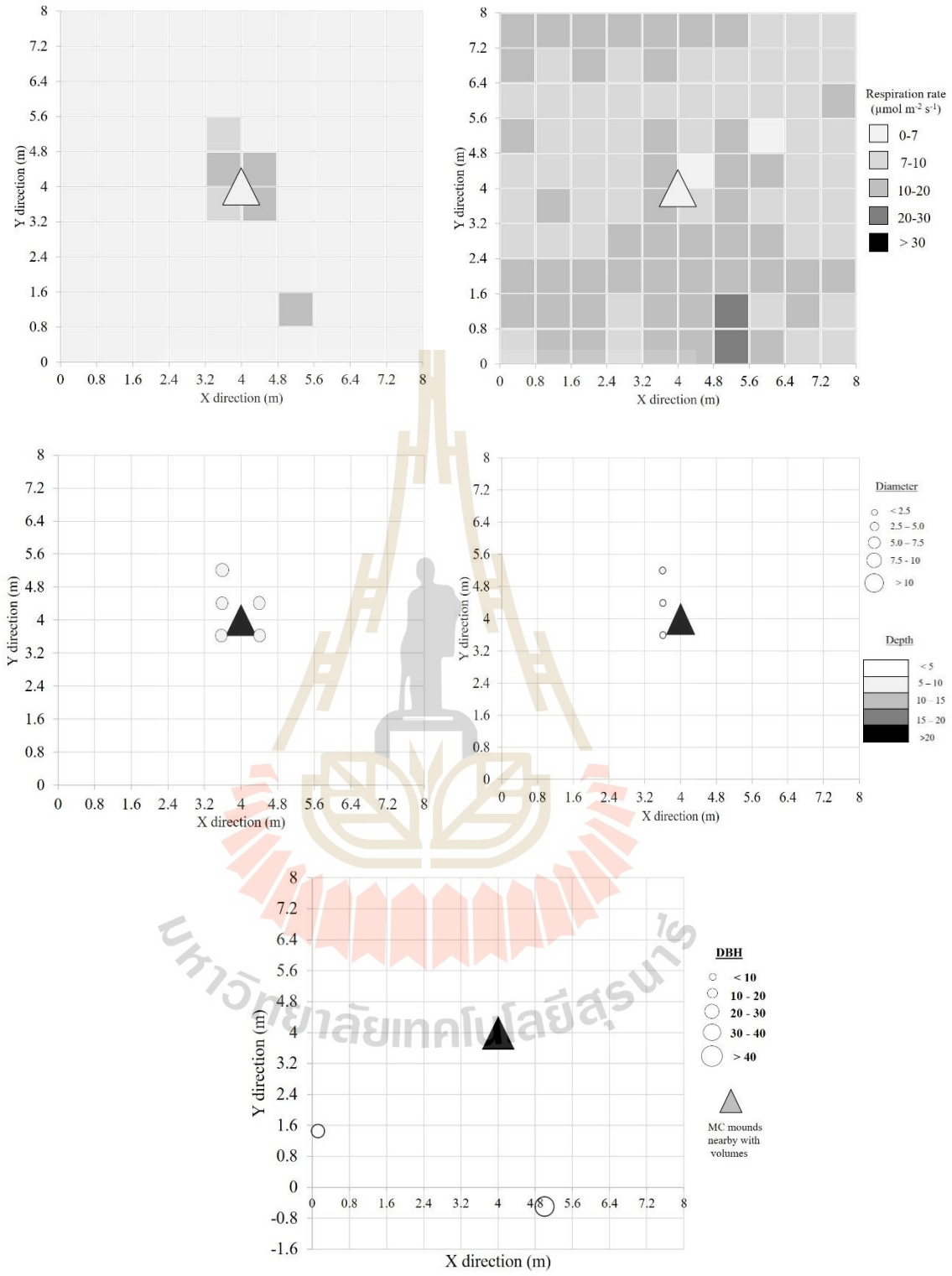

Figure 4.53 Distribution maps of CO_2 effluxes, underground passages in dry (left) and wet (right) seasons, and DBH of trees, and neighbor mounds (volumes) (bottom) of *M. carbonarius* plot (small mound 1).

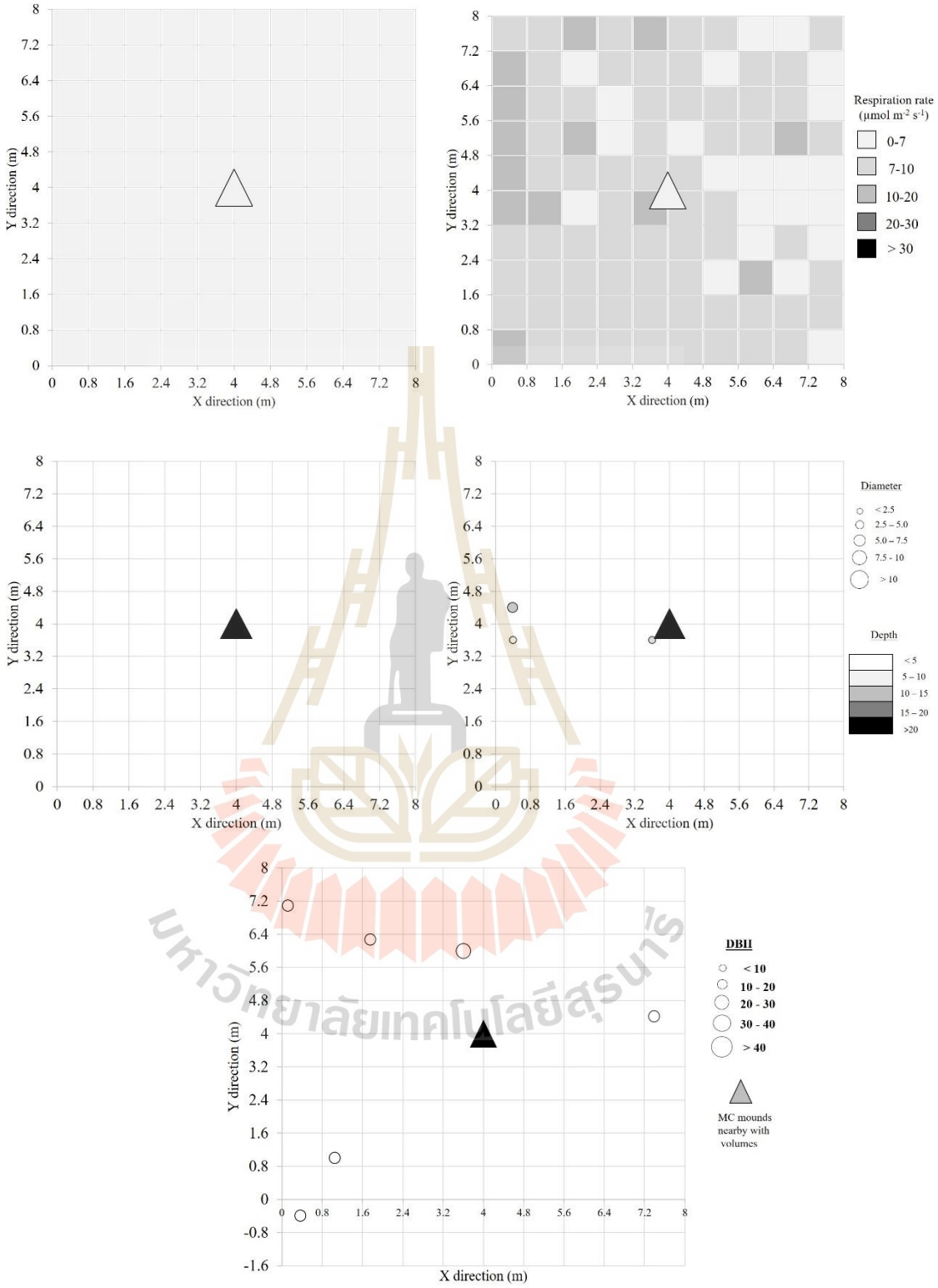

Figure 4.54 Distribution maps of CO_2 effluxes, underground passages in dry (left) and wet (right) seasons, and DBH of trees, and neighbor mounds (volumes) (bottom) of *M. carbonarius* plot (small mound 2).

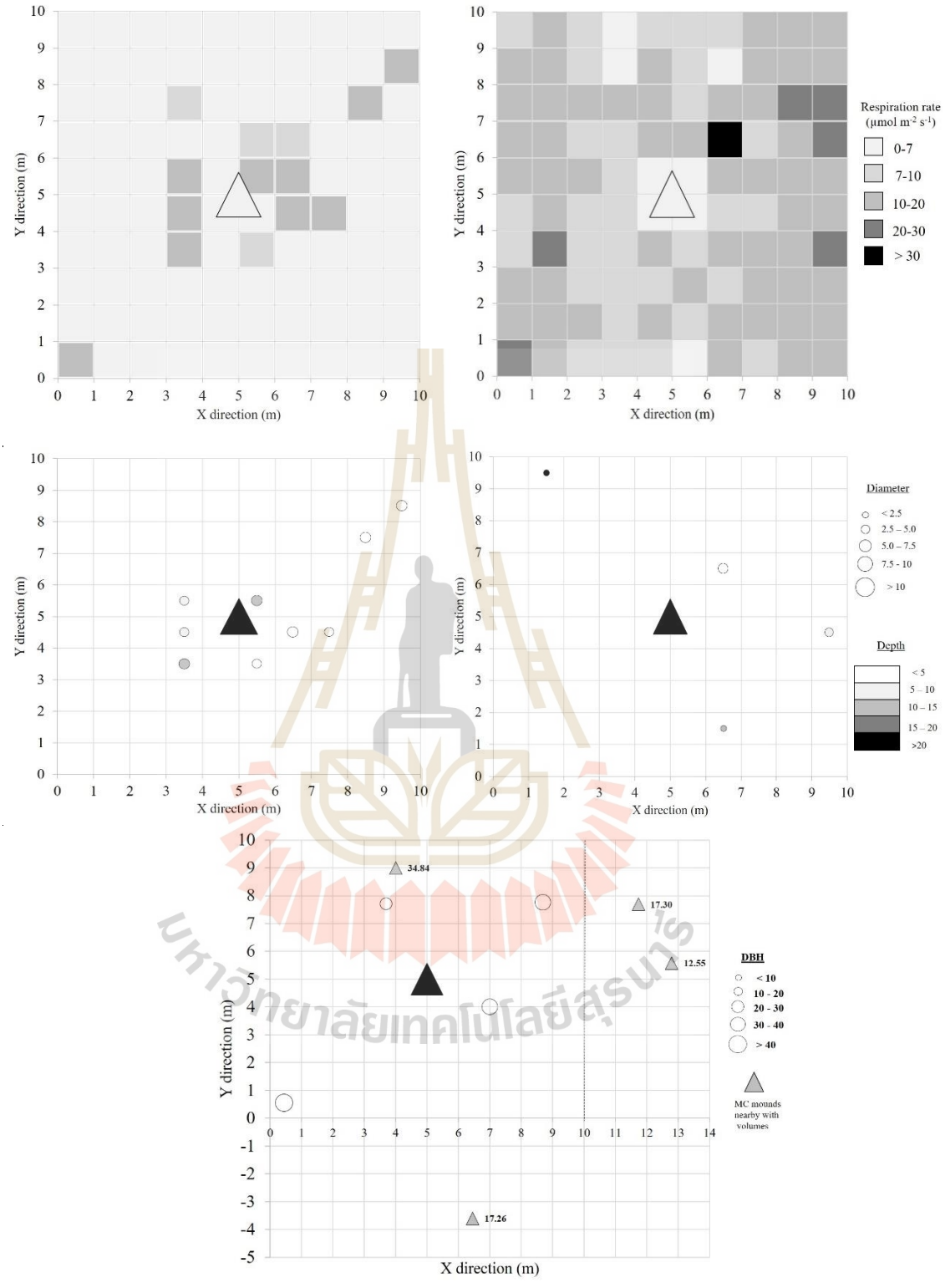

Figure 4.55 Distribution maps of CO_2 effluxes, underground passages in dry (left) and wet (right) seasons, and DBH of trees, and neighbor mounds (volumes) (bottom) of *M. carbonarius* plot (medium mound 1).

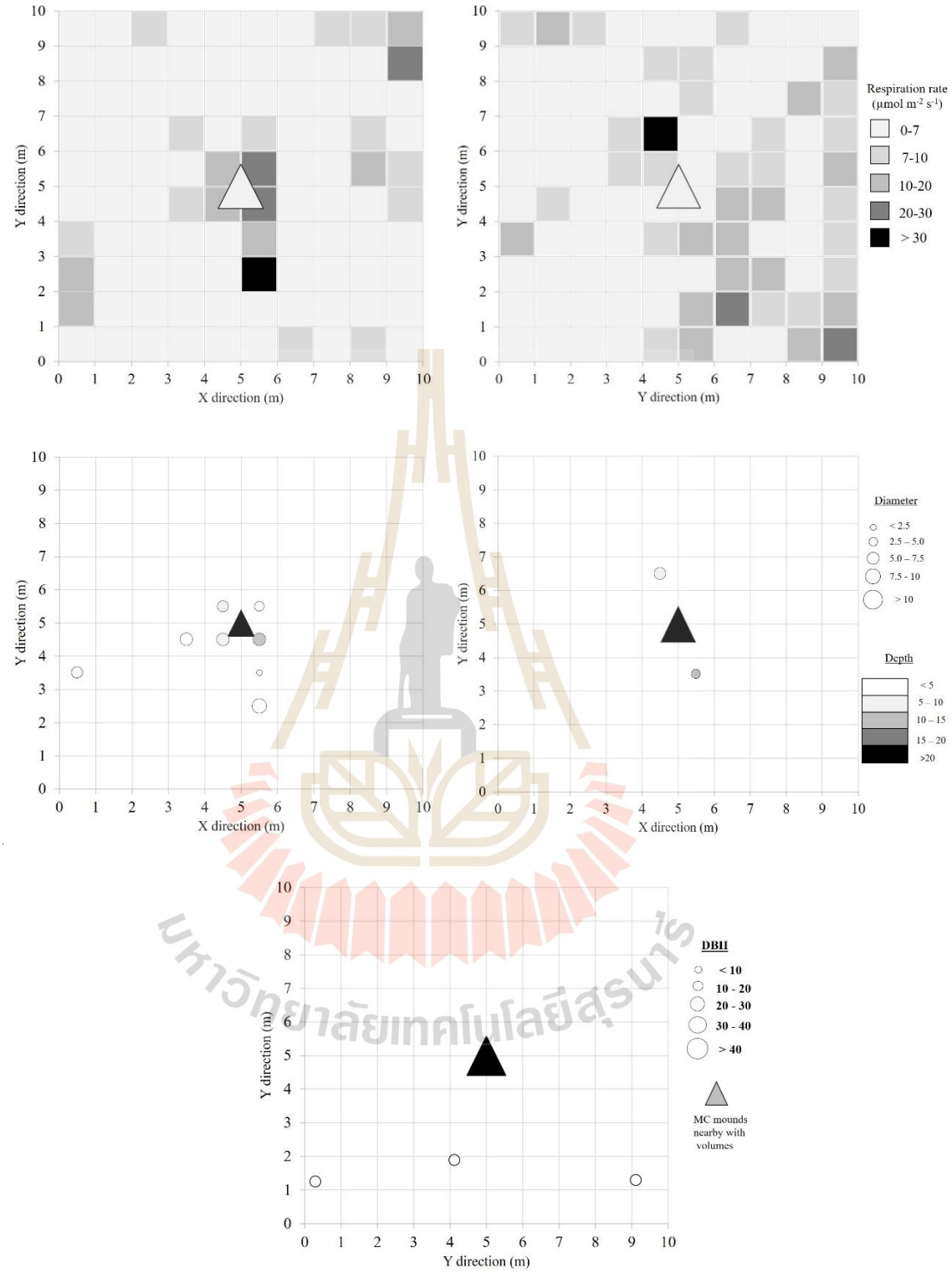

Figure 4.56 Distribution maps of CO_2 effluxes, underground passages in dry (left) and wet (right) seasons, and DBH of trees, and neighbor mounds (volumes) (bottom) of *M. carbonarius* plot (medium size 2).

