



# Soil respiration in a natural forest and a plantation during a dry period in the Philippines

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**Abstract** Climate change is forecast to increase the frequency of extreme hot temperatures and dryer days and is anticipated to have profound impacts on the global carbon budget. Droughts are expected to alter soil respiration ( $R_s$ ) rates, but the scarcity of data preclude a reliable estimate of this response and its future trajectory. A field experiment using an automated soil respiration machinery (LI-8100A) was conducted in a natural forest and a plantation during a dry period in the Philippines, with the goal of quantifying  $R_s$  rates and their relationship with soil temperature and moisture, and air temperature. The natural forest ( $5.81 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) exhibited significantly higher  $R_s$  rates ( $p < 0.0001$ ) compared with the plantation ( $1.82 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) and control ( $3.23 \mu\text{mol m}^{-2} \text{s}^{-1}$ ).  $R_s$  rates showed significant negative relationships with air ( $-0.71$ ) and soil temperatures ( $-0.62$ ), indicating that as temperatures increase, the  $R_s$  rates decrease. In contrast, the  $R_s$  rates exhibited a significant positive relationship with soil moisture ( $0.65$ ). Although the low  $R_s$  rates in the plantation and high  $R_s$  rates in the natural forest are indicators of sensitivities of these two types of tropical forests to warm,

dry soil, this observation is only conclusive during the dry period, but not necessarily during wet periods. Further studies are needed to determine the trend of  $R_s$  rates during wet periods, considering different site conditions and types of vegetation.

**Keywords** Climate change · Carbon · Air and soil temperatures · Soil moisture · Tropical stands

## Introduction

Climate change is a challenging environmental issue resulting from increasing concentrations of atmospheric greenhouse gases (GHG), particularly carbon dioxide ( $\text{CO}_2$ ). It is predicted that tropical forests will experience major changes in this century due to climate changes, thus affecting above- and belowground carbon pools (Zuidema et al. 2013). One of the measures promoted by the Intergovernmental Panel on Climate Change (IPCC) to mitigate climate change impacts is through carbon sequestration in terrestrial vegetation (IPCC 2001), where green plants utilize  $\text{CO}_2$  from the atmosphere through photosynthesis. The assimilated carbon is stored in above- and belowground biomass and soil until released back into the atmosphere through decomposition or burning (Houghton 2005; Justine et al. 2015). In the Philippines, among the strategies to mitigate the impacts of climate change include forest conservation, preservation, protection, and rehabilitation programs, resulting in the conservation and protection of about 4.6 million natural forests and 2.4 million hectares of plantations (DENR-FMB 2020). These stands could potentially sequester 0.7 Pg to 1.7 Pg C, assuming weighted C density of  $99 \text{ Mg ha}^{-1}$  to  $174 \text{ Mg ha}^{-1}$  for tropical forests (Dixon et al. 1994).

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It has been accepted that climate change is amplifying the hydrological cycle and is anticipated to increase the frequency of extreme wet and dry periods (Knapp et al. 2015). In the Philippines, it has been forecast an increased frequency of extreme hot temperatures and dryer periods over the next three decades, particularly during summer periods (DOST-PAGASA 2011; Salvacion 2021). Long dry periods could introduce profound effects, not only on biodiversity (Ifo et al. 2016; Raven et al. 2020), but also on global CO<sub>2</sub> fluxes due to reduced C sequestration capacity of forests (IPCC 2001; Lewis 2006; Pan et al. 2011; Cui et al. 2020) and increased ecosystem respiration (Cox et al. 2000; Peng et al. 2015), thus, providing positive feed backs to climate change (Dixon et al. 1994; Ifo et al. 2016; FAO and UNEP 2020). Among the most seriously threatened terrestrial ecosystems by lengthy periods of drought are tropical forests, considered the richest forest ecosystems and comprising about 1.52 billion hectares of the world forests (Dixon et al. 1994; FAO and UNEP 2020). The 40% estimated share of tropical forests to global terrestrial carbon (C) stocks (Cui et al. 2020; Pan et al. 2011) will be degraded by drought due to increased tree mortality (IPCC 2001; Lewis 2006) and high ecosystem respiration rates, indicating rapid release of stored C and decomposition rates of soil organic matter. While several studies support the idea that global warming results in profound changes in precipitation patterns (IPCC 2001; Dore 2005; Berg and Sheffield 2018), and thus feed backs to global C budgets, considerable uncertainties remain on CO<sub>2</sub> fluxes during dry periods, and therefore confusion on its current and future trajectory. Much of this is due to scarcity of data on total ecosystem respiration, a major component in the global C budget.

