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Spatial variation in soil respiration in relation to a logging road in an upper tropical hill forest in Peninsular Malaysia

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ABSTRACT The spatial gradient of soil respiration from a logging road to the inner part of a forest, and the major environmental factors controlling soil respiration were studied in a hill dipterocarp forest in Peninsular Malaysia to examine the spatial effects of logging road construction on soil respiration. Soil respiration, soil temperature, and soil water content were measured at six points along a total of twenty-five 35-m transects. The logging road at the study site was constructed in 2009. The soil respiration rate on the logging road was very low (0.376 μmol CO₂ m⁻² s⁻¹), and there were no significant differences between the roadside and inside the forest (4.76-5.95 μmol CO₂ m⁻² s⁻¹). Path analysis showed that the soil respiration rate was affected by soil temperature and distance from the logging road. This finding differs from those of previous studies conducted in lowland tropical rain forests. We speculate that the low soil respiration rate on the road is primarily because of soil compaction and low concentrations of carbon-containing material. The soil temperature at the roadside (which was positively correlated with soil respiration) was higher than inside the forest. Despite the differences in soil temperatures, differences in soil respiration between the roadside and the inner parts of the forest were not significant, probably because of the small amount of litter present as a substrate for microbial respiration at the roadside and/or the occurrence of different microbial communities and biomass between the roadside and the inner parts of the forest.

Key words: forest degradation, logging road, spatial variation of soil CO₂ efflux

INTRODUCTION
Carbon emissions from the forestry sector and land use changes are one of the major sources of carbon emission (IPCC 2007). Tropical forests retain one fourth of the carbon stored in the terrestrial biosphere (Bonan 2008), but excessive logging operations, which cause deforestation and forest degradation, are still conducted in those ecosystems. A common logging method used in tropical rainforests, especially in Southeast Asia, is selective logging (Biscoff et al. 2005, Okuda et al. 2003); this method involves not only the extraction of trees, but also the construction of logging roads that spread like a spider’s web around a forest. This type of logging contributes substantially to forest degradation. In tropical forests, approximately 12-25% of the forest area is covered by logging roads, skid trails, and log yards (Uhl and Vieira 1989, Pinard et al. 2000, Jackson et al. 2002). Forest degradation resulting from the excessive construction of logging roads and skid trails substantially reduces the above ground biomass, which affects the soil environment and the forest ecosystem (Sidle et al. 2004, Gullison and Hardner 1992). Additionally, a spatial gradient of environment from open space (logging road) towards a closed forest canopy is observed (Lawton et al. 1998, Laurance 1991). Logging road construction could potentially change soil respiration (CO₂ emissions from the soil surface) as a result of such a spatial gradient from the edge to the inner parts of a forest. Soil respiration consists of root respiration of plants and microbial respiration, and is an important component of the carbon cycle in forest ecosystems. Chambers et al. (2004) reported that soil respiration accounts for approximately 40% of the total respiration in forest ecosystems in tropical regions. Soil temperature and soil water content are well known to be major environmental factors controlling soil respiration because they affect microbial activity in soils and roots of plants (Nakane 1984, Atkin et al. 2005, Luo and Zhou 2006). Logging road construction may affect the soil temperature and soil water content of soil on logging roads. Additionally, the occurrence of gap areas produced by tree extraction during logging significantly influence the soil environment and, as a result, soil respiration is altered in forest gaps (Saner et al. 2009). Hence, the considerable reduction in vegetation resulting from the construction of
logging roads may influence soil temperature, soil water content, and soil respiration. If road construction affects soil respiration on the road, the carbon budget of the forest ecosystem will be altered. Moreover, if soil respiration is affected by the occurrence of a spatial gradient, the carbon balance will be influenced to an extent dependent on the distance from a logging road; in addition, it will be difficult to make accurate estimations of soil respiration for a whole forest ecosystem.

