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SOIL CO_2 EFFLUX IN RELATION TO SOIL TEMPERATURE AND RELATIVE HUMIDITY IN GMELINA, MAHOGANY AND PINE STANDS IN MALAYSIA

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Soil CO_2 efflux in mature plots of *Gmelina arborea* and *Swietenia macrophylla* (exotic broad-leaved trees) and *Pinus caribaea* (exotic conifer) was measured monthly in relation to soil temperature, air temperature and relative humidity from January till March 2016. Soil bulk density, pH, total C, total N and soil organic C were also measured at 0–15 and 15–30 cm depths. Soil CO_2 efflux was significantly different between plots: gmelina > mahogany > pine (0.76 ± 0.04, 0.49 ± 0.02 and 0.40 ± 0.01 g CO_2 m^{-2} h^{-1} respectively). Regression analysis revealed significant positive correlation of soil CO_2 efflux with soil temperature in the gmelina plot but no correlation with soil relative humidity in all three plots. Significant negative correlation was found between soil CO_2 efflux and soil temperature in the pine plot, which indicated the influence of other factors on soil CO_2 efflux in that plot. Monthly variations in soil relative humidity and soil properties of gmelina and pine plots were examined for possible influences on soil CO_2 efflux and temperature sensitivity (Q_{10}). Q_{10} of soil CO_2 efflux in the gmelina plot (1.19) was far higher than in the mahogany and pine plots (0.79 and 0.70 respectively).

Keywords: Climate change, environment, landuse, soil respiration, broad-leaved forest, coniferous forest, tropical forest

INTRODUCTION

Forest plantations, which are expanding worldwide and particularly in the tropics, serve many functions, e.g. supplying wood and non-wood forest products, as carbon (C) sinks to offset C emissions and rehabilitating degraded lands (FAO 2003). In Malaysia, selected exotic tree species were planted in 1980s under the Compensatory Forest Plantation Project to meet critical timber shortages and rehabilitate degraded lands (Krishnapillay & Appanah 2002). While tree species selection for plantation forest is generally based on growth performance and profitability, C sequestration rates and ability to remediate degraded soils could also be considered (Gahagan et al. 2015).

Soil respiration, closely related to forest productivity, C sequestration and soil fertility, is one of the largest C fluxes of CO_2 to the atmosphere (Raich & Schlesinger 1992). Soil respiration is a key indicator of soil health and quality and is primarily influenced by soil temperature and soil moisture, and other factors such as soil microbial activity, soil physical and chemical properties and types of vegetation (Raich & Tufekcioglu 2000). For example, compared with coniferous forests, soil respiration is greater in broad-leaved forests (Wang et al. 2006), which also produce more leaf litter (with lower carbon:nitrogen (C:N) ratio and faster nutrient turnover) than coniferous forests (Liu et al. 2016).

Only a handful of studies in Malaysia have investigated soil respiration in forests, and oil palm and rubber plantations and there is little available information for exotic forest plantations. Soil CO_2 efflux has been reported by Adachi et al. (2005, 2006) for primary and secondary forests and oil palm plantation adjacent to the Pasoh Forest Reserve in Negeri Sembilan. Soil CO_2 efflux was reported for primary and secondary forests, and rubber and oil palm plantations in Pasoh (Mande et al. 2014a) and a primary mixed-dipterocarp forest in Sungai Menyala Forest Reserve, Negeri Sembilan (Mande et al.

2014b). Soil CO_2 efflux has also been reported for 8-month-old plantings of *Jatropha curcas* and uncultivated idle land overgrown with wild shrubs (Firdaus & Husni 2012).

In view of the lack of information available for soil respiration in forest plantations in Malaysia, the objectives of our study were to determine if soil CO_2 efflux differed for three exotic plantation species, namely, two broad-leaved tree species, *Gmelina arborea* (gmelina) and *Swietenia macrophylla* (mahogany), and a needle-leaved conifer tree species, *Pinus caribaea* (pine), and examine the role of soil temperature and soil relative humidity on soil CO_2 efflux in the three tree species.

