Study on ecological matter cycle in Southeast Asian tropical forests by long-term measurement of soil CO_2 efflux

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Research Objective

1. To detect the effect of climate change on tropical forest carbon cycle by long-term monitoring soil CO_2 efflux.
2. To evaluate the effects of timber harvest and land use change on degradation of soil by measuring soil CO_2 effluxes in primary and secondary forests, rubber and oil palm plantations.
3. To partitioning soil CO_2 efflux by monitoring litterfall.

1. Introduction

The world's soils contain about 1550 Pg of organic carbon, which is more than twice the amount in the atmosphere (IPCC, 2007). Forests worldwide contain about 45% of the global carbon stock, a large part of which is in the forest soils. Recently, Bond-Lamberty and Thomson (2010) estimated that the global soil CO_2 efflux, widely referred to as soil respiration (R_s), was about 98 Pg C y^{-1} in 2008 based on a five-decade record of chamber measurements, which is more than 13 times the rate of fossil fuel combustion (IPCC, 2007), indicating that 20-40% of the atmosphere's CO_2 circulates through soils each year. Overall, R_s is the largest component of ecosystem respiration and the second largest flux in the global carbon cycle after gross primary production (GPP). It is therefore a key process that is fundamental to our understanding of the terrestrial carbon cycle (Davidson and Janssens, 2006). A relatively small change in the carbon flow into or out of soils can potentially strongly influence global cycles of carbon, nitrogen, and water. For example, it has been reported that the global R_s increased by 0.1 Pg C y^{-1} between 1989 and 2008 (Bond-Lamberty and Thomson, 2010), and the positive feedback from this enhancement of R_s by global warming would raise the CO_2 concentration in the atmosphere by 20-224 ppm by 2100, and that resulting higher CO_2 levels would lead to an additional temperature increase ranging between 0.1 and 1.5 °C (Friedlingstein et al., 2006;IPCC, 2007).

In forest ecosystems, micrometeorological studies (i.e., eddy covariance) have shown that, on average, ~80% of GPP is respired back to the atmosphere (Law et al., 2002), and R_s has been estimated to account for 60-90% of the total ecosystem respiration, with marked temporal as well as spatial variations (Law et al., 1999;Janssens et al., 2000;Liang et al., 2004a). Therefore, R_s has recently received much attention from researchers and its accurate measurement is critical for developing a reliable model of carbon exchange in forest ecosystems (Jassal et al., 2007;Zhou et al., 2009).

Because R_s is highly variable spatially and the soil medium is not easily accessible, R_s cannot be measured by large-scale remote sensing. FLUXNET has become an effective network for observing carbon sequestration or loss by global terrestrial ecosystems by the eddy covariance technique (Luyssaert et al., 2008). Unfortunately, the use of the eddy covariance technique for measuring soil CO_2 efflux, especially below forest canopies, is often hampered by relatively low wind speeds (Drewitt et al., 2002) as well as by an abundance of understory vegetation (Lee, 1998;Janssens et al., 2001). Therefore, to validate nocturnal, subcanopy, and bad-weather (e.g., rainy period) eddy covariance measurements as well as the partition of the net ecosystem production (NEP), the flux research community must use automated chamber systems, which can make continuous (i.e., half-hourly or hourly) measurements of R_s (Gaumont-Guay et al., 2009;Jassal et al., 2007). Moreover, the automated continuous measurements of R_s (see (Goulden and Crill, 1997;Savage and Davidson, 2003;Liang et al., 2004a)) provide insights about ecosystem processes, which were not possible to explore before (Vargas et al., 2010).

Tropical forests cover only about 7% of Earth’s land surface, however, they have high net primary production (NPP), and have the largest carbon pools on Earth (59% and 27% of global forest vegetation and soil C), and therefore play a pivotal role in the global carbon cycle. Understanding the role of the terrestrial tropics as an accelerator or buffer of the rate of climate change via additions and subtractions to the atmospheric CO_2 pool is essential. However, tropical forests are the least understood, particularly for that in Southeast Asia. The objectives of this study were to (1) detect the effect of climate change on tropical forest carbon cycle by long-term monitoring soil CO_2 efflux; (2) evaluate the effects of timber harvest and land use change on degradation of soil by measuring soil CO_2 effluxes in primary and secondary forests, rubber and oil palm plantations, and (3) partitioning soil CO_2 efflux by monitoring litterfall.