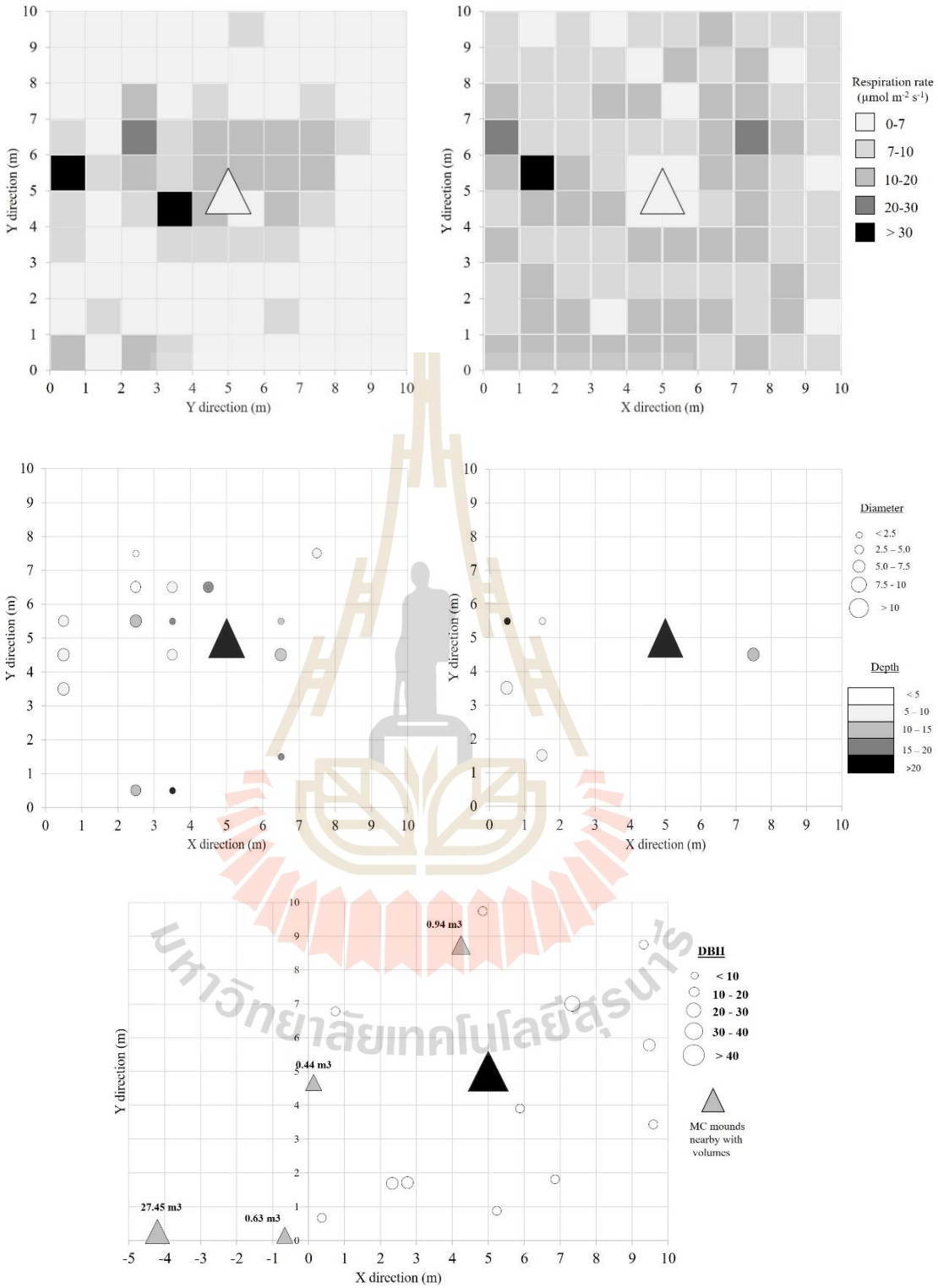

Figure 4.57 Distribution maps of CO_2 effluxes, underground passages in dry (left) and wet (right) seasons, and DBH of trees, and neighbor mounds (volumes) (bottom) of *M. carbonarius* plot (big size 1).

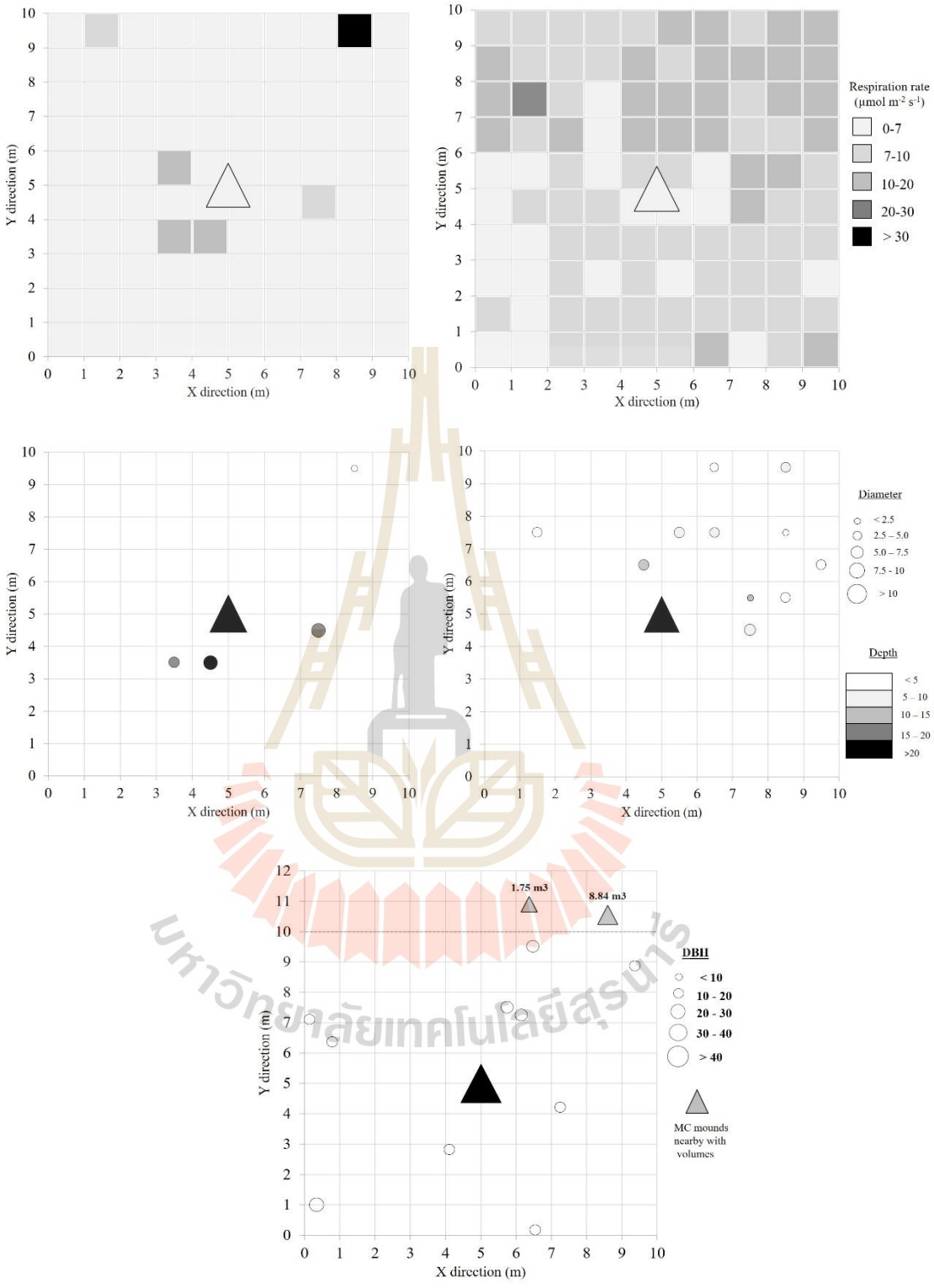

Figure 4.58 Distribution maps of CO_2 effluxes, underground passages in dry (left) and wet (right) seasons, and DBH of trees, and neighbor mounds (volumes) (bottom) of *M. carbonarius* plot (big size 2).

4.6.2 Distribution of *M. carbonarius*'s Mounds and Trees Contribution to Ground Soil Respiration

The effect of *M. carbonarius*'s mounds and the living trees on differences of mean soil respiration rates were evaluated by the number of mounds (NM) and tree's basal areas (tBA) (m^2) in every grids of the main plots, respectively. In dry season, the multiple linear regression analysis showed a significant positive relationship between soil respiration rates and existence of the mounds (P = 0.037), but there was no relationship for the basal area of trees (P = 0.128) (regression equation: y = 4.127 + 0.258(NM) + 0.483(tBA), R = 0.083, R^2 = 0.007, SE_{est} = 2.51). In contrast, there was no relationship between soil respiration rates and number of mounds (P = 0.121), but the significant relationship was found between soil respiration rates and the basal area of trees (P = 0.012) in the wet season (regression equation: y = 8.385 + 0.344(NM) + 1.434(tBA), R = 0.095, R^2 = 0.009, SE_{est} = 4.50). Spatial distribution of the rates of CO_2 effluxes together with *M. carbonarius*'s mounds and trees in the main plot 1 – 5 were shown in Figures 4.59 - 4.63.

Relationship between distribution of *M. carbonarius*'s mounds and soil respiration rates from the measurement points were showed a small or no relationship in both season, that because CO_2 efflux points of undergrounds passages radiating out from each mound were as small holds as specific – points and areas when compared with a large scale. The relationship with soil respiration was found in tree's basal area but not in *M. carbonarius*'s mound in the wet season that could be due to competition from the microbial activities on aboveground litterfall and root respiration.

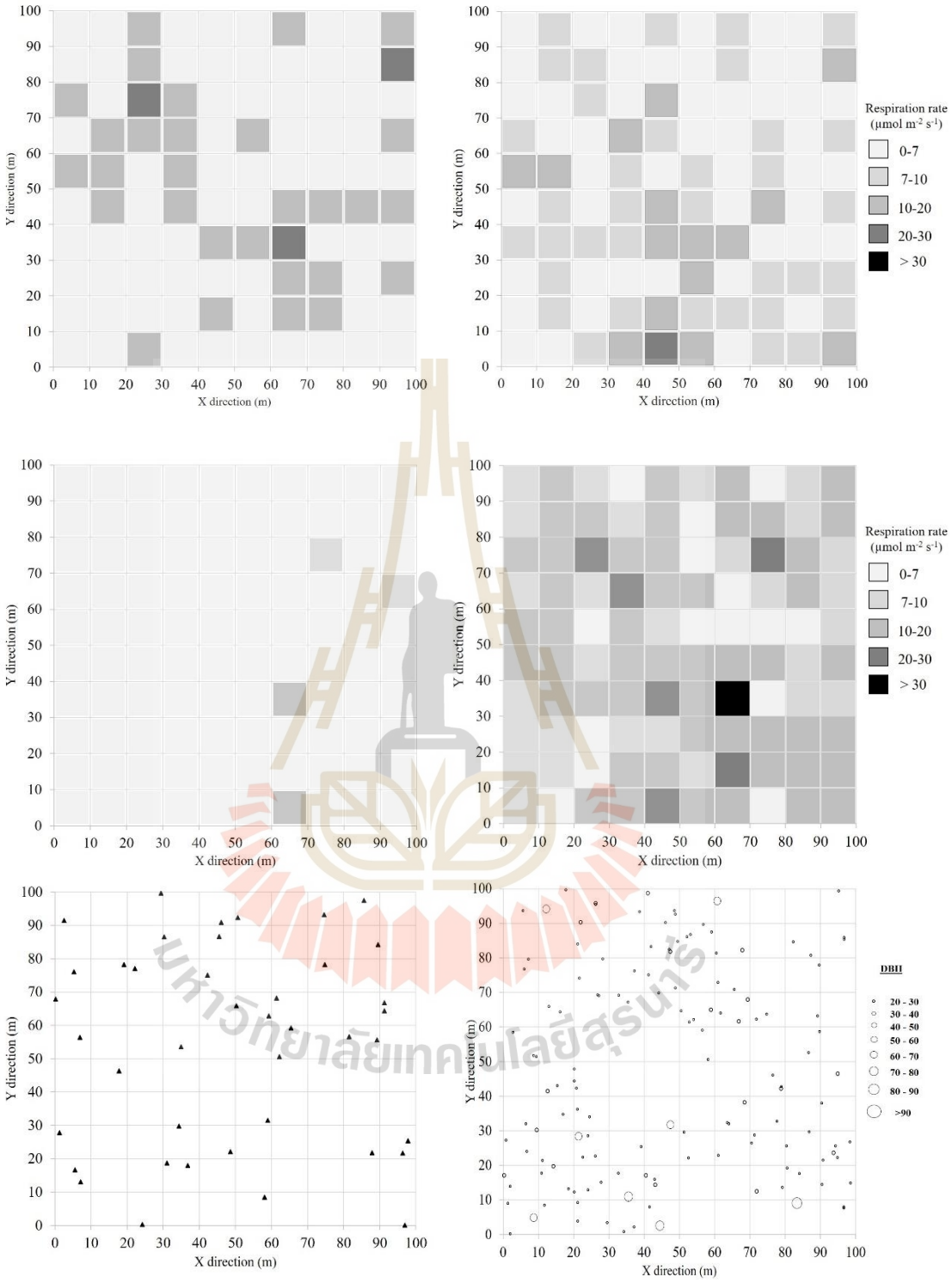

Figure 4.59 Spatial distribution of the rates of CO_2 effluxes in dry (left) and wet (right) seasons (above - center) together with *M. carbonarius*'s mounds (left) and trees (right) (bottom) in the main plot 1.