MATERIALS AND METHODS

Study site

The study was carried out in gmelina, mahogany and pine experimental plots located at the Institute of Bioscience (2° 59' N, 101° 43' E), Universiti Putra Malaysia, Serdang, Selangor. The three adjacent plots were previously planted to rehabilitate degraded pasture land (Malik et al. 2015). The gmelina and mahogany plots were on gently undulating terrain (62–70 m asl) while the pine plot, gentle slope (~10°, 60–87 m asl). Mean annual temperature and rainfall are 27 °C and 2201 mm respectively (Malik et al. 2015). The Serdang soil series is classified as Haplic Nitisols (FAO 2006). The study was carried out the middle of the north-east monsoon season from January till March 2016. Rainfall was 258.5 mm in December 2015 (the month before the study began) and the area received 158.3, 53.5 and 89.5 mm in the study months of January, February and March respectively.

Initial planting density was 1111 trees ha^{-1} for gmelina and mahogany (each area 0.22 ha, in 1988), and 1736 trees ha^{-1} for pine (2.14 ha, 1982). The survival rates in 2016 for gmelina, mahogany and pine were 22, 63 and 53% respectively (Table 1). Mortality rates were high because the plots were abandoned after planting. In the gmelina plot, mature trees of *Artocarpus elasticus* (inter-planted later), *Macaranga* spp. and rubber (*Hevea brasiliensis*) were present—the last likely volunteers from a former close by rubber plantation. Leaf litter was dense in the gmelina plot. Understorey species, in particular ferns as high as 1 m, were abundant in the pine plot. In the mahogany plot, litterfall was average, with grass cover and sparse undergrowth.

Experimental design

A 45-m line transect was established through the gmelina and mahogany plots, while a 160-m transect was established through the pine plot. The gmelina and mahogany transects had eight sampling points, 5 m apart. For the pine transect, the sampling points were set increasingly further apart from down to upslope—points 1–3 were 15 m apart, points 4–6 were 20 m apart and points 7 and 8 were set 30 m apart. The transects bisected the plots with sampling points that represented the topographic microclimatic variation of those plots.

Measurement of soil CO_2 efflux and environmental factors

Soil CO_2 efflux (g CO_2 m^{-2} h^{-1}) was measured using automatic soil CO_2 flux system connected to an infrared gas analyser. Six soil collars (10 cm high and 20 cm in diameter) were utilised

Table 1 Stand characteristics of the gmelina, mahogany and pine plots

Tree species	Surviving trees			DBH (cm)		Height (m)		Crown width (m)
	Year 1	1999	2016	1999	2016	1999	2016	2016
Gmelina arborea	244	200	54	17.2	21.2 ± 1.9	16.5	20.3 ± 0.6	5.1 ± 0.39
Swietenia macrophylla	244	191	154	19.1	30.1 ± 1.4	17.1	21.3 ± 0.4	7.2 ± 0.32
Pinus caribaea	3715	2444	1965	24.1	34.8 ± 1.2	21	23.4 ± 0.2	6.0 ± 0.36

Values for 2016 are from this study and are reported as means ± standard errors; DBH = diameter breast height; tree data for 1999 are from Rishzuan (1999)

throughout the data collection. Soil collars were installed into the soil to a depth of about 8 cm at each sampling point 2 weeks before soil respiration measurements were taken to allow the soil to stabilise after disturbance. All surface litter was removed from within the soil collar and 1 m around the collar. Measurements were taken in triplicate at each sampling point and soil CO_2 efflux was recorded for 2 min every hour between 10 a.m. and 2 p.m.

Soil temperature and soil relative humidity at 8 cm soil depth were measured concomitantly next to the collar using two probes connected to the gas analyser recorder. All measurements were taken in triplicate. Air temperature and relative humidity were recorded hourly throughout the study period using data logger weather station placed within 50 m of the study sites.