Ecosystem respiration is a major pathway in carbon cycling in which the sequestered C is naturally returned back to the atmosphere and is largely driven by temperature and moisture regimes (Gordon et al. 1987). A large proportion of the ecosystem respiration is composed of soil respiration (R<sub>s</sub>), about 30% to 80% (Janssens et al. 2001; Bond-Lamberty et al. 2004; Cisneros-Dozal et al. 2006; Davidson et al. 2006). As a result of this large contribution, the R<sub>s</sub> is a good indicator of global carbon cycle changes (Bae et al. 2013; Hashimoto et al. 2004) and climate change impacts. Some researchers reported that increased temperature and moisture stress result in a large contribution of R<sub>s</sub> to the atmospheric CO<sub>2</sub> because of greater root and microbial activities (Wood et al. 2013; Raich and Schlesinger 1992; Adachi et al. 2005; Cui et al. 2020). Therefore, insights into R<sub>s</sub> rates during dryer periods will provide valuable information about the role of forests in mitigating the buildup of CO<sub>2</sub> in the atmosphere (Ohashi et al. 2007; Bréchet et al. 2009).

However, despite the steady increase in R<sub>s</sub> and carbon budget studies in recent decades, particularly in temperate countries (Bréchet et al. 2009), the amount and variability

of R<sub>s</sub> rates and their relationship with the site and vegetation in tropical forests are still unclear. This knowledge gap precluded a reliable estimate of C budgets and projection of the R<sub>s</sub> trajectory in these tropical ecosystems, particularly during the dry season. In the Philippines, the limited R<sub>s</sub> data for different types of forest ecosystems is a major barrier that prevents researchers from generating reliable C budget estimates (Lasco and Pulhin 2003; Lasco et al. 2005; Racelis et al. 2008) and to understand forest-level carbon exchange and dynamics that could be used by policymakers to develop environmental policies and management options for mitigating climate change impacts. This study aims to quantify R<sub>s</sub> rates during one dry period in an old-growth forest and young plantation of fast-growing tree species, and to determine the relationship among R<sub>s</sub>, air and soil temperatures, and soil moisture. It is hypothesized that R<sub>s</sub> rates between the natural forest and the plantation during the dry period would not be significantly different. This is because, during the dry period, autotrophic and heterotrophic respiration decrease dramatically, regardless of type of vegetation and site conditions, due to soil moisture stress and high temperatures, the main controlling factors of R<sub>s</sub> rates. Understanding the relationships between R<sub>s</sub> and environmental factors under different climate change scenarios are important for predicting the direction of change in C stocks (Adachi et al. 2005; Cui et al. 2020), and for guiding the design and implementation of mitigation policies to address the projected atmospheric CO<sub>2</sub> increase (Pan et al. 2011). If the data used in policy formulation are not technically feasible and science-based, the resulting regulatory strategies will be uncertain and ineffective, which would be costly to the public, regulated industries and economic sectors, and to the environment (Braatz and Doom 2005).

## Materials and methods

### Site location and characteristics

The study was conducted in two types of tropical forests: an old growth natural stand dominated by white lauan (*Shorea contorta* S. Vidal) and a young plantation of fast-growing species consisting of falcata (*Paraserianthes falcataria* (L) Nielsen), mangium (*Acacia mangium* Willd.) and large-leaf mahogany (*Swietenia macrohylla* King). The natural forest is at Mindanao State University (MSU), Marawi City (8° 00' 12" N, 124° 17' 12" E) while the plantation is at the National Power Electric Corporation in Ditucalan, Iligan City (8° 10' 12.70" N and 124° 1' 55.87" E). Soils in both sites are highly weathered, with a silty clay loam texture, and high organic matter contents in the surface layers. Precipitation and temperatures are more or less homogenous, with the natural forest having an average monthly precipitation from 144 to

500 mm and temperatures from 18 °C to 28 °C. Precipitation for the plantation is 173 mm to 473 mm and temperatures from 22 °C to 29 °C. The climate, under the Köppen system of climate classification, is a sub-humid tropical climate with March and April as dry periods, and is classified as Af (i.e., based on the coolest month with temperatures greater than 18 °C and constantly moist, and the driest month with a minimum 60 mm precipitation).