Previous studies on the impact of logging on soil respiration have been conducted in tropical regions, and no significant impact was observed (Yashiro et al. 2008, Adachi et al. 2006). However, very few studies have considered the impact of logging road construction on soil respiration (e.g. Keller et al. 2005), and those do not consider spatial gradients in soil respiration that are dependent on the distance from logging roads. Also, most of those studies were conducted in lowland tropical forests, but the majority of logging is now done in hill forests and upper hill forests, rather than lowland forests. Almost all of the lowland forests in Peninsular Malaysia were cleared by the late 1970s for the development of agriculture crop land (mainly for the development of oil palm estates); consequently, commercial logging continues only in hill and upper dipterocarp forests (Okuda et al. 2003, Liow et al. 2002). In many forest ecosystems, temperature and precipitation patterns are known to affect soil respiration rates (Luo and Zhou 2006, Raich and Schlesinger 1992).

In upper tropical hill forests, these environmental factors are assumed to differ from those in lowland tropical rain forests, because upper tropical hill forests are located at higher elevations. Thus, in an upper tropical hill forest, the response of soil respiration to road construction will not necessarily be the same as that in a lowland tropical forest, and the response is thought to be unpredictable. Especially in high elevation logging concession areas, logging roads are maintained for a number of years and regularly used, so vegetation is not rapidly recovered. Therefore, logging road construction in upper hill forests is thought to have a long lasting impact on the ambient environment, and the impact of road construction on soil respiration needs to be investigated.

The objectives of this study were to (1) evaluate environmental factors affecting soil respiration in an upper tropical hill forest, and (2) examine the spatial gradient of soil respiration from a logging road to the inner part of the forest.

**MATERIALS AND METHODS**

**Study site**

The study site is located in the Perak Integrated Timber Complex (PITC) Concession Forest (5°24’–5°34’N, 101°33’–101°39’E) in the Temengor Forest Reserve, Perak, Peninsular Malaysia (Fig. 1). The altitude of the Temengor Forest Reserve is approximately from 400–1000 m and the Temengor Forest Reserve is located within a hill dipterocarp forest (Symington 1943). The dominant species are Shorea platyclados Sl. ex Foxis., Dipterocarpus costulatus V. Sl., Dipterocarpus crinitus Dyer., Intsia palembanica Miq., and some species of bamboo such as Schizostachyum grande Ridl. and Gigantochloa ligulata Gamble (PITC 2010). The PITC Concession area is located over either Silurian and Cambrian sedimentary rocks or acidic, undifferentiated granitic rocks. The climate of the region is similar to that of highland tropical rain forests. The locality of the Perak Integrated Timber Complex (PITC) concession area is shown in light gray and the study site, Block 5 (200 ha, 5°31’N, 101°54’E, 600–850 m asl), is shown in black. The study was conducted in Block 5 of the PITC Concession Forest (5°31’N, 101°36’E, 600–850 m asl).
of the East Coast region of Peninsular Malaysia, which experiences heavy rainfall associated with the North East Monsoons (WWF Malaysia 2002). Annual mean temperature was approximately 23.3°C, mean diurnal range of temperature was 8.8°C, and the annual temperature range was 1.1°C. Annual precipitation was approximately 2570 mm. Precipitation of the wettest quarter (from October to December) and driest quarter (from January to March) were 985 mm and 393 mm, respectively, (1950–2000) (WorldClim database from http://www.worldclim.org) (Hijmans et al. 2005).