Soil sampling was conducted to determine soil pH, bulk density, total C, total N and soil organic carbon (SOC). Using a 10-cm soil auger, three samples were collected randomly from each plot to yield composite samples of soil at 0–15 and 15–30 cm depths. The soil samples were then air dried for three days, ground, sieved through a 2-mm sieve and stored in sealed plastic bags before further laboratory analysis. SOC was determined using a conversion factor of 1.72 where organic matter was assumed to contain 58% organic C using the following equation:

$$\text{Organic matter (\%)} = \text{Total organic C (\%)} \times 1.72 \quad (1)$$

Total C and N concentrations were measured using a CN-element analyser. Soil pH was determined in salt solution 1:2.5 dilution of potassium chloride. Bulk density was determined using the soil analysis standard method.

$$\text{Bulk density (g cm}^{-3}) = M_d / V \quad (2)$$

where, M_d = mass of dry soil sample (g) and V = soil volume (cm^3).

Statistical analysis

All statistical analyses were conducted using SPSS software version 23. Data normality and homoscedasticity were tested with the Kolmogorov–Smirnov and Levene's tests respectively and no significant deviations from normality or homoscedasticity were found. One-way ANOVA and Tukey's honestly significant tests were used to examine the effects of season and plot on soil CO_2 efflux, soil temperature and soil moisture, with $p < 0.05$ being significant. To examine soil CO_2 efflux–soil temperature relations, regression analysis was conducted using a classic parametric exponential model (Lloyd & Taylor 1994):

$$\text{Soil } CO_2 \text{ efflux} = \alpha e^{\beta T} \quad (3)$$

where, T = soil temperature (°C) at 8 cm depth, and α and β = regression coefficients. The temperature sensitivity of soil respiration on soil temperature, expressed as Q_{10}, was the difference in respiration rates over a 10 °C interval, and calculated according to the following equation (Boone et al. 1998):

$$Q_{10} = e^{10\beta} \quad (4)$$

A polynomial function model (Tang et al. 2005) was used to describe the relationship between soil CO_2 efflux and soil relative humidity:

$$\text{Soil } CO_2 \text{ efflux} = \alpha_1 RH + \beta_1 RH + c \quad (5)$$

where, RH = soil relative humidity and α_1, β_1 and c are the fitted parameters.

RESULTS

Over the study period, soil CO_2 efflux in the gmelina plot (0.76 ± 0.04 g CO_2 m^{-2} h^{-1}) was significantly higher ($F = 62.35$, df = 2, 69, $p < 0.001$) than in the mahogany plot (0.49 ± 0.02 g CO_2 m^{-2} h^{-1}), which also was significantly higher than in the pine plot (0.40 ± 0.01 g CO_2 m^{-2} h^{-1}) (Figure 1). Soil temperature followed similar decreasing trend from gmelina plot (30.3 ± 0.4 °C) to mahogany (29.69 ± 0.7 °C) and pine (29.51 ± 0.8 °C) plots but the differences were not significant. Soil relative humidity was highest at the pine plot (85.3 ± 3.4%) and it was significantly higher than in the mahogany plot (77.1 ± 3.8 %), but not different compared with the gmelina plot (80.0 ± 2.3 %). Of the three plots, the mahogany plot had the lowest air temperature (31.8 ± 0.3 °C) and highest air relative humidity (49.8 ± 1.4 °C), but these differences were not significant.

Significant exponential relationships were found between soil CO_2 efflux and soil temperature in all three plots (Figure 2). The

