Available online at:
http://journal.unila.ac.id/index.php/tropicalsoil
DOI: 10.5400/jts.2014.19.3.121

CO_2 Flux from Tropical Land Uses on Andisol in West Java, Indonesia

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Received 25 June 2014 / accepted 3 September 2014

ABSTRACT

This study measured CO_2 flux by segregating effect of root respiration and organic matter decomposition by microbes. The study involved a mineral soil containing high organic matter (Andisols), in the tropic devoted to different land uses i.e. natural forest, tea plantation, and horticultural farm CO_2 emission from those land uses were compared to from peatland. Observed CO_2 fluxes came out in the following order: bare plot 7.32, tea plantation 10.22, horticultural farm 15.60, and natural forest 15.62 Mg C-CO_2 ha^{-1} yr^{-1}. While, root respiration accounted for substantial proportions: tea plantation 28%, horticultural farm 53%, and natural forest 53%. Soil temperature demonstrated a significant positive correlation with the CO_2 flux, except in the natural forest. On the other hand, water-filled pore spaces displayed varying correlation with site CO_2 flux: a negative relationship in both bare plot and tea plantation, appreciably positive in the horticultural farm, and weakly related in the natural forest. Soil respiration and C-organic content appeared to be strongly correlated; the rate of soil respiration increased with higher C-organic content. In field, CO_2 flux from organic matter decomposition in Andisols, Latosols, and peatland ranged from 5.35-13.22 Mg C-CO_2 ha^{-1} yr^{-1}, with root respiration contributing most of the flux, which was, in turn, influenced by type vegetation, humidity and soil temperature.

Keywords: CO_2 flux, decomposition, horticultural farm, natural forest, organic matter, tea plantation

INTRODUCTION

There has been a growing interest on the global issue of climate change, particularly in the last several decades, which have focused on greenhouse gases (GHG) such as CO_2, CH_4 and N_2O and these emissions are considered to be the principal causes of global warming and ultimately, climate change. The critical rise in the levels of CO_2, CH_4 and N_2O in the atmosphere have been known to emanate from anthropogenic emission largely from the use of fossil fuels for energy generation, and to a lesser extent, from land use changes (Bates *et al.* 2012).

CO_2 is by far the most important GHG that brings about *global warming*. Its cumulative concentration level in the atmosphere has increased by at least 40% from 278 ppm in the year 1750 to 390.50 ppm in 2011. During that time span, anthropogenic CO_2 emission reached 555 ± 85 Pg C, of which 375 ± 30 Pg C has been contributed by the burning of fossil fuel and production of cement, and the remaining 180 ± 80 Pg C has come from land use change (IPCC 2013).

It is thus, apparent from these figures that the principal causes of GHG emission are human activities rather than agricultural development. Even so, there are parties who, for one reason or another, have claimed otherwise, maintaining that the major source of GHG emission is agricultural land.

In this light, many researchers have pursued studies to delve into GHG emission from various land uses, particularly in peatland. Some of which have stirred controversial discussions after their findings had been presented or published. Consequently, for instance, there have been vigorous efforts to block or discourage the development of oil palm plantations and industrial tree plantations based on such research findings.

To cite some examples, Hooijer *et al.* (2006) highlighted that industrial pulpwood plantations in peatland released as much as 54 Mg CO_2 ha^{-1} yr^{-1} depending on soil water level. In another study, Jauhiainen *et al.* (2012) reported that peatland with *Acacia* tree plantation emitted up to 80 Mg CO_2 ha^{-1}

yr^{-1} due to the lowering of the soil water table level and the increased soil temperature leading to accelerated peatland oxidation. Similarly, Hooijer *et al.* (2012) and Dariah *et al.* (2013) attributed emission rates of 100 Mg CO_2 ha^{-1} yr^{-1}, and 44.7-47.8 Mg CO_2 ha^{-1} yr^{-1}, respectively to peatland subsidence, and to the effect of expansive root network of oil palms in plantations in peatland. Although exhibiting a wide range of variation, their findings tended to show considerably high levels of GHG emission in peatland which had been developed into plantations of oil palm or *Acacia* plantation. On a consolidated basis, according to Hergoualc'h and Verchot (2013), who compiled the results of such studies, the CO_2 fluxes in peatlands under different land uses in Southeast Asia averaged from 5 to 30 Mg C-CO_2 ha^{-1} yr^{-1}.