The study was conducted in Compartment 44, Block 5 (200 ha) of the 9765 ha PITC Concession Forest (5°31′N, 101°36′E, 600–850 m asl) (Fig. 1). In Block 5, logging has been conducted under two logging regimes. The first is a conventional logging regime, called Selective Management System, and the other is a new logging protocol to reduce logging impacts, called the New Harvesting Regime (NHR) designed by the Forest Research Institute of Malaysia (FRIM), Kepong Selangor, Malaysia. NHR specifies a minimum diameter cutting limit of 30 cm (diameter at breast height) for logged trees, and that trees selected for logging should be 20–30 m apart from each other, depending on their size (Liew 2009). Construction of the logging road and harvesting in Block 5 were conducted in 2009 and 2010, respectively. The logging road is approximately 7 m wide, runs for 7.89 km, and covers about 3% of the area of Block 5. The intensity of logging operations, including road construction, at this study site is markedly lower than in other logged forests in tropical regions (Uhl and Vieira 1989, Pinard et al. 2000, Jackson et al. 2002). Although open lands produced by logging operations include not only logging roads but also skid trails and log yards, we focused only on the logging roads for the comparison with inner parts of the forest. The effect of skid trails and log yards was not included in the comparison because skid trails and log yards were not used following the extraction of trees and the vegetation had rapidly recovered. The effects of the logging road on the ambient environment were considered to be greater than those of skid trails and log yards.

Thirty-five-meter long transects were established from the logging road into the forest, and soil respiration, soil temperature, and soil water content were measured at 0, 5, 10, 15, 20, and 35 m from the logging road on each transect (Fig. 2). The points at 0, 5 m, and between 10–35 m are on the logging road, roadside, and in the inner part of the forest, respectively. Twenty-five transects were placed within Block 5 (Fig. 3). Although the logging operation had already finished when we conducted the present study, it was not possible to identify stumps along the transects. Thus, it is assumed that there was no effect of felled trees on the transects. The roadside is located in the inner part of the forest and is covered with vegetation. The vegetation at the roadside did not differ from that of the inner part of the forest. The intensity of direct sunlight during the day on the roadside may be higher than that of the inner part of the forest because the roadside is located right beside logging roads, while the inner part of the forest and the roadside are located about 2–5 meters above the logging road. Soil compaction, such as that observed on the like logging road is not observed in the inner part of the forest or on the roadside. All measurements were taken between 10:00 and 14:00 from 14 to 27 August, 2011; this period did not occur in either the wettest or driest quarter. Each sampling point was measured once. During the measurement period, the study site experienced heavy rain four times; however it was sunny during the periods in which measurements were taken.

![Fig. 2. Locations of sampling points on two 35-m transects. Soil respiration, soil temperature, and soil water content were measured at the locations shown by the black circles at 0, 5, 10, 15, 20, and 35 m from the center of the logging road towards the forest. The width of the logging road is approximately 7 m.](image-url)
**Soil respiration, temperature, and water content**

The soil respiration rate was measured using a portable automated chamber system (LAC-02G, National Institute for Environmental Studies, Tsukuba, Japan) (Liang et al. 2013). The system comprises a portable control unit and two portable automated chambers (300 mm in radius and 300 mm in height) fitted on collars that were placed on the forest floor and buried to a depth of approximately 3 cm. The apparatus was placed at each measuring point for 3 minutes for the measurement of soil respiration rates. Soil temperature and soil water content, both of which affect soil respiration, were also monitored with the system at a depth of 5 cm at each measurement point using a soil temperature probe (Type E, MHP, Omega Engineering, Stamford) and a moisture sensor (ECH2O EC-5, Decagon Devices, Inc. Pullman, Washington) respectively. Soil water content was measured only in 15 transects because the ECH2O probe was not functional for a portion of the survey period. Additionally, soil respiration and temperature were not recorded at six and four points, respectively.

**Analyses**

Non-normal distribution of the data subsets was shown by the Shapiro–Wilk normality test. Therefore, nonparametric tests were used for statistical analysis of the data. The Kruskal–Wallis test with multiple comparisons was used to compare soil respiration rates, soil temperature, and soil water content at different distances from the logging road. We also tested the effects of soil temperature, soil water content, and distance from the logging road (environmental factors) on soil respiration using path analysis, which allowed us to categorize the effects of environmental factors on soil respiration as direct or indirect effects. We designed a path model, depicted in Fig. 4. Three environmental factors were assumed to affect soil respiration, and distance from the logging road was also assumed to affect the other environmental factors (soil temperature and soil water content). Soil temperature and soil water content were assumed to affect each other.