## Sampling method

### Experimental design

The experiment was a randomized complete block design (RCBD) with unbalanced replications, consisting of four and three replication plots for the natural forest and plantation, respectively. For each sampling plot, one point was established in the open area within the borders of each site to serve as a control. In all replicate plots, soil collars (9.9 cm inside dia. × 8.9 cm ht.) were inserted into the soil to a 7-cm depth, leaving a 2-cm above the soil surface. The installation of the collars was done three days prior to the start of the  $R_s$  measurements to stabilize  $CO_2$  fluxes and avoid the effects of soil disturbance. Sixty-eight soil collars were installed in both sites, 32 collars for the natural forest (i.e., 8 collars/replicate × 4 replicates) and 36 for the plantation (12 collars/replicate × 3 replicates).

### Soil respiration ( $R_s$ ) measurements

A point sampling survey technique was employed to quantify  $R_s$  using an automated soil respiration machinery (LI-8100A, LiCor BioSciences) consisting of an analyzer control unit (LI8100A), a 10-cm survey chamber (LI-8100-102.), an auxiliary sensor (LI-8100-104), a temperature probe (6000-09TC Omega), and a moisture probe (GS1). The measurements were conducted successively from one soil sampling point to another between 10:00 to 16:00 h. Previous research on the spatial and temporal variability of  $R_s$  rates, which employed continuous unattended measurements in the field using the LI-8100A multiplexer system, revealed no significant differences in soil  $CO_2$  effluxes between 11:00 and 16:00 h during the April to June growing season (Pacaldo et al. 2014). During the measurements, the survey chamber was mounted into the soil collar, and the total observation length for each measurement was 5-min, including a 3-min measurement of  $R_s$  rates and a 2-min air purging time. The measurements of all sampling points were done successively from one soil collar to another for all 68 sampling points in the three sites; the natural forest, the plantation, and the control.  $R_s$  measurements were conducted every 10-day interval during the middle of the dry period (March and April).

## Statistical analysis and calculations

The  $R_s$  data ( $\mu\text{mol s}^{-1} \text{m}^{-2}$ ) were statistically analyzed using a general linear model (PROC GLM). The hypothesis of equal means of  $R_s$  in all treatments was assessed employing an analysis of variance (ANOVA). When the null hypothesis was rejected, a multiple-wise means comparison with a least square means (LS means) was used for means separation of the significant differences among treatment means. The relationships between  $R_s$  and soil temperature, air temperature, and soil moisture content were also analyzed using correlation analyses. A probability of  $P \leq 0.05$  was considered statistically significant. All analyses were performed using a SAS Statistical Package (SAS 9.2). The  $R_s$  values, expressed as a standard metric unit per month, were transformed to soil organic matter equivalent, using conversion factors of 0.54 (i.e., MW of C/MW of  $CO_2$  divided by 0.5, the assumed carbon content in dry matter weight) was used to convert soil  $CO_2$  efflux to soil organic matter equivalent, expressed in short ton (2000 lbs), and 0.9072 to convert short ton to metric ton (Mt) (1000 kgs equals 2204 lbs).

## Results

### Soil respiration in a natural forest and a plantation

The  $R_s$  rates in the natural forest ( $5.8 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) was about three times higher than in the plantation ( $1.8 \mu\text{mol m}^{-2} \text{s}^{-1}$ ), and about 1.8 times the control ( $3.2 \mu\text{mol m}^{-2} \text{s}^{-1}$ ). In terms of  $CO_2$  and C equivalents, these values are equal to  $6.0 \text{ Mt } CO_2 \text{ ha}^{-1} \text{ mo}^{-1}$  or equivalent to  $1.5 \text{ Mt C ha}^{-1} \text{ mo}^{-1}$  of organic soil C losses for the natural forest,  $1.88 \text{ Mt } CO_2 \text{ ha}^{-1} \text{ mo}^{-1}$  or equivalent to  $0.5 \text{ Mt C ha}^{-1} \text{ mo}^{-1}$  of organic soil C losses for the plantations, and  $3.24 \text{ Mt } CO_2 \text{ ha}^{-1} \text{ mo}^{-1}$  or equivalent to  $0.8 \text{ Mt C ha}^{-1} \text{ mo}^{-1}$  of organic soil C losses for the control. The  $R_s$  rates of the control is approximately 1.8 times lower than the  $R_s$  rates of the natural forest, but 1.7 times higher than the plantation. In contrast, the  $R_s$  rates of the plantation is about three times lower to the  $R_s$  rates of the natural forest and 1.7 times lower than the control (Table 1).