At this point, it should be noted that the CO_2 fluxes measured in the above studies actually represented cumulative vegetation root respiration (*autotrophic respiration*) and organic matter decomposition by soil microbes (*heterotrophic respiration*). Hence, without this distinction, the calculated emission results would likely be over-estimated values. A more realistic means of determining CO_2 fluxes should have root exclusion technique or isolated the effect of plant roots when measuring soil respiration. Besides, CO_2 flux is affected by environmental factors such as the temperature, moisture content, and humidity of the soil, as well as the type and extent of vegetation cover.

In this regard, a number of recent studies have segregated root respiration from organic matter decomposition by soil microbes. For instance, researches by Sumawinata *et al.* (2012) and Melling *et al.* (2013) on tropical peatland, and that of Hazama (2012) on tropical mineral soil have yielded results demonstrating insignificant differences in CO_2 fluxes coming from soil organic matter decomposition between peatland and mineral soil despite the fact that the peatland contained a much higher level of organic matter. This finding has proven that the real source of the variation was plant root respiration.

Unfortunately, not much is known on mineral soil, which contains a higher level of organic matter but has a lower temperature, as in the case of Andisols. Thus, the objectives of this study were three-fold: (a) to estimate the total CO_2 flux rates in a tropical mineral soil (Andisols) under different land uses (natural forest reserve, tea plantation, and horticultural farm), (b) to determine the effects of organic matter and environmental factors on CO_2 flux, and (c) to compare CO_2 fluxs between peatland and mineral soil.

MATERIALS AND METHODS

Site Description

This study was conducted over a 36-week duration (from September 2012 until May 2013) in a representative portion of the Telaga Warna Conservation Forest (total area 368.25 ha), which represents a tropical rainforest within the Gunung Gede Pangrango Forest Reserve (total area 21,975 ha), with an altitude range of 1400-1450 m above sea level and an adjoining tea plantation area (total area 553.43 ha) owned and operated by a private company, PT Sumber Sari Bumi Pakuan, in Cisarua sub-district, Bogor Regency, West Java, Indonesia.

The tea plantation estate had been developed originally in 1922 by the Dutch company *NV. Rolley Davies*. The tea variety used then was TRI 2024, and the plantation was regenerated in 1988-1989. Sometime later, the horticultural farm was added in a patch inside the tea plantation area. The local soil type is Andisols with vulcanic ash parent material. The specific study site locations were as follows: natural forest S 06°41' 22.6" E 106°59' 51.6", tea (*Camellia sinensis L.)* plantation S 06°41' 22.3" E 106°59' 37.5", horticultural farm with inter-planting of Red pepper (*Capsicum annuum* L.) and Cabbage (*Brassica oleracea* L.) S 06°41' 20.6" E 106° 59' 35.5", and a bare plot used to serve as comparison treatment. In each study site (natural forest, tea plantation, and horticultural farm), treatment plots of "no roots, no litter" in namely bare plot were also provided. Bare plot of 1.5m x1.0 m was establised to estimate CO_2 flux from soil organic matter decomposition.

The study site falls under Type A (Very Wet) climate based on the Schmidt and Ferguson Classification. Based on data taken from the nearby Gunung Mas Weather Station, the mean precipitation over the last 10-year period (2003-2013) amounted to 3429 mm yr^{-1}, with a minimum of 2678 mm yr^{-1} and a maximum of 4718 mm yr^{-1}. During the study period, rainfall reached 2665.50 mm, with the lowest level occurring in September 2012 (83 mm), and the highest level in Desember 2012 (527.50 mm).

The Andisols in the study site contained 0.12-0.36 % Nitrogen, with a bulk density of 0.52-0.72 g cm^{-3}, soil porosity of 73.11-77.21%, and a textural class of clay loam, except that of the horticultural farm which was silty clay.

CO_2 Measurement from Soil Surface

Field CO_2 gas samples were collected using a closed chamber method which was similar to the one employed by Toma and Hatano (2007). Over the duration of 25 weeks duration (from September 2012 until Februari 2013), gas samples were obtained from three observation points (or closed chambers) in each study location, which had been randomly located in both natural forest and bare plot; while in the the horticultural farm and tea plantation, the chambers were placed systematically at "on row" points.

The closed chambers were installed a day before gas sample collection. Water was placed at the sides of the chamber base to prevent the gas from escaping or leaking, and the chamber, measuring 20 cm in diameter and 25 cm in height, was placed over the chamber base.