To examine place-specific differences in the response of soil respiration to soil temperature, soil respiration rates were divided into roadside (5 m from the logging road) and inside the forest (points occurring between 10–35 m along the transects); we then drew regression lines between the square root of soil respiration rate and the soil temperature, following the methods of Pietikäinen et al. (2005). They reported a good linear relationship between the square root of the soil respiration rate and the soil temperature, following the methods of Pietikäinen et al. (2005). They reported a good linear relationship between the square root of soil respiration rate and the soil temperature, following the methods of Pietikäinen et al. (2005). They reported a good linear relationship between the square root of soil respiration rate and the soil temperature. Both the square root of soil respiration and soil temperature include errors and Model II regression is apparently appropriate for this analysis (Sokal and Rohlf 1995). We then used standard major axis regression to determine the regression lines. Two regression lines were compared using the SMATR (Standardized Major Axis Tests & Routines) software (Version 2, http://bio.mq.edu.au/research/groups/ecology//SMATR/), with ANCOVA-like analysis based on SMA regression.

Other analyses were conducted using R version 2.15.2 software (R Core Team 2012). Significant differences were determined at a probability level of 0.05.
RESULTS

$\text{CO}_2$ emission from the soil surface was $0.376 \pm 0.19$ (mean $\pm$ S.E.) $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ on the logging road (0 m on the transect). The soil respiration rate on the roadside (5 m) was $5.30 \pm 0.77 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and the rates inside the forest (10, 15, 20, and 35 m) were $5.15 \pm 0.68, 5.05 \pm 0.60, 4.76 \pm 0.42$, and $5.95 \pm 0.74 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, respectively (Fig. 5A). Only on the logging road (0 m on the transect) were soil respiration rates significantly lower than at the other sampling points (5, 10, 15, 20, and 35 m from the center of the logging road) (Kruskal-Wallis test, $df = 5$, $P = 0.0322$). The soil respiration rate on the roadside (5 m from the center of the logging road) was not significantly different from that inside the forest (10–35 m from the logging road).

Previous studies conducted in lowland tropical rainforests in Peninsular Malaysia have reported that soil respiration in March was $4.9 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (Adachi et al. 2005) and $5.2 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in August (Adachi et al. 2006), the annual range of soil respiration was $2.8–3.5 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (Yashiro et al. 2008) and $2.5–6.8 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ (Kosugi et al. 2007). Diurnal soil respiration in upper tropical hill forests is not thought to differ widely from those in lowland tropical rainforests, although seasonal sampling is limited.

Soil temperatures on the logging road (0 m) and the roadside (5 m) were $22.8 \pm 0.45$ and $23.6 \pm 0.35 \degree C$, respectively. The mean soil temperatures at four points inside the forest (10–35 m) were between $22.1$ and $22.0 \degree C$ (Fig. 5B). Soil temperatures at the roadside (5 m) were significantly higher than those inside the forest (10–35 m) (Kruskal-Wallis test, $df = 5$, $P < 0.001$). The mean soil water content of the six points on the transects ranged from $0.14–0.22 \text{ m}^3 \text{ m}^{-3}$ (Fig. 5C). We observed no clear trend in soil water content as a function of distance from the logging road (Kruskal-Wallis test, $df = 5$, $P = 0.303$).

Path analysis demonstrated that soil temperature, soil water content, distance from the logging road, and soil respiration explained approximately 18% of the spatial variation in the soil respiration rate. Soil temperature and distance from the logging road directly affected the soil respiration rate. Soil temperature and soil water content were significantly negatively correlated. Distance from the logging road negatively affected soil temperature but did not directly affect soil water content (Fig. 4, Table 1). However, soil respiration did not vary significantly between the roadside and the inner parts of the forest, although soil temperatures on the roadside were significantly higher than those in the inner parts of the forest.