Statistical analyses revealed significant differences in the mean  $R_s$  rates among the two stand types ( $p < 0.0001$ ) and also varied among sites ( $p < 0.0001$ ) and significantly interact with site and forest sites ( $p = 0.0084$ ). However, the  $R_s$  rates did not show any significant variations with time ( $p = 0.4485$ ) and interaction with site (time × forest types) ( $p = 0.527$ ) (Table 2).

The natural forest had higher upper and lower ranges of  $R_s$  rates compared to the plantation and control. These ranged from 4.8 to  $6.0 \mu\text{mol m}^{-2} \text{s}^{-1}$  for the natural forest, 2.6 to  $3.5 \mu\text{mol m}^{-2} \text{s}^{-1}$  for the control, and 1.7 to  $2.1 \mu\text{mol m}^{-2} \text{s}^{-1}$

**Table 1** Average soil respiration ( $R_s$ ) of a natural forest ( $n=128$ ), a plantation ( $n=272$ ), and a control and the equivalent soil  $\text{CO}_2$  emissions, soil organic matter (SOM), and soil organic carbon (SOC) during the dry period

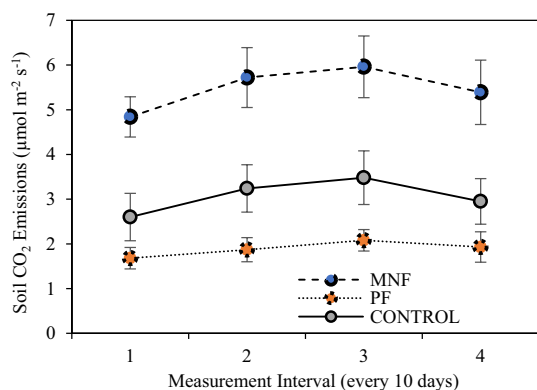
Forest types	Mean $R_s$ rates ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	Equivalent soil $\text{CO}_2^*$ ( $\text{Mt CO}_2 \text{ ha}^{-1} \text{ mo}^{-1}$ )	Equivalent SOM* ( $\text{Mt SOM ha}^{-1} \text{ mo}^{-1}$ )	Equivalent SOC* ( $\text{Mt C ha}^{-1} \text{ mo}^{-1}$ )
Natural	5.8***	6.0	3.0	1.5
Plantation	1.8***	1.9	0.9	0.5
Control	3.2***	3.3	1.6	0.8

\*Scaled up to monthly basis only

\*\*\*Highly significantly at 95% probability

**Table 2** Summary of treatment effects of stand types, time, and site and interaction effects on soil respiration ( $R_s$ )

Variable	df	MS	F-value	P value
Forest type*	2	45.34	16.75	<0.0001
Time	3	1.33	0.56	0.6445
Site	2	18.79	7.87	<0.0001
Time $\times$ forest type	6	0.96	0.40	0.8770
Site $\times$ forest type	5	7.61	3.19	0.0084
Site (time $\times$ forest type)	24	5.65	2.15	0.0148

\*Error term: site (time  $\times$  forest type)**Fig. 1** Comparison of soil respiration rates among the mixed natural forest (MNF), plantation forest (PF), and control showing the significant differences in the quantity of  $\text{CO}_2$  emitted

for the plantation. Although the  $R_s$  values are inconsistent during the measurements, statistical analyses did not detect significant variation of  $R_s$  rates over the duration of the study (Fig. 1, Table 1), suggesting that temporal variation is not significantly affecting  $R_s$  during the dry period.

### Soil respiration, air and soil temperatures, and soil moisture

Generally, soil temperatures (29 °C to 45 °C) are warmer than the air temperature (23 °C to 39 °C) during the dry