CO_2 samples (250 ml volume) were collected from the chamber in a time series at 0, 3, and 6 minutes intervals, and placed inside tedlar bags with the use of a 25 ml syringe. The initial (0 minute) gas sample collection was undertaken before the chamber was installed, whereas the following (3 and 6 minutes) gas sample collections were made after the chamber had been closed. All gas samples were brought to the laboratory for analysis using an Infrared Gas Analyzer (IRGA) [ZFP9GC11, Fuji Electric, Tokyo, Japan] which had been pre-calibrated using soda lime and standard CO_2 gas 1701 ppm. Towards calculating CO_2 flux, the ambient air temperature was measured at about 1 m height above the ground, while soil temperature was taken at a depth of 5 cm, at the same time as gas sample collection. Sampling for CO_2 flux and measurement of microclimate parameters were conducted weekly between 7.30 and 10.00 a.m. in the morning, and at 12.30-15.00 p.m. in the afternoon.

Following the model described by Hu *et al.* (2004), the amount of CO_2 flux was calculated using the formula below:

$$F = \rho \ x \ \frac{V}{A} x \ \frac{\Delta c}{\Delta t} \times \frac{273}{273 + T} x \ \alpha$$

where: F (mg C-CO_2 m^{-2} min^{-1}) is the soil respiration rate or CO_2 flux, ñ is density of CO_2 (1.98 x 10^3 g m^{-3}) under standard condition, V (m^3) and A (m^2) are volume and cross-sectional area of the chamber base, *c* (m^3 m^{-3}) refers to the rate of change in CO_2 concentration inside the chamber during the period *t* (min), T (°C) is air temperature, and á is the conversion factor for CO_2 to C (12/44). Daily CO_2 flux is the average of the three observation points of each location in the morning and the afternoon measurement. While the annual flux is the average flux from each location being converted into units of Mg ha^{-1} $year^{-1}$.

The approach to determining the share of plant root respiration in the total CO_2 flux followed the root exlusion technique used by Hanson *et al.* (2000), while for comparative analysis of the role of roots in CO_2 flux (expressed in Mg C-CO_2 ha^{-1} yr^{-1}) generation, data from Hazama (2012) for Andisols and Latosols, along with data from Sumawinata *et al.* (2012) and *Melling et al.* (2013) for peatland were referred to. To assess root respiration rate used total flux CO_2 and bare plot data. The following equation was used:

Root Respiration= Total CO_2 flux - Bare Plot CO_2 Flux

Soil Analysis and Soil Respiration

Soil organic matter content (% by volume) and soil respiration rates were measured in the laboratory. Soil samples were collected at layers of 0-5, 5-10, 10-20, and 20-30 cm depth. Total soil organic C values were analyzed by applying the Walkley and Black method (Nelson and Sommers, 1982), while soil respiration was determined using the soil incubation method and KOH titration with HCl 0.1 N. Soil bulk density of each 10 cm layer in each location was determined using ring 100 ml.

To determine soil humidity or water-filled pore space (WFPS), 100-ml sample rings were also taken at 0-10 cm soil depth at the periphery of the chamber, at the same time as the gas sample collection. Soil humidity was calculated by analyzing the water content at different WFPS (%) using a reference volumetric water filled pore space (based on soil that had been oven-dried at a temperature of 105 °C over a period of 24 hours) and soil bulk density, and applying the formula below:

$$\text{WFPS (\%)} = \frac{\text{Gravimetric Water Content x Bulk Density x 100}}{\text{Total Soil Pore Space}}$$

Statistical Analysis

Pearson's Correlation Test was used to examine the relationship between CO_2 flux and soil temperature and humidity. The variation in CO_2 flux, soil temperature and soil humidity among the study sites were also analyzed using statistical *t*-test ($p< 0.05$).

RESULTS AND DISCUSSION

The resulting means and associated statistical sampling errors in CO_2 flux, particularly the portion coming from root respiration, are summarized in Table 1 below.

It can be observed that the mean (allowing for sampling error) annual CO_2 flux from the natural forest came out highest, followed very closely by

Table 1. Calculated means ± standard deviations in CO_2 flux and root respiration.

