Seasonal changes in spatial variation of soil respiration in dry evergreen forest, Sakaerat Biosphere Reserve, Thailand

Warin Boonriam¹, Pongthep Suwanwaree⁶,⁷, Sasitorn Hasin⁸, Taksin Archawakom⁹, Phuvasa Chanonmuang¹⁰, Akinori Yamada¹¹,¹²

¹ School of Biology, Institute of Science, Suranaree University of Technology, Nakhon Ratchasima 30000 Thailand
² Innovation of Environmental Management, College of Innovative Management, Valaya Alongkorn Rajabhat University under the Royal Patronage, Pathum Thani 13180 Thailand
³ Sakaerat Environmental Research Station, Nakhon Ratchasima 30370 Thailand
⁴ Expert Centre of Innovation Clean Energy and Environment, Thailand Institute of Scientific and Technological Research, Pathum Thani 12120 Thailand
⁵ Department of Biological Sciences, Tokyo Institute of Technology, Tokyo 226-8501 Japan
⁶ Graduate School of Fisheries and Environmental Sciences, Nagasaki University, Nagasaki 852-8521 Japan

*Corresponding author, e-mail: pongthep@sut.ac.th

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ABSTRACT: Soil respiration in tropical forests is an important source of 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 investigate the seasonal changes in spatial variation of soil respiration in a dry evergreen forest of Sakaerat Biosphere Reserve, Nakhon Ratchasima Province, 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. The average rate (± SD) of annual aboveground soil respiration was 6.57 ± 4.29 µmol CO₂ m⁻²s⁻¹. Soil respiration considerably varied with space and time. The mean ranges were from 2.66 to 11.72 µmol CO₂ m⁻²s⁻¹ with a maximum rate of 42.68 µmol CO₂ m⁻²s⁻¹. The wet season soil respiration rate (8.81 µmol CO₂ m⁻²s⁻¹) was two times higher (p < 0.001) than in the dry season (4.33 µmol CO₂ m⁻²s⁻¹). The seasonal changes clearly affected the spatial variation of soil respiration. Wet season produced higher and more widespread soil respiration. Although soil respiration rates increase with increasing soil temperature and soil moisture content, the rate starts to drop at 27 °C soil temperature (p < 0.001) and 21% soil moisture content (p < 0.05). This study suggests more investigation of soil features and animal influences on CO₂ emission hot spots in order to accurately estimate soil respiration in tropical forests.

KEYWORDS: soil respiration, CO₂ efflux, spatial variability, seasonal tropical forest

INTRODUCTION

An important component of the global CO₂ balance has been recognized as CO₂ emission from the soil (soil respiration). Indeed, soil respiration is the second largest terrestrial carbon flux in the forest ecosystems, which contributes 50–95% of the total ecosystem respiration [1,2]. Tropical forest is an important contributor to the global carbon cycle through storing 45% of global terrestrial carbon stocks in vegetation [3]. Generally, compared with boreal and temperate forests, tropical forests have higher rates and variations of soil respiration [4]. Thus, tropical forests could strongly influence future CO₂ concentrations in the atmosphere. However, the range of variability in soil respiration from tropical forests remains difficult to assess, and it may lead to inaccurate soil respiration estimates at the ecosystem level.

Soil respiration comes from CO₂ production of all living organisms in the soil, including plant roots, soil microbes, and animals [5,6]. In tropical forests, soil CO₂ emission showed strong seasonal variations with higher rates in the hot humid seasons and
lower values in the cool dry seasons [7]. Although soil microorganisms and plant roots dominantly constitute soil respiration, published data reported that root/rhizosphere respiration is responsible for 10–90% of total soil respiration [8]. The rate of soil respiration has been shown to change and fluctuate at an unexpectedly large scale. It was quite difficult to be explained by known environmental factors, such as soil water content and temperature. In order to accurately estimate soil respiration in the forest ecosystems, it is essential to have information on spatial and temporal variability for estimating the average rate of soil respiration at regional scales.

The annual and seasonal dynamics of soil respiration is preferably considered by the spatial distribution patterns. Seasonal tropical forests occasionally encounter climate fluctuations; therefore, this study aimed to investigate the spatial and seasonal patterns of soil respiration at plot-scale in a seasonal tropical forest at Sakaerat Biosphere Reserve, Nakhon Ratchasima, Thailand.