2. Materials and methods

2.1. Site description

Field measurements were carried out in the Pasoh Forest Reserve (lat 2º58'N, long 102º18'E) in the state of Negeri Sembilan, about 70 km southeast of Kuala Lumpur, the capital city of Peninsular Malaysia. The landscape in the region is predominantly hilly, with elevations varying between 75 and 150 m above mean sea level; it is covered with lowland dipterocarp stands (Symington 1943; Wyatt-Smith 1961, 1964). Annual rainfall from 1974 to 1996 at Pasoh-dua (lat 2º56'N, long 102º18'E), about 6 km south of the reserve, averages 1842 mm, and ranges from 1700 to 3200 mm (Kochummen et al. 1990). The air temperature over the forest canopy at a height of 53 m above the ground averaged 25.7ºC from 1992 to 1999. There is no marked seasonal drought, but the climate is influenced by two monsoon periods (April/May and November/December); the study was conducted from September through October 1998. Geologically the soils of the reserve are characterized by shale, granite, and fluviatile granitic alluvium (Allbrook 1973).

The reserve comprises a core area of 650 ha of lowland primary dipterocarp "Meranti-Keruing" forest, surrounded by a 2000-ha buffer zone of regenerating forest, portions of which were selectively logged during 1954 and 1963 (Kochummen et al. 1990). This forest is representative of the lowland forest of south-central Peninsular Malaysia, and is characterized by a high proportion of Dipterocarpaceae (Kochummen et al. 1990, Manokaran and LaFrankie 1990). Surveys revealed 335 240 stems in a 50-ha plot with a diameter at breast height (DBH) ≥1 cm, comprising 814 species, 290 genera, and 78 families (Manokaran et al. 1992, Appanah and Weinland 1993, Kochummen 1997). Stem densities averaged 6769 trees ha^{-1} with DBH ≥ 1 cm, 530 trees ha^{-1} with DBH ≥ 10 cm, and 3 trees ha^{-1} with DBH ≥ 90 cm (Manokaran and LaFrankie 1990). Approximately 25% of the total number of tree and shrub species recorded in the Malay Peninsula (3197 species) were found in the plot (Kochummen et al. 1990). The primary forest has a basal area (timber species) of about 42.2 m^2 ha^{-1} for trees with DBH ≥ 1 cm and of 36 m^2 ha^{-1} for trees with DBH ≥ 10 cm.

The leaf area index (LAI), which was measured using an LI-2000 canopy analyzer (LI-COR Inc., Lincoln, Nebraska, USA), averaged 6.52. This value of LAI may be smaller than the actual LAI of the natural forest stand at Pasoh because the LI-2000, though accurate, underestimates the LAI in natural multistory forest stands as a result of self-shading by the leaves (Sampson and Allen 1995, Nicotra et al. 1999). New canopy gaps (with mean size of *ca.* 65 m^2) covered 2 to 4% of the total area of the primary forest from 1992 to 1997, with a canopy height within the gaps of < 15 m (Yasuda 1998, values estimated using a spherical densitometer; Adachi et al., *unpublished data*, values estimated from stereo-pair aerial photographs; *see also* Thomas and Bazzaz 1999). Most of the seedlings of late-successional species occurred in the shaded understory, most likely because light levels were too high in the gaps for seed germination, opening of seedling primary leaves, and shedding of cotyledons (Itoh 1995).

2.2. Soil CO_2 efflux measurement

2.2.1. Multichannel automated chamber system

Liang et al. (2003) designed a multi-channel automated chamber system that applied a steady-state technique to continuously measure R_s. However, the pressure inside the chamber was 0.22 Pa higher than that outside the chamber, which is likely to lead to underestimation of the actual R_s (Fang and Moncrieff, 1998). Therefore, we have modified and improved this system using a flow-through, non-steady-state design. In brief, the system comprises a control unit that is contained within a waterproof field access case (0.70 m long × 0.50 m wide × 0.35 m high), and can drive maximum 24 automated chambers. The main components of the control unit are an infrared gas analyzer (IRGA, LI-840; LI-COR, Lincoln, NE, USA), a datalogger (CR10X, Campbell Scientific Inc., Logan, UT, USA), a gas sampler, and an air compressor (Fig. 1). The automated chambers (0.9 m long × 0.9 m wide × 0.5 m tall) are constructed of clear PVC (1 mm thick) glued to a frame constructed from plastic-coated steel pipe (30-mm-square cross-section) (Fig. 2a). Between measurements, the two sections of the chamber lid are