Land Use	Flux (Mg C-CO_2 ha^{-1} yr^{-1})	Root respiration (Mg C-CO_2 ha^{-1} yr^{-1})	Root respiration (%)
Bare plot	7.32 ± 2.78	0	0
Horticultural Farm	15.6 0 ± 6.23**	8.28	53.08
Tea Plantation	10.22 ± 1.95**	2.90	28.38
Natural Forest	15.62 ± 5.14**	8.32	53.26

** = Significant at probability level $p < 0.01$.

(almost the same level as that of) the horticultural farm, and much lower than that was in the tea plantation; flux was lowest in the bare plot. The CO_2 flux rates of all three land uses or vegetation types (natural forest, horticultural farm, and tea plantation) were significantly different compared to that coming from the bare plot (*t*-test, $p < 0.01$). In natural forest CO_2 flux was generally high owing to the greater volume of leaf fall (litter) and litter decomposition rate. Therefore, high soil respiration observed in the present study may have been due to high microbial activity.

Root respiration have relationship with soil microbes activity during decomposition of organic matter. In addition CO_2 flux was also influenced by the availability of soil nutrient elements on each location. Interestingly however, it can also be noted that plant root respiration accounted for a substantial portion of the respective CO_2 flux rates, which was logically none in the bare plot, more than half in both natural forest and horticultural farm, and nearly one-third of the CO_2 flux in the tea plantation. Aside from plant root respiration, the other sources of CO_2 flux were from the decomposition of organic matter (*e.g.* ground litter), and from surplus organic fertilizer (particularly from livestock manure) that had been applied in the horticultural farm. On the other hand, root respiration in the monoculture tea plantation was most likely much lower. Sainju *et al.* (2010) reported management practices, such as crop residue input to the soil, tillage, and cropping sequence, can emit CO_2 as a result of soil organic matter and crop residue mineralization and root and microbial respiration.

Influence of Environmental Factors on CO_2 Flux

In General the average WFPS (Table 2) are significantly differences between locations based on the t-test ($p<0.01$). Soil temperature was only significant on the natural forest based on t-test ($p<0.01$). Increased in soil temperature will decrease soil moisture, it is due to the influence of the water content in the soil pores.

Soil temperatures in the different land use type (vegetation cover) were varied significantly and generally increased as soil humidity (WFPS) went down: in the natural forest (18.27 ± 0.55°C), horticultural farm (20.42 ± 2.35°C), and bare plot (19.78 ± 2.40°C) based on statistical *t*-test ($p < 0.01$). However, in the case of the tea plantation, soil temperature was 19.3 ± 1.16°C. Our findings were consistent with studies conducted by Berglund *et al.* (2010), Kechavarzi *et al.* (2010), where CO_2 flux increased with soil temperatures. Correspondingly, soil humidity (WFPS) averaged as follows: natural forest (73.41 ± 16.36%), followed by bare plot (56.46 ± 10.44%), tea plantation (49.54 ± 15.28%) and horticultural farm (49.51 ± 9.19%).

The analysis (Table 3) of data demonstrated a significant positive correlation between soil temperature and CO_2 flux in all study plots, but the natural forest showed the least degree of correlation, even lower than in the bare plot. On the other hand, soil humidity and WFPS exhibited a strong positive relationship with CO_2 flux only in the horticultural farm and natural forest, whereas it manifested weakly in the bare plot, and a markedly negative relationship was observed in both tea plantation. The point to be considered is the influence of soil water content and WFPS on soil gas diffusiveness and underground biotic activity. A higher soil water content decreased soil gas diffusiveness.

Figure 1 depicts a largely comparable or consistent pattern in temporal variation in daily CO_2 flux at all study plots, which ranged from 0.60 to 9.36 g C-CO_2 m^{-2} day^{-1}. There occurred a marked increase in the CO_2 flux during the 9th week, but it fell back again in the succeeding weeks, which could

Table 2. Average ± standar deviation soil temperature and water-filled pore space (WFPS).

Land use	Soil temperature (°C)	WFPS (%)
Bare plot	19.78 ± 1.20	56.46 ± 10.44
Horticultural farm	20.42 ± 1.12	49.51 ± 15.28**
Tea plantation	19.29 ± 0.62	49.54 ± 11.84**
Natural forest	18.27 ± 0.44**	73.41 ± 16.36**

** = Significant at probability level $p < 0.01$.

Table 3. Calculated correlation coefficients for CO_2 fluxes of different land uses in relation to observed environmental factors

Land Use	Pearson's Correlation Coefficient (r^2)			
	N'	Soil Temperature	N'	WFPS
Bare Plot	145	0.19^{ns}	50	-0.13
Horticultural Farm	142	0.26*	48	0.20
Tea Plantation	289	0.19*	99	-0.16
Natural Forest	135	0.03^{ns}	50	0.03*

n' = Sample size, ns= No significance, * = Level of significance ($p < 0.05$)

have been due to intensive weeding and soil recultivation activities in the horticultural farm during this time period.