MATERIALS AND METHODS

Study site

Field studies were performed in the dry evergreen forest (DEF) at Sakaerat Environmental Research Station (SERS) (14°30′N, 101°56′E; about 500 m above sea level) in Nakhon Ratchasima Province, Northeastern Thailand (Fig. 1). The study period was from November 2014 to August 2016, with dry season from November to March and wet season from May to October. The total annual rainfall was 1751.2 mm, and monthly rainfall was less than 40 mm during the dry season. The average percentage of relative humidity, evaporation, and annual temperature were 74%, 1.2 mm, and 26.7°C (7.9–40.6°C), respectively. The DEF covers an area of 29.5 km², where the dominant tree species are *Hopea ferrea* and *Hopea odorata* with canopy trees reaching generally 23 to 40 m in height [9]. Litterfall accumulated on the forest floor was approximately 25 t/ha, and the thickness of litter layer was 2–5 cm [10].

Field study design and measurements of soil CO₂, temperature, and moisture

Soil respiration was measured in 5 main plots (100 × 100 m²), and each plot was divided into 100 subplots (10 × 10 m²). The measurement points were at the center of individual subplots. The plots were established at different locations in the DEF according to the vegetation, elevation, and soil characteristics. Soil respiration were observed two times for each season; November to December 2014 and March 2016 for dry season and October 2015 and July to August 2016 for wet season.

At the measurement point, a PVC collar (10 cm in diameter and ca. 3 cm in height) was placed at least one day before the measurement to avoid disturbing soil activities. CO₂ emissions were measured using a portable infrared gas analyzer (IRGA, EGM-4, PP Systems, Hitchin, UK) with a closed soil CO₂ efflux chamber (diameter 10 cm; SRC-1, PP Systems). Immediately after CO₂ measurement, soil temperature and soil moisture were measured around the PVC collar at about 10 cm depth using a digital thermometer waterproof probe (types H-1 and H-2, Shinwa Co., Ltd., Japan) and a soil moisture sensor (SM150, Delta-T Devices Ltd., Cambridge, UK). The measurements took 3 to 5 min per point and started from 9:00 am until 6:00 pm in normal condition without rainfall.

Statistical analysis

Soil respiration was assessed as the mean, skewness, range, and standard deviation using the frequency distribution from 2000 sampling data. For all analyses, the normality and homogeneity were tested by the Kolmogorov-Smirnov test. The significant differences in CO₂ effluxes among the seasons were tested by a Student’s t-test. Also, the relationship of soil respiration between dry and wet seasons was tested by Pearson’s correlation. In both seasons, the spatial distribution pattern maps of CO₂ emission, temperature, and moisture from the soil were created using the MATLAB program. The relationship between CO₂ effluxes and environmental factors (soil temperature and moisture) was tested by linear
regression analysis. All statistical calculations were performed in SPSS ver. 20.0.0 for Windows.

RESULTS AND DISCUSSION

Temporal variation in soil respiration

The temporal pattern of soil respiration was seasonal and changed with the fluctuation range of soil temperature and soil moisture. The overall mean of soil respiration rate ($\pm$ SD) was 6.57 ± 4.29 µmol CO$_2$ m$^{-2}$s$^{-1}$, with variation mean from the five plots ranged from 2.66 to 11.72 µmol CO$_2$ m$^{-2}$s$^{-1}$. The distribution estimates of soil respiration rates displayed a positively skewed frequency distribution with a skewness of 2.06 ± 0.05. The minimum and maximum rates were 0.08 and 42.68 µmol CO$_2$ m$^{-2}$s$^{-1}$, respectively (Fig. 2). The mean value of soil respiration rates from this study (6.57 ± 4.29 µmol CO$_2$ m$^{-2}$s$^{-1}$) was quite similar to the results of 6.05 and 6.76 µmol CO$_2$ m$^{-2}$s$^{-1}$, respectively obtained from DEF in Kog-Ma Experimental Watershed, Northern Thailand [7] and Huai Kha Khaeng Wildlife Sanctuary, Western Thailand [11]; but almost 3 times higher than the value obtained from the dry dipterocarp forest in Western Thailand [12]. Moreover, the value from this study was in the range of soil respiration (1.8–6.8 µmol CO$_2$ m$^{-2}$s$^{-1}$) reported from tropical forests in Thailand, Central Amazon [13], and Malaysia [14].