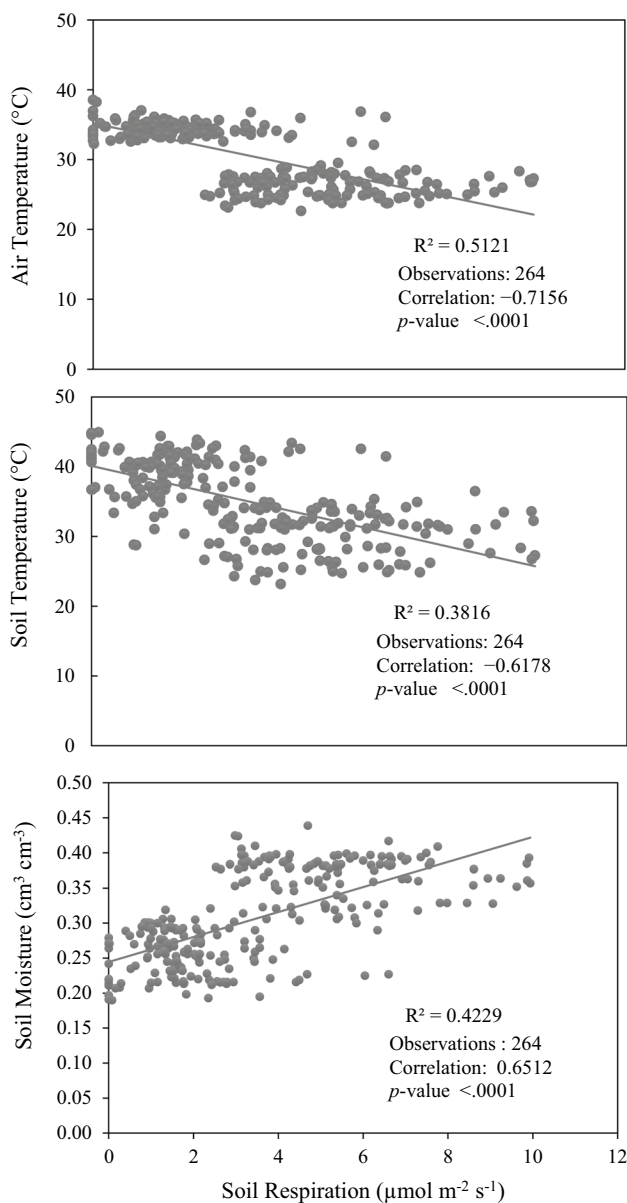
season. The  $R_s$  rate was significantly negatively correlated ( $p < 0.0001$ ) with air temperature ( $-0.71$ ) and soil temperature ( $-0.62$ ) (Fig. 2), suggesting that it tends to decrease at elevated air and soil temperatures. In contrast, the  $R_s$  rate had a positive relationship with soil moisture (0.65) (Fig. 2), suggesting that the  $R_s$  rate tends to increase or decrease with soil moisture. The natural forest had a higher volumetric soil moisture contents (0.30 to 0.37  $\text{cm}^3 \text{cm}^{-3}$ ) compared to the plantation (0.19 to 0.32  $\text{cm}^3 \text{cm}^{-3}$ ).

Soil moisture also negatively correlated with soil temperature ( $-0.81$ ) (Fig. 3), indicating that the soil moisture decreases with increasing soil temperatures. In contrast, soil and air temperatures were positively correlated (0.86) (Fig. 4), suggesting that air temperature, in which data are widely available in meteorological stations, could provide a good approximation of soil temperature, and therefore to predict  $R_s$  rate in cases of a paucity of soil temperature data.

## Discussion

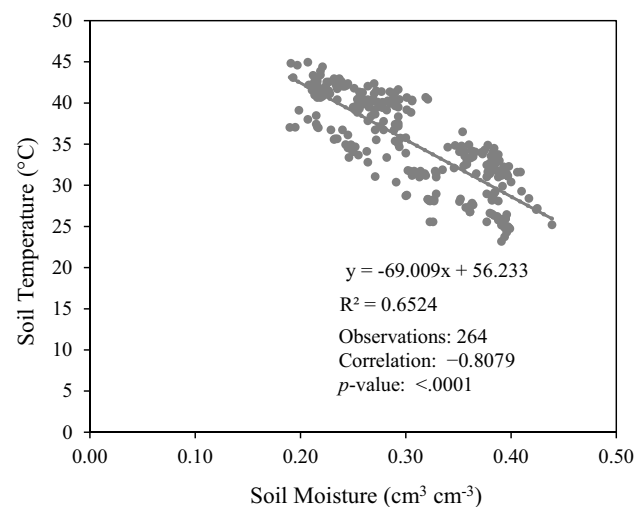
In the Philippines, the estimated area of remaining tropical forest is about 7 million hectares, comprising of 66% uneven-aged natural stands, and 34% plantations dominated by fast growing and commercially valuable species (DENR-FMB 2020). These two stand types could potentially sequester 0.70 Pg to 1.75 Pg C based on the weighted carbon densities for tropical forests (i.e., 99  $\text{Mg ha}^{-1}$  to 174  $\text{Mg ha}^{-1}$ ) (Dixon et al. 1994). However, the C stocks in these stands could be dramatically reduced due to the impacts of climate change, which have resulted in lengthy droughts in tropical regions, weakening carbon sequestration capacity with resulting feed backs to future climate changes (Corlett 2016).

