

CHAPTER 5

DISCUSSION AND CONCLUSION

Tropical forests are important to the global carbon cycle because they are large reservoirs of carbon. It also contains higher carbon storage than other regions, approximately 60 percent of total carbon in biomass stock on the Earth (Dixon, *et al.*, 1994). Houghton, (2003) reported that almost all of the global carbon flux occurs in the tropical regions (2.2 PgC / yr in the 1990). Outside the tropics, the net flux is a small sink (0.2 PgC yr⁻¹ during the 1990). In addition, the litter production (6-12 ton dry matter.ha⁻¹.yr⁻¹) and decomposition rate constant ($k = 0.162-2.813$) in tropical forest were highest values in the world (Landberg and Gower, 1997). Hence, the carbon cycle in tropical forest was more important as one of the main global carbon cycle components.

Soil CO₂ efflux is the result of CO₂ production by autotrophic root respiration (R_b) and heterotrophic microbial respiration (R_m) from the rhizosphere and bulk soil (Fang and Moncrieff, 1999), and of CO₂ transportation through soil layers. The quantity and spatial and temporal variations of soil CO₂ effluxes are therefore modified by physical, chemical and biological aspects of its environments. From the climate change perspective, CO₂ emission from the soil to the atmosphere is one of the important pathways of CO₂ inputs into the atmospheric pools, thus contributing to the increase or decrease atmospheric CO₂ concentrations. Since CO₂ concentrations in the atmosphere is key to global warming and climate change, our understanding of carbon dynamics in various emissions sources is crucial.

Concerning soil respiration, besides our understanding on the total respiration, the partitioning of soil CO₂ efflux into various important components helps to improve our understanding of the environmental changes that drive carbon cycling (Kuzyakov and Cheng, 2001; Bond-Lamberty, *et al.*, 2004) and to accurately estimate carbon budgets of ecosystems and turnover rates of soil organic matter (Wang, *et al.*, 2006). The partitioning of soil respiration into two main components as microbial and root respiration and defining the variables controlling each component is difficult but important, and it can help us better understand the belowground carbon dynamics as well as the variation of carbon sources and sinks in terrestrial ecosystems (Kelting, *et al.*, 1998; Ohashi, *et al.*, 2000).

Generally, the factors controlling soil respiration and determining its temporal and spatial variations at large scales are mostly abiotic in nature (e.g. soil texture, soil temperature soil moisture and precipitation). Their impacts on soil respiration are reasonably well

understood for a variety of forest ecosystems (Hanson, *et al.*, 1993; Davidson, *et al.*, 1998; Rey, *et al.*, 2002; Khomik, *et al.*, 2006; Bonal, *et al.*, 2008). However, at smaller spatial scales, soil respiration varies considerably beyond environmental drivers (Epron, *et al.*, 2006; Katayama, *et al.*, 2009; Martin and Bolstad, 2009). This residual variation appears to be related to biotic rather than abiotic factors, but biotic control over soil respiration is poorly understood (Grayston, *et al.*, 2001).

Understanding how both soil respirations respond to such biotic factors is fundamental to accurate prediction of climate impacts on carbon cycling. Increased global temperature and moisture could stimulate root activity and microbial-mediated organic carbon decomposition, and thus, CO₂ emission from soil. In addition, the soil respiration rate was highly related to other biotic factors such as soil microbial and root biomass (Yi, *et al.*, 2007), phenology of growth of aboveground and belowground plant tissue (Davidson, *et al.*, 2006), litter production (Epron, *et al.*, 2004), and litter decomposition (Sulzman, *et al.*, 2005). However, there are few data on partitions of microbe and root respiration related with biotic factors, especially root biomass and microbial biomass in tropical forest.

5.1 Comparison of annual CO₂ emissions through soil respiration in dry dipterocarp forests with other forest ecosystems

The large quantities of carbon pools (about 3800 PgC) in terrestrial ecosystems are storage in soil and plants (Luo and Zhou, 2006). Consequently, even small changes in the magnitude of this pool via soil respiration could have a large effect on the concentrations of CO₂ in the atmosphere. Hence, there have been many studies in the past attempting to quantify the amount of carbon cycled via soil respiration. According to the global database of soil respiration data (Bond-Lamberty and Thomson, 2010), there were about 2,373, 415 and 353 records of soil respiration published in temperate-biome, boreal and tropical regions. The relatively lower number from the tropical regions reflects our poor understanding when compared to other regions, despite the fact that tropical ecosystems plays the crucial roles in global carbon cycle.

The results obtained from the current study show that the mean soil respiration in the dry dipterocarp forest during 2008-2011 was 1031.39 ± 391.05 gC m⁻² yr⁻¹ (range between 935.15 and 1129.66 gC m⁻² yr⁻¹). This is relatively high compared to other ecosystem outside tropics but relatively lower within the tropic. Due to its high productivity and dynamics, it is common that the soil respiration in tropical region is higher than in other regions. According to the global database of soil respiration, the annual means of annual soil respiration were

109±109, 383±228, 745±421, 813±436, 776±380, and 1,286±663 gC m⁻² yr⁻¹ in Arctic, boreal, temperate, Mediterranean, subtropical, and tropical ecosystems, respectively (Bond-Lamberty and Thomson, 2010). Annual soil respiration rate was limited by many factors. However, temperature, precipitation, and litter production are the main factors (Bond-Lamberty and Thomson, 2010).

Firstly, the temperature is the best predictor of the annual and seasonal dynamics of the soil respiration rate. On global scales, the monthly and annual CO₂ fluxes correlate significantly with the soil temperature (Raich and Schlesinger, 1992). The soil respiration in the dry dipterocarp forest was highly correlated with soil temperature in the range of 20 - 26 °C (Figure 5.12). Above this temperature range, soil respiration tended to decrease ($r^2=0.40-0.78$, p -value < 0.01, $n = 101$) (Figure 5.12).

Secondly, precipitation and soil moisture are other important factors influencing soil respiration, especially in semiarid tropical forests as well as at the Ratchaburi site. The general pattern of soil water content characterizes the two-phase effect of soil water on soil respiration: soil respiration increases with increasing soil water content up to 20 %WFPS and decreases exponentially at higher soil water contents in DDF (Figure 5.13). Similar patterns of relationships were also found in semiarid tropical forest (Rey, *et al.*, 2002, Luo and Zhou, 2006). For example, Shi, *et al.* (2011) demonstrated very high soil respiration rates immediately after summer precipitation events in the forest because during summer the soil respiration was generally limited by drought.

Saigusa, *et al.* (2008) studied the seasonal patterns of CO₂ flux in boreal, temperate, and tropical forests in East Asia. They found that annual precipitation in temperate zone (640-2060 mm) was higher than tropical zone (1200-1700 mm) and sub-arctic zone (250-360 mm) but the CO₂ efflux in temperate zone was lower than tropical zone. Despite high precipitation in temperate zone it did not produce CO₂ from soil respiration because the normal soil moisture in temperate zone was higher than the tropical zone. Thus, precipitation event may immediately reduce the soil respiration rate to a very low level by saturating the soil pore spaces, a phenomenon also observed in an Amazonian rain forest (Buchmann, *et al.*, 1997), and subtropical montane forest in Taiwan (Chang, *et al.*, 2008). In addition, the temperature in tropical zone was higher than temperate zone. The both factors are mainly controlled the soil respiration in each region.

Finally, respiratory release of CO₂ is controlled by the breakdown of carbon-based organic substrates. Litter production is the main carbon substrate to microbial respiration. As a consequence, soil respiration usually increases with the amount of litter. O' Neill & De

Angelis, (1980) reported that the average litter productions in arctic zones, cooling zones, and warm zones were 3.30, 4.60 and 4.70 ton ha⁻¹ yr⁻¹, respectively, and the highest was in tropical zones at 9.30 ton ha⁻¹ yr⁻¹. The average litter production in the dry dipterocarp forest was 7.07 ton ha⁻¹ yr⁻¹. These results vary depending on the temperature, moisture and photosynthetic activity in each zone (Saigusa, *et al.* 2008). Normally, the tropical zone consists of more appropriate conditions for litter production, including the soil temperatures (approximately, 20-25 °C), precipitation (1200-1700 mm), and long light period than the other zones. Maier and Kress, (2000) manipulated the aboveground litterfall at the soil surface in a loblolly pine forest and found a linear relationship between the increase in soil respiration and the amount of litter added to the soil surface. Similar relationships between the litter amount and soil respiration have been found in other ecosystems (Bowden, *et al.*, 1993; Sulzman, *et al.*, 2005).

5.2 Temporal variations of soil respiration in dry dipterocarp forest

5.2.1 Diurnal variations

This study used the combination of high frequent (hourly) soil respiration measurements and the trenching method to partition soil respiration components in order to investigate their contributions to multi-scale temporal variations in the tropical dry dipterocarp forest. On diurnal time scales, variation of soil respiration and its components during both wet and dry seasons showed a similar pattern; CO₂ peaked in the late afternoon. However, in the wet season the daily CO₂ peaked about 2 hrs earlier than in the dry season (Figure 4.19). Root respiration did not show a clear diurnal change in the dry season.

At the site, potential factors that change on diurnal time scales are temperature, photosynthetically active radiation, and CO₂ exchange (Sangwangsri, *et al.*, 2011). We have analyzed the relationship among these and found that only diurnal scale change of temperature give a significant relationship with soil respiration. However, the volumetric soil water content at 0.05 m depth had no significant diurnal variation in either season. The diurnal patterns of R_s between dry and wet season differed because the soil warmed up earlier during the wet season. It was related to the time of sun rise and cooling temperature during winter in the dry season. Toshie, *et al.* (2002) found the soil CO₂ flux was strongly correlated with the soil surface temperature. Pingintha, *et al.* (2010) found that the soil CO₂ flux was strongly correlated to soil temperature at 0.05 m soil depth. Yoshiko and Hasegawa, (2000) estimated the soil CO₂ profiles based on CO₂ production and gas diffusivity. They described the diurnal changes of soil CO₂ concentration to be similar to those of soil temperature.

Similar to other studies, thus it seems that diurnal pattern of soil respiration is driven mainly by soil temperature.

The coefficient of diurnal soil respiration variations (CV) for R_s , R_m , and R_b averaged during the four years of measurements were 59.79, 60.63, and 61.69% in dry season and 30.28, 32.30 and 58.97% in wet season, respectively (Table 5.1). Thus, overall variations in soil respiration in dry season were relatively higher than in the wet season. The higher variations in dry season were due to high variations in R_m and R_b while relatively lower variations in the wet season were due to low variations in R_m . It is noted that CV of R_b was always higher than that of R_m .

There have been several studies in the past suggesting that root respiration contributes significantly to the diurnal variations. A tight linkage between plant photosynthetic activity and root respiration has previously been suggested from isotopic data and relationships with GPP and with PAR (Tang and Baldocchi, 2005). Lambers *et al.* (1996) found that more than 50% of the daily accumulated photosynthetic substrate was respired by the roots (Buoma, *et al.* 1997). Analysis among these parameters does not show the clear relationship between diel pattern of R_b and any of these drivers. However, it was found that R_b was greater during daytime than during nighttime especially during wet season, suggesting the roles of photosynthesis and a time lag between photosynthesis and root respiration. This time lag varies greatly from few hours for grasses, 7-12 hrs for oak tree (Tang, *et al.*, 2005), to 4-5 days for mature trees in general (Kuzyyakov and Gavrichkova, 2010). In dry dipterocarp forest, from lack of clear diurnal variations of R_b the lag time would be at least longer than several hours time. From these data, it can be concluded for diurnal time scale that the magnitude of soil respiration is controlled mainly by microbial respiration while the variations is controlled by root respiration. It is noted that variations stemmed from R_m are always lower than R_b .

Table 5.1 The mean, S.D., and coefficient of variations (CV) of soil respiration and its components on different time scales

Year	R _s and its components	Daily time scale				Seasonal time scale				Annual time scale	
		Dry		Wet		Dry		Wet		Mean±SD	CV (%)
		Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)	Mean±SD	CV (%)		
2008	R _s	356 ± 124	35	427 ± 146	34	336 ± 110	33	429 ± 111	26	392 ± 143	37
	R _m	220 ± 90	42	297 ± 102	35	209 ± 86	41	293 ± 45	15	260 ± 106	41
	R _b	137 ± 77	56	130 ± 78	61	128 ± 49	39	136 ± 71	52	132 ± 78	59
2009	R _s	365 ± 148	41	537 ± 100	19	350 ± 134	38	537 ± 86	16	459 ± 163	35
	R _m	249 ± 138	55	427 ± 76	18	236 ± 116	49	425 ± 66	15	346 ± 154	45
	R _b	116 ± 47	41	110 ± 59	54	114 ± 31	27	112 ± 38	34	114 ± 60	53
2010	R _s	305 ± 98	32	484 ± 100	21	307 ± 74	24	476 ± 49	10	404 ± 133	33
	R _m	188 ± 62	33	335 ± 76	23	190 ± 49	26	330 ± 39	12	270 ± 101	38
	R _b	117 ± 44	38	150 ± 59	40	117 ± 28	24	147 ± 44	30	135 ± 55	41
2011	R _s	313 ± 100	32	619 ± 190	31	321 ± 97	30	623 ± 99	16	473 ± 217	46
	R _m	183 ± 63	35	414 ± 130	32	188 ± 60	32	418 ± 75	18	304 ± 155	51
	R _b	138 ± 49	36	228 ± 105	47	133 ± 39	29	205 ± 42	21	169 ± 94	56

5.2.2 Monthly and seasonal variations

On the seasonal time scale, the main drivers for soil respiration were soil moisture and temperature. During the dry months, soil respiration and its components remained relatively constant. Once the rain comes and soil moisture increases, soil respiration becomes active (Figures 4.4 and 4.21). The magnitudes of response differed between R_m and R_b . R_m increases more rapidly than R_b . This well-known effect is a result of the stimulation of biological activity in the soil (Borken, *et al.* 2003; Lee, *et al.* 2004; Liu, *et al.*, 2002). Importance to microbial activity is also the substrate availability. In this dry dipterocarp forest, litter fall occurs starting at the wet season and finishes by the end of February-March (Hanpattanakit and Chidthaisong, 2012). There is therefore about one or two months that this forest is mostly without leaves and forest floor is directly exposed to sunlight, driving up soil temperature. However, litter decomposition starts only when soil moisture increases to certain levels. Rapid decline in leaf and branch residual weights were noticed during rainy months of June – October, nearly 70% of leaf and 35% of branch were losing weights. Normally, the relative mass loss of litter in the dry dipterocarp forest was observed during 13-month period, but these were promptly decomposed around 5 months in wet season. This agrees with the increase in microbial biomass during the same period (Figure 4.22). The means microbial biomass during wet season was about 4 times higher than in dry season ($p < 0.05$).