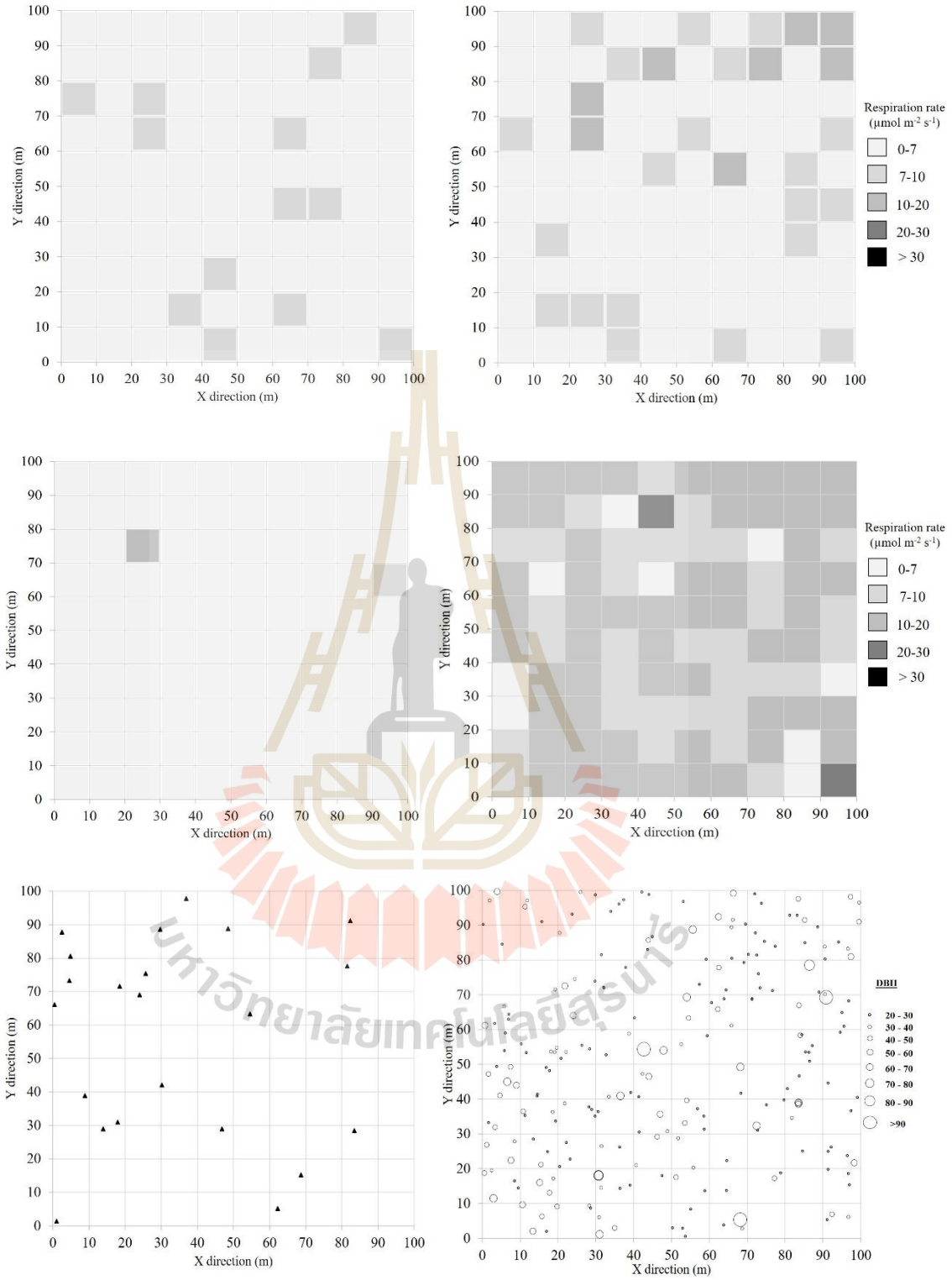

Figure 4.60 Spatial distribution of the rates of CO_2 effluxes in dry (left) and wet (right) seasons (above - center) together with *M. carbonarius*'s mounds (left) and trees (right) (bottom) in the main plot 2.

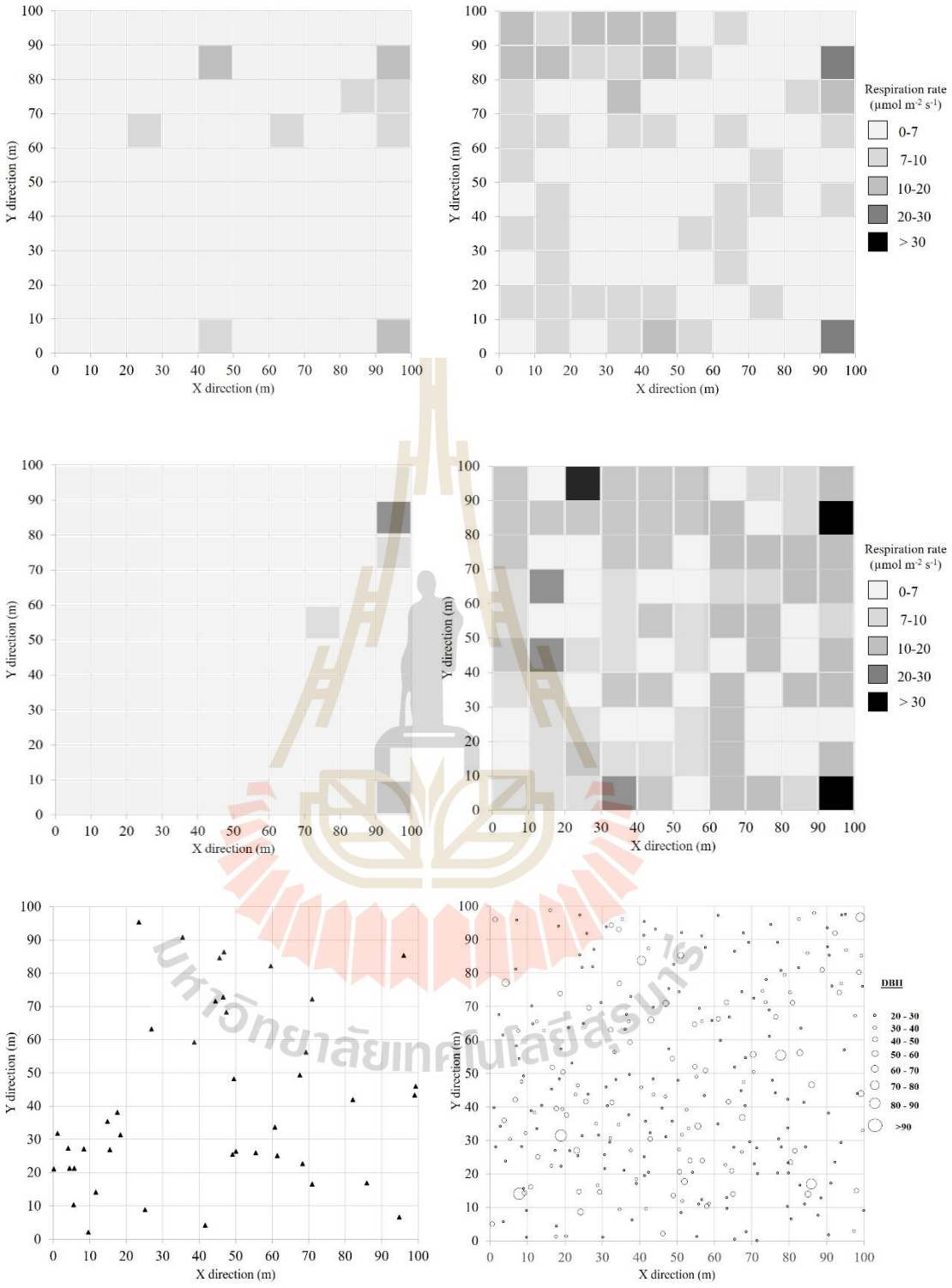

Figure 4.61 Spatial distribution of the rates of CO_2 effluxes in dry (left) and wet (right) seasons (above - center) together with *M. carbonarius*'s mounds (left) and trees (right) (bottom) in the main plot 3.

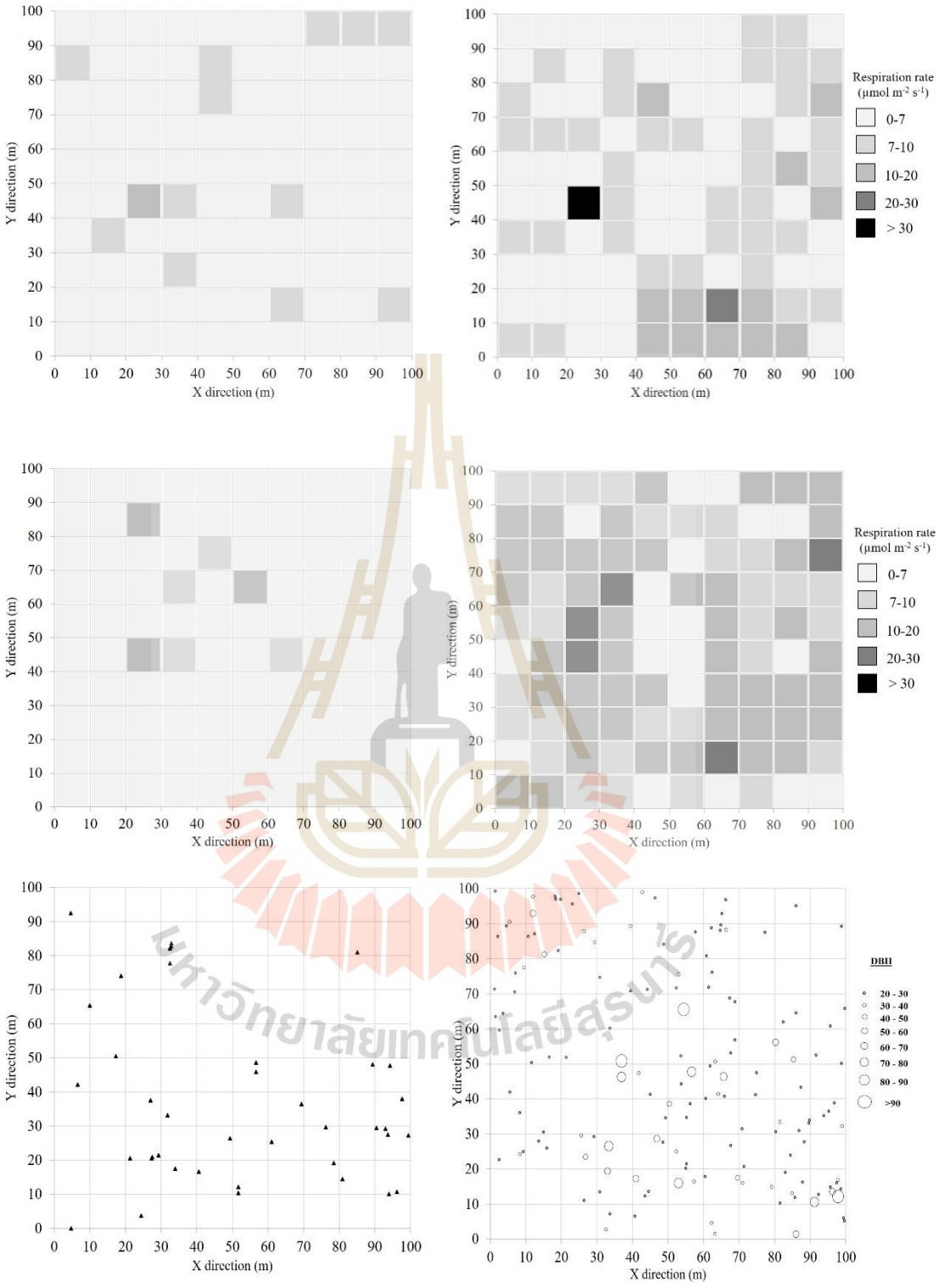

Figure 4.62 Spatial distribution of the rates of CO_2 effluxes in dry (left) and wet (right) seasons (above - center) together with *M. carbonarius*'s mounds (left) and trees (right) (bottom) in the main plot 4.