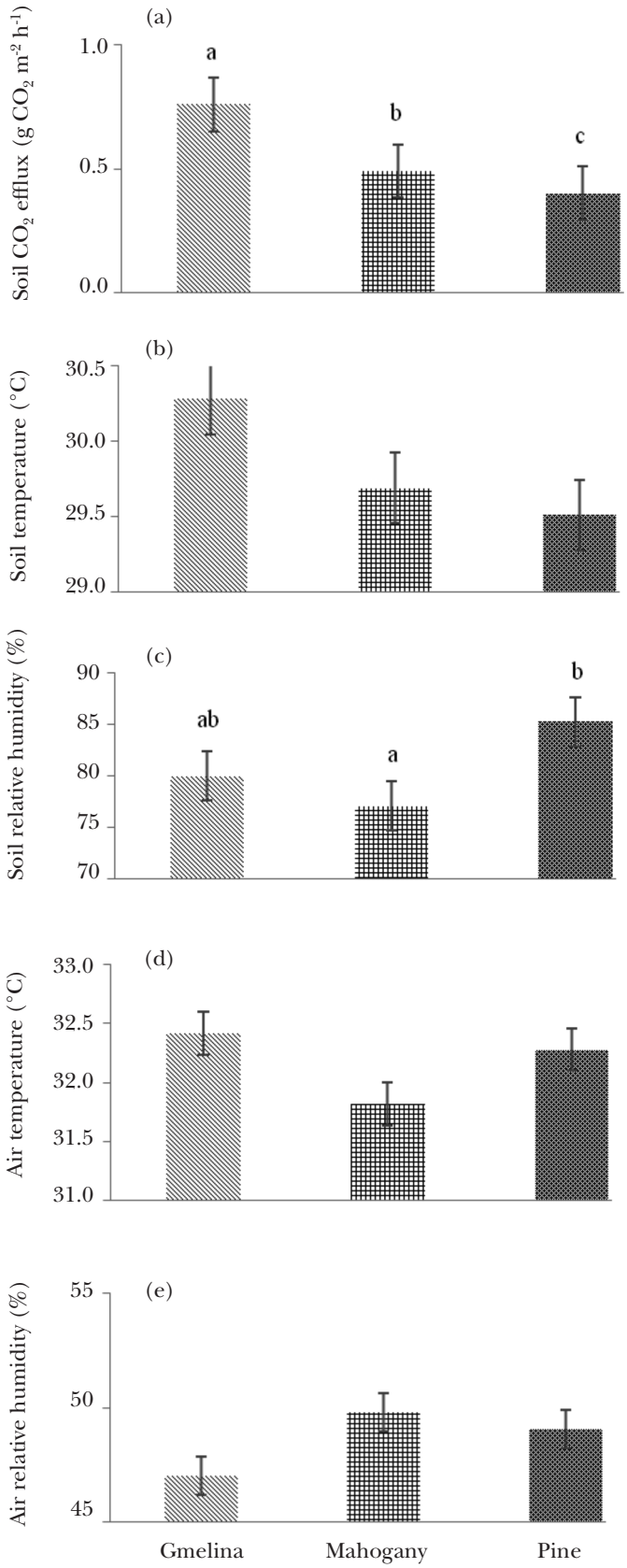

Figure 1 Mean values (± standard errors) across the study period of (a) soil CO_2 efflux, (b) soil temperature, (c) soil relative humidity, (d) air temperature and (e) air relative humidity for gmelina, mahogany and pine study plots; different letters indicate significant differences between tree species

correlation was positive in the gmelina plot and negative in the mahogany and pine plots, but a poor fit for mahogany (r^2 = 0.63). Q_{10} of soil respiration was greatest in the gmelina plot (1.19), followed by mahogany (0.78) and pine (0.70) plots. No significant correlation between soil CO_2 efflux and soil relative humidity was observed in the three plots. Polynomial relationship between soil CO_2 efflux and soil relative humidity was negative in gmelina and positive in mahogany and pine plots.