The square root of soil respiration and the soil temperature were significantly correlated in the inner part of the forest (Pearson’s product-moment correlation, $r = 0.34$, $df = 92$, $P = 0.001$), but at the roadside, there was no significant correlation ($r = 0.32$, $df = 22$, $P = 0.123$). These two regression lines were significantly different from one another ($P = 0.020$) (Fig. 6).
Effective environmental factors in an upper tropical hill forest

In the present study site, soil respiration was affected only by soil temperature. Soil water content did not affect the soil respiration rate, but indirectly affected soil respiration thorough soil temperature (Fig. 4, Table 1). However, soil water content is generally thought to be one of the major factors affecting soil respiration rates in tropical regions (Kosugi et al. 2007). In many forest ecosystems, soil temperature and soil water content are thought to be the major environmental factors controlling soil respiration because they are the main environmental factors that control soil microbial activity (Nakane 1984, Rastetter et al. 1991, Ito and Oikawa 2002, Ito 2002, Luo and Zhou 2006). However, especially in tropical regions, soil water content has been considered to be a primary and distinct factor explaining spatial variation in soil respiration, while the effect of soil temperature on soil respiration is low (Ohashi et al. 2007). This is because soil temperature in tropical regions dose not reach values low enough to prohibit microbial activity throughout the year and the temporal variation in soil temperature is very small (Ohashi et al. 2007, Kosugi et al. 2007). However, our soil respiration results from an upper tropical hill forest differ from those of previous studies conducted in lowland tropical rainforests. Our results possibly reflect the characteristics of soil respiration in hilly forests; however, the present study was only conducted in normal season and surveys have not been conducted in other seasons. Environmental conditions may vary between seasons, particularly between the wettest and driest seasons. Additional field surveys throughout the year are needed.

Table 1. Path coefficient and correlation coefficient in the path model.

<table>
<thead>
<tr>
<th>Coefficient</th>
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<tbody>
<tr>
<td>p1</td>
<td>0.32</td>
</tr>
<tr>
<td>p2</td>
<td>0.31 *</td>
</tr>
<tr>
<td>p3</td>
<td>0.04</td>
</tr>
<tr>
<td>p4</td>
<td>0.37 **</td>
</tr>
<tr>
<td>p5</td>
<td>0.33 **</td>
</tr>
</tbody>
</table>
| r           | 0.30 **     

*p<0.05; **p<0.01. p1, p2, p3, p4, p5 and r correspond to Fig.4.

Spatial gradient of soil respiration from the logging road to the inner part of the forest

The results of the path analysis demonstrate that the soil respiration rate was also affected by distance from the logging road (Fig. 4, Table 1). Soil respiration rates increased with soil temperature and distance from the logging road. Soil respiration rate on the logging road was very low, but did not vary between the roadside and the inner part of the forest, so a spatial gradient from the logging road to the closed canopy of the forest was not observed. The finding that distance from the logging road strongly affected the soil respiration rate is mostly attributed to low soil respiration on the roads. Low CO₂ efflux from the road surface may be the result of minimal accumulation of carbon-containing material, and soil compaction by heavy vehicles during logging road construction and its subsequent use. Deeper soil layers with a low carbon content are present at the surface of the logging road because logging road construction involves excavation of deep soils using heavy machinery. Soil organic carbon is known to decrease with depth (Jobbágy and Jackson 2000). Also, soil compaction is strongly affected by logging road construction, and soil bulk density usually increases as a result (Jusoff and Majid 1986). An increase in soil bulk density causes a decrease in microbial activity. Soil microbial activity is known to depend on the amount of pore space occupied by water, and the structure and size of soil pores, which are altered by compaction (Torbert and Wood 1992). Thus, as soil bulk density increases, soil respiration is thought to decrease. Additionally, CO₂ efflux from the soil surface is known to mainly occur as gas diffusion, and high bulk density of soil hinders gas diffusion (Jassal et al. 2005); this is also assumed to decrease soil respiration.