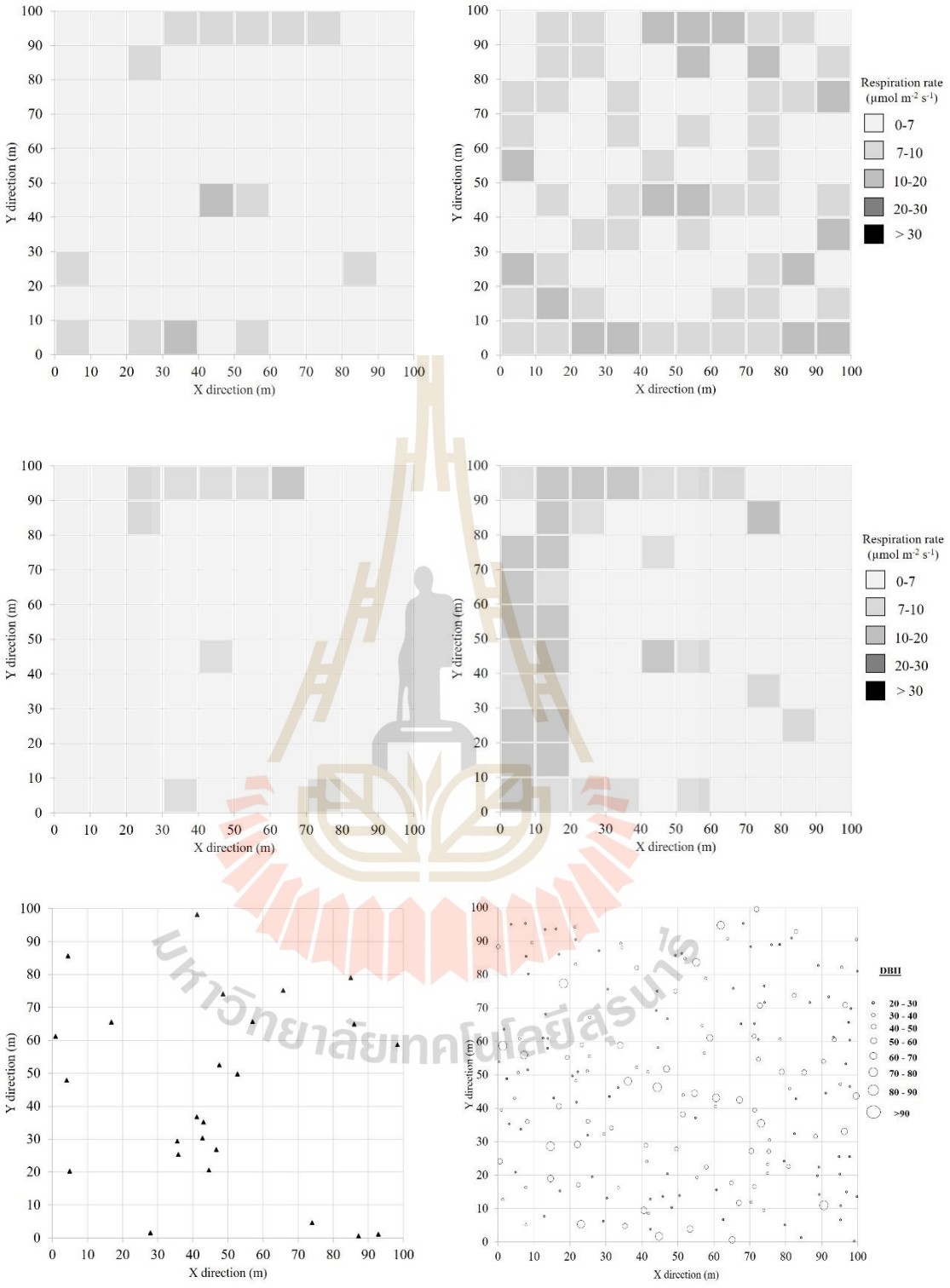

Figure 4.63 Spatial distribution of the rates of CO_2 effluxes in dry (left) and wet (right) seasons (above - center) together with *M. carbonarius*'s mounds (left) and trees (right) (bottom) in the main plot 5.

4.7 Total Soil Respiration from the Forest (DEF)

From the measurement data, the mean of CO_2 efflux rate from *M. carbonarius* (100 m^2 in average) was assumed for calculating of the estimation of total average of soil respiration rate from the DEF. In case of thin – wall mounds, the mean of CO_2 efflux rates were directly measured from the nests varied with sizes in each species. Total average of soil respiration rate from the forest floor was estimated by considering CO_2 effluxes from all the termitaria of predominate epigeal nest/mound species, associated with seasonal variation in DEF (Table 4.12). The total average of soil respiration rate was 6.76 µmol CO_2 m^{-2} s^{-1} from the DEF, mean rate of soil respiration in the wet season was higher almost twice than in the dry season. The attribute values from measurements were assumed to estimate the accuracy value, and percentage of relative error was 2.85%. CO_2 effluxes from termiraia of *M. carbonarius* was contributed of 34.88% to the total soil respiration which mean of 36.5% and 34.1% obtained from dry and wet season, respectively. There was higher than the other species. Although, both *G. sulphureus* and *M. crassus* were emitted high CO_2 on their nests due to wall thickness, but there were less of density and area, respectively (Figure 4.64).

As a matter of fact, the total average of soil respiration rate from the DEF was estimated by considering actual means of CO_2 efflux from the mound and underground passage of *M. carbonarius*, and also including the thin – wall mounds (Table 4.13). The total average of soil respiration rate was 6.61 µmol CO_2 m^{-2} s^{-1} from the DEF with 0.59% of relative error. The termitaria of *M. carbonarius* was to contribute 2.93%, which consist of their mound and underground passage which contribute 0.26% and 2.67% to the total soil respiration, respectively (Figure 4.65).

Table 4.12 Estimation of total average of soil respiration rate from the DEF by considering CO_2 efflux from the termitaria of predominate epigeal nest species.

Sources of soil respiration	Mean area (m^2)	Density mound (mound/ha)	Total area (m^2/ha)	Average of soil respiration from the sample sites (µmol CO_2 m^{-2} s^{-1})			Total average of soil respiration from the forest (DEF) (µmol CO_2 m^{-2} s^{-1})		
				Dry season	Wet season	Total	Dry season	Wet season	Total (%)
Thick –wall mound									
*M. carbonarius**	100	33.2	3320	5.03	9.17	7.10	1.67	3.04	2.357 (34.88)
M. annandalei	n.a.	1.2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Thin – wall mound									
D. makhamensis	0.04	53.2	2.26	1.01	2.56	1.79	0.0002	0.0006	0.0004 (0.01)
G. sulphureus	0.46	6.6	3.06	27.18	48.23	37.71	0.0083	0.0148	0.012 (0.17)
M. crassus	0.08	60.4	4.89	11.33	19.67	15.50	0.0055	0.0096	0.008 (0.11)
T. comis	0.40	32.8	13.21	4.46	8.43	6.45	0.0059	0.011	0.009 (0.13)
T. propinguus	0.04	50.0	1.92	0.89	3.08	1.98	0.0002	0.0006	0.0004 (0.01)
Background soil			6654.65	4.33	8.81	6.57	2.88	5.86	4.372 (64.70)
Total			10000				4.57	8.94	6.757 (100)

* Mean area of *M. carbonarius* was assumed to be 100 m^2 in average that including their surrounding soil

Table 4.13 Estimation of total average of soil respiration rate from the DEF by considering actual mean of CO_2 efflux from the mounds and their underground passages of *M. carbonarius*, and the thin – wall mounds.

Sources of soil respiration	Mean area (m^2)	Density mound (mound/ha)	Total area (m^2/ha)	Average of soil respiration from the sample sites (μmol CO_2 m^{-2} s^{-1})			Total average of soil respiration from the forest (DEF) (μmol CO_2 m^{-2} s^{-1})		
				Dry season	Wet season	Total	Dry season	Wet season	Total (%)
Thick –wall mound									
M. carbonarius									
Mound	1.79	33.2	59.43	3.86	2.05	2.94	0.02	0.01	0.017 (0.26)
Underground passages	5.83	33.2	193.67	7.52	11.37	9.11	0.15	0.22	0.176 (2.67)
Thin – wall mound									
D. makhamensis	0.04	53.2	2.26	1.01	2.56	1.79	0.0002	0.0006	0.0004 (0.01)
G. sulphureus	0.46	6.6	3.06	27.18	48.23	37.71	0.0083	0.0148	0.012 (0.17)
M. crassus	0.08	60.4	4.89	11.33	19.67	15.50	0.0055	0.0096	0.008 (0.11)
T. comis	0.40	32.8	13.21	4.46	8.43	6.45	0.0059	0.011	0.009 (0.13)
T. propinguus	0.04	50.0	1.92	0.89	3.08	1.98	0.0002	0.0006	0.0004 (0.01)
Background soil			9721.56	4.33	8.81	6.57	4.21	8.56	6.387 (96.64)
Total			10000				4.40	8.83	6.609 (100)

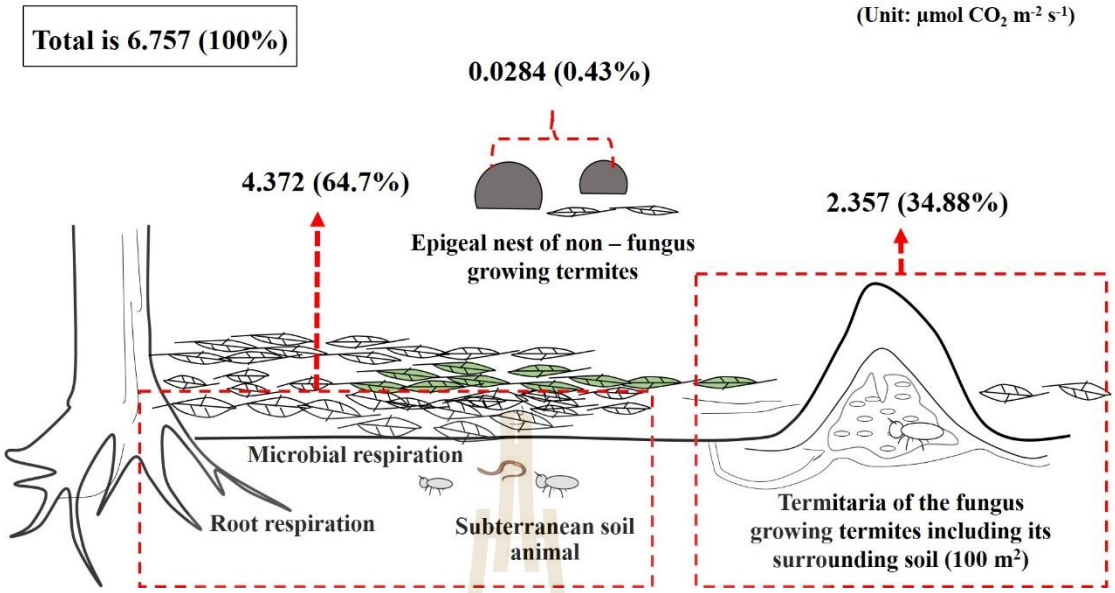

Figure 4.64 Schematic of CO_2 efflux from the termite mounds (epigeal nest) contribution to soil respiration in Thai seasonal tropical forest.

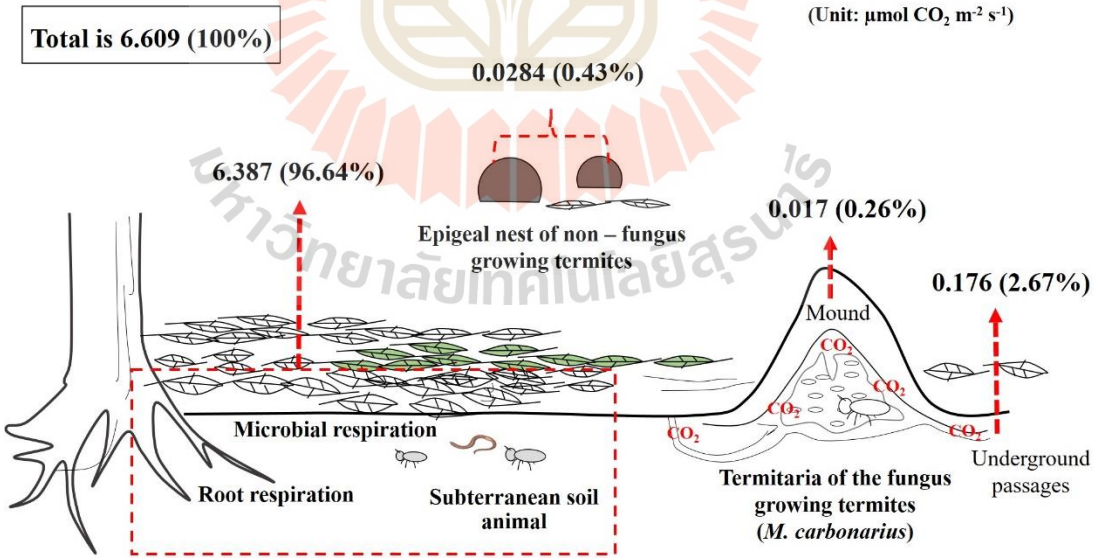

Figure 4.65 Schematic of CO_2 efflux from the mounds and underground passages of *M. carbonarius*, and the thin – wall mounds contribution to soil respiration in Thai seasonal tropical forest.

Due to previous studies suggest that the point of CO_2 sources cause by the nest of soil animals (i.e. termites and ants) on spatial variation in soil respiration in tropical forest (Khalil et al., 1990; Stoyan et al., 2000; Risch et al., 2005; Ohashi et al., 2007). And the recent studies were carry out on this issue (Table 4.14). According to Yamada et al. (2005) showed that about 11.2% of the fractions of annual above ground litterfall mineralized by termite populations and fungus combs. On the other hand, Song et al. (2013) reported that termite mounds did not account for the respiration hot spot with the mean ranged from 1.63 to 3.71 μmol CO_2 m^{-2} s^{-1} in a seasonal rain forest, China. But the study was carried out to measurement for investigating of termites at points on only above of large mounds, so that would be a typical of the thick – wall mound which have surrounding of underground passages. Hasin et al. (2014) elucidated the CO_2 efflux from subterranean nests of ant communities in a tropical seasonal forest, Thailand. The mean of CO_2 efflux was varied from 4.3 to 27.5 μmol CO_2 m^{-2} s^{-1} from 13 dominate species, 61 subterranean ant nests. However, this was depend on colony characteristics (e.g. abundance and behavior).

The impact of termite mounds of *G. sulphureus and Odontotermes* termites on soil respiration in the monsoon tropical forest of southern Vietnam was studied. The result showed that the average of the CO_2 efflux from the termite mounds was two times and more high than background soils during wet and dry seasons. Termite mounds occupy about 4% of the area, and contributed to 10% of the total soil respiration (Lopes de Gerenyu et al., 2015). However, in order to quantify the contribution of termite mounds, they were selected only one and two mounds for *G. sulphureus and Odontotermes*, respectively.

Table 4.14 The studies of CO_2 emission from the termite mound and ground soil.

Ecosystem and site	Respiration ($\mu mol\ CO_2\ m^{-2}\ s^{-1}$)		Studies	Remark
	Termite mound	Ground soil		
Tropical forest				
Sakaerat , Thailand (DEF)	3.36%	96.64%	Present	Termitaria of dominant epigeal mound species (nests and underground passages) contribution to the total soil respiration
Sakaerat , Thailand (DEF)	11.2%		Yamada, et al. (2005)	Fractions of annual above ground litterfall mineralized by termite populations and fungus combs
Xishuangbanna Natural Reserve, China	1.63 to 3.71	2.71 to 4.09	Song et al. (2013)	CO_2 flux from above the termite mounds was lower than ground soil
Cat Tien National Park, Vietnam	10%		Lopes de Gerenyu, et al. (2015)	Only 1 and 2 mounds for *G. sulphureus* and *Odontotermes*, respectively.
Savannas				
Lamto, Ivoiry Cote	4.9% (11.3%*)		Konate´ et al. (2003)	Represented from the mounds with fungus combs of *A. cavithorax* and *O. pauperans* which contribute to the total above-ground net primary production (*% of the carbon not mineralized by annual fires.)