At 0–15 depth, SOC was greatest in the pine plot followed by the mahogany and gmelina plots (Table 2). Total C at 0–15 cm increased

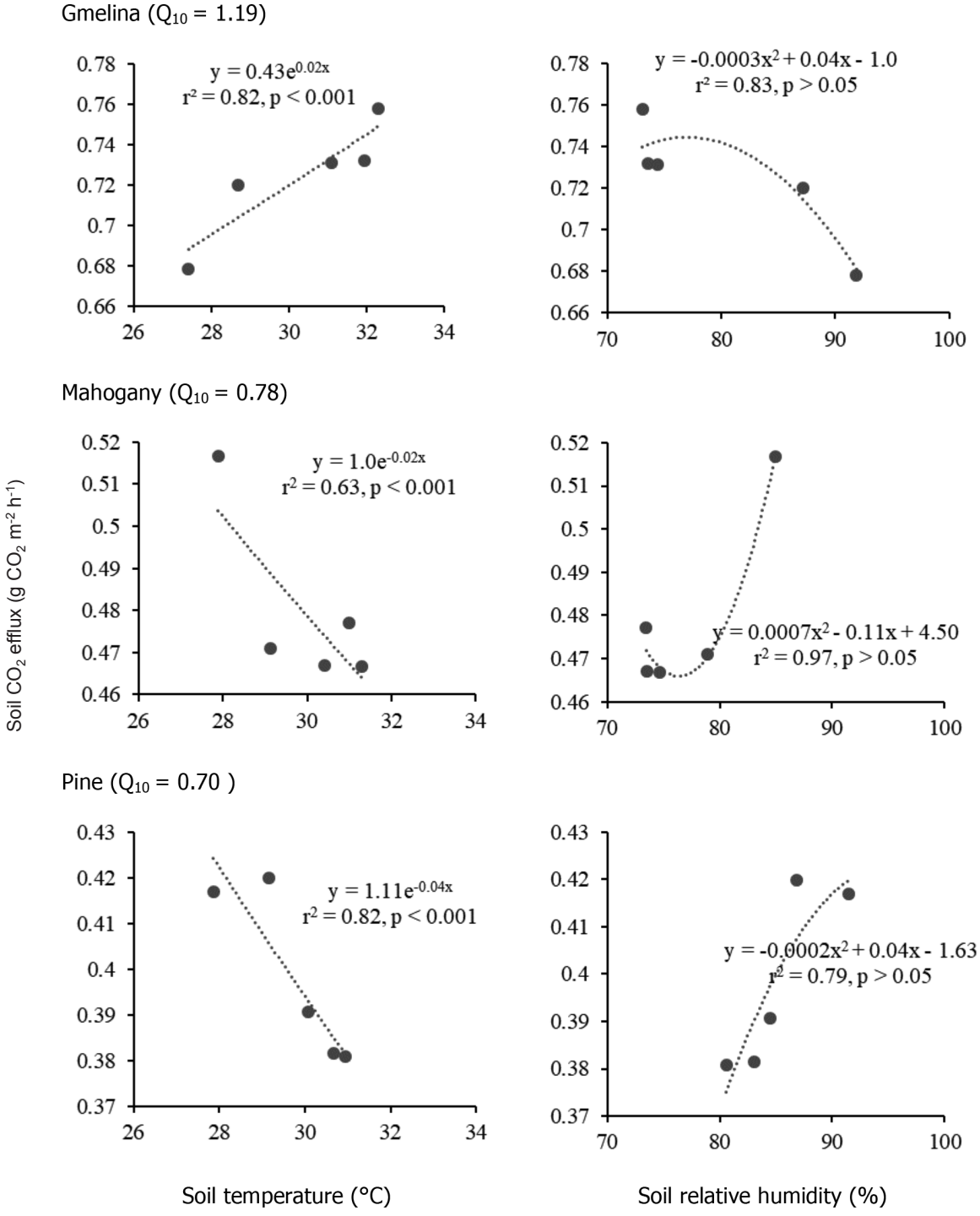

Figure 2 Relationship between soil CO_2 efflux and soil temperature and soil relative humidity at the three study plots

with increased SOC (from gmelina to mahogany and pine). Across all three plots, SOC and total C showed sharp decrease from 0–15 to 15–30 cm depths (Table 2). Total N decreased from 0–15 to 15–30 cm in the gmelina plot, but increased in the mahogany and pine plots. Soil pH and bulk density only increased slightly from the 0–15 to 15–30 cm depths for all plots except the former decreased slightly in the pine plot.