The 25-week series of field measurements yielded the following ranges of CO_2 fluxes: 0.60-3.66, 2.08-9.36, 1.77-3.93, and 1.58-8.07 g $C\text{-}CO_2$ m^{-2} day^{-1}, respectively in the bare plot, horticultural farm, tea plantation, and natural forest.

In this respect, Davidson *et al.* (2000) observed that, in the tropical region, the fluctuation in temperature, humidity, and water availability during a one-year period was relatively small or even constant, so that soil respiration in that same year would also be almost fixed. In general, CO_2 flux in land without vegetation can be expected to be much lesser than in vegetated land. According to Rochete *et al.* (1999) and Fu *et al.* (2002), the effect of vegetation on year-long CO_2 flux depends on the type of vegetation and its stage of development (pioneer to climax), which play an important direct and indirect role in soil respiration processes, such as their impact on the microclimate, and on the production of litter that falls to the ground, and decomposed over time.

The correlation coefficients between the observed environmental factors and CO_2 flux in all study plots appeared relatively low, such as those exhibited by soil temperature, most likely because of the prevailing local microclimatic conditions, particularly the relatively constant year-round precipitation. To a large extent, microclimatic factors, such as soil temperature and humidity (WFPS), directly and indirectly influenced the presence of soil microbes and their biophysical activities in the ground that, in turn, affected soil respiration as well as organic matter decomposition. This has been confirmed, for example, by Chapin *et al.* (2002) who noted that organic matter decomposition increased with higher levels of soil humidity, up to a certain upper limit.

The natural forest study site produced the highest level of soil humidity (averaging 76.34%) compared to the other land use plots, and this condition abetted the more rapid decomposition of organic matter, thereby resulting into higher total CO_2 fluxes. Gholz *et al.* (2000) reported consistent findings: decomposition in tropical rainforests was high because of high soil humidity, which was resulted from the relatively high oxygen availability for soil microbes, and the ensuing high rate of gas diffusion into the land surface.

In short, the temporal variation in CO_2 fluxes, which came out markedly higher in the natural forest site than in the horticultural farm, bare plot, and tea plantation, in that order, can be attributed to the net composite effects of air temperature, air humidity, and rainfall in the locality (Melling *et al.* 2005; Shimizu and Marutani 2009; Toma *et al.* 2010; Balogh *et al.* 2011).

Soil Respiration and Organic Matter

As depicted in Figure 2 below, in all study plots, the level of organic C decreased with deeper soil layer (0-30 cm). In terms of mean organic C levels (% by volume), the ranking of the different land use type or vegetation cover in this study, was as follows: tea plantation (5.81%), natural forest (5.09%), horticultural farm (2.31%), and bare plot (1.93%).

Also portrayed in Figure 2 are the comparative quantities of soil respiration at varying soil depths and land use type or vegetation. It can be observed that soil respiration rate is closely related to C-organic content. Both displayed a consistently similar pattern: lower organic carbon values and lesser soil respiration rates at deeper soil layers. However, in the case of the horticultural farm, an entirely different result was obtained: even with low organic matter content, soil respiration registered a high rate. This could have been due to the supplemental application of animal manure into the field thereby jacking up the amount of organic matter in the study site. Hence, average respiration at soil depths of 0-30 cm at the bare plot, horticultural farm, tea plantation and natural forest measured 27.52, 33.70, 35.55, and 37.97 mg dm^{-3} day^{-1}, respectively.