CHAPTER V

CONCLUSIONS

The study was conducted to quantify the annual aboveground soil respiration from 5 main plots (1 ha in each). Each plot was divided into 100 subplots. The rates of soil respiration were measured by using a portable infrared gas analyzer (IRGA, EGM – 4, PP Systems) with a closed soil CO_2 efflux chamber (SRC – 1, PP Systems) (diameter 10 cm) on every PVC collars where placed at each center of each subplot for two times per dry and wet seasons in the DEF from November 2014 to August 2016. After the measurement in each subplot, soil temperatures and soil moisture contents were measured immediately by portable probes. The mean rate of soil respiration was 6.57 µmol CO_2 m^{-2} s^{-1} with ranged from 2.66 to 11.72 µmol CO_2 m^{-2} s^{-1}. Seasonal soil respiration rate was two times higher in wet season (8.81 µmol CO_2 m^{-2} s^{-1}) than dry season (4.33 µmol CO_2 m^{-2} s^{-1}). Although, the difference in soil respiration rates were increased with increasing soil temperature and soil moisture content, but there were not reached to more than 27°C and 21%, respectively.

The study was performed to determine CO_2 efflux from two different nest structures types as thick and thin – wall mounds in the DEF by using IRGA, EGM-4, PP Systems from November 2014 to August 2016 as follows; CO_2 efflux from termitaria of the thick – wall mound (*Macrotermes carbonarius*).was evaluated from 6 extra plots (100 m^2 in each) varied with the mound sizes; small, medium, and big for two mounds per each. CO_2 efflux on the mound for 6 measurement points and 100

measurement points for the surrounding soil were measured for 1 time per dry and wet seasons. The mean of CO_2 efflux rate was 7.10 µmol CO_2 m^{-2} s^{-1}, there were found the extremely high CO_2 efflux rates (extremely high up to 50 µmol CO_2 m^{-2} s^{-1}). After checking of the measurement points, 69.31% (15.97 µmol CO_2 m^{-2} s^{-1} in average) of the extremely high CO_2 efflux rates were found from an active underground passages with varying depth and diameter, 26.73% from under the flat roots (close to the big trees), and 3.96% from the normal soils. CO_2 efflux rates from surrounding soil including the underground passages (7.36 µmol CO_2 m^{-2} s^{-1}) was significantly higher than soil alone around the mound (6.86 µmol CO_2 m^{-2} s^{-1}). Thus, mean of CO_2 efflux rate was 9.11 µmol CO_2 m^{-2} s^{-1} from the underground passages of thick – wall mound only, due to the CO_2 efflux rate of soil alone around the mound was excluded. While CO_2 efflux from above the mound was only 2.94 µmol CO_2 m^{-2} s^{-1}.

For the thin – wall mound, 5 epigeal nest species (5 nests in each) of the thin – wall mound as *D. makhamensis*, *G. sulphureus*, *M. crassus*, *T. comis*, and *T. propinguus*, were directly measured of CO_2 efflux at the above of the nests by using IRGA, EGM – 4, PP Systems. Also, the surrounding the mound (reference points) with soil temperature and moisture were measured. There was observed for 1 time per dry and wet seasons. The averages of CO_2 efflux rates (µmol CO_2 m^{-2} s^{-1}) from *G. sulphureus* (37.71) and *M. crassus* (15.50) were significant difference from among the thin – wall species. While CO_2 efflux rates from *T. comis* (6.45), *T. propinguus* (1.98), and *D. makhamensis* (1.79), there were no significant difference.

In addition, the influence of termite castes, fungus combs, and nest materials of the thick – and thin wall mounds on the termitaria CO_2 efflux were investigated by using LI-820 CO_2 Gas Analyzer. In July 2016, 7 species of randomly selected mounds for 3

mounds in each in the DEF. After measurements, counting and weighing of each cast of termites and also fungus-comb were weighed. As results showed that respiration rate from termite population in smaller body weight have efficiency to arising the greater variation in metabolic rate.

The distribution of termite mound species and trees were performed by counting number and measuring of DBH, respectively in the 5 main plots. The effect of *M. carbonarius*'s mounds and the living trees on differences of mean soil respiration rates were evaluated by the number of mounds and tree's basal areas in every grids of the main plots, respectively. The relationship between distribution of *M. carbonarius*'s mounds and soil respiration rates from the measurement points were showed a small and no relationship in dry and wet season, respectively, because the CO_2 efflux points of underground passages radiating out from each mound were as small holds as specific – points and areas when compared with a large scale. In the wet season, the relationship with soil respiration rate was found in the tree's basal area, this could be due to competition from the microbial activities on aboveground litterfall and root respiration.

To estimate the total average of soil respiration, the thick – wall mound (*M. carbonarius*) was assumed the surrounding soil to be the radius of underground passages as well as CO_2 effluxes from the nest. The mound of *M. carbonarius* was estimated about 34.9% as a high contributed to the total soil respiration in the forest. While less than 0.5% of total respiration was emitted from the thin – wall mounds. There was 2.85% of relative error.

In fact, the total average of soil respiration rate from the DEF was estimated by considering actual means of CO_2 efflux from the mound and underground passage of *M. carbonarius*, and also including the thin – wall mounds. Consequently, the epigeal

termite mounds were to contribute 3.36% to the total average of soil respiration, which was 2.93% of the termitaria of *M. carbonarius* and 0.43% of the thin – wall mounds, with only 0.59% of relative error. The differentiation of these were due to the dispersal of CO_2 from area, nest structure, and nest density.

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APPENDICES

APPENDIX A

SOIL TEMPERATURE AND MOISTURE CONTENT ON SOIL RESPIRATION

1. Annual ground soil respiration of the main plot 1

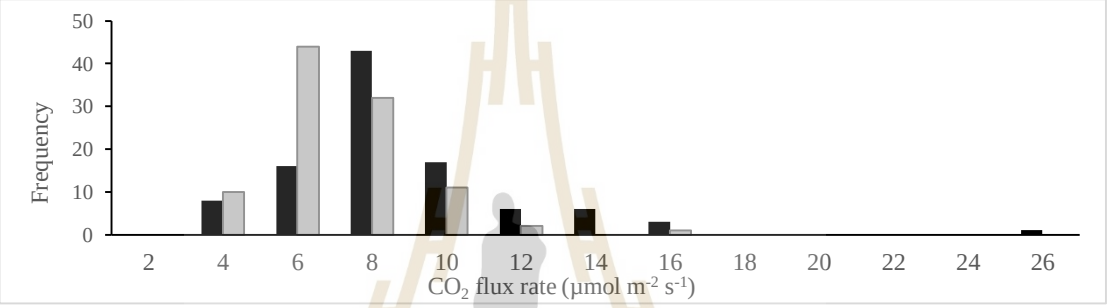

Figure 1 Frequency distribution of CO_2 efflux in dry season (n = 100, gray bars) and wet season (n = 100, black bars) of the 1st year in plot 1.

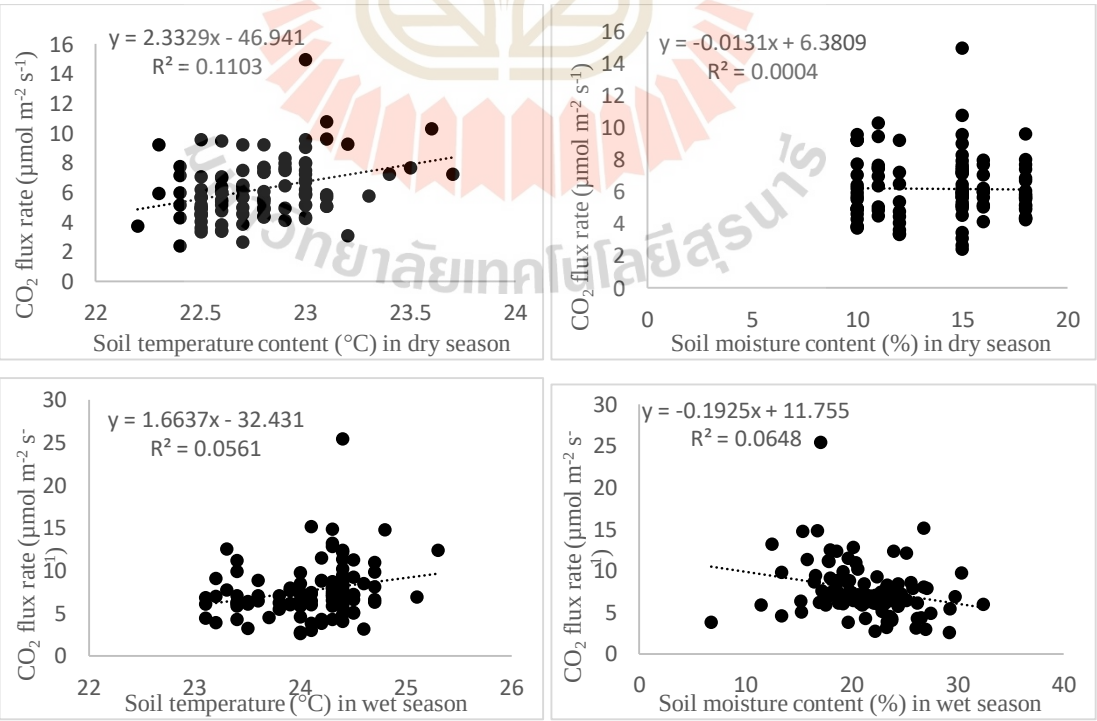

Figure 2 The relationship between soil respiration and its soil temperature and soil moisture at depth of 5-10 cm of dry and wet season of the 1st year in plot 1.

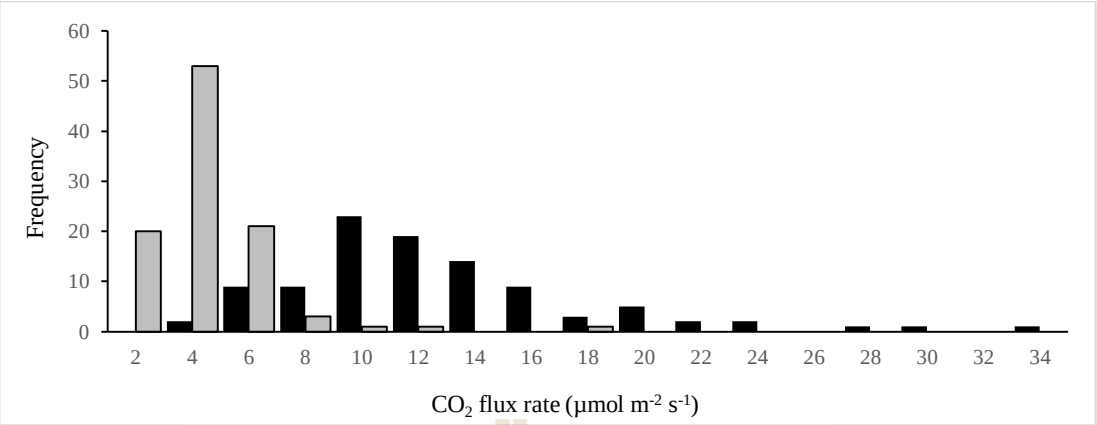

Figure 3 Frequency distribution of CO_2 efflux in dry season (n = 100, gray bars) and wet season (n = 100, black bars) of the 2nd year in plot 1.

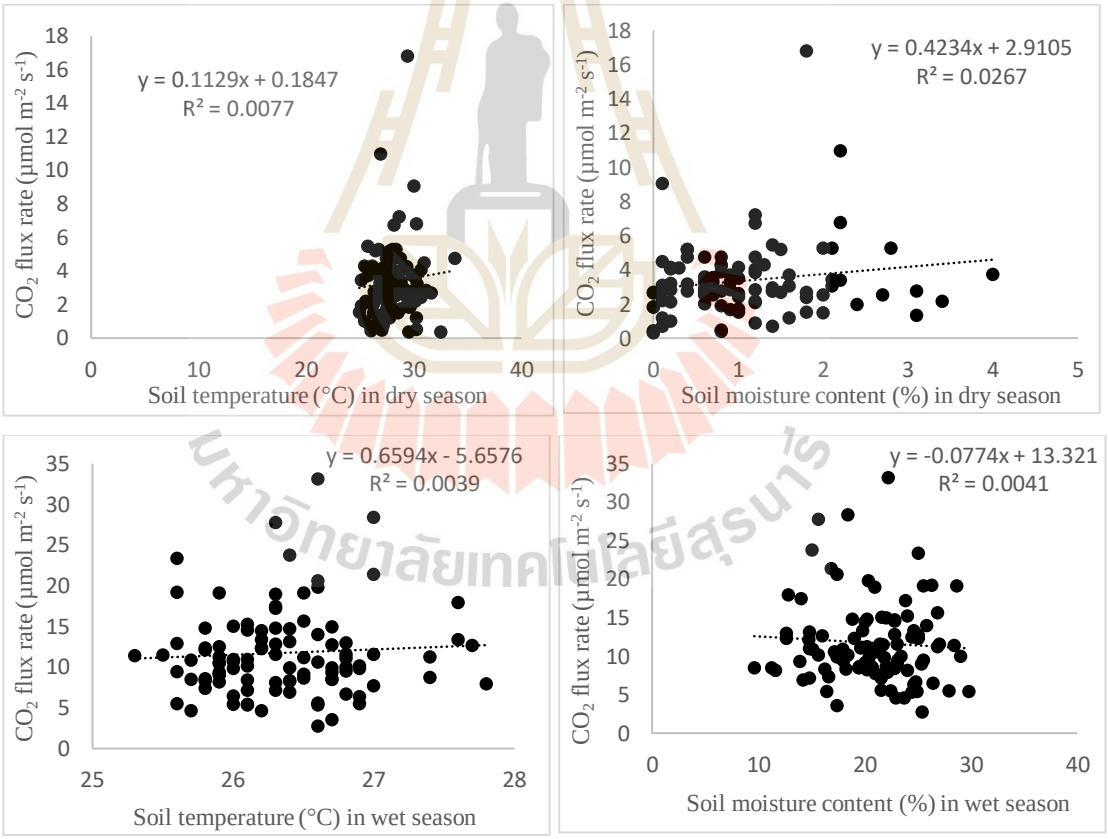

Figure 4 The relationship between soil respiration and its soil temperature and soil moisture at depth of 5-10 cm of dry and wet season of the 2nd year in plot 1.