Significant monthly variation in soil CO_2 efflux was observed in gmelina ($F = 54.46$, $df = 2,21$, $p < 0.001$) and pine ($F = 15.74$, $df = 2,21$, $p < 0.001$) plots but not for mahogany ($F = 0.94$, $df = 2,21$, $p > 0.05$; Figure 3) plot. For gmelina plot, soil CO_2 efflux increased significantly from January to February and March (0.54 ± 0.01, 0.81 ± 0.04 and 0.92 ± 0.02 g CO_2 m^{-2} h^{-1} respectively). Soil temperature in the gmelina plot was significantly higher in March than in January and February, similar to the drop in air temperature and air relative humidity in those months. While soil temperature variation in the gmelina plot followed the monthly changes in air temperature and air relative humidity, the opposite was observed for soil relative humidity. Soil CO_2 efflux in the pine plot showed significant decrease from January to February and March (0.46 ± 0.02, 0.40 ± 0.02 and 0.34 ± 0.01 g CO_2 m^{-2} h^{-1} respectively). The drop in soil CO_2 efflux in the pine plot from January to February reflected the decrease in soil temperature and air temperature, and corresponding increase in soil relative humidity and air relative humidity for those months. However, continued decline in soil CO_2 efflux in the pine plot in March as soil and air temperatures rose significantly was notable. In the mahogany plot, soil CO_2 efflux remained constant throughout the study months as reflected in the relatively stable soil and air temperatures, and soil relative humidity and air relative humidity recorded in that plot.

DISCUSSION

The soil CO_2 efflux values for gmelina (0.76 g CO_2 m^{-2} h^{-1}) were at the lower end of soil CO_2 efflux values reported for forests in Malaysia, and the 0.40 and 0.49 g CO_2 m^{-2} h^{-1} for pine and mahogany plots were far lower. Adachi et al. (2006) reported soil CO_2 efflux rates of 0.71, 0.95 and 0.97 g CO_2 m^{-2} h^{-1} for secondary forest, primary forest and oil palm plantation respectively, while Mande et al. (2014a) reported values of 0.85, 0.81, 0.52 and 0.74 g CO_2 m^{-2} h^{-1} for secondary forest, primary forest, oil palm plantation and rubber plantation respectively. Soil CO_2 efflux rates for pine and mahogany plots were in the bottom of the range of values (0.45–2.47 g CO_2 m^{-2} h^{-1}) reported for uncultivated land overgrown with wild shrubs (Firdaus & Husni 2012).

In the present study, higher soil CO_2 efflux rates in the mahogany and gmelina plots compared with the pine plot, concurred with previous reports on broad-leaved forests having higher soil respiration rates than coniferous forests (e.g. Raich & Tufekcioglu 2000). Vegetation type can influence soil CO_2 efflux by indirectly affecting

Table 2 Soil parameters (0–15 and 15–30 cm depths) for the three study plots

Parameter	Soil depth (cm)	Plot mean value (± SE) of parameter			p-value
		Gmelina arborea	*Swietenia macrophylla*	*Pinus caribaea*	
BD (g cm^{-3})	0–15	1.62 ± 0.01 a	1.62 ± 0.00 a	1.66 ± 0.00 b	< 0.01
	15–30	1.63 ± 0.01 a	1.67 ± 0.02 b	1.74 ± 0.01 c	< 0.001
pH	0–15	4.67 ± 0.20 a	4.65 ± 0.28 a	4.81 ± 0.06 a	ns
	15–30	4.92 ± 0.04 a	4.93 ± 0.03 a	4.76 ± 0.05 b	< 0.01
Total C (%)	0–15	2.91 ± 0.10 a	3.19 ± 0.07 b	3.31 ± 0.08 b	< 0.01
	15–30	1.67 ± 0.11 a	2.32 ± 0.09 b	1.28 ± 0.05 c	< 0.001
Total N (%)	0–15	0.26 ± 0.05 a	0.22 ± 0.22 a	0.19 ± 0.19 a	ns
	15–30	0.14 ± 0.01 a	1.59 ± 0.04 b	0.85 ± 0.63 ab	< 0.01
SOC (kg C m^{-2})	0–15	11.80 ± 0.49 a	13.40 ± 0.07 b	14.40 ± 0.16 c	< 0.001
	15–30	7.40 ± 0.34 a	10.20 ± 0.31 b	5.80 ± 0.29 c	< 0.001