The mean  $R_s$  of 5.8  $\mu\text{mol m}^{-2} \text{s}^{-1}$  in this study for the natural forest is consistent with the values in the literature. In a comparison study of the seasonal variation of  $R_s$  between a secondary forest and two agroforestry systems dominated by *Gmelina arborea* Roxb. and Dipterocarps (*Shorea* spp.) in the Philippines, Bae et al. (2013) reported  $R_s$  values from 4.8 to 5.1  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , with higher  $R_s$  during the dry season in the secondary forest compared to the agroforestry

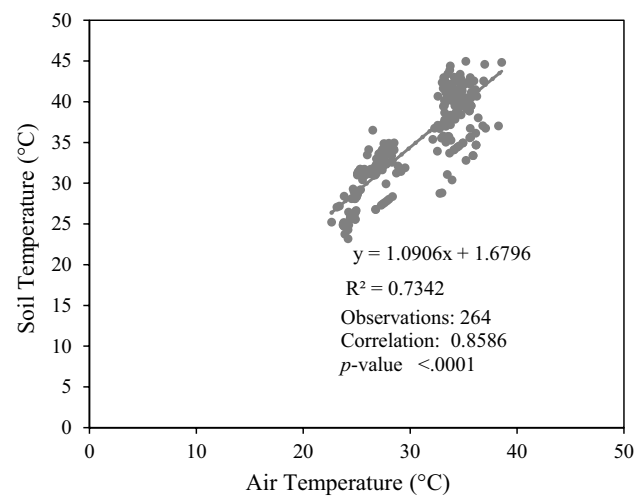


**Fig. 2** Soil respiration ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) as a function of air temperature, soil temperature, and soil moisture. The correlations show negative relationships of  $R_s$  rates with air and soil temperature, but positive with soil moisture

plots. Ohashi et al. (2007) also reported a range of  $R_s$  values from 4.6 to 5.3  $\mu\text{mol m}^{-2} \text{s}^{-1}$  for an intact Asian tropical rainforest with little temporal variation, but highly in space. In contrast, the 6.0 metric ton  $\text{ha}^{-1} \text{mo}^{-1}$  of  $\text{CO}_2$  or 1.5 Mt C  $\text{ha}^{-1} \text{mo}^{-1}$  of soil organic C in the natural forest (Table 1), is higher compared with the reported 14.8 t C  $\text{ha}^{-1} \text{a}^{-1}$  total ecosystem respiration rates in tropical forests (Malhi and Grace 2000) or approximately 0.74 t C  $\text{ha}^{-1} \text{mo}^{-1}$  (i.e.,  $14.8/12 \times 0.6$ ), assuming 60 percent  $R_s$  of total ecosystem respiration rates (Janssens et al. 2001; Lamberty et al. 2004; Cisneros-Dozal et al. 2006).



**Fig. 3** Relationship between soil temperature and soil moisture with best fit regression line, coefficient of determination ( $r^2$ ), correlation value, and significant level of correlations



**Fig. 4** Relationship between soil temperature and air temperature with best fit regression line, coefficient of determination ( $r^2$ ), correlation value, and significant level of correlations. The high coefficient of determination value ( $r^2=0.73$ ) suggests that near-surface air temperature provides a good approximation of the soil surface temperature

The high  $R_s$  in the natural forest could be associated with high microbial activities and root respiration (Adachi et al. 2005) due to total canopy closure and thick forest litter layer in the natural forest that prevents excessive soil evaporation during the dry period, hence creating favorable microenvironmental conditions for microbial activities and vegetation growth. Some researchers attribute the variations in  $R_s$  during droughts to the differences of types of vegetation and structure, to the differences of canopy closure and its effects

on the soil microclimate, and to the quantity and quality of detritus supplied to the soil (Raich and Tufekcioglu 2000; Bréchet et al. 2009). Moreover, the deep and expansive rooting systems of Dipterocarp species also allow them to occupy large volume of rhizosphere that enable the capture of water and nutrients in wider spaces and in deep soil profile (Noordwijk et al. 2015), beyond the reach of shallow rooting fast-growing species. This is a competitive advantage of a mixed natural stand compared to a plantation during dry periods, which possibly explains insensitivity to hot temperatures and limited water availability during droughts.