2. Annual ground soil respiration of the main plot 2

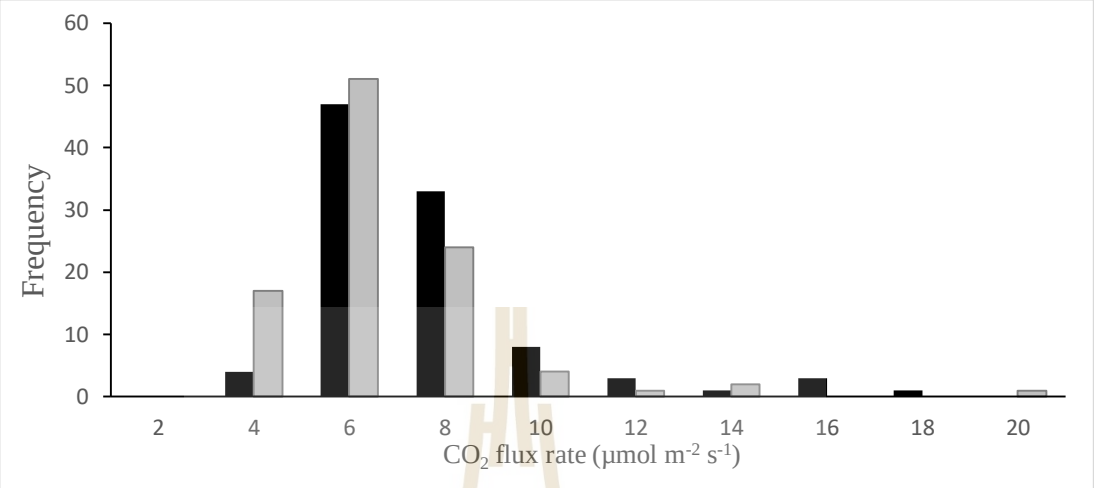

Figure 5 Frequency distribution of CO_2 efflux in dry season (n = 100, gray bars) and wet season (n = 100, black bars) of the 1st year in plot 2.

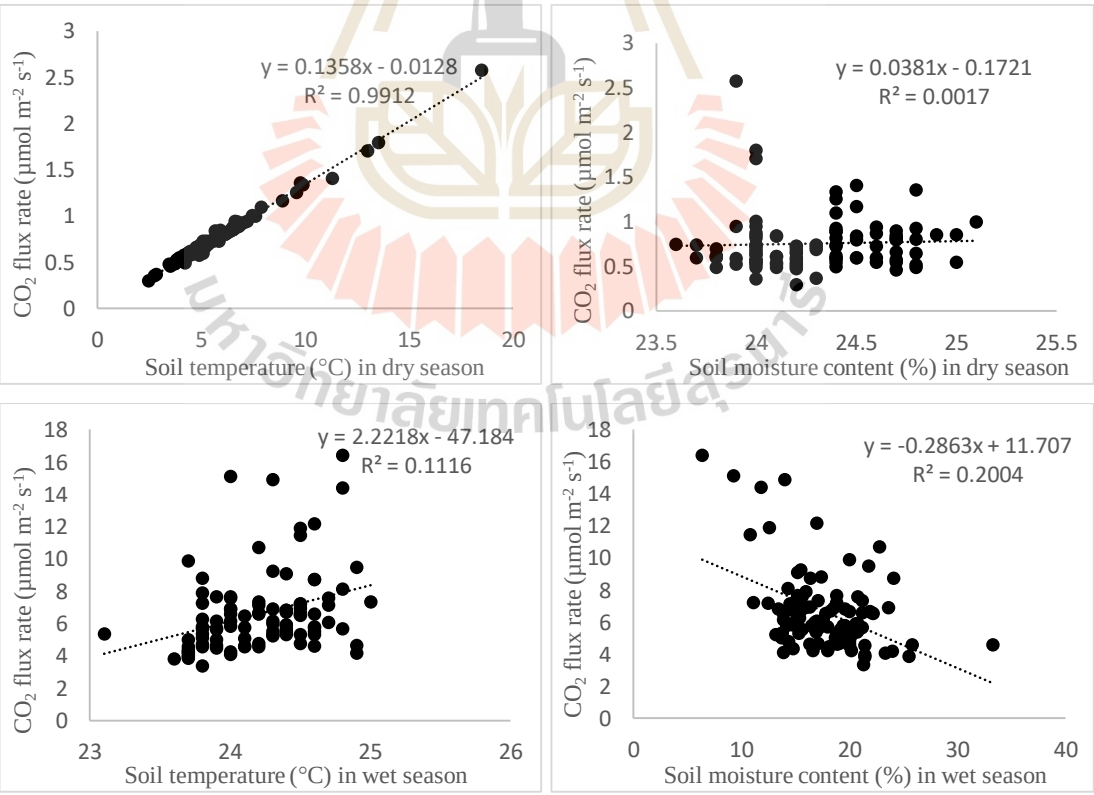

Figure 6 The relationship between soil respiration and its soil temperature and soil moisture at depth of 5-10 cm in dry and wet season of the 1st year in the plot 2.

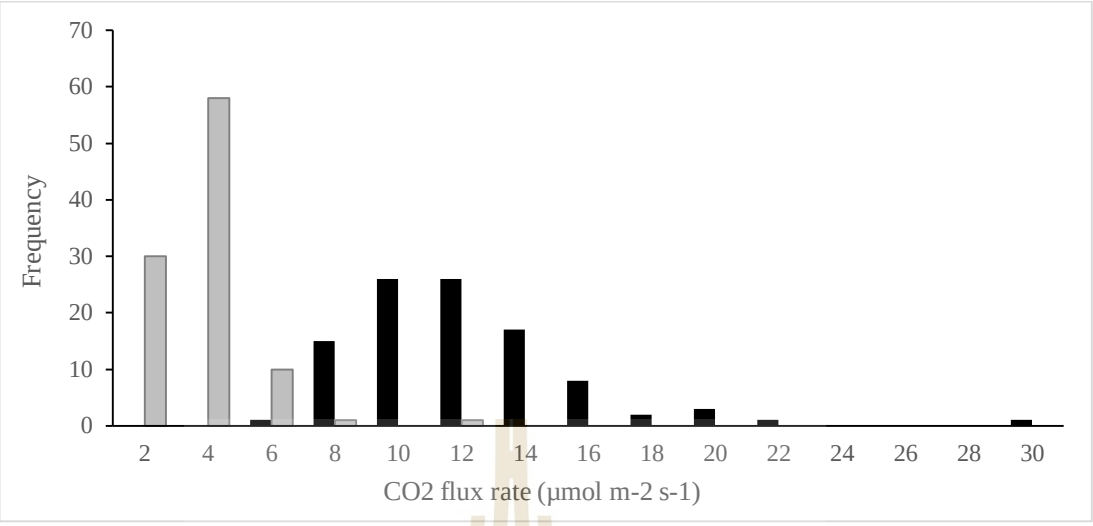

Figure 7 Frequency distribution of CO_2 efflux in dry season (n = 100, gray bars) and wet season (n = 100, black bars) of the 2nd year in plot 2.

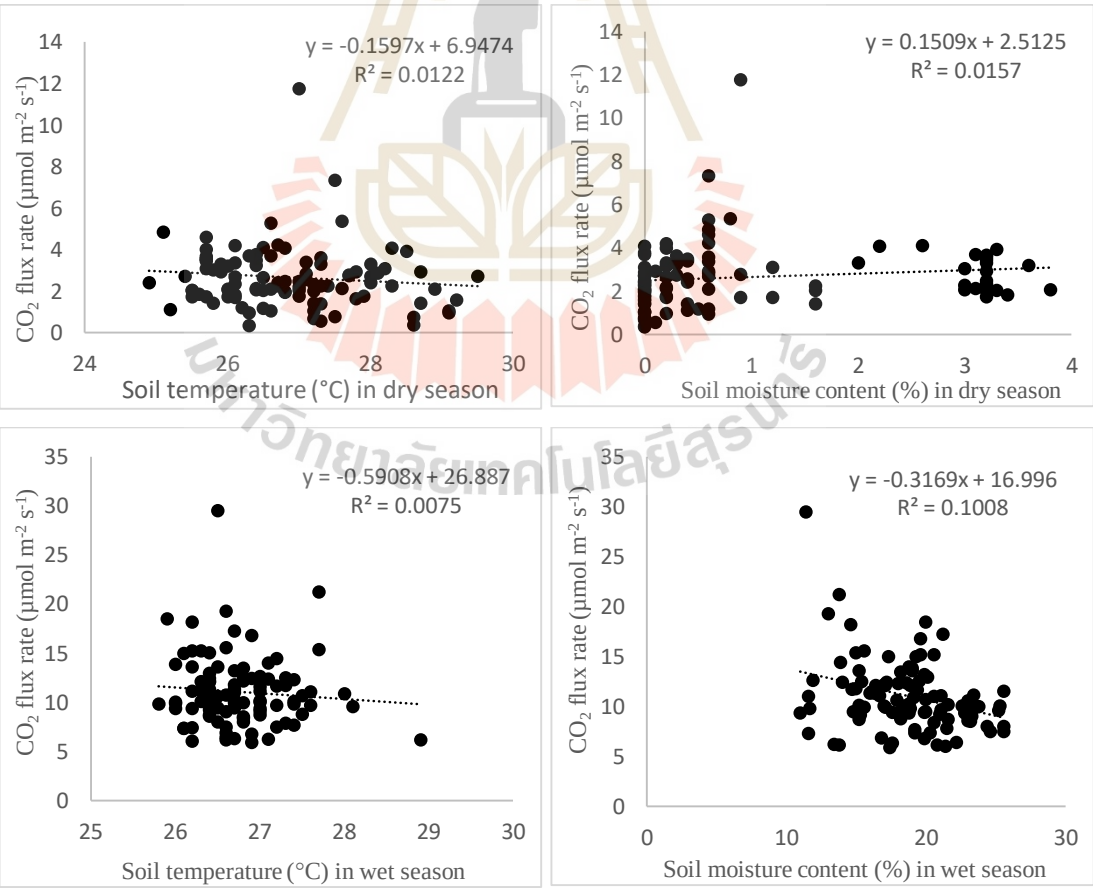

Figure 8 The relationship between soil respiration and its soil temperature and soil moisture at depth of 5-10 cm of dry and wet season of 2nd year in the plot 2.

3 Annual ground soil respiration of the main plot 3

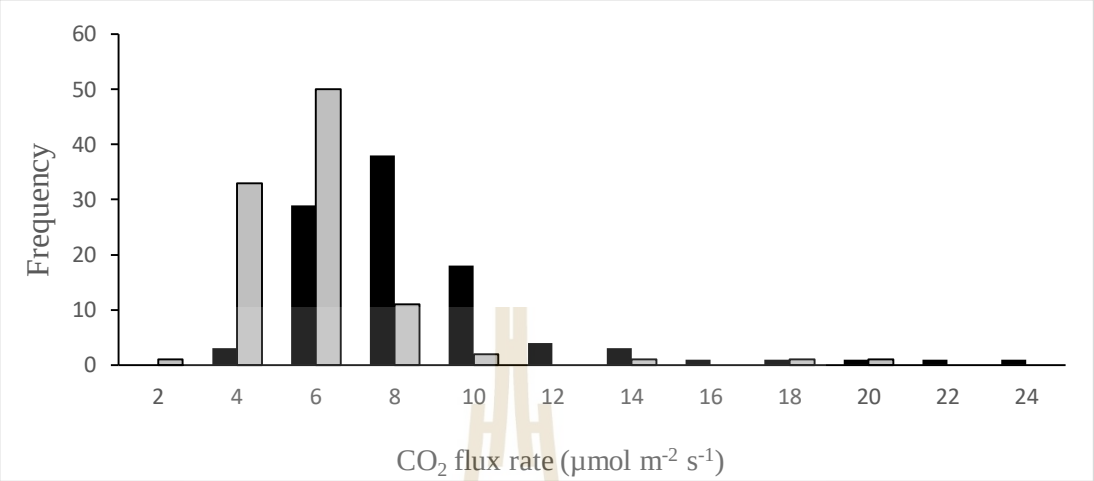

Figure 9 Frequency distribution of CO_2 efflux in dry season (n = 100, gray bars) and wet season (n = 100, black bars) of the 1st year in plot 3.

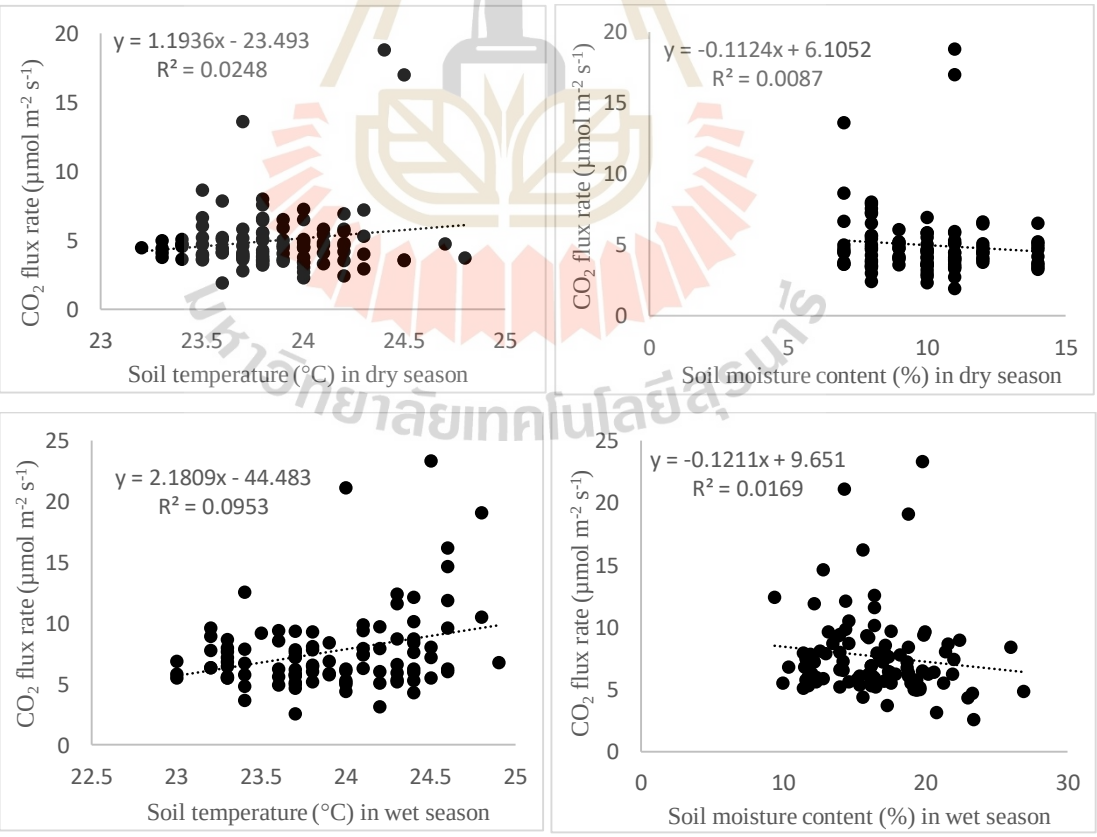

Figure 10 The relationship between soil respiration and its soil temperature and soil moisture at depth of 5-10 cm of dry and wet season of the 1st year in the plot 3.