The soil temperature at the side of the logging road was significantly higher than inside the forest. The increased soil temperature perhaps results from the high intensity of direct sunlight during the day. Path analysis indicated that soil temperature had a positive effect on soil respiration, and thus soil respiration is expected to be higher at an open site, such as the roadside, than inside the forest. However, this was not the case. Soil respiration at the roadside was not significantly different than that in the inner part of the forest. Relationships between soil temperature and soil respiration at the roadside and in the inner part of the forest are shown in Fig. 6. The relationship between square root of soil respiration and the soil temperature in the inner part of the forest were significantly correlated, while the correlation was marginally insignificant at the roadside. The marginally insignificant correlation at the roadside
seems to be the result of the small number of samples (15) from the roadside. A comparison of the regression lines between the roadside and the inner part of the forest shows that the regression line of the roadside is always located below that of the inner parts of the forest within the range of the soil temperature in the present study (20.7–31.0°C), although the two regression lines were significantly different from one another. This indicates that the potential for heterotrophic respiration at the roadside is lower than that in the inner parts of the forest. Possible reasons for this may be that most of the litter is removed during the construction of logging roads, with only small amounts of litter remaining on the roadside after logging. Saner et al. (2009) showed that in gaps in a tropical lowland forest, soil temperature was higher, and litterfall and fine root biomass were lower than in other parts of the forest. Consequently, soil respiration rates in gaps were significantly lower than those inside the forest. The roadside can be considered an intermediate point between inside the forest and a gap, and thus the amount of litter at roadside areas can be assumed to be low. In this study, although there was no quantitative assessment of litter, the amount of litter on roadside areas near logging roads was clearly smaller than inside the forest. The absence of this substrate might offset the expected increased decomposition rate resulting from higher soil temperatures at the side of the logging road. Previous studies showing the contribution of litter to soil respiration in high elevation forests in tropical regions (approximately 800–3000 m asl) have indicated that respiration in the litter layer represents about 20–40% of total soil respiration (Zhou et al. 2013, Zimmermann et al. 2009). It is also possible that the microbial community and microbial biomass at the roadside differ from those in the inner parts of the forest. Consequently, the roadside area may have a low potential for microbial respiration. Logging operations have large impacts on soil physical and chemical properties because of soil compaction and reduced canopy cover (Pritchett and Fisher 1987). Also, it is well known that soil nutrients are lost during logging operations. Some studies have shown that land-use change causes alteration of microbial communities (Borueman and Triplett 1997, Fraterrigo et al. 2006).

Through the above discussion of the results of the study, we address the possibility that a low potential for heterotrophic respiration at roadside areas offsets the effect of high soil temperature on soil respiration. The potential for root respiration may also be low in roadside soils as a result of the lower root biomass at the roadside compared with the inner part of the forest because roadside soils are located right besides logging roads that lack vegetation. Consequently, low root respiration in roadside soils may offset the effect of high soil temperature. Root biomass of roadside soils and that of soils from the inner part of the forest should be compared to further examine this relationship.

**CONCLUSION**

In an upper tropical hill forest in Peninsular Malaysia, spatial variation in soil respiration was revealed to be affected not by soil water content but by soil temperature; this trend is different from that reported in previous studies conducted in lowland tropical forests, though the soil respiration values are in the range of those of previous studies conducted in lowland tropical rain forests in Peninsular Malaysia. This study demonstrated that soil respiration on the logging road was almost zero, and soil respiration did not vary between the roadside and the inner part of the forest. A spatial gradient of soil respiration from the logging road to the inner part of the forest was not observed.

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