R_b also shows a clear seasonal variation, though not as obvious as in the case of R_m . Beside soil moisture, R_b is significantly correlated with monthly GPP ($R_b = 0.13(\text{GPP}) - 162.27$, $R^2 = 0.75$) (Figure 5.1). However, this correlation was observed only during the wet season. This was not observed on the diurnal time scale, supporting the assumption that the transport of photosynthetic substrate to the roots may take longer than several hours and may be up to days. Diurnal data would not be of capable capturing such an effect. Changes in R_b also reflect changes in root biomass. Although total root biomass between wet and dry was not significantly different (444.8 kg m^{-2} in the dry and 503.86 kg m^{-2} in the wet season, Figure 4.8), fine root biomass (size $< 2\text{mm}$) was significantly higher ($p < 0.05$) in wet ($242.60 \pm 53.92 \text{ kg m}^{-2}$) than in dry season ($144.21 \pm 21.52 \text{ kg m}^{-2}$). Fine root gradually decreased after the wet season and became stable during dry season until middle wet season (Figure 5.2). Many reported that fine roots play a key role in the carbon and nutrient cycling in forest ecosystems (McClagherty, *et al.* 1982; Hendrick and Pregitzer, 1993; Gu, *et al.* 2008), and account for large portions of total net primary productivity

(Raich and Nadelhoffer, 1989; Vogt, *et al.* 1996). As a consequence, measured soil respiration is well correlated with fine-root density (Shibistova, *et al.*, 2002; Maier and Kress, 2000). Soil respiration was well correlated with fine-root density along a gradient from an open area to lichen or vaccinium areas in a central Siberian Scots pine forest in Russia (Shibistova, *et al.*, 2002) and in loblolly pine plantations in North Carolina, with and without irrigation and fertilization (Maier and Kress, 2000).

In addition, the growth and senescence of fine root were observed and analyzed in the current study by using root lengths. The fine root elongation and decomposition along the 2.5-m soil profile in dry dipterocarp forest were shown measured for every month. The means root length in wet season (May - October) significantly higher in the dry season at p -value < 0.05 , $n=12$ (Figure 4.9). The growth of fine roots was strongly correlated with fine root biomass and root respiration in the wet season. While, the fine root senescence and disappearance did not differ significantly between wet and dry season (at p -value < 0.05). It means that the fine root were usually decomposed at the similarly rate about $10.98 \pm 2.76 \text{ m m}^{-2} \text{ month}^{-1}$. Thus, the CO_2 emission from fine root decomposition was constant. However, the seasonal variation of R_s was controlled by microbial respiration refers to litter production and decomposition. R_s and R_m in wet season were higher CO_2 flux than dry season (Figure 4.20-4.21-4.22). Wende, *et al.* (2013) studied the impacts of changed litter inputs on soil CO_2 efflux in central south China. They found that increased CO_2 respiration rate in the Mixed forest was 12% when double litter addition, while means non-litter input significantly reduced soil respiration rate by approximately 39%, 24%, and 22% in Camphor tree forests, the Mixed forest, and Masson pine forests, respectively

Variations of soil respiration on the seasonal time scale have resulted from the interplay between root and microbial respirations. As with the diurnal time scales, root respiration contributes more than microbial respiration to the overall variability in respiration. However, at this time scale, microbial respiration contributes more to the overall magnitude of soil respiration. The R_m to R_s ratio is high during wet season (0.7-0.8) and low during dry season (below 0.6). In this seasonal dry forest, the R_b to R_s ratio is below 0.4 during dry and about 0.2 during wet season. One of the unique characteristics of this forest is that the root to shoot ratio in this forest is usually higher than one. Due to the past disturbances, this forest may have adapted so that instead of actively transporting the fixed carbon to root, the majority of it may be invested in building up above ground biomass. This might be the strategy that individual trees used to counter the repeated loss

of aboveground biomass through tree trunk harvest for charcoal and energy use. As a result, although there was a large amount of belowground biomass, the amount of CO₂ emitted from the soil surface was still controlled mostly by soil microbial activity rather than by root activity.

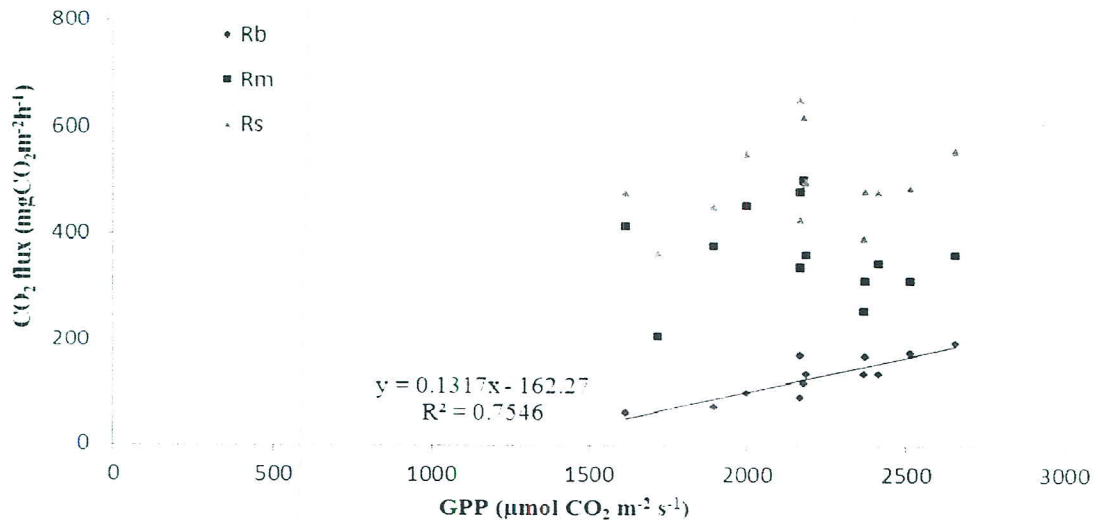


Figure 5.1 Relationships between R_s , R_b , R_m and mean GPP for 2011. Only R_b is significantly related with GPP ($Y = 0.1317x - 162.27$, $R^2 = 0.7546$).

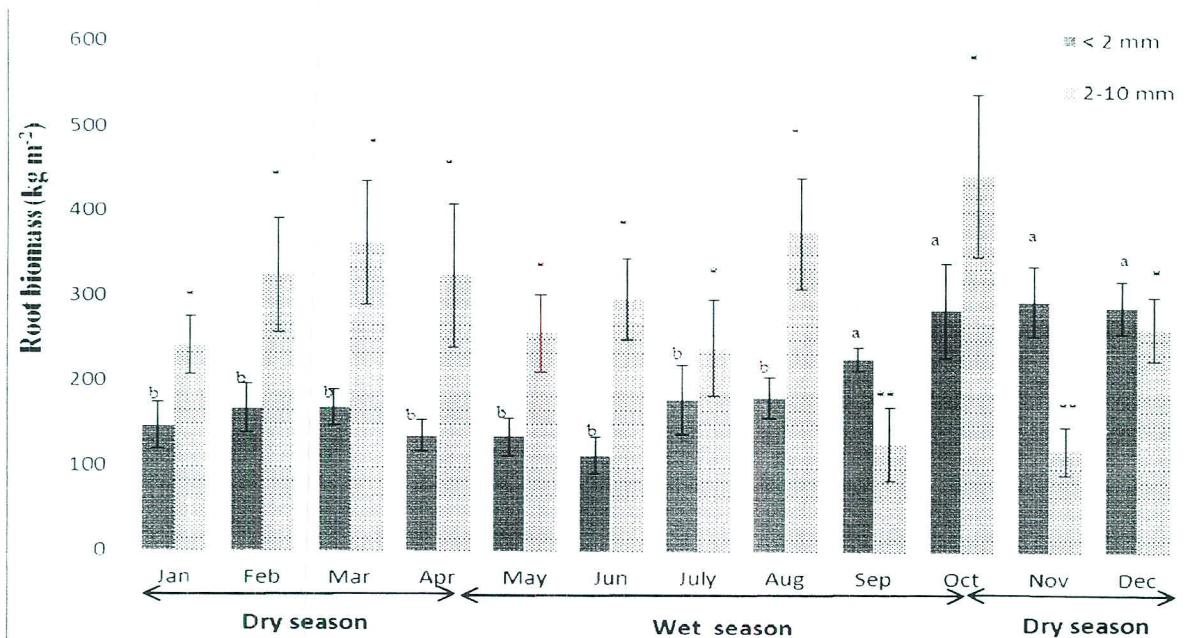


Figure 5.2 Seasonal variations in fine roots (< 2 mm) and 2-10 mm root biomass during September 2010–August 2011 at 0 to 0.6 m depth. Bar refers to standard deviation ($N=3$). Different letters or asterisks indicate significant difference in fine root biomass, or root with diameter 2-10 mm.

5.2.3 Annual variations

On an annual time scale, the average flux and the accumulated emissions during the four years were not significantly different. However, variations of R_b are still higher than R_m at annual time scales and thus contribute most heavily towards year-to-year variations in soil respiration in this forest (Table 5.1). It is interesting to note that although there were substantial differences in the length of the dry period and consequently in the distribution and amount of rainfall, the annual amounts of soil respiration were similar during these four years measurements. Cleveland, *et al.* (2006) studied the seasonal pattern and CO_2 production of soil respiration in a lowland tropical rain forest, Costa Rica. The results suggested that the annual variation of soil respiration were driven by interactions between leaf litter fall (a large labile C source) and precipitation, which provides a vehicle for the movement of decomposable C from the litter to the soil. The litter productions in the current study that were available for three years during 2009 – 2011 were 6.68 ± 0.72 , 6.44 ± 0.64 , and 8.06 ± 0.62 ton dry matter $ha^{-1} yr^{-1}$, respectively, while the cumulative microbial respirations in the similar years were 19.5, 23.3, and 26.6 ton $CO_2 ha^{-1} yr^{-1}$, respectively.

It is not known whether these small year to year variations of R_m were due to the difference in the amount of substrate supply throughout the litter fall. However, higher microbial respiration was observed when there was higher litterfall production. Moreover, regression analysis between soil respiration and soil temperature or moisture indicates that both influence soil respiration but in contrasting way. Significantly negative correlations between soil respiration and soil temperature, and positive correlation between soil respiration and soil moisture were found (Figure 5.3). The relationship between cumulative soil respirations and soil moisture were positively linear ($r^2=64-72\%$, Figure 5.3 b), while negatively linear with soil temperature ($r^2=50-64\%$, Figure 5.3 a). From these correlations, it seems that R_m is more responsive to changes in temperatures and moisture at annual time scale. Since soil temperature and moisture did not vary much annually, this may reflect to the fact that annual variation in the amount of soil respiration and its component did not vary significantly.

In addition, the distribution of rainy days during a year was one of the important factors for controlling CO_2 production in this forest soil. Many researches show positive correlation between soil respiration rate and soil moisture. The changes of annual means soil moisture can be influenced by precipitation and evapotranspiration (Wang, *et al.*,

2011). The rainfalls during 2009 – 2011 were 1,164.20, 1,330.10, and 1,007.70 mm, respectively. Whereas, the rainfall quantity in 2011 was less than other years but the number of rainy days was highest about 135 days while these were 99 and 119 days in 2009 and 2010, respectively. The heavy rainfall (approximate = 250 mm day⁻¹) occurred only one day in the both years. It had effects to the soil moisture during a year. The number of day with soil moisture higher than the mean value in the wet season in this forest during 2008-2011 were 178, 215, 203, 221 days per year in 2008, 2009, 2010 and 2011, respectively. Thus, soil moisture had no relation with precipitation amount but had a strong relation with rainfall frequency (Figure 4.7).

Normally, the rainfall pattern at the site was heavy rain in beginning and/or ending of wet season and little or lack of rainfall in middle of wet season (dry spell/break). The exception was in wet season of 2011 where there was no clear dry break period. With the loamy soil texture containing sand particle more than 70% and with very small fraction of clay content, it might be possible that the water in soil space was easy evaporated and water drains almost immediately when soil temperature was increased. Teepe, *et al.* (2003) explained the relation between gas diffusion and soil texture that soil with sand particle had high porosity and rates of diffusion can be relatively more rapid than in heavier clay soils even during times of stronger rainfall. Moreover, high soil temperature could stimulate water evaporation in soil lead to low soil moisture when little or lack rainfall during wet season (Xu and Wan, 2008). Hence, the distribution of rainfall affects the soil temperature and soil moisture. The mean soil temperature for 2011 was lower than other years but the mean soil moisture was highest in this year.

A manipulated experiment indicated that the decreased rainfall frequency had obviously depressed soil respiration (Harper, *et al.*, 2005; Wang, *et al.*, 2011). The rainfall frequency drives interannual variation in soil respiration by affecting soil moisture might be explained as follows. High rainfall frequency may greatly increase mean soil moisture as this discussed above. However, the heavy and small rain (< 1.5 mm) did not find the relationship between rainfall frequency and soil moisture because small rainfall event was mainly intercepted by the forest canopy and could not reach the soil (Wang, *et al.*, 2011), while heavy rainfall might be lost via surface runoff (Sharpley, 1985). Normally pattern of precipitation in DDF was unevenly distributed throughout the year, which results shown quite different of heavy and small rainfall in each year. Hence, the soil moisture showed a strong relationship with rainfall frequency instead of rainfall amount in this study.

Therefore, annually soil respiration and its components during 2008 - 2011 were indirectly affected by effective rainfall frequency. Variation in precipitation amounts usually explains interannual variability in soil moisture, which subsequently influences annual soil respiration as in a temperate forest (Borken, *et al.*, 1999, 2006), a Mediterranean forest (Concilio, *et al.*, 2009), and a Hesse forest (Epron, *et al.*, 2004).