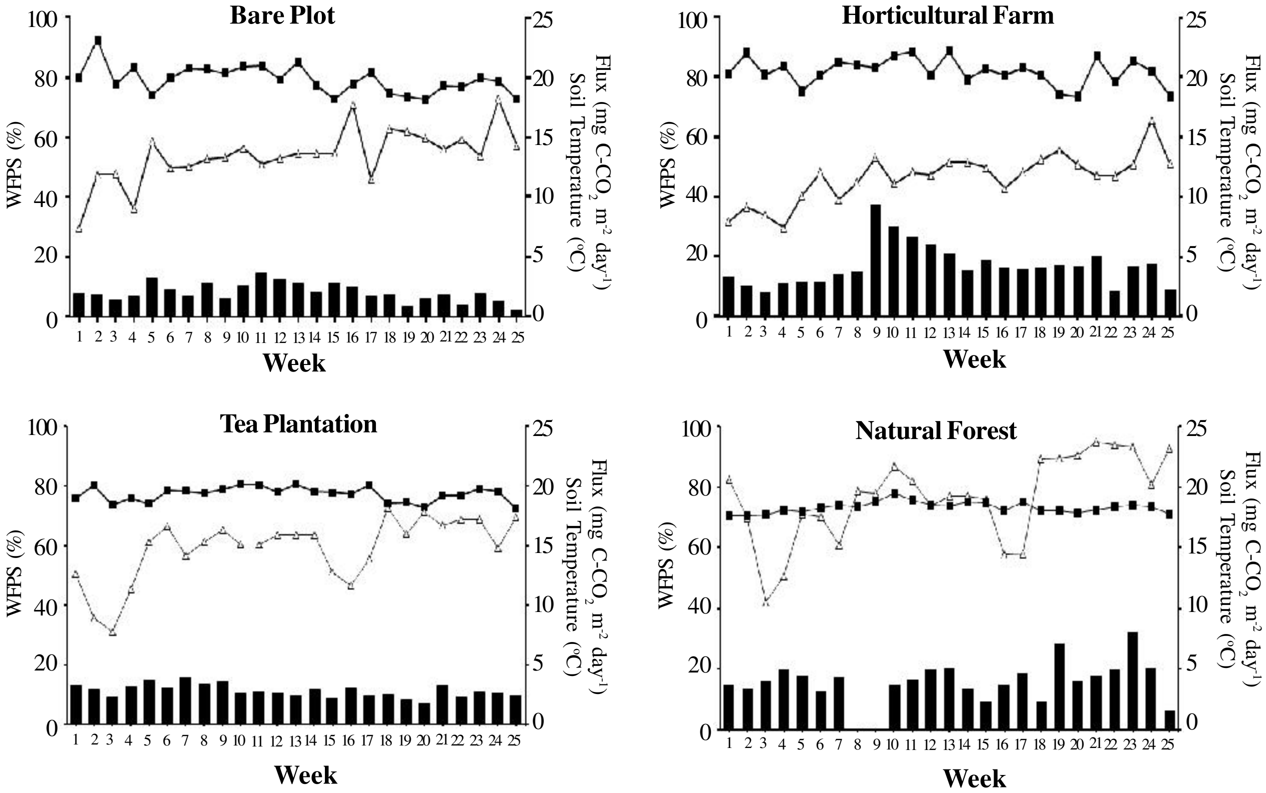

Figure 1. Relationship between CO_2 flux and soil humidity (WFPS), soil temperature, in the different study sites (land use type). ▬ : flux, ─■─ : soil temperature, ─△─ : WFPS.

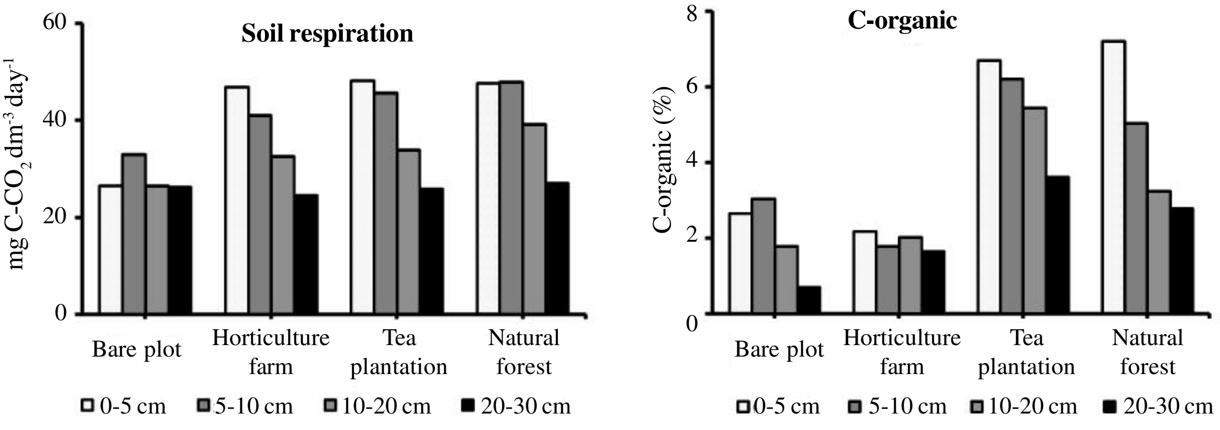

Figure 2. Soil Respiration and Organic C rates at varying soil depths (in cm) on land with different types of vegetation.