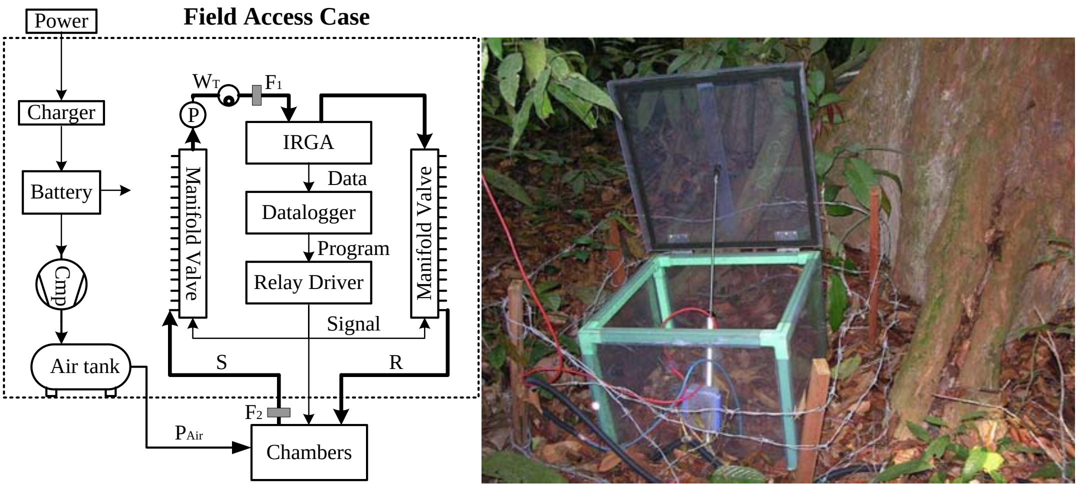

Fig. 1. Schematic illustration of the multi-channel automated chamber system for continuous measurement of soil CO_2 efflux (left). The dashed square means a water proofed aluminum casing (Field Access Case). Bold arrows indicate the direction of chamber airflow. Abbreviations: Power = DC 12 V or AC 85–240 V for the system; Charger = AC-DC convert for charging and controlling a 12 V (7.2 A·h) lead-acid battery that drives the system; Cmp = air compressor; P_{Air} = compressed air from the air tank to the pneumatic cylinders for opening and closing the chamber lids; F_2 = air filter (0.5 mm mesh); S = sample air from the chamber; P = sample pump; W_T = water trap; F_1 = air filter (1 μF mesh); IRGA = infrared gas analyzer; R = sampled air returned to the chamber. Image of the multi-channel automated chamber systems installed at the site (right).

vertically raised to allow precipitation and leaf litter to reach the enclosed soil surface, thus keeping the soil conditions as natural as possible. The chamber lids are raised and closed by two pneumatic cylinders (SCM-20B, CKD Corp., Nagoya, Japan) at a pressure of about 0.2 MPa, which is generated by a micro-compressor (M-10, Hitachi Ltd., Tokyo, Japan; Fig. 1a). During the measurement, the chamber is closed and the chamber air is mixed by two micro-blowers (MF12B, Nihon Blower Ltd., Tokyo, Japan). The chamber air is circulated through the IRGA by a micro-diaphragm pump (5 L min^{-1}; CM-50, Enomoto Ltd., Tokyo, Japan), and CO_2 concentration is monitored by the IRGA. The average power consumption of the whole system is 13 W; thus, the system can be continuously driven by three 75-W solar cells with three 100-A·h deep-cycle batteries.

In October 2004, we installed 8 chambers at the site randomly on the forest floor within a circular area 40 m in diameter for continuous measurement of soil CO_2 efflux (Fig. 1b). In August 2007, the 8 chambers were divided into two groups, each with 4 chambers, to measure the total soil CO_2 efflux (R_s) and heterotrophic respiration (R_h), respectively. The R_h chambers were installed in 1 × 1 m root exclusion plots. Trenches were dug down to 0.5 m along the plot boundaries and then PVC sheets were installed in the trenches to a depth of 0.50 m to prevent root penetration (Fig. 2).

Fig. 2. Installation of trench plots.