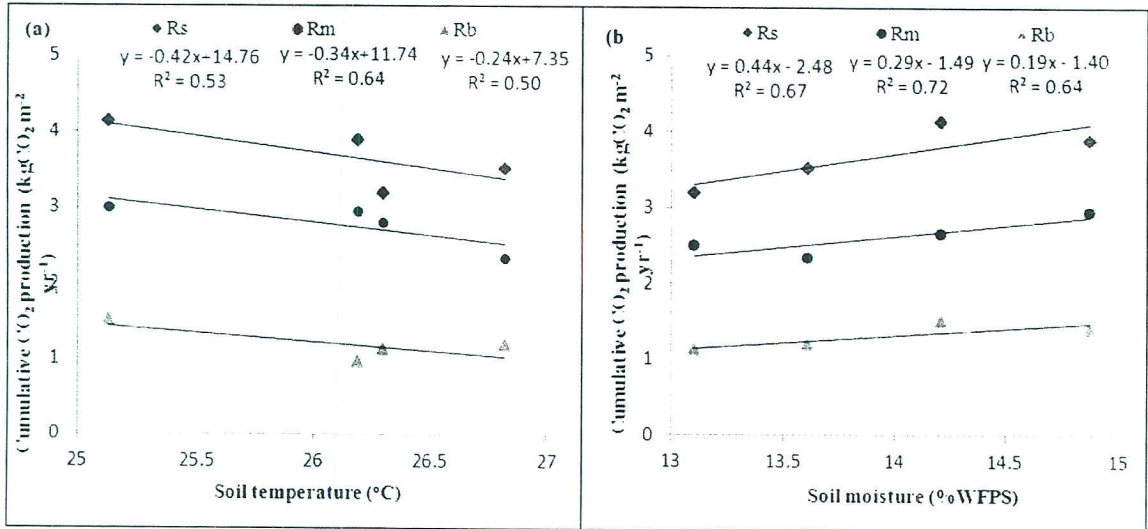


Figure 5.3 Relationships of cumulative CO₂ emissions as R_s, R_m, R_b with (a) mean soil temperature and (b) mean soil moisture during 2008-2011.

5.2.4 Partitioning of soil respiration

In the dry dipterocarp forest, the mean contributions of R_m to R_s and R_b to R_s were 66% and 34%, respectively. These are in the same range as reported by others (Raich and Tufekcioglu, 2000; Hanson, *et al.*, 2000). However, there were wide ranges of the reported values in the major biomes worldwide in response to soil types, vegetation types, forest age, environmental conditions and methods employed (Kelting, *et al.* 1998; Andrew, *et al.* 1999; Hanson, *et al.* 2000; Chen, *et al.* 2006). The proportions of R_b to R_s using the trenching method were 33% for 35-year old European beeches (*Fagussylvatica* L.) and 19% for mixed stand for 20-year old European beeches (Ngao, *et al.* 2007). With the root excision method, Yi, *et al.* (2007) reported the root respiration proportion in monsoon evergreen broad-leaf forest (BF), the pine forest (PF), and the pine and broad-leaf mixed forest (MF) was 39%, 23% and 26%, respectively. However, this study shows that the ratio

of R_m to R_s is very dynamic seasonally, increasing from 50% in dry season to 75% during the wet season and the contribution from roots decreased accordingly.

The different ratios between the wet and dry seasons could be attributed to the different responses of autotrophic and heterotrophic respiration to soil water content (Andersen, *et al.* 2005). The results were attributed to the rapid microbial activity and accentuated leaching due to rainfall. The better correlation of the litter decomposition rate with soil moisture is also attributed to the latter's favorable influence on earthworm and microbial activity (Figure 4.18). This suggests that soil microorganisms contributed to soil respiration and that this was stimulated by increased moisture. Adachi, *et al.* (2006) also found that soil respiration increased with fine root biomass and microbial biomass in tropical forests. These results suggested that the temporal change in soil respiration was affected not only by the seasonal change of soil temperature and soil water content but also by biotic factors.

5.2.5 Temporal variations of soil profile CO₂ concentration

Subsurface soil CO₂ concentration is an important component of the terrestrial C budget. Site specific information on the spatial and temporal variability, and how they respond to environmental factors is needed for accurately estimating ecosystem C budgets (Bekele, *et al.*, 2007). Normally, the CO₂ concentration is controlled by the rate of CO₂ produced by roots and microbes (source factors), which are influenced largely by soil temperature and moisture content, and soil physical characteristics (transport factors) mainly determine the variability in subsurface soil CO₂ concentration (Hamada and Tanaka, 2001; Jassal, *et al.*, 2004; Oh, *et al.*, 2005; Raich and Schlesinger, 1992). The measured CO₂ concentration in the dry dipterocarp forest shows increasing concentration with soil depth. The means CO₂ concentration at 0, 25, 75, 150, 250 cm during January – December, 2011 were 512.19±148.21, 1,102.53±336.86, 2,384.34±2,485.90, 6,637.79±6,405.80, and 19,360.89±10,529.89 ppm, respectively. The CO₂ concentration in the deep soil layers was 40 times the concentration at the DDF soil surface.

In other studies, it was found that the CO₂ concentrations in the deep soil layers at two forests in California, USA were 32 and 54 times the concentration at the soil surface (Lewicki, *et al.*, 2003). Moreover, the CO₂ concentration in the deep soil layers was increasing from 80 (range = 364-29,016 ppm) times to 200 (range = 407 – 81,053 ppm) times the CO₂ concentration at the soil surface, when clear cut the forest in Nova Scotia

Canada (Bekele *et al.*, 1983). The higher concentration of CO₂ in deeper soil horizons is caused by CO₂ accumulation from microbial and root CO₂ generation with a much slower rate of CO₂ diffusion rates between the subsurface and the atmosphere (Fernandez, *et al.*, 1993; Jassal, *et al.*, 2004).

Sudden increases in soil water content due to rain, especially when the soil was initially dry, resulted in significant increases in soil CO₂ concentrations. The sum of the CO₂ concentrations at 2.5-m suddenly increased after rain fall of 8,359.34 ppm (March) to 22,090.33 ppm (April), as show in Figure 4.28. The soil CO₂ concentration versus depth were shown seasonal shift between wet and dry season in dry dipterocarp forest. CO₂ concentration increased about 2.64 times when seasonal change from the dry (March) into wet season (April). Moreover, the means difference of CO₂ concentration profiles from the dry season shift to the wet season were increasing of 264.73 ppm (1.56 times) at 0 cm, 492.46 ppm (1.38 times) at 15 cm, 1,491.77 ppm (1.43 times) at 75 cm, 2388.05 ppm (1.38 times) at 150 cm, and 9,992.21 ppm (1.56 times). The mean CO₂ concentration increased about 1.5 times at 2.5 m soil depth (Figure 4.28).

The strong fluctuation in the CO₂ concentration over season is driven largely by changes in soil CO₂ production. Normally, the CO₂ is produced more in the surface layer than in the deep layers by root and microorganisms along a soil profile soil (Hui and Luo, 2004). After rain coming to the soil, the root and microbial were rapidly started growth because the soil moisture in all layers was increased and soil temperature was decreased during the wet season (Figures 4.2 and 4.5). This study shows that relationship between microbial biomass and soil moisture was positively exponential (microbial biomass = $44.37e^{0.123(\text{soil moisture})}$, $R^2=0.81$, $p\text{-value} = 0.05$). Moreover, fine root biomass also increased, as elongation and expansion of root were observed (Figure 4.9). The total fine root length and biomass was significantly higher in wet season than in dry season at $p\text{-value} < 0.05$.

The relationship between CO₂ concentration and soil temperature can be fitted by exponential functions, while the relationship between CO₂ concentration and soil moisture can be shown by positive linear functions (Figure 5.4). For 0.15 and 0.75 cm soil depths, CO₂ concentration increased when decreasing soil temperature and increasing soil moisture. No consistent relationship of soil temperature and soil moisture with CO₂ concentration was observed in below 150 cm soil depth. Normally, soil temperature and soil moisture are often the best predictor for soil respiration and CO₂ concentration. The correlations of soil temperature and soil moisture were positively with CO₂ concentration

only soil surface (15-75 cm soil depth). Jobbagy and Jackson, (2000) suggested that temperature and moisture has a larger effect on the decomposition of shallow, labile soil organic carbon than deep soil organic carbon. However, both factors did not relate to controlled CO₂ concentration below 150 cm soil depth. The variation of soil temperature and soil moisture below 150 cm soil depth were quite stable than soil surface (25-28 °C and 10-20 %WFPS) (Figure 5.4 g-h). Schwendenmann and Veldkamp, (2006) found that the CO₂ concentration of soil profiles was positively correlation with PAR below 60 cm soil depth. It indicates that CO₂ concentration in higher soil depth was controlled by root activity. Photosynthetically active radiation may stimulate root growth and activity through aboveground controls on carbohydrate availability (Wofsy, *et al.*, 1988). Hence, seasonally, soil CO₂ concentrations as well as CO₂ production were well correlated with variations in soil temperature and soil water content in 15 – 75 cm, while CO₂ concentration below 150 cm was controlled by root activity.

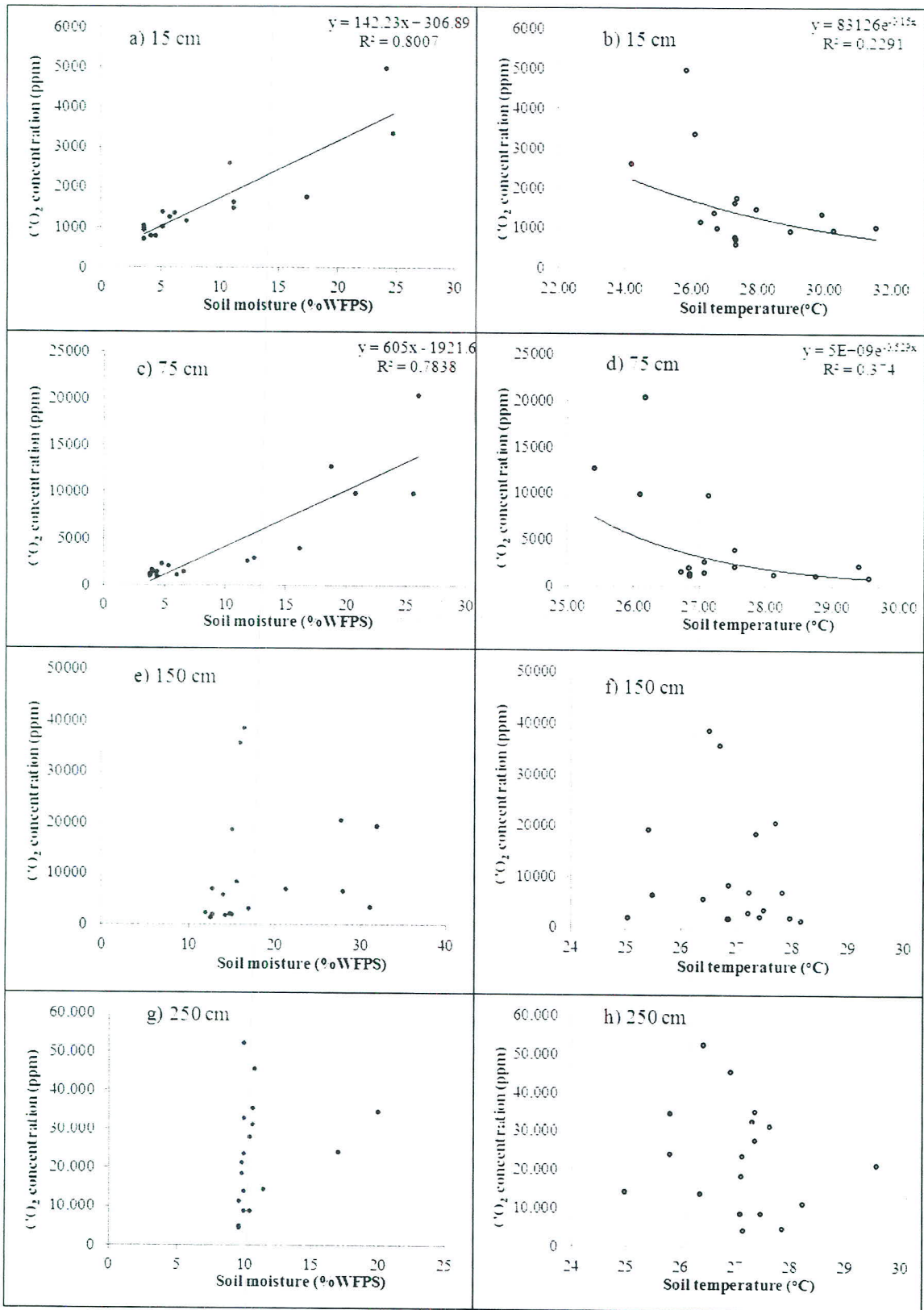


Figure 5.4 Relationship of CO₂ concentration versus soil temperature and soil moisture at 15, 75, 150, and 250 cm soil depths.

5.3 Relationships between forest activity and soil respiration

The mean annual soil respiration in the present study had a good correlation with biotic factors. The typical seasonal pattern of soil respiration during a year was increasing at the beginning of the wet season and remained high until the end of the wet period (Figure 4.20). However, during the dry season, the soil respiration rate was quite low and stable. It was related to the change in biological processes as plant growth, death and decomposition during a year. Normally, the plants in deciduous forest started growth during wet season (May-October) or after the rain came, by budding leaf, branch, flower, and fruit, and gradually reducing growth during the dry season (November-April), reflecting in CO₂ production from soil respiration during a year. The soil respiration during the dry season was lower than during the wet season. CO₂ emission occurred during the dry season was about 37% of the total CO₂ emission from soil respiration in the dry dipterocarp forest.

5.3.1 Aboveground living biomass

The average monthly soil respirations in February, May, August, and November during 2009–2012 were 257.04 ± 97.92 , 472.99 ± 78.13 , 518.63 ± 41.24 , and 400.33 ± 29.56 mgCO₂ m⁻² hr⁻¹, respectively (Figure 5.5). The CO₂ emissions in May and August (wet season) were higher than in the dry season (February and November) during a year, which had a positive correlation with the increasing biomass rate. The biomass stocks in W_{S+B} , W_L , and W_R were higher in the wet season than in the dry season, approximately 74-77% of total biomass stock in plant. The relationship between soil respiration and biomass growth can be fitted by linear functions. It was applied to the datasets of CO₂ emission from soil respiration and biomass increase by plant growth in this study. The results show that the linear equation of these was $y = 0.0005$ (biomass increase) + 0.80, $R^2 = 0.80$, p -value = 0.006 (Figure 5.6). Thus, the plant growth was related to live leaf and soil respiration during wet season in the dry dipterocarp forest. Lambers, *et al.* (1996) found that more than 50% of the daily accumulated photosynthetic was respired by the root, with the overall fraction determined by metabolic efficiency and plant growth conditions (Buoma, *et al.*, 1997).