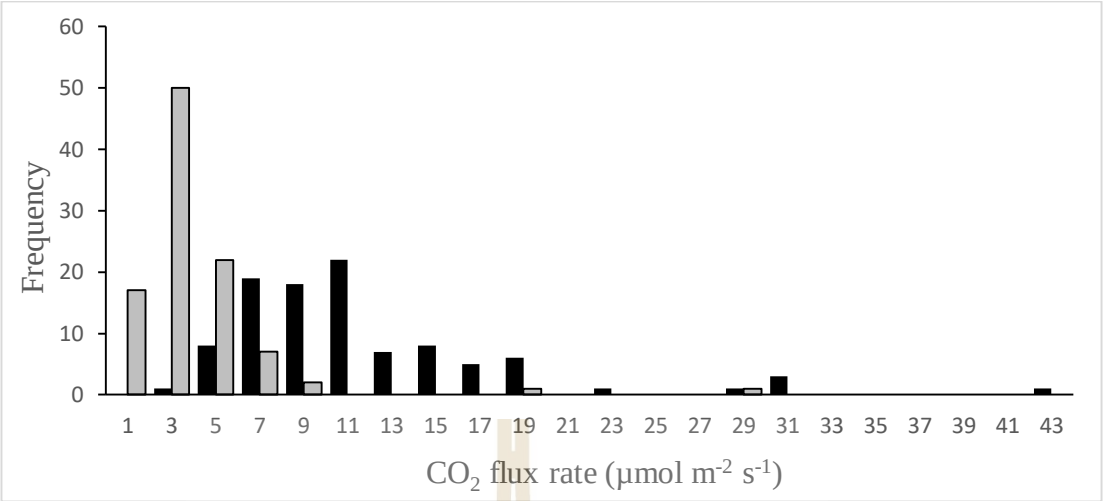

Figure 11 Frequency distribution of CO_2 efflux in dry season (n = 100, gray bars) and wet season (n = 100, black bars) of the 2nd year in plot 3.

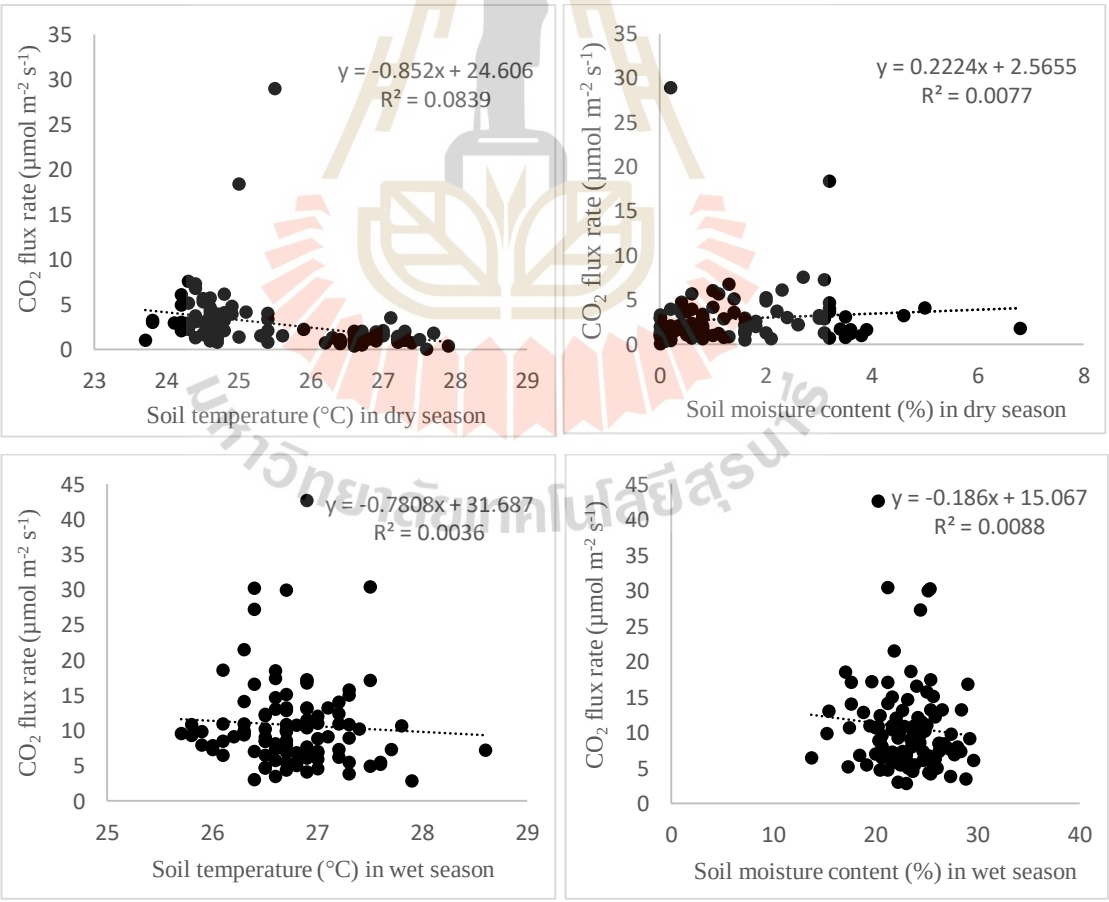

Figure 12 The relationship between soil respiration and its soil temperature and soil moisture at depth of 5-10 cm of dry and wet season of 2nd year in the plot 3.

4 Annual ground soil respiration of the main plot 4

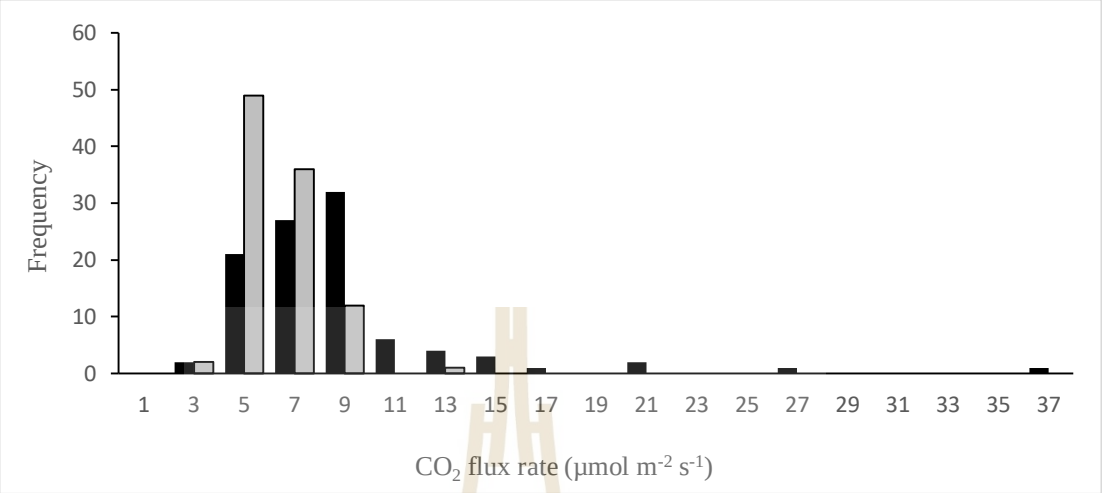

Figure 13 Frequency distribution of CO_2 efflux in dry season (n = 100, gray bars) and wet season (n = 100, black bars) of the 1st year in plot 4.

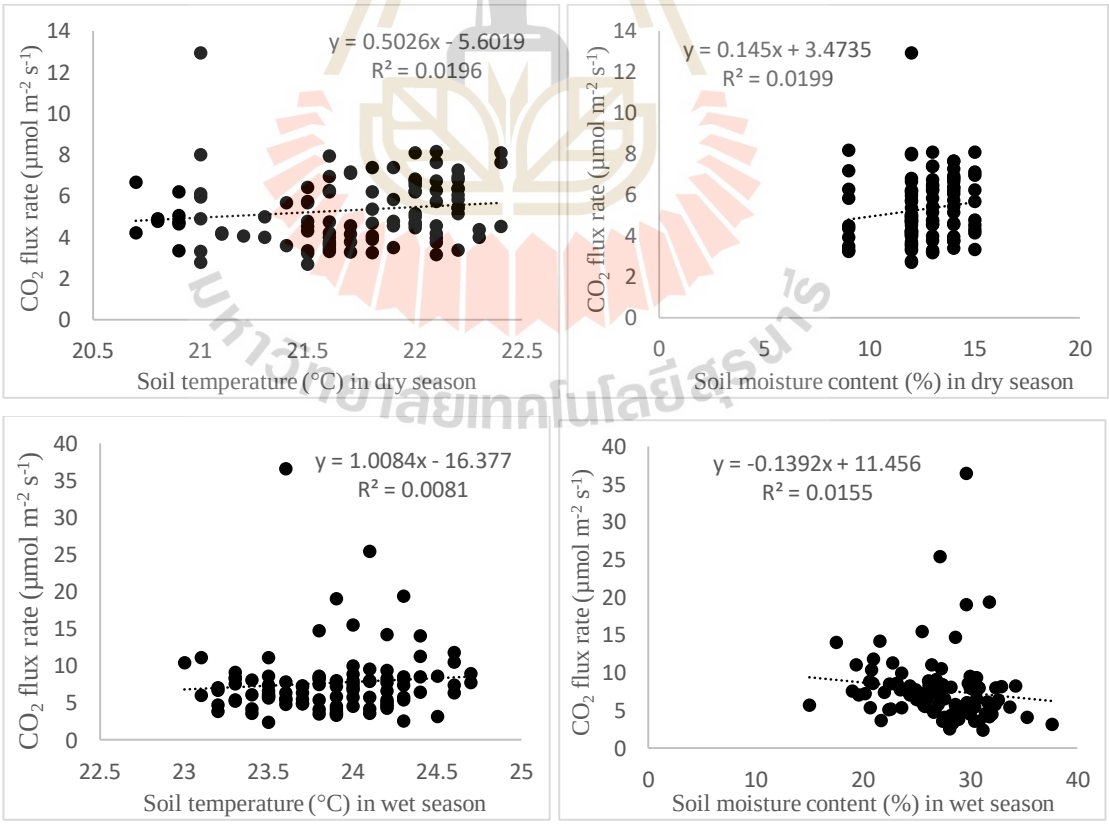

Figure 14 The relationship between soil respiration and its soil temperature and soil moisture at depth of 5-10 cm of dry and wet season of the 1st year in the plot 4.

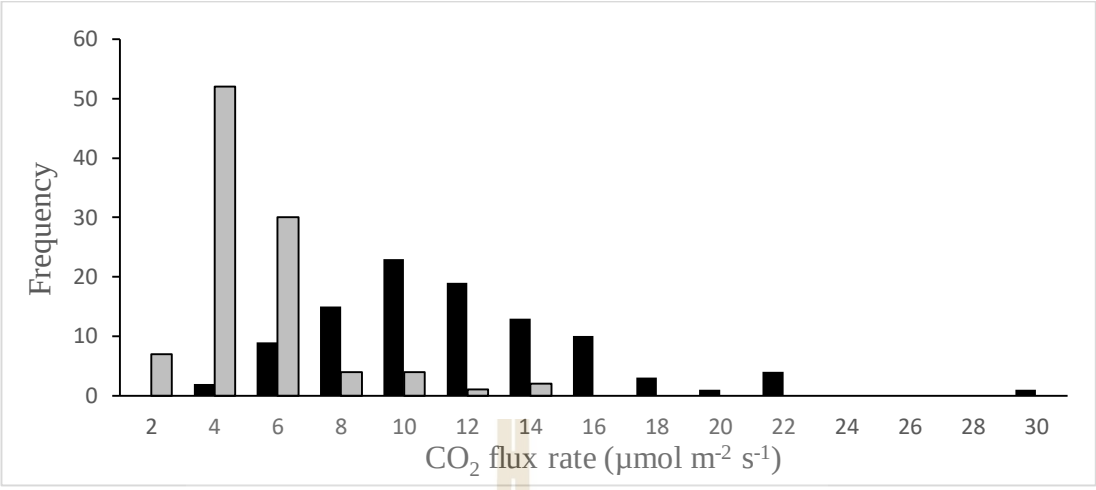

Figure 15 Frequency distribution of CO_2 efflux in dry season (n = 100, gray bars) and wet season (n = 100, black bars) of the 2nd year in plot 4.

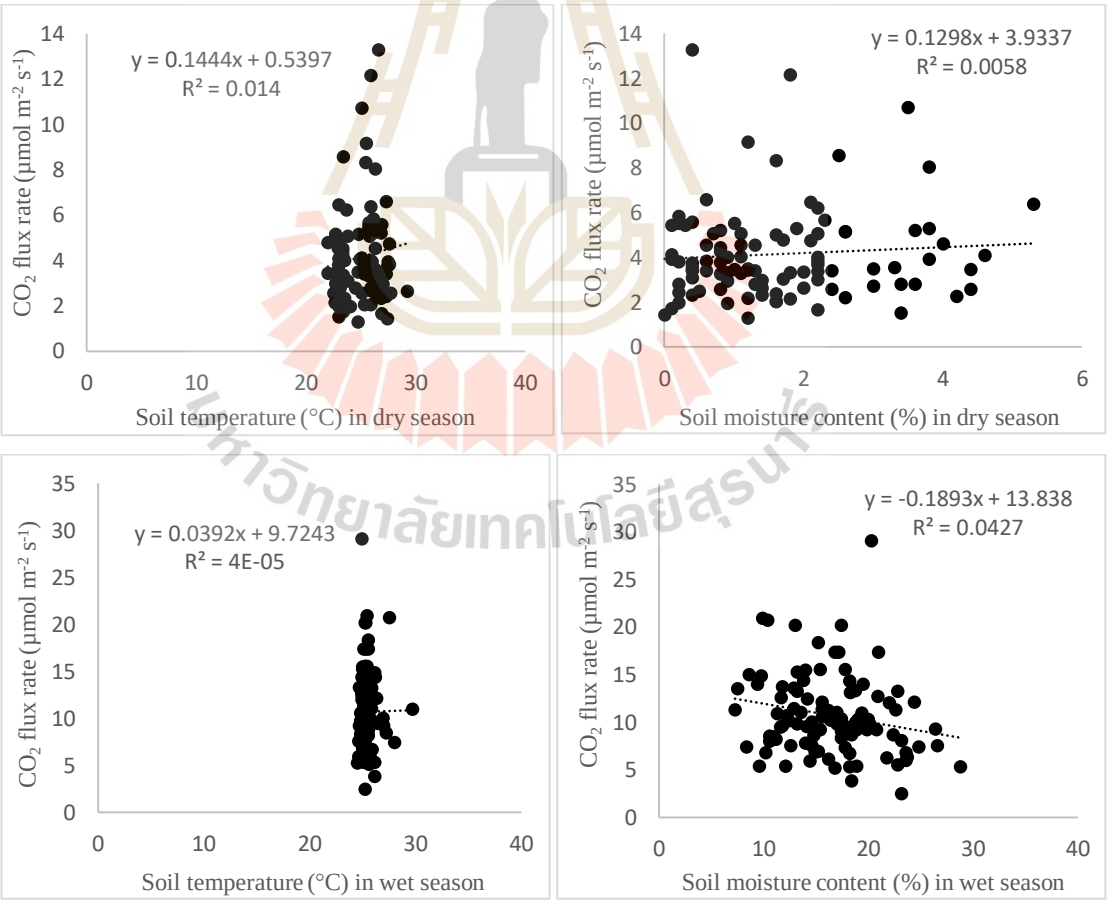

Figure 16 The relationship between soil respiration and its soil temperature and soil moisture at depth of 5-10 cm of dry and wet season of 2nd year in the plot 4.