The seasonal variation of soil respiration showed a significant difference between dry and wet seasons ($p < 0.001$; Fig. 3). The mean respiration rate in the wet season was significantly two times higher (8.8 ± 4.5 µmol CO$_2$ m$^{-2}$s$^{-1}$) than in the dry season (4.3 ± 2.5 µmol CO$_2$ m$^{-2}$s$^{-1}$). The average soil temperatures also significantly differed between dry and wet seasons (24.7 ± 0.7°C and 25.0 ± 0.4°C, respectively), but the difference is less than 1°C. In addition, the average soil moisture content in the wet season (18.4 ± 0.4%) was significantly higher than in the dry season (7.0 ± 0.8%). Therefore, the results from this study demonstrated that soil moisture is a major factor contributing to increase soil respiration. When compared with another study done in 1982 at the same site as this study, the rates of soil respiration were much lower in both seasons, especially in the dry season [15]. In the 1982 study, the soil respiration rates in the dry and the wet seasons were 2.4 and 7.3 µmol CO$_2$ m$^{-2}$s$^{-1}$ with the average soil temperatures of 20.2°C and 23.1°C, respectively. The lower temperature and thus lower soil respiration were due to a factor that the study was conducted in a colder year.

Spatial variation in soil respiration

Soil respiration considerably varied with space. The spatial distribution map, as well as the frequency distribution, expressed the uneven and unusual rates of CO$_2$ efflux as extremely high over 40 µmol CO$_2$ m$^{-2}$s$^{-1}$ (Fig. 4). These CO$_2$ “hot spots” were found in many locations in the main plots. Some hot spots persisted in both seasons but with higher
magnitude in the wet season. In addition, greater distribution of higher soil respiration subplots was shown in the wet season than in the dry season. The correlation of soil respiration between dry and wet seasons was significant and slightly positive \((p < 0.01; R = 0.228; \text{Fig. 5})\). Therefore, soil respirations of the same locations tend to produce more \(\text{CO}_2\) in the wet season.

The spatial distribution of soil respiration apparently could not be explained by soil temperature distribution even though it quite coincided with the distribution of soil moisture (Fig. 4). However, both factors could limit soil respiration at some point. The spatial variation of soil respiration could be influenced by other factors, such as soil texture, soil organic matter, soil organic carbon, and especially soil animals. The spatial fluctuation in soil respiration in this study, especially the hot spot locations, was possibly caused by subterranean nests of ants and termites because these insects are highly abundant in number and biomass in the tropical forests. Ohashi et al \([14, 16]\) indicated that subterranean nests of ants and termites were the main causes of the extremely high rates of soil respiration as

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**Fig. 4** Examples of soil respiration distribution maps in dry (a) and wet (b) seasons, soil temperature distribution in dry (c) and wet (d) seasons, and soil moisture distribution in dry (e) and wet (f) seasons.
the hot spots (> 10 µmol CO$_2$ m$^{-2}$s$^{-1}$) in the tropical forests of Malaysia, contributing to 10% of the total soil respiration. Moreover, the termite mounds contributed up to 10% of the total soil respiration in a tropical monsoon forest of Southern Vietnam, showing the maximum rate of the mound CO$_2$ emissions of 20 µmol CO$_2$ m$^{-2}$s$^{-1}$ [17]. As the hot spots showed highly temporal and spatial variations, it was proposed to be attributed from unrevealed activities of soil animals, especially social insects (e.g. termites) because it is well known that termites are superabundant soil animals in seasonal tropical forests of Thailand [10, 18].