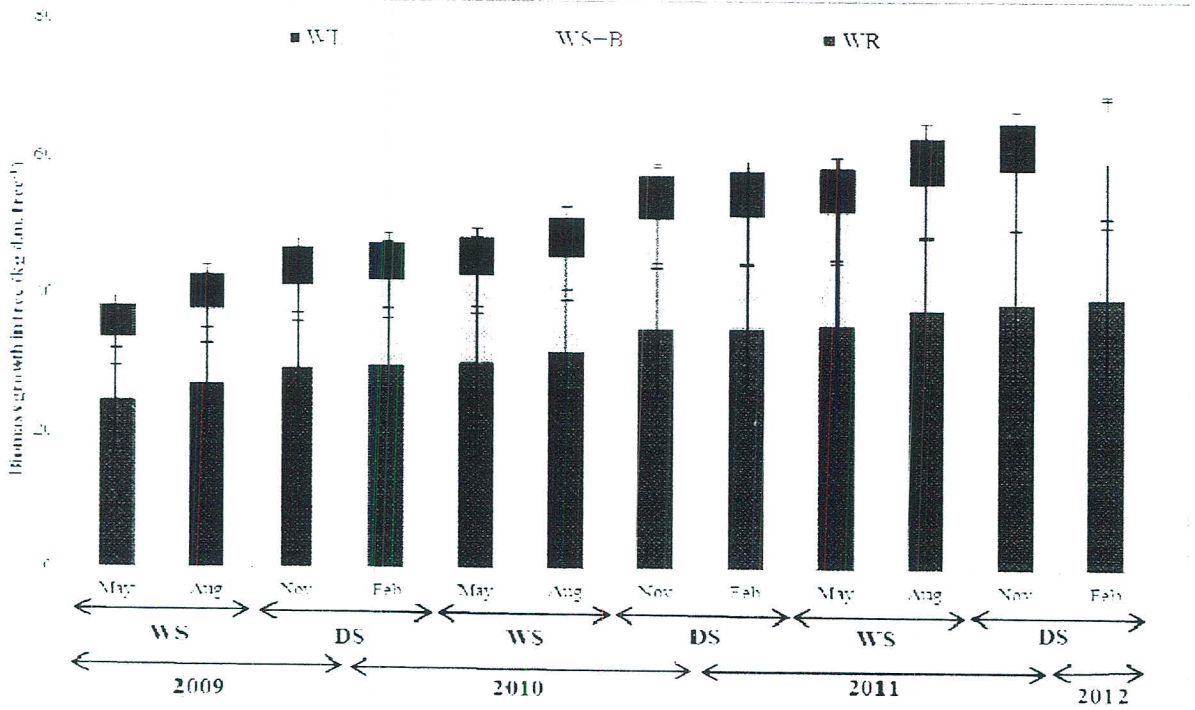


Figure 5.5 Mean biomass increasing rate of leaves (W_L), stems and branches (W_{S+B}), and roots (W_R) estimated by automated-close chamber and allometric equation method during May 2009 – February 2012. WS refers to wet season and DS refers to dry season

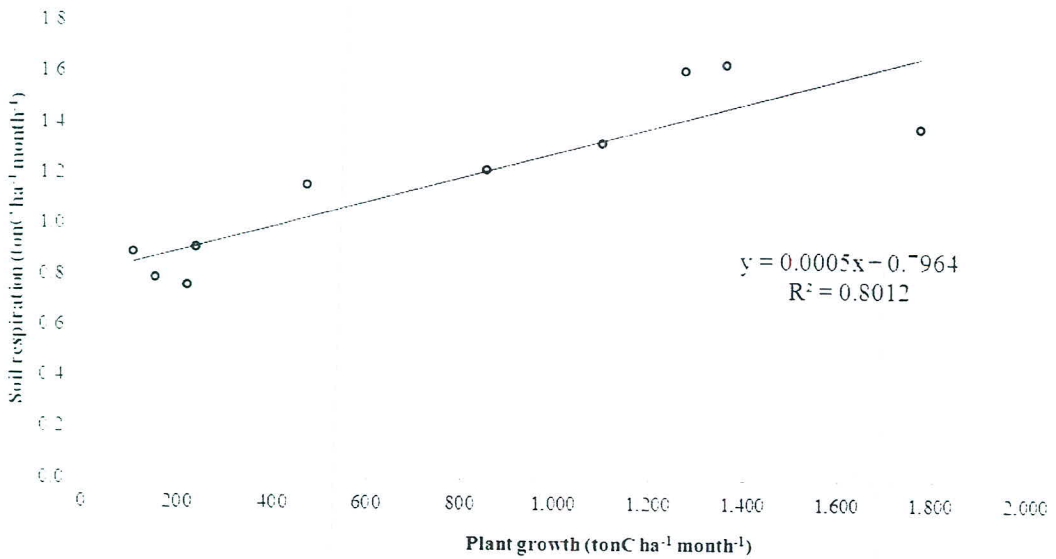


Figure 5.6 Relationships of linear correlation between soil respiration and plant growth every three months in the dry dipterocarp forest.

5.3.2 Litter production

Litter is the main substrate source of microbial activity. But to decompose such substrate the environmental conditions must support the growth of microbes. Maier and Kress, (2000) manipulated the aboveground litterfall at the soil surface in a loblolly pine forest and found a linear relationship between the increase in soil respiration and the amount of litter added to the soil surface. Similar relationships between the litter amount and soil respiration have been found in other ecosystems (Boone, *et al.*, 1998; Bowden, *et al.*, 1993; sulzman, *et al.*, 2005).

Quantitatively, the litterfall in tropical forests produces more than in the temperate zones and polar zones (Bray and Gorham, 1964). Accordingly the CO₂ emissions in a tropical forest were usually higher than in temperate and sub-arctic zones (Figure 2.4). O' Neill & De Angelis, (1980) reported that the average litter productions in arctic zones, cooling zones, and warm zones were 3.30, 4.60 and 4.70 ton ha⁻¹ yr⁻¹, respectively, and the highest was in tropical zones at 9.30 ton ha⁻¹ yr⁻¹. These results are different depending on the temperature and precipitation in each zone. Normally, the tropical zone consists of higher temperatures (approximately, 20-25 °C) and precipitation (more than 2000 mm.) than the other zones.

The litterfall in the present study was concentrated during the cool and dry period (November-April) of the year and about 76% of the total litterfall occurred during this period. However, soil and microbial respiration started only when soil moisture increased to allow the microbial activity, which was around May of every year (Figure 5.7). Patterns of litterfall in this study were comparable with other results in other tropical forests in Thailand (Chinsukjaiprasert, 1984; Jampanin, 2004; Jamroenprucksas, 1981; Suksawang, 1989; Tanee, 1997). The tendency of litterfall to be concentrated in the cool and dry season is related to a combination of decline in temperatures and lowered soil moisture during the dry period. Pascal, (1988) had also reported that heavy litterfall of leaf occurred during the dry season in the evergreen forests of Attappadi, Western Ghats, India. This pattern can be explained by annual cycles of moisture and temperature. Leaf fall would occur to avoid seasonal moisture and temperature stress during dry period (Hardiwinoto, *et al.*, 1996).

The seasonal variation between soil respiration and litterfall production in each month are shown in Figure 5.7. The results shown about the litterfall on the ground was high production in the dry season, especially January to March, while soil respiration was lowest in this period. The litter production is mainly substrate of microorganism. However,

the litter production in dry season was very high foliage but the environmental factors were not appropriated to biotic activity. After rain fall towards the end of April, the soil moisture increased and started to affect the litter decomposition. Hence, the soil respiration was lower in dry season than in wet season. The total carbon input to the dry dipterocarp forest soil from litter productions during 2009 – 2011 were 3.34 ± 0.36 , 3.22 ± 0.32 , and 4.03 ± 0.31 ton C ha⁻¹ yr⁻¹, respectively, while the cumulative microbial respirations in the similar years were 19.5, 23.3, and 26.6 ton CO₂ ha⁻¹ yr⁻¹, respectively. The carbon of litter production represents a major pathway of carbon from vegetation to soil for used to the microbial activity. However, the microbial respiration for 3 years changed along with changes in litter production. In addition, the seasonal variations of meteorology data during 2008 – 2011 were similar from year to year. For example, soil temperature at dry season was higher than wet season, while soil moisture at dry season was lower than in wet season (Figure 4.1 and 4.4). The average soil temperature and soil moisture during 2008 – 2011 were similar during these years (25.13 – 26.82 °C of soil temperature and 13.10 – 14.21 %WFPS). Since meteorology data were relatively constant during these years, the strong seasonal variation in soil respiration can result only from changes in substrate supply from the aboveground parts of plants.

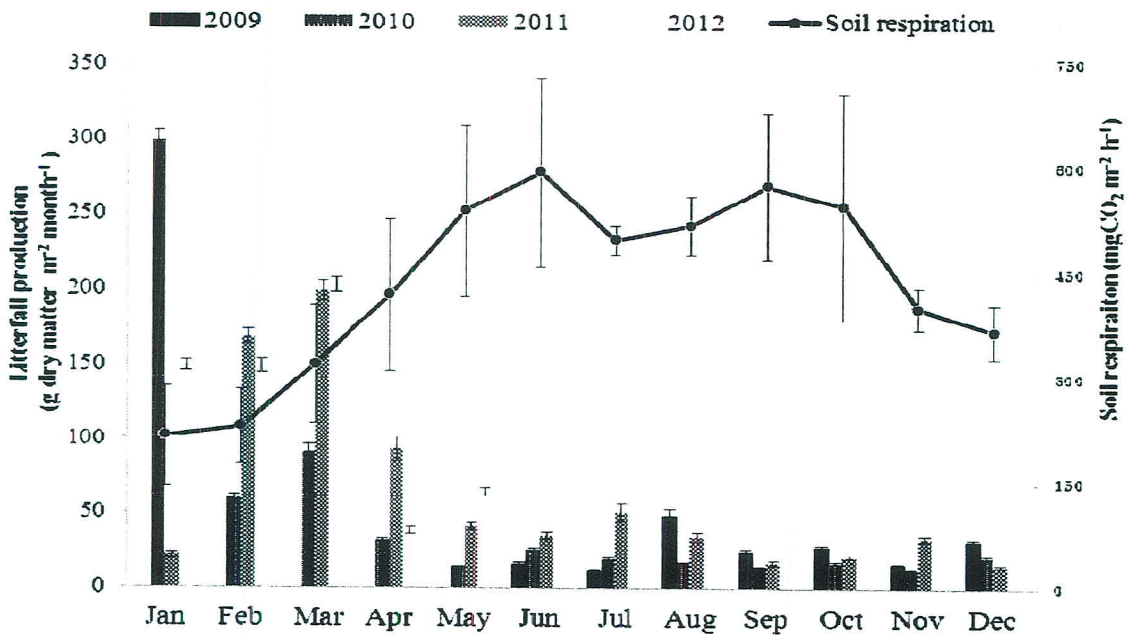


Figure 5.7 Monthly litterfall produced in the dry dipterocarp forest and means soil respiration during June 2009-May 2012.

5.3.3 Litter decomposition

The k value is normally derived from the loss of biomass through decomposition over time. If the initial amount of biomass is available, the mass loss of biomass over time via decomposition in any environment could be estimated. The k value is therefore quite useful to describe the dynamics of litter decomposition. The decomposition constant k is primarily controlled by climate and litter quality. Higher k -values correspond to faster rates of decomposition, while lower values correspond to slower decay. The decomposition rate constant (k -value) of leaf litter in the dry dipterocarp forest was increased in the order: DT (0.17 month^{-1}) < BA (0.21 month^{-1}) < DO (0.29 month^{-1}) < AX (0.36 month^{-1}). While, the branch litter decomposition rate was increased in the order: AX (0.10 month^{-1}) < DT (0.13 month^{-1}) < BA and DO (0.17 month^{-1}) (Table 4.4). The k -value of each plant was different and the decomposition rate depends on litter quality (Wang *et al.*, 2009). The result of litterfall production in the dry dipterocarp forest can be separated into 87% of leaf, 11% of branch and 2% of others, including flowers and fruits. The mainly substrate of microbial activity was residual from leaf production. Barnes, *et al.* (1998) determined chemical composition of litter in the forest. They found that the chemical compositions of litter were composed of 15-60% cellulose, 10-30% hemicellulose, 5-30% lignin, 2-15% protein, 1% lipid and 10% other soluble organic compound such as sugar, amino acid, nucleic acid and other organic acids. Whippee, (2006) explained the chemical compositions of wood that were composed of 38-50% cellulose, 23-32% hemicellulose, and 15-25% lignin. In addition, percentage of nutrient concentration in tree will change from highest to lowest concentration as leaf > bark > branch > stem > root (Curlin, 1970).

The leaf litters as decomposed faster than the branch litters of all plant species. The litter decomposition rate constants (k -value) of leaf and branch in the forest were 0.26 and 0.14 per month⁻¹ at 0 cm and 0.86 per month⁻¹ and 0.25 at 10 cm soil depth, respectively. Placing biomass at different depths also results in different decomposition rates. Placing it at 10 cm depth has resulted in a better decomposition than at the top soil (Table 4.4). The highest decomposition rate occurred at 10 cm soil depths level much more related to biological action and micro-environmental conditions within litter and soil horizons, such as moisture the changing litter quality (Figure 4.5). Osono, *et al.* (2006) demonstrated that both litter depth and decomposition stage were important factors affecting fungal colonization to decomposition. Lignin is considered to be the primary variable in determining the decay rates of litter, because of its resistant to decay, as well as how it

slows down the decay of other cell constituents (Chesson, 1997). On the other hand, cellulose serves as an immediate source of energy for the soil decomposing organisms and thus promotes the breakdown of litter. However, lignin is known to impair decomposition by protecting cellulose from. When litter enters a later stage in its decomposition, lignin contents are high and there is apparently a lack of energy source for microbial growth (Bosatta and Agren, 1985). Phenols inhibit growth and activity of soil decomposers and hence lower the decay rates. Normally, lignin is mainly component of wood and an integral part of the secondary cell walls of plants (Berg and Laskowski, 2006). Hence, the branch was difficultly decomposed by microbe in soil than leaf composition.