5. Annual ground soil respiration of the main plot 5

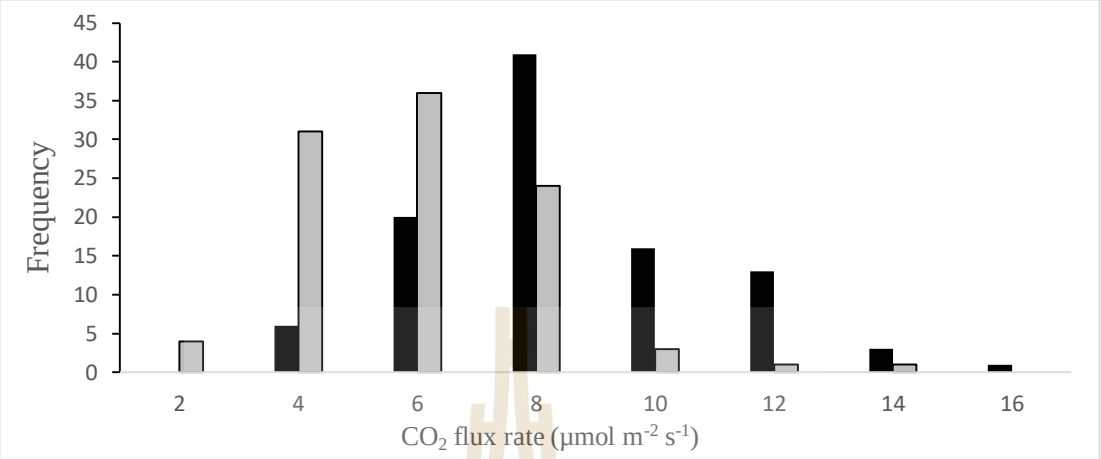

Figure 17 Frequency distribution of CO_2 efflux in dry season (n = 100, gray bars) and wet season (n = 100, black bars) of the 1st year in plot 5.

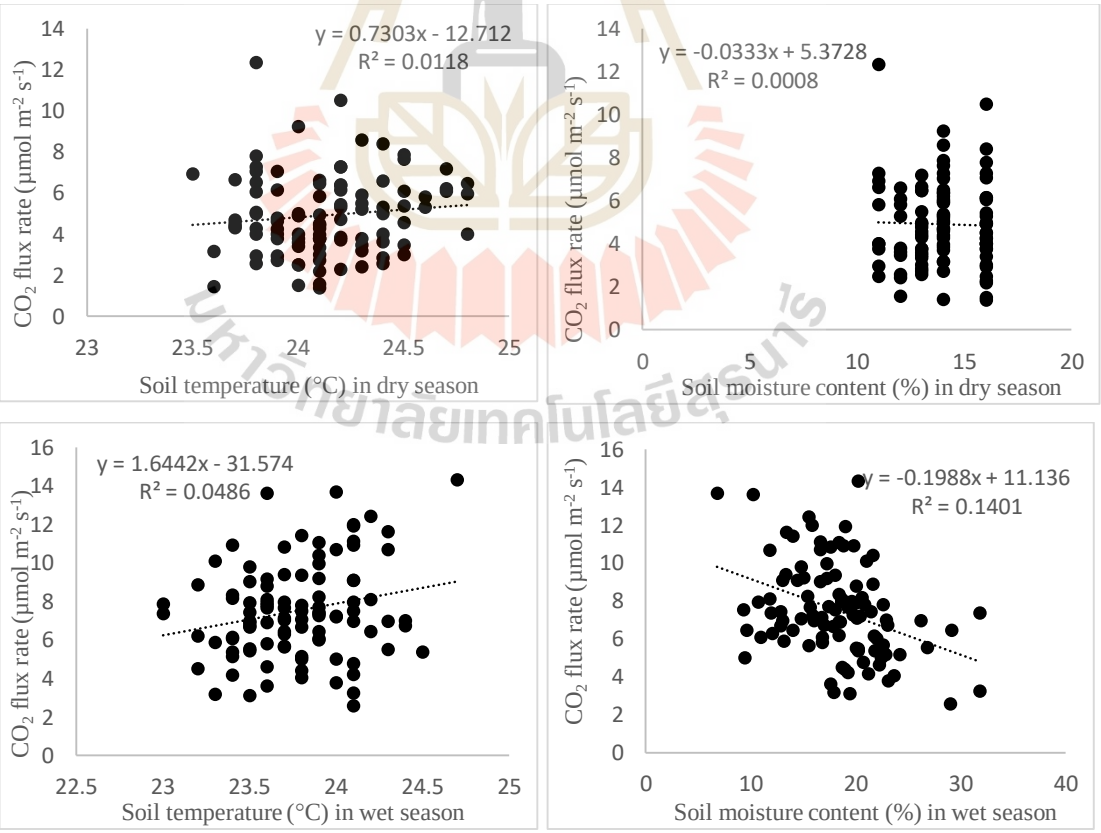

Figure 18 The relationship between soil respiration and its soil temperature and soil moisture at depth of 5-10 cm of dry and wet season of the 1st year in the plot 5.

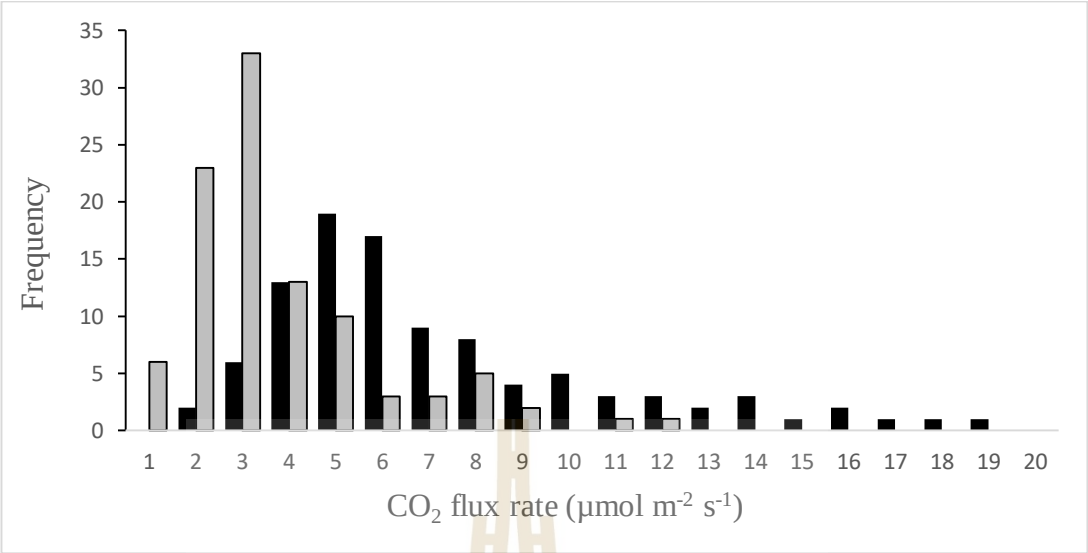

Figure 19 Frequency distribution of CO_2 efflux in dry season (n = 100, gray bars) and wet season (n = 100, black bars) of the 1st year in plot 5.

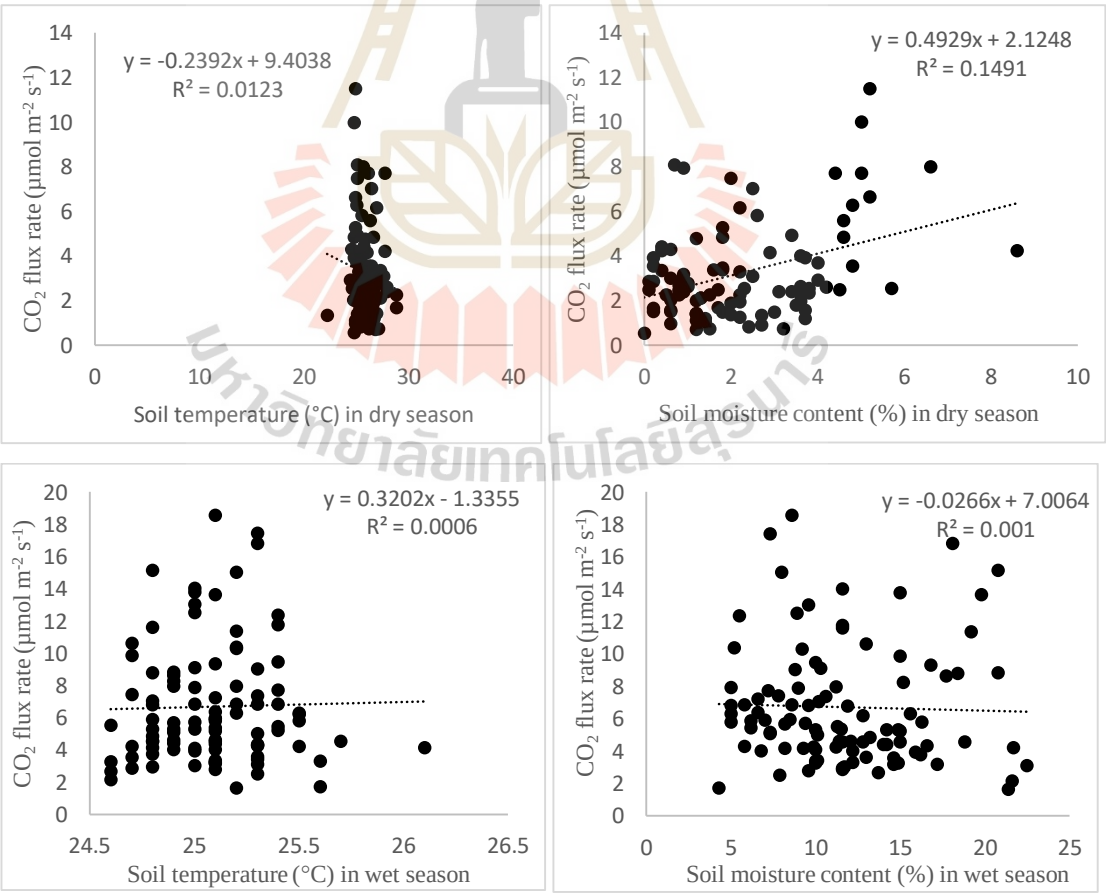

Figure 20 The relationship between soil respiration and its soil temperature and soil moisture at depth of 5-10 cm of dry and wet season of 2nd year in the plot 5.

APPENDIX B

CO_2 EFFLUX FROM THE THIN – WALL MOUNDS

Table 1 CO_2 efflux (µmol CO_2 m^{-2} s^{-1}) from DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus*.

Species	Volume of nest (m^3)	Dry season		Wet season	
		Nest	Soil surrounding	Nest	Soil surrounding
DM1	0.0012	0.42	2.05	3.47	9.28
DM2	0.0051	1.52	2.84	1.55	7.61
DM3	0.0005	1.00	2.24	2.39	7.70
DM4	0.0080	0.92	2.73	2.24	7.35
DM5	0.0013	1.20	1.77	3.15	9.38
Average	0.0032±0.32	1.01±0.40	2.33±0.45	2.56±0.76	8.26±0.98
GS1	0.11	31.89	2.97	39.34	5.92
GS2	0.04	46.49	3.52	55.15	9.25
GS3	0.07	22.24	2.47	51.48	7.81
GS4	0.15	23.31	2.31	43.66	7.22
GS5	0.02	12.01	1.76	51.50	5.49
Average	0.078±0.05	27.18±12.8	2.61±0.67	48.23±6.5	7.14±1.51
Mcc1	0.004	13.19	1.72	34.28	7.18
Mcc2	0.008	15.01	1.14	22.20	5.66
Mcc3	0.007	11.04	2.08	16.62	7.79
Mcc4	0.001	9.44	2.89	15.73	7.24
Mcc5	0.001	7.96	1.39	9.53	5.00
Average	0.0043±0.03	11.33±2.83	1.84±0.68	19.67±9.3	6.57±1.18

Table 1 CO_2 efflux (µmol CO_2 m^{-2} s^{-1}) from DM: *D. makhamensis*, GS: *G. sulphureus*, Mcc: *M. crassus*, TC: *T. comis*, and TP: *T. propinguus* (Continued).

Species	Volume of nest (m^3)	Dry season		Wet season	
		Nest	Soil surrounding	Nest	Soil surrounding
TC1	0.09	4.98	2.64	7.93	13.62
TC2	0.02	4.20	3.03	11.11	12.69
TC3	0.01	4.17	2.17	8.28	7.32
TC4	0.06	4.70	0.91	7.87	7.57
TC5	0.05	4.27	3.00	6.96	6.29
Average	0.044±0.03	4.46±0.36	2.35±0.88	8.43±1.57	9.50±3.39
TP1	0.0040	0.17	2.81	0.84	5.44
TP2	0.0013	1.03	2.15	5.65	9.07
TP3	0.0006	1.00	2.47	4.56	7.75
TP4	0.0002	1.63	1.87	2.51	8.08
TP5	0.0004	0.65	2.53	1.82	7.09
Average	0.0013±0.01	0.89±0.54	2.36±0.36	3.08±1.98	7.48±1.35

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Akinori Yamada, Masashi Higuchi, **Warin Boonriam**, Nathawut Thanee, Taksin Artchawakom, Decha Wiwatwitaya, Hiroshi Takeada and Jun-ichi Azuma. (2009). Architecture, thermoregulation and gas exchange of mounds of *Macrotemes carbonarius* in a tropical forest of Northeast Thailand: Are tropical forest optimal habitats for Macrotemes? **Proceeding of The Sixth Conference of The Pacific Rim Termite Research Group**. 2-3 March 2009, Kyoto, Japan. TRG6: 10-17.

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