Within-row values with different letters indicate significant differences (Tukey's HSD); BD = bulk density, SOC = soil organic carbon, ns = not significant, SE = standard error

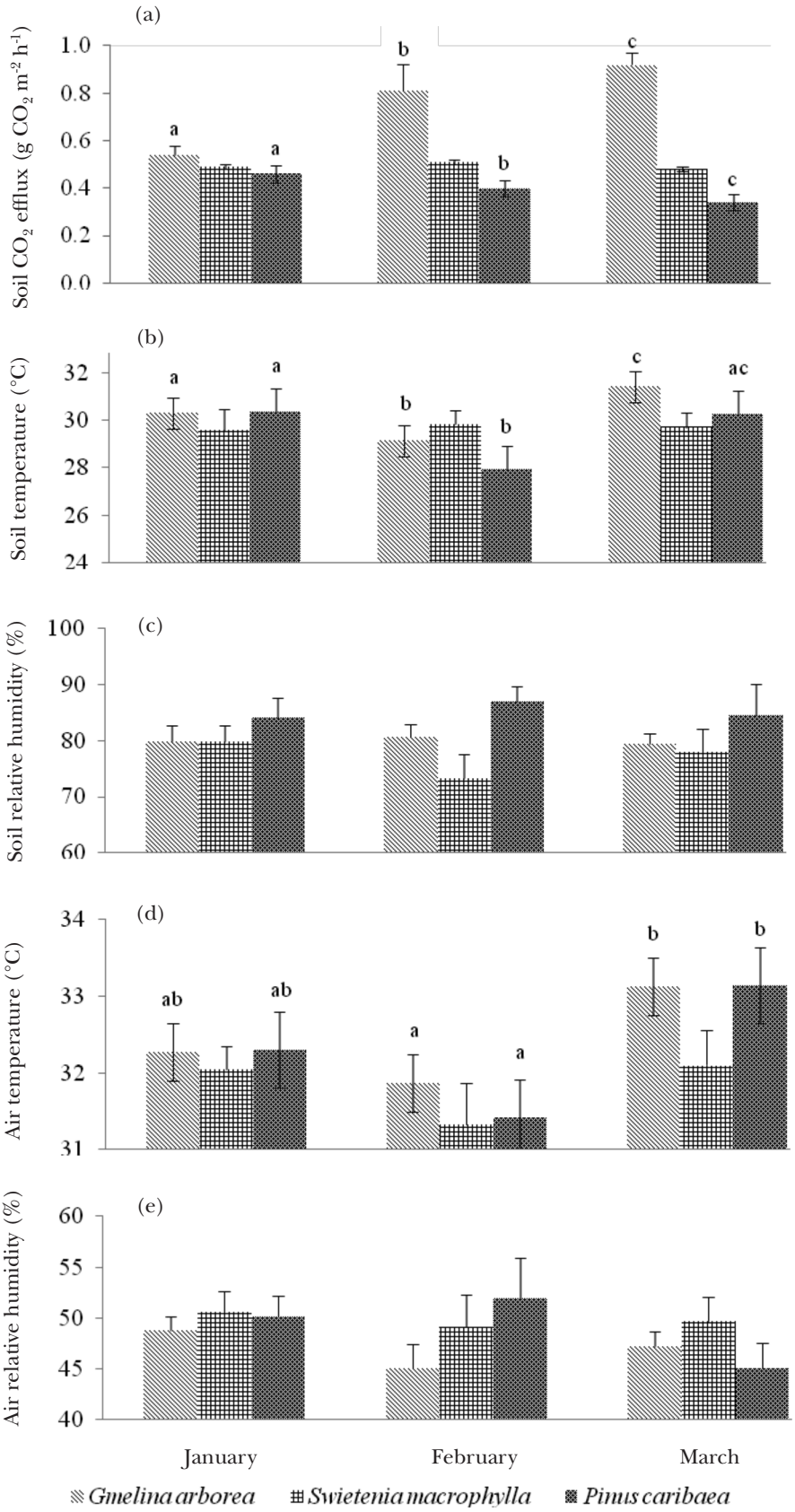

Figure 3 Mean monthly values (± Standard errors) of (a) soil CO_2 efflux, (b) soil temperature, (c) soil relative humidity, (d) air temperature and (e) air relative humidity, for the three study plots; different letters indicate significant differences between months for the tree species ($p < 0.01$)

soil microclimate and structure, litterfall quality and quantity and root respiration (Yan et al. 2013). The higher soil respiration rate in broad-leaved forests is partly because litterfall quality is better than that of coniferous forests (Tewary et al. 1982). Litterfall in broad-leaved forests decomposes faster than in coniferous forests (Wang et al. 2006) because of the higher N and lower lignin content of the former (Kara et al. 2016).

In the present study, regression analysis revealed that soil temperature, and not soil moisture, significantly influenced soil CO_2 efflux in the three plots. Similar results have been reported for subtropical forest types in China (Kim et al. 2010, Yan et al. 2014) and the Sungai Menyala Forest in Malaysia (Mande et al. 2014b). However, soil moisture, and not soil temperature, influenced soil respiration in vegetation types in Pasoh, Malaysia (Adachi et al. 2006). In general, soil temperature and soil moisture are the most important environmental factors controlling soil respiration, and these factors interact to affect the rates of decomposition of soil organic matter and soil respiration (Luo et al. 2012). In tropical forests where soil temperature is relatively constant, soil water content or rainfall is considered the most influential factor affecting soil respiration (Kursar 1989). The positive correlation of soil CO_2 efflux with soil temperature in the gmelina plot meant that soil CO_2 efflux increased with soil temperature. The negative correlation observed in the pine plot indicated interaction with another factor (or factors).