In the wet season (May-October), the maximum weight loss of litter decomposition was observed, and this constituted nearly 46-68% of leaf and 36-63% of branch weight loss for which the total average annual mass loss in the dry dipterocarp forest was 83% per year. Normally, patterns of high litter production in this forest occurred during January until April. Then, the seasons changed from the dry season to the wet season in May, or when the rain started. The soil respiration was increasing because the microbial organisms and plant were starting to get more active again. The litter on the ground floor is the main carbon supplied to microbial activity. The soil respiration during the dry season, especially January to March was very low, while the amount of remaining litter on the ground in this time was very high. Thus, the microbial biomass during dry season is very low and increased again when the soil moisture increased and soil temperature decreased during wet season (Figure 5.17). Effects of water stress on microbial growth vary with rates of biosynthesis, energy generation, and substrate uptake, as well as the nature and mode of water perturbation (Luo and Zhou, 2006). Extreme dry conditions induce dormancy or spore formation in soil microorganisms (Griffin, 1981, Harris, 1981, Schjonning, *et al.*, 2003) and /or cell dehydration (Stark and Firestone, 1995). Thus, at low moisture in dry season, bacteria maintain only a basic metabolism although high substrate on the soil surface.

The litterfall production and the decomposition rate in the forest are related to CO₂ emissions from the soil surface. Both soil respiration and microbial respiration in dry dipterocarp forest were high during wet season (Figure 4.21-4.22). The soil respiration and litter decompositions as leave and branch were positively correlated. It can be fitted by exponential functions. The results showed that the exponential equation of litter decomposition with soil respiration were $y=0.887e^{0.0046x}$, $R^2=0.35$ and $y=1.8077e^{0.0043x}$,

$R^2=0.35$ with microbial respiration. As mentioned before the regressions of soil respiration and microbial respiration were significantly related to leaf and branch decomposition at p -value ≤ 0.01 , $n=65$, but were not significantly related to root respiration (Fig 5.8 a-b). Hence, the CO_2 emissions during the wet season in the dry dipterocarp forest were mainly produced by leaf decomposition rather than root respiration.

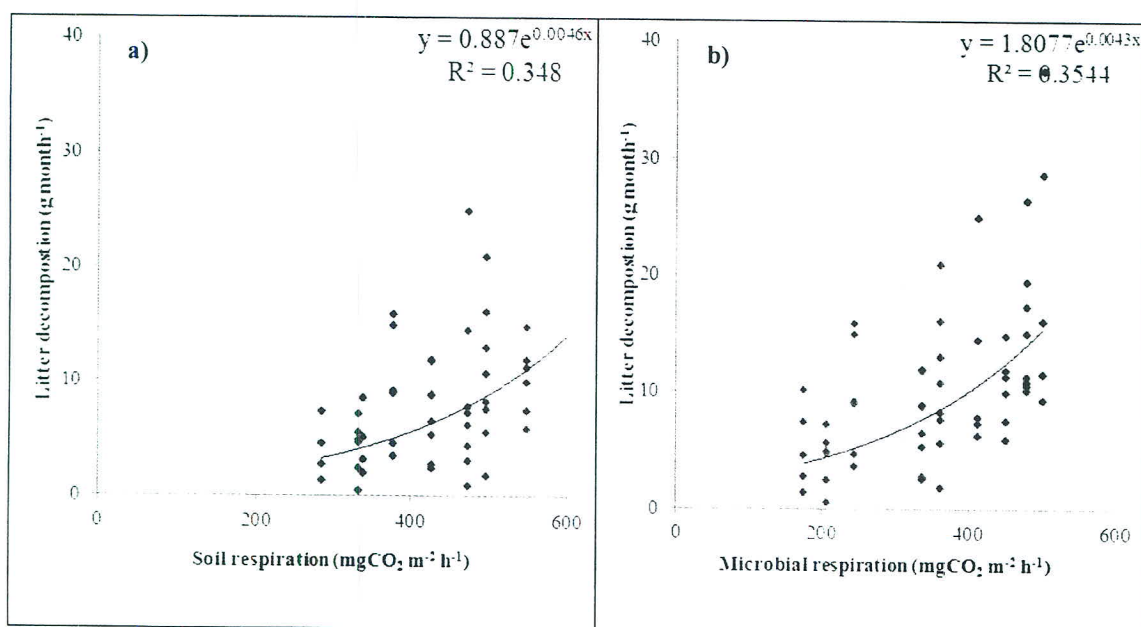


Figure 5.8 Relationships between (a) soil respiration and weigh loss of litter, and between (b) microbial respiration and weigh loss of litter at ground floor.

5.3.4 Root biomass and fine root activity

The root respiration was well correlated with only fine-root density in this forest (Figure 5.2). The root size is an important element related to the metabolic activity and CO_2 production from root respiration (Pregitzer, *et al.*, 1998). For example, the general fine roots were not as energetic in nutrient and water uptake as the smaller diameter fine roots whose main functions were associated with sustaining and transporting of the nutrients and water from fine roots in smaller diameter class to other organs of the trees (Pregitzer, *et al.*, 1998; Wang, *et al.*, 2006). Puttsepp, *et al.* (2006) also showed that the fine roots in smaller diameter exhibited much higher growth, mortality and decomposition rates than those of roots in larger diameter class.

The fine root growth and senescence in DDF were observed for the root length in every month by using the root window. Fine root length is arguably one of the most commonly measured parameters, largely because of its value as a general, integrative indicator of plant response to environmental factors (Edwards *et al.*, 2004), because of its role in the control of water and nutrient fluxes (Clothier and Green, 1997). The fine root growth and senescence occurred throughout the year. The annual mean root growth and senescence along the 2.5-m soil profile in dry dipterocarp forest were 10.46 ± 2.78 and 7.33 ± 1.90 g m⁻² month⁻¹, respectively. The highest root growth in monthly variation was shown on April about 16.22 ± 7.61 g m⁻² month⁻¹, while the lowest root growth shown on March about 5.77 ± 0.84 g m⁻² month⁻¹ (Figure 5.9). From the eye observation, the fine root growth was relatively corresponding to different leaf phenological periods. For example, the fine root was rapidly growth on April, a period during which environmental conditions favor photosynthesis in dry dipterocarp forest because the new leaves were fast regrowth after rain coming in the month.

Typically, fine root growth commences in early wet season until early dry season (April - November). Normally, the soil moisture was increasing after rain coming during early the wet season. The plant was start up to produce the new leaves on April – May, and continued the leaf growth from young to old leaf during June - November. Then, the old leaf was death and falling onto the floor during January – March (Figure 5.6). The seasonal pattern of fine root growth was highly elongation during early wet season on April about 16.22 ± 7.61 g m⁻² month⁻¹, while the lowest shown during dry season on March about 5.77 ± 0.84 g m⁻² (Figure 5.9). The root production and turnover of fine roots are synchronized with canopy development in the spring and leaf senescence in the wet season (McClougherty, *et al.*, 1982; Hendrick & Pregitzer, 1993, 1996). The fine root length in the wet season was higher than dry season (at p -value = 0.05, $n=12$), while the means root senescence did not differ significantly between both seasons (at p -value = 0.05, $n=12$). In addition, the relationships between R_b to find root biomass was linear and can be expressed as $R_b = 0.6684(\text{weight of fine root growth}) + 3.1868$, ($R^2 = 0.44$; $n=12$), $p \leq 0.05$, but the R_b not related to root senescence as shown in Figure 5.10.

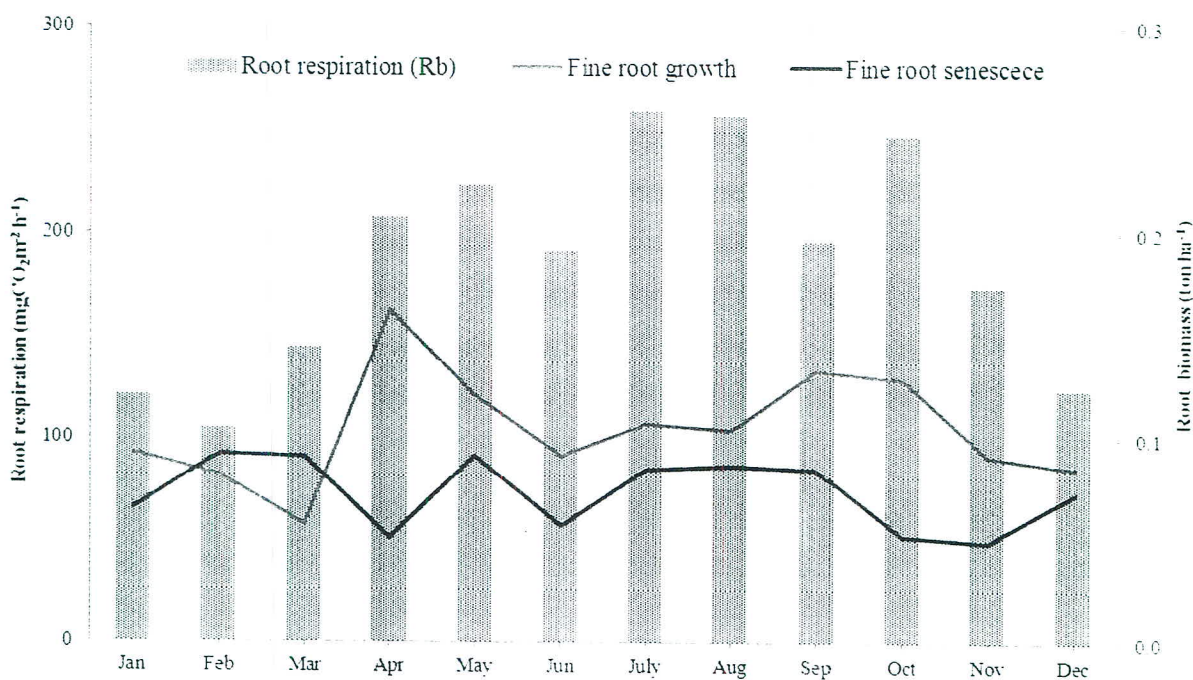


Figure 5.9 Seasonal variation of mean root respiration, fine root growth and senescence (< 2 mm of diameter) during September 2010-August 2011

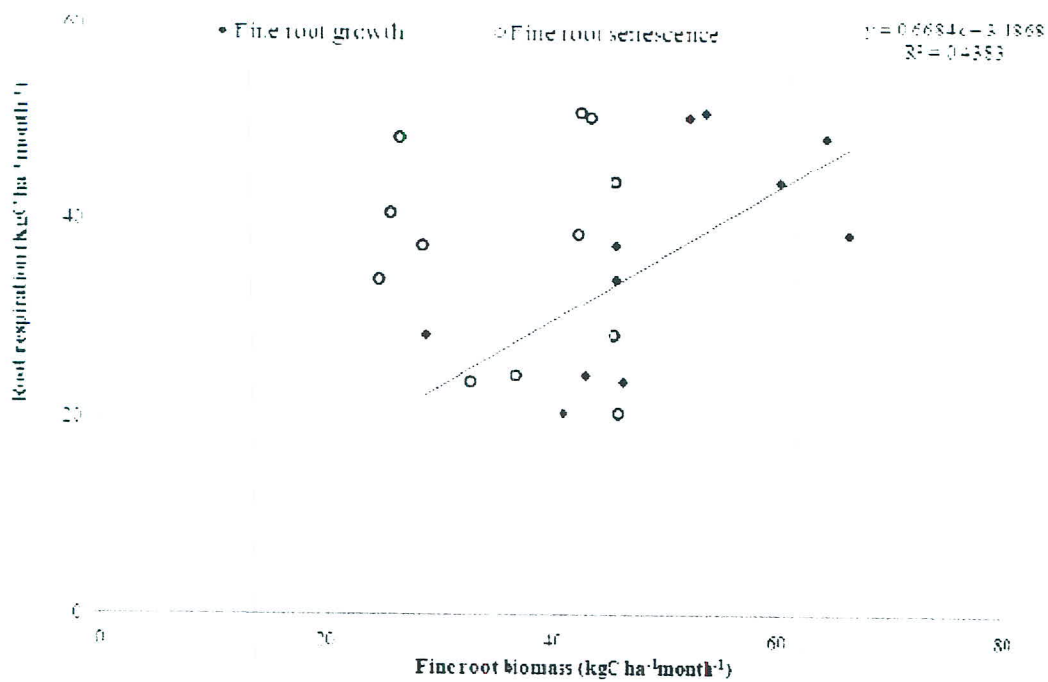


Figure 5.10 Relationships between R_b and fine root growth and senescence during September 2010-August 2011.

5.3.5 Microbial biomass

Other biotic factors, such as microbial biomass, also influence soil respiration. Several lines of evidences suggest the magnitude and temporal variations of soil respiration in this forest was largely controlled by microbial activity. The seasonal pattern between monthly average microbial respiration and microbial biomass from January to December were show in Figure 5.12. The results show that the microbial biomass was increasing during wet season, relating the CO₂ emission from microbial activity such as litter decomposition. Normally, litter fall in the forest starts at the end of wet season and finishes by the end of February-March and rapidly declines after rain coming at the end of April to October. This agrees with the increase in microbial biomass and microbial respiration during the same period (Figure. 5.12). The results agree d with the other studies. The highest total soil respiration rate in monsoon evergreen broad-leaf forest (BF) was related to the higher density of root biomass and soil microbial biomass in BF than pine and broad-leaf forest (MF) and pine forest (PF) in China, respectively (Yi *et al.*, 2007). This suggests that soil microorganisms contributed to soil respiration and that this activity was stimulated by increased moisture. Adachi, *et al.* (2006) also found that soil respiration increased with fine root biomass and microbial biomass in the tropical forests The relationship between R_m to total microbial biomass was linear and can be expressed as $R_m = 0.10 (\text{total microbial biomass}) + 210.53$, ($R^2 = 0.37$; $n=12$), $p \leq 0.05$.