Over the course of a half-hour, the 8 chambers were closed sequentially by a home-made relay board controlled by the datalogger (Fig. 1). We set the sampling period for each chamber to 225 s. Therefore, the chambers were open for 87.5% of the time: during each 30 min cycle each chamber was open for 26.25 minutes and closed for 3.75 minutes. Thus, most of rainfall and leaf litter could enter the chambers, and the interior of each chamber had good exposure to any atmospheric turbulence. Soil temperature at 0.05 m depth inside each chamber was measured with home-made thermocouples and volumetric soil moisture at 0.10 m depth was monitored with TDR sensors (CS615, Campbell Scientific), and recorded by the datalogger via a multiplexers (AM25T, Campbell Scientific). Moreover, air pressure at 0.30 m height around the center of the measurement plots was monitored with a pressure transducer (PX2760, Omega Engineering, Inc., Stamford, CT, USA). The datalogger acquired outputs from the IRGA and the other sensors at 1-s intervals and recorded the averaged values every 5 s. Soil CO_2 efflux (R_s, μmol m^{-2} s^{-1}) was calculated with the following equation:

$$R_s = \frac{VP(1-W)}{RST}\frac{\partial C}{\partial t}, \quad (1)$$

where V is the effective chamber-head volume (m^3), S is the measured soil surface area (m^2), P is the air pressure (hPa), T is the air temperature (K), and W is the water vapor mole fraction (mmol mol^{-1}) inside the chambers; $\partial C/\partial t$ is the rate of change in the CO_2 mole fraction (μmol mol^{-1} s^{-1}) calculated by the least-square method, and R is the gas constant (8.314 Pa m^3 K^{-1} mol^{-1}). Note that the pressure is not the pressure inside the IRGA cell but the pressure inside the chambers and we assumed that there was null pressure difference between the inside and outside of the chambers.

2.2.2. Portable automated chamber system

We also developed a portable automated chamber system that can be applied in combination with the above multichannel chamber system for evaluation of spatial variation of soil CO_2

Fig. 3. A portable automated chamber system for measurement spatial variation of soil CO_2 efflux at different ecosystems.

efflux in different ecosystems. In brief, the system comprises a waterproof control case (orange color in figure 3; 0.47 m long × 0.36 m wide × 0.20 m high, about 12 kg in weight) and 2 automated chambers (blue color in figure 3; 0.30 m in diameter and 0.30 m in height, about 4 kg in weight).

3. Results and discussion

3.1. Seasonal change in soil CO_2 efflux (R_s) in Pasoh primary forest

R_s showed notable seasonal patterns that corresponding to the seasonal change in soil moisture (Fig. 4). As compared to R_s in temperate and boreal ecosystems (Liang et al., 2004a;Liang et al., 2004b), R_s in Pasoh forest was not dependent on soil temperature, probably due to variation of

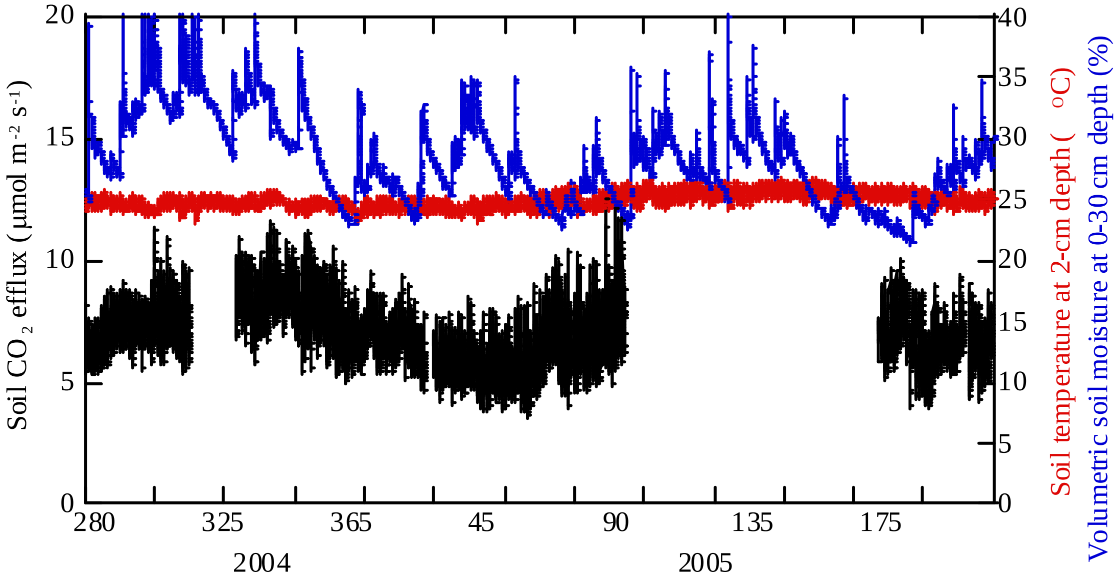

Fig. 4. Seasonal change in soil CO_2 efflux in Pasoh primary forest.

soil temperature was within ±1°C. Mean R_s was 7.24±0.82 μmol m^{-2} s^{-1} and annual R_s was estimated to be about 27.41 tC ha^{-1} y^{-1}, which was much higher than that reported from the same forest (Adachi et al., 2006;Kosugi et al., 2007). However, our results matched R_s that measured in Amazonian tropical forests (Chambers et al., 2004).