Variability (monthly and between plots) observed in other factors was examined to help explain the negative correlation between soil CO_2 and soil temperature in the pine plot. The drop in soil CO_2 efflux in March even as soil temperature rose that month could have contributed to the negative correlation. Although soil relative humidity did not influence soil CO_2 efflux (Figure 3), soil relative humidity was higher in the pine plot (85%, Figure 2) and might have lowered soil CO_2 efflux (Wood et al. 2013). The very low Q_{10} of soil CO_2 efflux in the pine plot (0.70) could have been influenced by high soil relative humidity, as Q_{10} declined when soils were very dry or very wet (Gritsch et al. 2015). While Q_{10} for the gmelina plot (1.19) was within the range reported previously for a teak plantation (Wangluk et al. 2013), Q_{10} values for the mahogany (0.79) and pine (0.70) plots were far below that reported previously for global terrestrial ecosystems (1.3–5.6) (Lenton & Huntingford 2003).

Litterfall was observed deeper at the gmelina plot than at the pine plot, but SOC (at 0–15 cm) was significantly higher in the pine plot (Table 2). Total C was higher and total N was lower in the pine plot, reflecting the lower quality litterfall typically produced by conifers (Gilliam 1991), while soil bulk density was significantly greater. In a temperate forests in China, many such environmental factors affected soil respiration and Q_{10}, with 51% of the variation explained by the soil pH, diameter at breast height and the coefficients of variation of soil bulk density, total N and soil pH (Zhou et al. 2013). The influence of these variables on soil CO_2 efflux and Q_{10} in broad-leaved and coniferous forests needs further investigation.

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