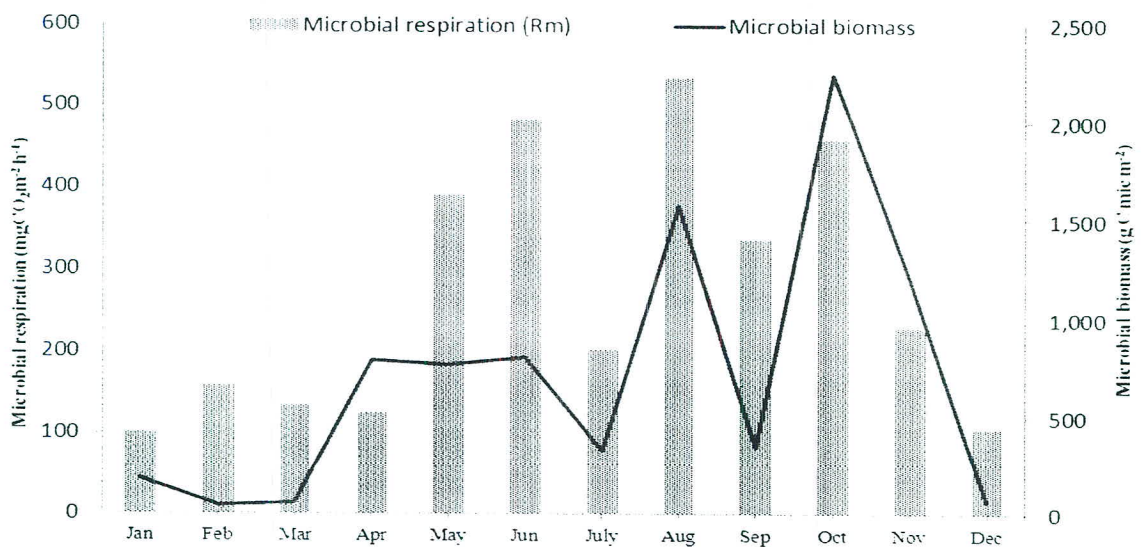


Figure 5.11 Seasonal variations of monthly mean microbial respiration and microbial biomass during January to December.

5.4 Soil respiration and physical factors

5.4.1 Soil temperature and soil moisture

Generally, soil moisture and soil temperature strongly affect CO₂ release into the forest ecosystems. In these ecosystems, soil moisture is the main factor limiting soil respiration on seasonal and annual time scales. Thus, seasonal patterns of soil respiration closely follow dynamics of soil moisture (Davidson, *et al.*, 2000). In the Amazon basin, where the seasonal variation in temperature is not large, while variation in soil water content is substantial, soil respiration in pastures and forests correlates significantly with water-filled pore space in soil (Salimon, *et al.*, 2004). In tropical climate regimes with cold, wet rainy winters and hot, dry summers, water usually constrains biological activity in summer (Xu, *et al.*, 2001). The soil respiration in this site was limited during the dry season. While, the seasonal patterns of soil respiration are largely determined by soil water availability, soil respiration rates correlate positively with soil water content and negatively with soil temperature. It has been reported that the relationship between soil respiration and soil moisture can be fitted by several functions including linear, exponential and logarithmic, as well as asymptotic and polynomial functions (Chen, *et al.*, 2008).

Under such high temperature and dry conditions during the dry season, soil respiration was minimized. When plotting the relationship between soil respiration and temperature for the whole period, lowest emission was coincided with the time of highest temperature, with lowest moisture and thus the negative correlation was resulted as shown in Figure 5.12. Upon comparison of different functions, linear functions were applied to the datasets of soil respiration and its components with soil temperature during both wet and dry seasons in this study. The exponential form of relationship was found. However, positive relationship was observed only when soil temperature at 0.05-m was less than 26°C (Figure 5.12). Above this temperature point, negative correlation was found. Soil respiration and its components exhibited an optimum response to soil temperature with maximum rates of respiration at a soil temperature of 26 °C. Hence, the relation analysis of soil respiration and its components in DDF revealed that it was positively correlated with soil temperature was lower than 26 °C ($r^2=0.40-0.78$, p -value < 0.01, $n = 158$), while negatively correlated with soil temperature was higher than 26 °C ($r^2=0.23-0.33$, p -value < 0.05, $n = 101$). Positive relationship could be found in much lower temperature ranges than this which is not found in other tropical climate.

The relationship between respiration and temperature is well-known, and understanding how temperature affects soil respiration is important to predicting the soil responses to changes in the climate. The soil temperature in the dry season could be as high as 32 °C and air temperature as >35 °C. Under such high temperatures and dry conditions, soil respiration was minimized. However, the soil temperature during the wet season was similar but the soil respiration was higher than during the dry season. Thus, it had more biotic activity from plants and microbes. For example, photosynthesis and litter decomposition was increased when moisture increased in the soil. The negative relationship between soil respiration rate and soil temperature suggests that soil temperature was a limiting factor in biotic activity in the forest. For example, the plant growth correlated well with soil temperature as low as 26 °C (Figure 5.14a) but it was negatively correlated when the temperature increased above 26 °C. The negative relationship between plant growth and high soil temperature was $y=364.26 e^{-0.178x}$, $r^2 = 0.44$. It means that the plant growth during the high temperature and low moisture in dry season was quite low. These results can explain that the high soil temperature and low soil moisture stimulated to leaf fall of the trees.

In addition to soil temperature, soil moisture influences soil respiration via physiological processes of roots and microorganisms. The general pattern of soil water content characterizes the two-phase effect of soil water on soil respiration: soil respiration increases with increasing soil water content up to 20 %WFPS and decreases exponentially at higher soil water contents in the dry dipterocarp forest. The correlation between soil respiration and soil moisture was observed: R_s and R_m exhibited an optimum response at a soil moisture equivalent to 20%WFPS, while, R_b was exhibited at less than 16 %WFPS (Figure 5.13 a). However, the correlation between R_b and soil moisture at higher than 16%WFPS did not shown the relation (Figure 5.13 b). Moreover, the soil CO₂ effluxes in this study were very low under dry conditions (4-5 %WFPS), reaches the maximal rate in intermediate soil moisture level (6-20 %WFPS), and decreasing soil respiration at high soil moisture (20-35 %WFPS) (Figure 5.13 a). At high soil moisture, respiration is regulated primarily by oxygen concentration. Water in soil pores at high water content slows exchanges of gaseous O₂ and CO₂ at sites of microbiological and root activity (Luo and Zhou, 2006). The effect of moisture on microbe growth varies with rates of biosynthesis, energy generation, and substrate uptake, as well as the nature and mode of water perturbation (Luo and Zhou, 2006).

In fact, soil temperature and moisture, as well as their interaction, show significant effects on the temporal change of soil CO₂ efflux. Then, the rate of soil respiration was controlled by both soil temperature and soil moisture. The correlation of CO₂ emission and both factors were linear and significant at p -value = 0.01 (Figure 5.14 a-c). The linear equation of R_s , R_m , and R_b were $R_s = 209.27 + 1.03(T_s) + 14.32(M_s)$ ($R^2 = 0.40$), $R_m = 72.45 + 2.99(T_s) + 10.52(M_s)$, ($R^2 = 0.37$), and $R_b = 106.85 + 0.24(T_s) + 4.34(M_s)$, ($R^2 = 0.25$), respectively. The temporal variation of soil respiration was concurrently influenced by these two factors. These similar correlations between the soil respiration and the temperature and soil moisture were also found by other studies (Bowden, *et al.* 1998; Fernandez, *et al.* 1993, Yi, *et al.* 2007).

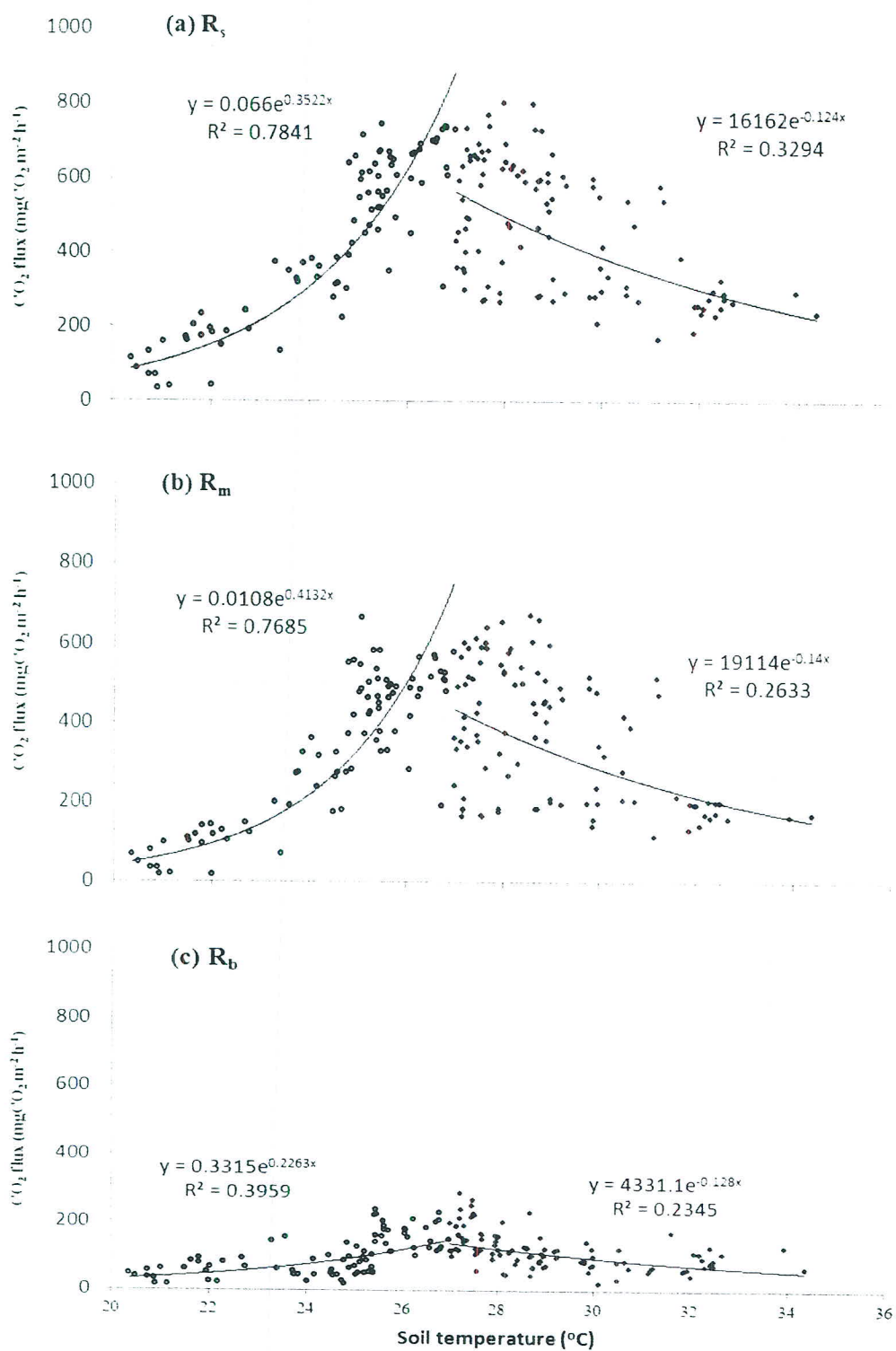


Figure 5.12 The correlations between daily CO_2 effluxes of R_s , R_m , R_b and soil temperature were positive at 0.05 m when soil temperature at $< 26^{\circ}\text{C}$ and negative when soil temperature was $> 26^{\circ}\text{C}$.

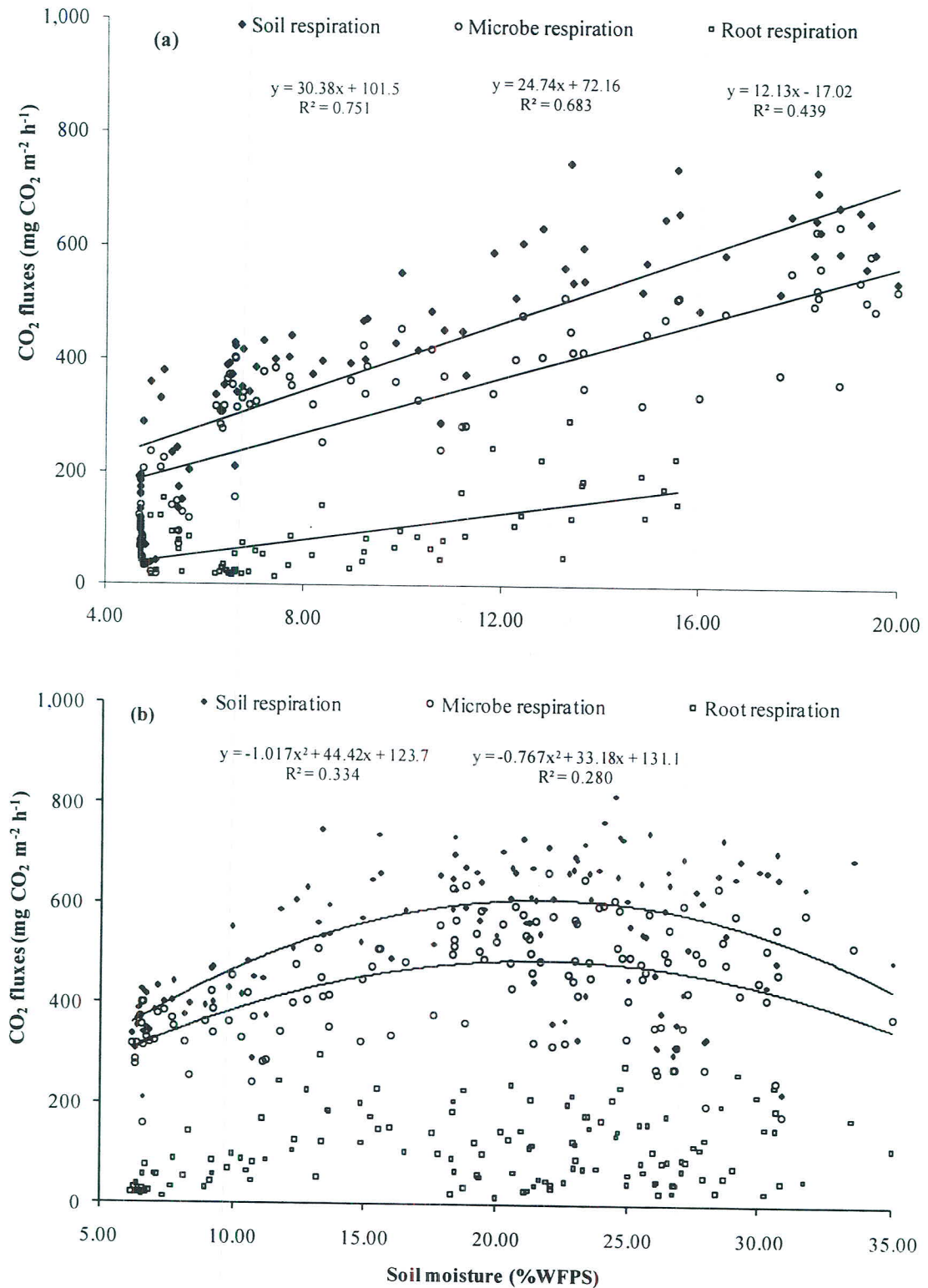


Figure 5.13 (a) The correlation between soil CO₂ efflux and water filled pore space (%WFPS) at 0.05 m were positive when %WFPS was < 20% (except R_b<16 %). (b) shows the overall pattern of relationship between daily CO₂ effluxes and soil moisture.