In contrast, the  $R_s$  rates in the plantation are lower compared to some  $R_s$  values in the literature. In French Guiana, researchers observed  $R_s$  values from 2.8 to 6.8  $\mu\text{mol m}^{-1} \text{s}^{-1}$  in 16 plantations, which is 1.5 to 3 times higher than the range of  $R_s$  values (1.7 to 2.1  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) in this study. Bae et al (2013) also reported higher  $R_s$  values during dry season, ranging from 3.2 to 3.7  $\mu\text{mol m}^{-2} \text{s}^{-1}$  and 3.6 to 4.1  $\mu\text{mol m}^{-2} \text{s}^{-1}$  for a dipterocarp and a *Gmelina arborea* Roxb.—dominated agroforestry systems, respectively. They found high correlations between  $R_s$  and fine root biomass, microbial biomass, and soil organic matter. Similarly, the 1.9 Mt  $\text{CO}_2 \text{ ha}^{-1} \text{ mo}^{-1}$  or 0.5 Mt C  $\text{ha}^{-1} \text{ mo}^{-1}$  of soil organic C in the plantation (Table 1), is also lower compared with the estimated 0.74 t C  $\text{ha}^{-1} \text{ mo}^{-1}$  soil organic C losses in tropical forests (Malhi and Grace 2000). Other factors that possibly explained the differences between the two ecosystems are the quantity and quality of litterfall (Bréchet et al. 2009), root biomass (Pacaldo et al. 2014), and biological activities in the soil (Högberg et al. 2001; Hashimoto et al. 2004), which affect  $R_s$  rates. Another explanation of low  $R_s$  rates in plantations is the possibility of sensitivity of roots and microbes to high temperatures and dry soils owing to the shallow root system of fast-growing trees, light canopy density, and large canopy gaps that allows direct solar heating of the soil surface. Soil temperatures in plantations reached up to 41 °C during the hottest hour of the day, and  $R_s$  rates decreased dramatically at the soil temperatures above 32 °C. Possibly the roots responded to soil moisture stress and increased surface and soil temperatures by reducing metabolic activities to minimize water loss through transpiration. Reduced root activities in young plantations during dry spells retards growth that may lead to death, risks that young plantations will have to endure in light of increasing drought incidence due to global warming.

The negative and significant strong correlation between  $R_s$  and temperature (Fig. 2), indicates that, as temperatures increase,  $R_s$  rates decrease. Conversely, the positive and significant correlation between  $R_s$  rate and soil moisture indicates that, as soil moisture decreases,  $R_s$  rate also decreases. Temperature is major controlling factor of  $R_s$  because it regulates soil microbial activities, root respiration, and related processes (Cui et al. 2020). Ohashi et al. (2007) found that

any increase or decrease of  $R_s$  was closely related to temperature, soil moisture, types of vegetation, and site quality. In temperate forests, Peng et al. (2015) demonstrated that soil warming resulted in increased  $\text{CO}_2$  emissions during the rainy season and carbon sequestration during the dry season. Generally, the  $R_s$  increased during warm weather and in wet soils (Jannsens et al. 2001; Peng et al. 2015) due to the positive influence of these factors to autotrophic and heterotrophic respirations (Raich and Schlesinger 1992).

A positive relationship between  $R_s$  and soil moisture during the dry season was also reported by Raich and Schlesinger (1992), Wood et al. (2013) and Peng et al. (2015). However, others have also reported negative relationships (Adachi et al. 2005) or no significant relationships (Borken et al. 2006; Bréchet et al. 2009). Cui et al. (2020) observed an increasing trend of  $R_s$  rates with soil temperatures at 15% soil water content but restricted rates at higher or lower percent content. Some studies also reported a similar trend in which  $R_s$  rates declined in both saturated and in dry soils (Scott-Denton et al. 2006; Bréchet et al. 2009; Wood et al. 2013), indicating that soil moisture exerts a stronger influence than soil temperatures over  $R_s$  during dry periods. In saturated soil conditions, the reduction of  $R_s$  rates may be explained by decreased soil gas diffusion and underground biotic activities due to a barrier at the soil-atmosphere surface continuum, hence oxygen deprivation of roots and soil organisms (Raich and Schlesinger 1992; Cui et al. 2020; Adachi et al. 2005; Wood et al. 2013).