The observation that soil organic matter content and soil respiration tend to decrease with deeper soil layer implies that CO_2 flux comes more from organic matter decomposition in the upper soil layer (1-10 cm). Similar findings have been presented by Huygent *et al.* (2005) and Dube *et al.* (2009) on mineral soils, as well as on peatland (Djajakirana 2012). The probable explanation for such phenomenon is that as the soil gets deeper, it would be increasingly harder for the soil microbes to decompose the organic matter, and the limited availability of oxygen would also mean limited substrate which the microbes need for food. On the other hand, soil respiration and CO_2 flux could also be boosted by the dominant presence of plant roots and mycorrhiza at soil depths of 5-20 cm thereby encouraging soil microbe activity; as well as by the effect of root exudates that likewise adds to total CO_2 flux (Kusyakov 2006; Chapin *et al.* 2002).

Furthermore, Allison (2006) and Xu *et al.* (2012) highlighted that organic matter availability and decomposition are either facilitated or limited by the kind, amount and quality of ground litter, the physical local environment, and microbe composition. Soil microbes and their capacity to decompose organic matter are likewise influenced by soil temperature

Table 4. Comparative CO_2 flux rates in peatland and in mineral soils under different land use type or vegetation cover

Soil Type	Land Use Type	Total Flux	Organic Matter Decomposition		Soil Temperature	References and Location
		(Mg C-CO_2 ha^{-1} yr^{-1})	(Mg C-CO_2 ha^{-1} yr^{-1})	%	(°C)	
Andisols	Horticulture farm	15.60	7.32	47	20.4	This Study
	Tea Plantation	10.22	7.32	72	19.4	Bogor, West Java, Indonesia
	Natural Forest	15.62	7.30	47	18.4	
Andisols	Corn	6.61	5.35	81	11.7	Hazama (2012)
	Grassland	9.80	7.13	73	11.7	Hokkaido, Japan
Latosol	Cassava	14.26	12.48	88	26.4	Hazama (2012)
	Corn	15.69	13.22	84	26.8	Bogor, Indonesia
Peatland	*A. crassicarpa*	37.59	11.21	30	26.9	Sumawinata *et al.*
	Natural Forest	33.04	13.01	39	26.9	(2012) Sumatra, Indonesia
Peatland	Oil Palm	18.11	6.93	38	30.7	Melling *et al.*
	Natural Forest	24.97	9.93	40	25.8	(2013) Sarawak, Malaysia
	Sago	15.97	7.62	48	30.2	

and humidity (Meentemeyer 1978), and plant roots emit root exudates which serve as food for the soil microbes.

Laboratory analysis in this study has clearly demonstrated the strong positive relationship between organic matter content of a given soil and its respiration rate (Figure 2). However, field observations have established more the distinct influence of vegetation on CO_2 flux; more specifically, in the natural forest and horticultural farm locations thus proving that root respiration poses more pronounced effect on CO_2 flux than organic matter decomposition. On the contrary, in the tea plantation site, high organic matter did not directly translate into high CO_2 flux. This could have been explained by the fact that organic matter mainly came from falling tea leaves and pruned limbs, hence, it contained more lignin and phenols that tended to inhibit microbe activity. In addition, the tea monoculture would mean the production of a generally homogeneous litter. The reverse was true in the case of the horticultural farm site, probably since the vegetable crop grew much faster, and its organic matter tended to decompose more easily and rapidly.

CO_2 Flux and the Role of Root Respiration in Peatland and Mineral Soil of Varying Land Use Type

Table 4 summarizes the proportion of annual CO_2 flux by source (*i.e.* organic matter decomposition by soil microbes and root respiration) of various types of mineral soil and peatland, together with mean soil temperature data. Firstly, it can be readily seen that root respiration actually accounts for a large share of the total CO_2 flux, taking up even more than half in some occasions, particularly in the Andisols mineral soil, and more so, in peatland. Secondly, although the Bogor Andisols produced far higher rates of CO_2 flux compared to the Hokkaido Andisols, a closer look reveals that organic matter decomposition contributes the largest share in the flux rates in the Hokkaido Andisols, which is attributable mainly to the much lower soil temperature in the Hokkaido soil. Nevertheless, the percentage share of organic matter decomposition in the Bogor tea plantation (72%) is practically the same as that of the Hokkaido grassland (73%).