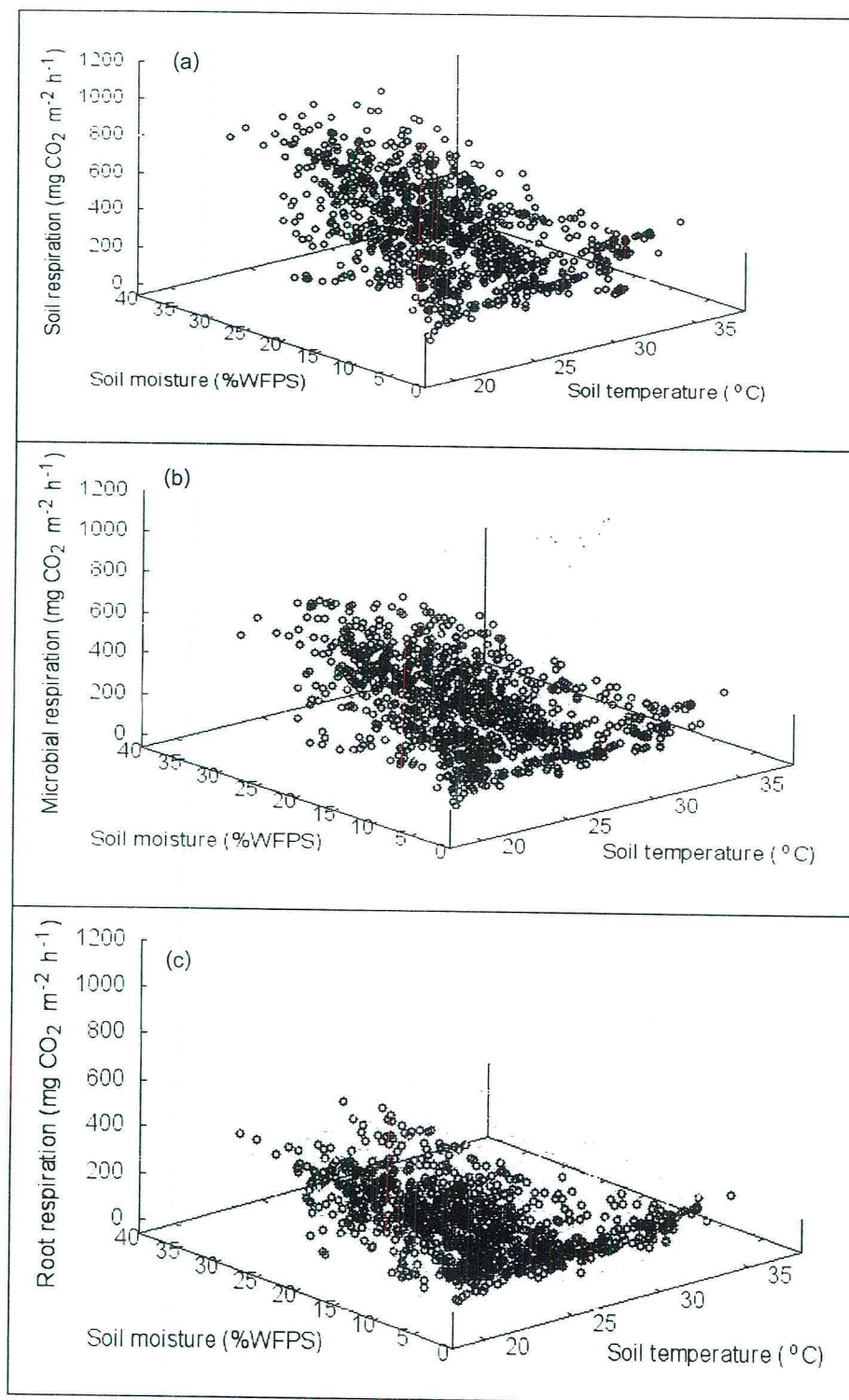


Figure 5.14 Correlation between soil temperature and soil moisture of (a) mean soil respiration, (b) microbial respiration, and (c) root respiration of dry dipterocarp forest during February 2008-December 2011. (Significant at $p \leq 0.01$, $N=1,204$).

5.5 Environmental factors controlling forest activity

5.5.1 Plant growth

The dry dipterocarp forest in Ratchaburi Province is a secondary forest. Lugo, *et al*, (1988) explain the definition of secondary forest is a consequence of human and natural disturbances impact on forest lands. The secondary dry dipterocarp forest was disturbed from continuous human uses of forest such as grazing, fuelwood collection and burning for easy to find some food and medicine such as, *Astraeus hygrometricus* (Pers.) Morgan, *Melientha Suavis Pierre*, etc. Hence, the general pattern of plant growth in secondary forest is quite different with undisturbed or primary forest. Brown and Lugo, (1990) studied the characteristic of tropical secondary forest. The results explained the secondary forests develop maximum leaf biomass early in their development and maintain these values through to maturation. Root biomass accumulates at a somewhat slower rate than leaves and continues to increase slowly with age. However, fine roots biomass (< 2 mm diameter) may reach values similar to mature forests at a young age.

The fine root biomass was rapidly increasing biomass in the wet season, while big root biomass (2-10 mm diameter) studied the same (Figure 5.1). In contrast, the relative amount of woody biomass in secondary forest was rapidly increasing growth at first period and slow rate growth to maturity when older age (Brown and Lugo, 1990). The growth rates of the trees in the dry dipterocarp forest were rapidly growth as 0.62 m year⁻¹ for height and 0.51 cm year⁻¹ for trunk diameter. The results of biomass stock increased during the wet season and remained quite stable during the dry season (Figure 5.5). The temperature and moisture ranges are probably the main driver for biomass increasing or plant growth rate in the dry dipterocarp forest. There are strong (95% confidence level) relationships between plant growth rate and soil moisture ($r^2 = 0.71$), and soil temperature ($r^2 = 0.94$) as shown in figure 5.15 a-b. However, the plant growth in the dry season was very low because the soil temperature was high and the soil moisture was low. The relationship between plant growth and high soil temperature (> 26 °C) in the forest was negatively correlated ($y = 364.26 e^{-0.178x}$, $r^2 = 0.44$). This means that growth of this forest is both temperature and moisture limited.

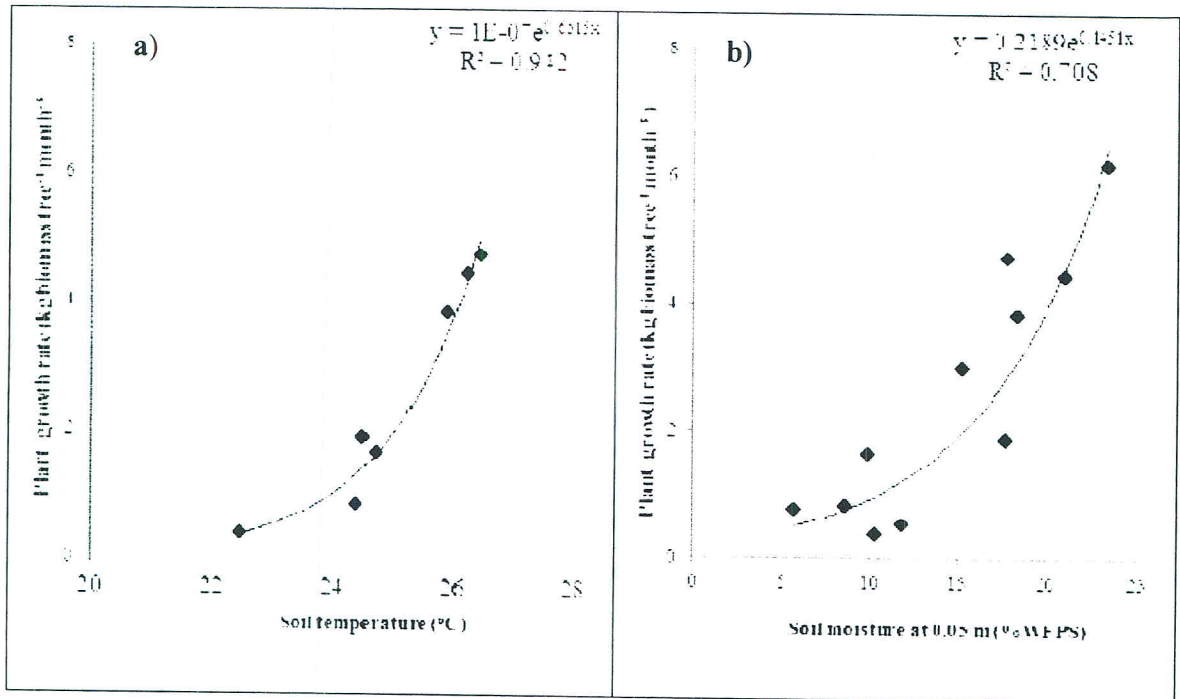


Figure 5.15 The relationship between plant growth and environmental factors as soil temperature (a) and soil moisture (b)

5.5.2 Litter production

There are strong relationships ($p \leq 0.01$) between litterfall production and environmental factors, such as soil moisture and soil temperature, as shown in Figures 5.16 a-b. The results show positive correlation between litterfall production and soil temperature and negative correlation with soil moisture. The linear equation between litterfall production and soil temperature was $y=3.49x-61.0$, $r^2=0.32$, and exponential equation of litterfall production and soil moisture was $y=84.37e^{-0.072x}$, $R^2=0.37$. As mentioned, both of environmental factors was significantly related to litterfall production at p -value ≤ 0.01 , $n=31$. As mentioned above the annual litterfall in the dry dipterocarp forest occurred in the dry period because the trees must adapt themselves to conform in dry-air condition by shedding their leaves to reduce evaporation, therefore the amount of litterfall in this period is high. In addition, water stress could cause to synthesize abscisic acid in the foliage of plants which could stimulate senescence of leaves and other parts (Landsberg, *et al.*, 1997).

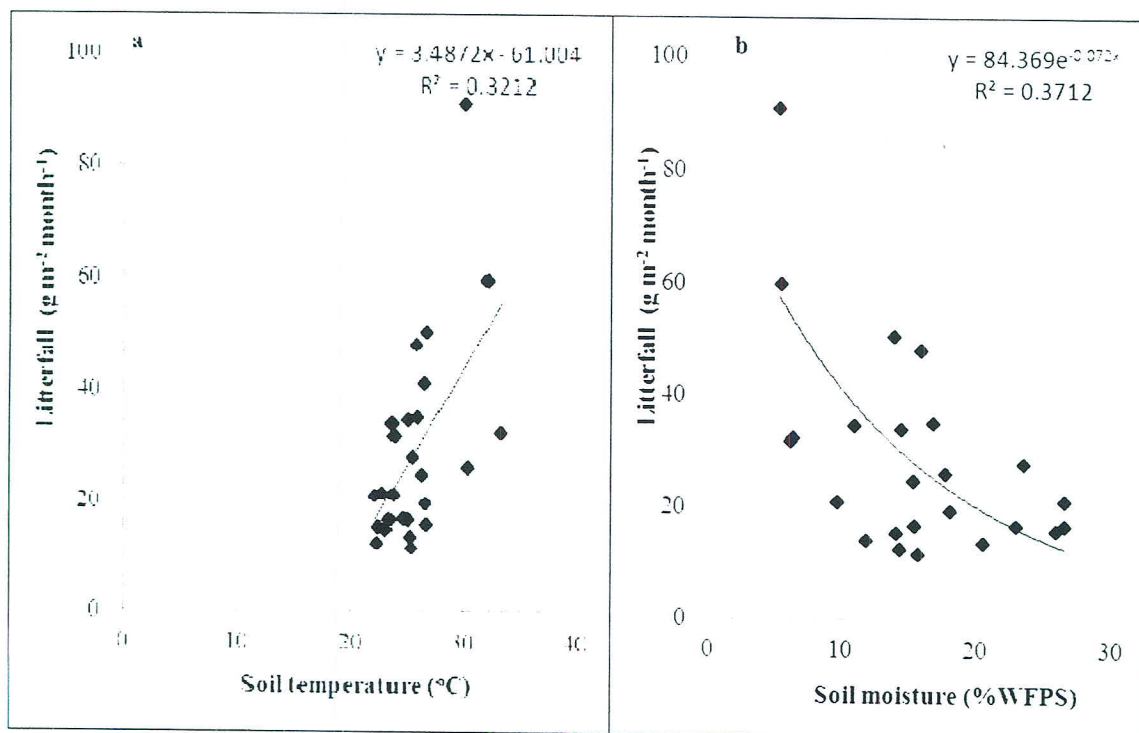


Figure 5.16 The relationships between litterfall and environmental factors such as (a) soil temperature and (b) soil moisture ($n = 31$; p -value < 0.01)

5.5.3 Litter decomposition

The relative mass loss of litter in the dry dipterocarp forest was observed during a 13-month period, but some species had decomposed completely within a year. Lavelle, *et al.* (1993) had speculated that litter decomposition in the warm, humid tropics is more rapid than that in the temperate ecosystems as the prevailing environmental conditions are conducive for rapid decay. For example, the annual mass loss of hill evergreen forest, Doi-pui, Chiang Mai, Thailand was 56% per year (Thaiutsa, *et al.*, 1978). In the dry evergreen forest, Sakaerat Environment Research Station, Nakhon Ratchasima was 48.77% per year (Chunkaew and Boonyawat, 1980), mangrove forest, Chanthaburi was 54.90% per year (Aksornkoae and Khemnark, 1980). Tropical rain forest, Trinidad was 100% (Conforth, 1970). The results from the current study show that the annual mass loss of the dry dipterocarp forest was 83% per year. The important issues relating microorganism activity to biomass decomposition is the physical and chemical properties of biomass, such as the value of the C/N ratio.