Other studies also reported that both mound and subterranean nest of termites [16, 19, 20] and ants [16, 21] emitted significantly higher CO$_2$ than the surrounding soils. For termite, the mound CO$_2$ emission rate in a tropical savanna was about 10–19 µmol CO$_2$ m$^{-2}$s$^{-1}$ compared with 5–10 µmol CO$_2$ m$^{-2}$s$^{-1}$ from the surrounding soils [22]. In a tropical forest, the mean of CO$_2$ emission from termite mound was reached up to 27.9 µmol CO$_2$ m$^{-2}$s$^{-1}$, which was much higher than the surrounding soil (3.96 µmol CO$_2$ m$^{-2}$s$^{-1}$) [16]. For ant, the CO$_2$ efflux rates from the subterranean nests in the tropical forests reached up to 27.5 [21] and 45.5 µmol CO$_2$ m$^{-2}$s$^{-1}$ [16]. In addition, other soil organisms, such as earthworms, have no effect on the emission of CO$_2$ from soil (0.20 µmol CO$_2$ m$^{-2}$s$^{-1}$) [23]. However, earthworms increased soil carbon content and other nutrients [5] which, as a result, enhanced soil respiration by microbial activities. Since other soil characteristics, such as carbon, nutrients, pH, and soil animal activities, were not investigated in this study, the causes of the hot spots could not be proved.

**Effects of temperature and moisture on soil respiration**

Soil respiration, together with soil temperature and soil moisture content, showed strong seasonal variations with higher rates in the hot humid seasons and lower values in the cool dry seasons. The annual soil respiration rates were significantly and positively correlated with both soil temperatures ($R = 0.053$, $p < 0.05$) and soil moisture contents ($R = 0.452$, $p < 0.001$) but with a much higher relation with soil moisture. However, this result includes both temporal and spatial variation, which makes it ambiguous between the effects of soil temperature and soil moisture on variability of soil respiration. Therefore, the relationships of soil respiration with soil temperature and soil moisture content in the dry and wet seasons were examined (Fig. 6). The results showed that relationships between soil respiration and soil temperature were significantly negative in the dry season ($R = -0.345$, $p < 0.01$), but significantly positive in the wet season ($R = 0.357$, $p < 0.01$). While the relationship between soil respiration and soil moisture was significantly positive only in dry season ($R = 0.429$, $p < 0.01$), but showed no significant correlation in the wet season ($R = -0.41$, $p = 0.198$). The results imply that soil respiration was limited by soil moisture in dry season. This means that the increase in soil temperature (to a very high degree) decreased soil moisture thus reducing soil respiration. In contrast, soil moisture was not a major driving factor in the wet season because there was enough water for soil microbial activities. Therefore, soil temperature (also not so high) was a major factor contributing to the increase of soil respiration in wet season.

Generally, soil respiration rate increases with increasing soil temperature and soil moisture content [24–26], but at certain points, the soil respiration rate could be negatively correlated with soil temperature and soil moisture content. In this study, it was found that soil respiration decreased when soil temperature was higher than 27°C in the dry season (Fig. 7a), and when soil moisture content was greater than 21% in the wet season (Fig. 7b). The finding of 21% soil moisture cutting point is the same value as what was found in the Western Thailand forest [11], but more than what was found (18%) in the previous study of DEF at the same site of this study [21]. In wet season, the
Fig. 6 Changes in soil respiration with soil temperatures and soil moisture contents in dry and wet seasons.

Fig. 7 Relationships between soil respiration and soil temperatures (a) and soil moisture contents (b) for dry and wet seasons. Note the cutting points at 27 °C soil temperature and 21% soil moisture content. The regression was run separately for soil temperature < 27 °C and > 27 °C and soil moisture content < 21% and > 21%.
available precipitation influences soil microbial activities. However, high soil moisture content creates a barrier at the soil atmosphere surface, which could inhibit the diffusion of CO$_2$ out from the soil [13] or lower oxygen in soil texture. This variability in the timing and magnitude of precipitation events can affect soil respiration.

CONCLUSION

In a seasonal tropical forest, soil respiration was highly variable spatially and temporally. The seasonal change clearly affects soil respiration as it significantly increases in the wet season more than the dry season. Seasons also significantly alter spatial variation of soil respiration. Wet season significantly increases spatial variation of soil respiration as well as soil temperature and soil moisture more than dry season. This study also suggests the importance of other soil features such as soil texture, soil nutrients, and subterranean nests on high CO$_2$ emission locations in order to depict soil respiration at a large scale area, and the results can be applied for tropical forest ecosystems.

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