On the other hand, in the Bogor Latosol soil, the contribution of root respiration to the total CO_2 flux amounted to a mere 12% and 16%, respectively for cassava and corn field. Meanwhile, research in Sarawak peatland in Malaysia showed a majority proportion (62, 60 and 52% in the oil palm and natural forest and sago plantations, respectively) of the total CO_2 flux came from root respiration. Similarly, Sumawinata *et al.* (2012) found that root respiration in a 4-year old *Acacia crasicarpa* plantation on peatland contributed at least 70% of the total CO_2 flux. In this study, the proportion of the total CO_2 flux that came from root respiration in the horticultural farm amounted to approximately 53%, but in the tea plantation, the corresponding figure was a mere 28%.

Interestingly, these field investigations demonstrated that even natural forests did produce substantial amounts of CO_2 flux, which were comparable or even greater than in agricultural plantations or *planted forests* (*e.g.* industrial tree plantations). For instance, in this study, the natural forest on Andisols mineral soil produced a CO_2 flux (15.62 Mg C-CO_2 ha^{-1} yr^{-1}) which was almost the same as that coming from the horticultural farm, but nearly 50% higher than in the tea plantation. More than half (53%) of the total CO_2 flux in the natural forest in this study came from root respiration, compared to the figures reported by Sumawinata *et al.* (2012) and Melling *et al.*(2013), which reached at least 60%.

Further, Table 4 shows that CO_2 flux from the varying land use type (vegetation cover) on land mineral soil (Andisols and latosol) and peatland soil ranged from 6.61 to 37.59 Mg C-CO_2 ha^{-1} yr^{-1}, which came predominantly from root respiration. In comparison, the proportion that originated from organic matter decomposition amounted to 5.35-13.22 Mg C-CO_2 ha^{-1} yr^{-1}. Aside from soil temperature, farm management and operational practices (*e. g.* fertilizer application) significantly influenced total CO_2 flux.

On a 4-year old *Acacia crassicarpa* plantation in peatland, CO_2 flux was generally high owing to the greater volume of leaf fall (litter), as well as the tremendously fast growth and high yield resulting into very high organic matter decomposition and root respiration. Suwardi *et al.*(2011) disclosed that as much as 9.20 Mg ha^{-1} yr^{-1} of litter is produced by an *Acacia crassicarpa* plantation, at least 60% of which is decomposed in only 3 months or less, compared to only 40% of the much lower volume of natural forest litter.

In the oil palm and sago plantations in peatland in Sarawak, Malaysia organic matter decomposition proceded at a faster and higher rate than root respiration owing to the combined effects of higher temperature and lower soil water tables (Melling *et al.* 2013).

In summary, total CO_2 flux comes as the result of the net combined effects of microclimatic factors such as soil temperature, air temperature, and soil humidity; as well as other contributing conditions including the type and volume of litter fall on the ground that also serves as substrate food for soil microbes.

CONCLUSIONS

This study has produced realistic estimates of the total CO_2 flux rates in a tropical soil mineral soil (Andisols) under different land uses, namely: natural forest reserve, tea plantation, and horticultural farm. Results showed that CO_2 fluxes in the horticultural field and natural forest were comparatively higher than in the tea plantation: bare plot 7.32, tea plantation 10.22, horticultural farm 15.60, and natural forest 15.62 Mg C-CO_2 ha^{-1} yr^{-1}. Contribution of plant root respiration in aggregate CO_2 fluxes: tea plantation 28%, horticultural farm 53%, and natural forest 53%.

Root respiration tended to peak at 0-20 cm soil depth, diminishing appreciably at deeper layers. Observed soil temperature demonstrated a significant positive correlation with the CO_2 flux, except in the natural forest. On the other hand, water-filled pore spaces (WFPS) displayed varying correlation with site CO_2 flux: a negative relationship in both bare plot and tea plantation, appreciably positive in the horticultural field, and weakly related in the natural forest.

CO_2 flux from organic matter decomposition in Andisols, Latosols, and Peatland ranged from 5.35-13.22 Mg C-CO_2 ha^{-1} yr^{-1}, with root respiration contributing most of the flux, which was, in turn, influenced by environmental factors such as the temperature, moisture content, and humidity of the soil, as well as the type and condition of vegetation.

ACKNOWLEDGEMENTS

This research was funded by Indonesian Agency for Agricultural Research and Development Ministry of Agriculture and IPN colaborated with ICCC and CIFOR to support our publication fund. We thank private company, PT Sumber Sari Bumi Pakuan, in Cisarua, Bogor Regency, West Java, Indonesia for location permit.

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