It is important to understand the relationship between soil moisture at the surface and temperature because temperature influences soil moisture (Dinca et al. 2018), and surface soil water often reflects the soil water profile because of a strong correlation between surface water and soil moisture content at deeper layers (Akbar et al. 2018). In this study, soil moisture was significantly negatively ( $p > 0.0001$ ) related to air temperature ( $-0.87$ ) and soil temperature ( $-0.81$ ), indicating that soil moisture decreases with increasing air and soil temperatures. However, though most modern  $R_s$  machines are capable of simultaneous and unattended measurements of soil moisture and temperature, and soil temperature, it remains difficult to monitor soil temperatures continuously over large-scale and long-term periods (Su et al. 2014). Because meteorological stations monitor and record air temperature data over long-term periods, in most instances, air temperatures are inputs to model climate change impacts on  $R_s$  over a large-scale (Vancutsem et al. 2010). The positive correlation between air and soil temperatures (0.87) demonstrates that air temperatures provide a good approximation of soil temperatures, and therefore could be used as an alternative of soil temperature in predicting  $R_s$ , particularly in instances when soil temperature and moisture data are lacking or insufficient. This is particularly important because of the projected increase of air

temperatures with global warming that will adversely affect forest growth due to higher respiration maintenance (Amthor 2000; Lewis 2006).

The high  $R_s$  rate of the natural forest compared to the plantation does not suggest that an undisturbed natural forest is a net source of  $\text{CO}_2$  emissions. Some researchers argued that a mature forest is considered as carbon neutral because of the balance between  $\text{CO}_2$  emissions and C sequestration (Smil 1999; Koskela et al. 2000; Harmon 2001; Pacaldo 2015). In contrast, low  $R_s$  rate in plantations does not also mean that they are a source of C sequestration, although actively growing trees are considered a C sink (Brown et al. 1986; Koskela et al. 2000; Harmon 2001). Although these claims may remain debatable due to uncertainties in carbon budget estimates of different types of forest ecosystems, it is clear in this study that a natural forest emitted large quantities of  $\text{CO}_2$  from the soil, and this would probably increase multiple times if natural forests are removed and converted to other land uses.

## Conclusion

The carbon budget in tropical forests depends on the balance between ecosystem respiration and carbon sequestration in above- and below-ground biomass of plantations and natural forests. This study demonstrated that, during a dry period, the natural forest released a significantly higher quantity of soil  $\text{CO}_2$  ( $5.8 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) compared with the plantation ( $1.8 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) and the control ( $3.2 \mu\text{mol m}^{-2} \text{s}^{-1}$ ). This indicates that global warming may either increase or decrease  $R_s$  rates depending on the sensitivity of the plants to soil moisture stress and temperature. Because the plantation has a shallow rooting system and light canopy to protect the soil against direct sunlight, it is highly prone to negative effects of soil moisture stress and high temperatures during dry spells, and therefore would be particularly at risks during a long drought. In contrast, the old-growth natural forest had high  $R_s$  rates, suggesting its resiliency during drought, possibly due to its deep rooting system and full canopy with numerous layers of vegetation, and therefore less susceptible to moisture stress and warm temperatures and have higher survival rates during long dry periods. The  $R_s$  is negatively correlated with air temperatures ( $-0.71$ ) and soil temperatures ( $-0.62$ ), indicating that  $R_s$  rate decreases with increasing air and soil temperatures. In contrast, the  $R_s$  is positively correlated with soil moisture ( $0.65$ ), indicating that it decreases with soil moisture during the dry season.

As a qualification, although the differences in  $R_s$  rates in both forest types could be an indication of differences in the level of sensitivity to dry season and high temperatures, this observation is not conclusive to conditions outside dry season because it is unclear how the  $R_s$  rates act

during wet periods. This study was limited only to dry season and specific site conditions, species and age, and further studies should be carried out during rainy periods and consider other factors affecting  $R_s$  rates. Nevertheless, though this study covered only a dry period, the data and methods of  $R_s$  quantification are important information and contribute to the knowledge gap related to  $R_s$  tropical forests and quantification techniques, important inputs to generating a reliable estimate of  $R_s$  and carbon budgets and to  $R_s$  dynamics in tropical forest ecosystems.

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