3.2. Spatial variation of soil CO_2 effluxes at the primary and logged forests

Figure 5 showed the spatial variation of R_s in the primary (control site) and logged (logged site) forests in the 47 segment of Pasoh forest. R_s was 8.7±4.1 and 9.4±5.1μmol m^{-2} s^{-1} at the primary forest and logged forest, respectively. Results suggest that even the logging event could reduce

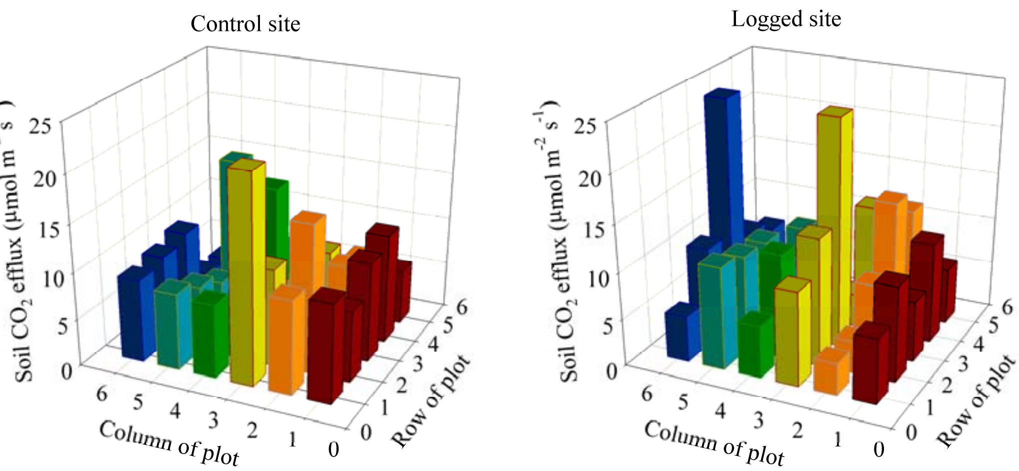

Fig. 5. Spatial variation of soil CO_2 efflux at a Primary and logged forests.

the root respiration as well as reduce litterfall, the increase in soil temperature could enhance the soil heterotrophic respiration. Moreover, the residual coarse wood debris (CWD) and dead roots might increase the spatial variation of R_s in the logged forest.

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5. Research Output (FY 2009-2010)

Publications

Takagi K., Fukuzawa K., ***Liang N.***, Kayama M., Nomura M., Hojyo H., Sugata S., Shibata H., Fukazawa T., Nakaji T., Oguma H., Mano M., Akibayashi Y., Murayama T., Koike T., Sasa K., Fujinuma Y. 2009. Change in the CO2 balance under a series of forestry activities in a cooltemperate mixed forest with dense undergrowth. Global Change Biology 15: 1275-1288

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Sano T., Hirano T., ***Liang, N.***, Hirata R., Fujinuma Y. 2010. Carbon dioxide exchange of a larch forest after a typhoon disturbance. Forest Ecology and Management, 260: 2214-2223

6. Conference/Symposia

Liang N. and Nakane K. 2009. How long the Japanese Forests can sustain 3.8% of carbon sink ~ from forest warming experiments ~, The 56 Annual meeting of JES, March 2009, Morioka, Japan

Liang N. and Takagi K. 2009. CarboEastAsia ~ multi-approach for evaluation of terrestrial ecosystem carbon balance ~, Annual meeting of JAMS, March 2009, Koriyama, Japan

Liang N. and Hirano T. 2010. JapanFlux/CarboEastAsia: Carbon Balance of East Asian Terrestrial Ecosystems, The 57 Annual meeting of JES, March 2010, Tokyo, Japan

7. Research plan 2011-

1. Continuation of the continuous measurement of soil CO_2 efflux around the Pasoh tower by using a multichannel soil CO_2 efflux system.
2. Continuation of the periodical measurement of soil CO_2 effluxes in primary and secondary forests, rubber and oil palm plantations around Pasoh and Temengor Forests by using a portable soil CO_2 efflux system.
3. Continuation of monitoring litterfall around the Pasoh tower.