Climatic conditions affect the activity and the amount of microorganisms available. The important components of climatic conditions are temperature and moisture (Vitousek,

et al., 1986). The annual average k -value of leaves and branch in the dry dipterocarp forest were 0.26 and 0.14 at 0 cm and 0.79 and 0.25 at 10 cm, respectively (Table 4.4). The high temperature and moisture ranges are probably the main driver for leaf and branch litter decomposition in the dry dipterocarp forest. There are strong ($p \leq 0.01$) relationships between soil moisture ($r^2 = 0.53$), and soil temperature ($r^2 = 0.48$) as shown in figure 5.17 a-b. These are related to the favorable conditions for decay-high litter with soil moisture contents and congenial atmospheric temperature, all indirectly favouring the soil biological activity. The higher decay rate in the wet months accords with the results of Pandey and Singh, (1982), and is attributed to rapid microbial activity and accentuated leaching due to rainfall. The seasonal pattern of microbial biomass in this forest was increasing during wet season, especially August and October, while it was decreasing during dry season (Figure 4.18). The better correlation of the weight loss with soil moisture noticed may be also due to the latter's favourable influence on earthworm and microbial activity.

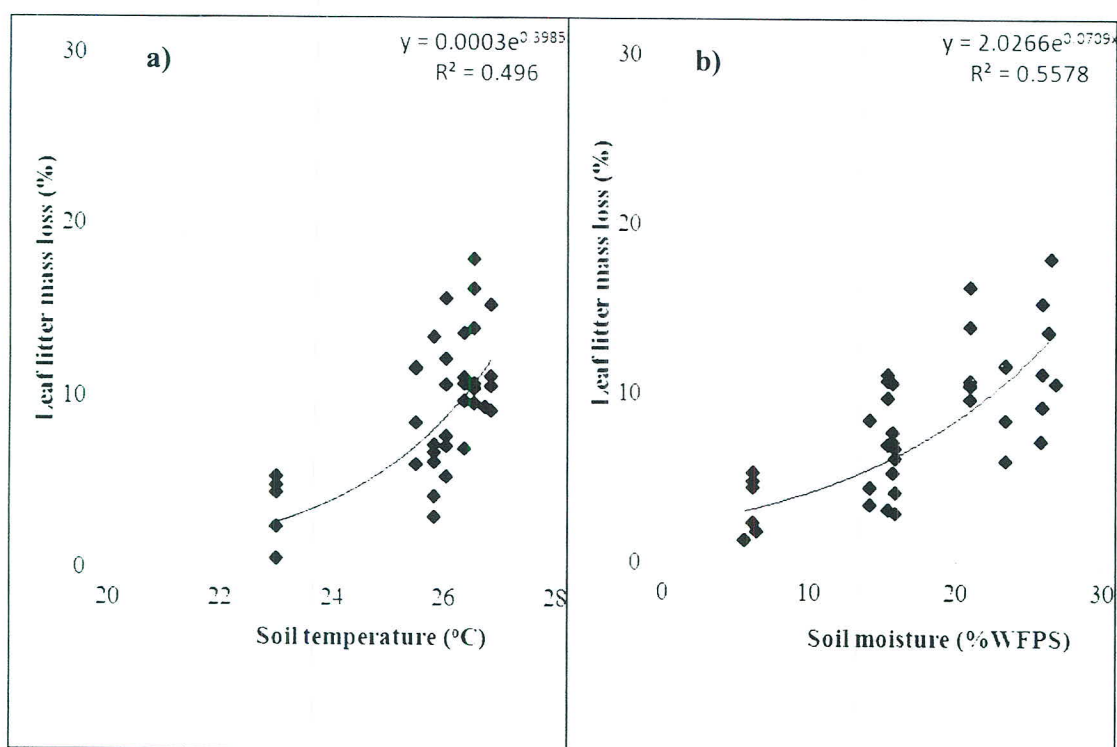


Figure 5.17 The relationship between litter mass loss and environmental factors, such as (a) soil temperature and (b) soil moisture ($n = 52$; p -value < 0.01).

5.5.4 Microbial biomass

The mean microbial biomass differed significantly between the wet season and the dry season ($p < 0.05$). Moreover, total microbial mass of different soil layer did not differ between layer 0-20 and 20-40 cm but significantly lower for the soil layer 40-60 cm ($p < 0.05$) (Figure 4.8). Normally, the microbial biomass was well established that it decreased quantity with increasing soil depth (Anderson and Domsch, 1989; Fierer, *et al.*, 2003). However, the microbial biomass in layer 20-40 cm soil depth was higher than on top layer during dry season because the top soil temperature was higher than in bottom soil while soil moisture in top soil was lower than bottom during dry season (Figure 4.2, 4.5).

The microbial biomass increased when the soil moisture increased and the soil temperature decreased at the beginning of the wet season (Figure 5.18). However, the microbial biomass was decreasing in the mid of wet season as July and September. Normally, the rainfall pattern at the site study consisted of heavy rain in beginning and/or ending of the wet season and a little rainfall in middle of the wet season (Figure 4.7). The lack of rainfall in the mid wet season reduced the soil moisture and microbial activity. The relationship between microbial biomass with soil moisture was positive ($y=44.37e^{0.123x}$, $R^2=0.81$), while the relationship between microbial biomass and soil temperature was negative ($y=4E+07e^{-0.43x}$, $R^2=0.66$) (Figure 5.19).

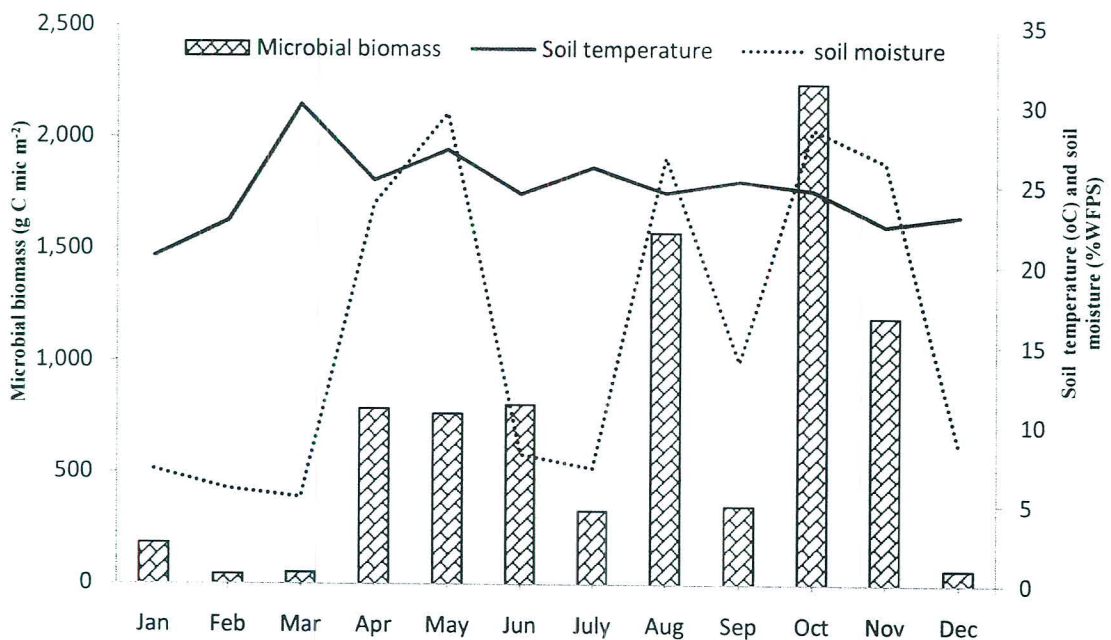


Figure 5.18 Monthly change in microbial biomass in the dry dipterocarp forest and mean soil temperature and soil moisture during January - December 2011.

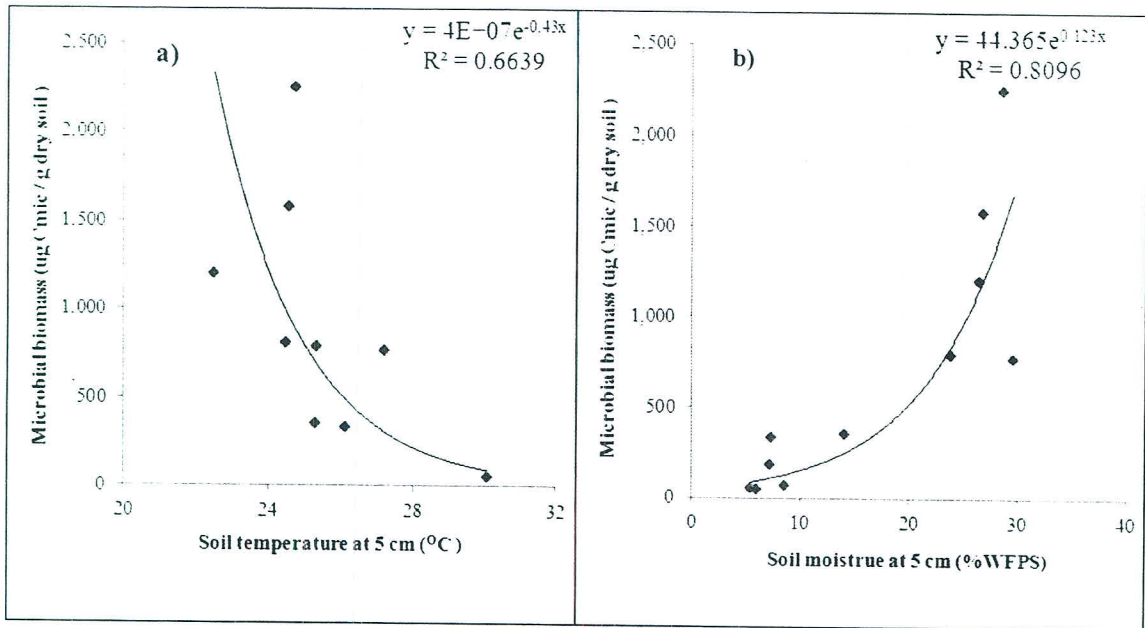


Figure 5.19 The relationship between microbial biomass and environmental factors, such as (a) soil temperature and (b) soil moisture ($n = 65$; p -value < 0.01).

5.6 Relationship between soil respiration and ecosystem respiration

CO_2 produced in the soil by roots and microorganisms is transferred through the soil profiles to the soil surface. At the soil surface, CO_2 is released into the air by both diffusion and air turbulence. The released CO_2 is then mixed in plant canopy, partly absorbed by photosynthesis during daytime, and mostly released to the atmosphere through a planetary boundary layer. The belowground respiration (R_s) represents 40-90% of the forest ecosystem respiration (Schlesinger, *et al.*, 2000). Thus, soil activity in forests plays an important role in the carbon exchange of the forest ecosystem.

The mean soil respiration during 2009 – 2010 was 459.10 ± 162.67 and $404.28 \pm 133.31 \text{ mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$, and average ecosystem respiration during the same year were 497.30 ± 336.12 and $686.32 \pm 416.04 \text{ mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$, respectively (Hanpattanakit, *et al.*, 2012). Normally, both R_s and R_e increase in beginning of wet season and remained high until beginning of dry season (April - November). The CO_2 released during this period was 80% of total CO_2 emission during the year. The aboveground respiration is combining between leaf respiration and wood respiration. It was reported that up to 35% of the total carbon assimilated may be lost as CO_2 by leaf respiration (Athin, *et al.*, 1998). Plant respiration varies between species (Reich, *et al.*, 1992; Wright, *et al.*, 2001) and leaf

respiration accounts for approximately half of the whole plant respiration (Poorter, *et al.*, 1990).

Curtis, *et al.* (2005) studied the relationship between R_s and R_e in an aspen-dominated mixed hardwood forest in Michigan from 1999 to 2003. They found that the average contribution of R_s is 71% of R_e . However, the relative contribution of R_s to R_e varies considerably in a year. R_s contributes nearly 100% of R_e for most of the winter. The contribution drops to about 60% during the period of fast last leaf expansion and then gradually increases during the growing season as soil warms, reaching about 75% at the time of leaf abscission in the autumn (Curtis, *et al.*, 2005). Typically, R_s contributes 30-80% of R_e in forests.

In this study, annual estimates of soil and ecosystem respiration indicate that the annual R_s/R_e ratio ranges from 0.24-1.20, with a mean of 0.57. R_s/R_e ratio was relatively high in dry season dry [0.91, during November to April] when compared with during wet season [0.55, during May to October] (Figure 4.29). Remaining variation may include responses to synoptic weather patterns, spatial and temporal mismatches between R_s and R_e measurements, and measurement errors (Davidson, *et al.*, 2006). These results indicating about the factors controlling the R_s/R_e were temperature and moisture in soil. In our study, the ratios were increased and decreased with soil moisture. In addition, high contribution of R_s to R_e during dry season was due to the low aboveground respiration associated with leaf fall in the periods. Thus, the major CO_2 releasing in the forest during dry season was soil respiration. The R_s/R_e ratio was gradually decreasing during wet season because of aboveground respiration from leaf as mentioned above.

5.7 Conclusion

The results of this study indicate that R_s , R_m , and R_b vary significantly with the variations of biotic factors (microbial, plant growth, litter decomposition) and abiotic factors (soil temperature, soil moisture, precipitation, and soil texture). The biological activities from plant and microbial in forest were stimulated to CO_2 emission from soil respiration. The plant growth, litterfall production, litter decomposition were positively correlated with soil respiration. The means of soil respiration in the forest during 2008-2011 was $1031.39 \pm 391.05 \text{ gC m}^{-2} \text{ yr}^{-1}$. This is relatively high compared to other ecosystem outside tropics but relatively lower within the tropic due to high productivity and

dynamics. It is common that the soil respiration in tropical regions is higher than in other regions. Annual soil respiration in the dry dipterocarp forest was limited by temperature, precipitation, and litter production.

On the diurnal scale, variations are likely controlled by soil temperature during the wet and dry seasons. However, R_b during dry season was quite stable because of leaf fall and dry moisture condition. On the seasonal scale, R_s , R_m , and R_b were positively correlated with soil moisture and soil temperature. Moreover, the fine root biomass and microbial biomass were high positive correlation with R_m and R_b during both seasons. The soil temperature decreasing and moisture increasing was stimulated the root and microbial activity during wet season. For annual scale, the soil moisture, soil temperature and rainfall distribution controlled the R_s , R_m , and R_b rate in this forest.

The higher variations of soil respiration in the dry season were due to high variations in R_m and R_b , while relatively lower variations in the wet season were due to low variations in R_m . It is noted that CV of R_b was always higher than that of R_m . The general pattern of plant growth in the dry dipterocarp forest is quite different with undisturbed or primary forest. The results explained the secondary forests develop maximum leaf biomass early in their development and maintain these values through to maturation. Root biomass accumulates at a somewhat slower rate than leaves and continues to increase slowly with age. However, fine root growth in the forest is an important controlling CO_2 flux in wet season.