Introduction

Forest growth is of great interest because of its effectiveness in mitigating the increase in carbon dioxide in the atmosphere. In fact, increases in tree biomass are the visible effect of fixing carbon in the ecosystem. However, soil carbon dynamics should also be identified because changes in soil carbon stock, which is the biggest carbon pool in the terrestrial ecosystem, might significantly affect CO$_2$ concentration. Therefore, soil respiration, i.e., CO$_2$ flux from the forest floor, is a key parameter for determining carbon balance in the forest ecosystem.

For plantation forestry, teak (*Tectona grandis*) is a popular species in tropical countries. In Thailand, teak is an indigenous species and has a relatively fast growth rate with a straight stem, which is a desirable characteristic in the commercial market. In addition, the fast growth rate of teak may promote carbon accumulation in the soil as well as in tree biomass. However, carbon dynamics and soil respiration in teak plantations have not been studied in Thailand. Located in monsoon Asia, Thailand has a seasonal climate pattern that includes a rainy season and a dry season. Following the seasonality, soil respiration has a pattern of high soil respiration in the rainy season and low respiration in the dry season, which is mostly controlled by the soil moisture regime.

Soil respiration is composed of heterotrophic respiration by soil biota and autotrophic respiration by roots. Separation of heterotrophic and autotrophic respiration is important for evaluating carbon balance in the soil. Contribution of root respiration to total respiration was reviewed and found to range from 10 to 90%, although there are methodological difficulties in measuring root respiration.

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The paper reports the results obtained in the joint project on “Changes in tropical forests and their influences” sponsored by the Science and Technology Agency of Japan and the National Research Council of Thailand.

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Received 14 October 2008; accepted 19 January 2009.
tion in the field. One common method for estimating root respiration is to make a trench to exclude roots around the chamber, although there is a possibility that trenching will produce some artificial effects on root decomposition and soil moisture.

The objective of this study was to compare i) soil respiration at different stand ages of teak plantations, and ii) separation of CO₂ sources, i.e., organic layer, roots, and soil, in total soil respiration by eliminating these CO₂ sources. We also analyzed the controlling factors for soil respiration and estimated the annual CO₂ efflux from the forest floor at the study sites in Kanchanaburi, western Thailand.

Materials and methods

1. Sites

The study was conducted at the Mae Klong Watershed Research Station (14°35'N, 98°52'E), Thong Pha Phum, Kanchanaburi Province, Thailand (Fig. 1). Annual mean air temperature at the station is about 25°C, ranging from 9.3°C to 42.2°C, and the annual mean precipitation is 1,650 mm, most of which falls during the rainy season from April to October. Figure 2 shows monthly rainfall and air temperature measured at the station office from 1997 to 1999. The amounts of annual rainfall during the study period were 1,927 mm in 1997, 1,243 mm in 1998, and 1,733 mm in 1999. Altitude at the study site ranged from 150 to 200 m asl. Soil is classified as Alfisols derived from sedimentary rock, gneiss and limestone. Undergrowth bamboo also influences surface soil conditions at the sites. Soil properties in the teak plantation (T-Y plot, see below) are shown in Table 1. The plantation area had been used as cultivated land. Forest vegetation in the watershed is described in Marod et al.

2. Plots for measuring soil respiration

Soil respiration was compared in 1997 for teak plantation areas in the T-Y, T-S, and T-M plots at the Mae Klong Watershed Research Station, Kanchanaburi, Thailand (Fig. 1). The amount of annual rainfall during the study period were 1,927 mm in 1997, 1,243 mm in 1998, and 1,733 mm in 1999. The amounts of annual rainfall during the study period were 1,927 mm in 1997, 1,243 mm in 1998, and 1,733 mm in 1999. Altitude at the study site ranged from 150 to 200 m asl. Soil is classified as Alfisols derived from sedimentary rock, gneiss and limestone. Undergrowth bamboo also influences surface soil conditions at the sites. Soil properties in the teak plantation (T-Y plot, see below) are shown in Table 1. The plantation area had been used as cultivated land. Forest vegetation in the watershed is described in Marod et al.

Table 1. Soil properties in the plot of T-Y in the Mae Klong Watershed Station

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>C</th>
<th>N</th>
<th>C/N</th>
<th>pH(H₂O)</th>
<th>pH(KCl)</th>
<th>CEC cmol kg⁻¹</th>
<th>Ca cmol kg⁻¹</th>
<th>Exchangeable Mg cmol kg⁻¹</th>
<th>K cmol kg⁻¹</th>
<th>Na cmol kg⁻¹</th>
<th>BS</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>13</td>
<td>19.00</td>
<td>1.20</td>
<td>15.8</td>
<td>7.11</td>
<td>6.32</td>
<td>10.29</td>
<td>5.78</td>
<td>1.37</td>
<td>0.54</td>
<td>0.06</td>
<td>75.3</td>
<td>SL</td>
</tr>
<tr>
<td>Bw</td>
<td>52</td>
<td>8.64</td>
<td>0.61</td>
<td>14.2</td>
<td>7.13</td>
<td>6.13</td>
<td>7.47</td>
<td>3.48</td>
<td>0.63</td>
<td>0.20</td>
<td>0.30</td>
<td>61.7</td>
<td>SL</td>
</tr>
<tr>
<td>Bt1</td>
<td>84</td>
<td>5.84</td>
<td>0.47</td>
<td>12.5</td>
<td>6.56</td>
<td>5.78</td>
<td>7.99</td>
<td>2.08</td>
<td>0.81</td>
<td>0.18</td>
<td>0.39</td>
<td>43.2</td>
<td>SCL</td>
</tr>
<tr>
<td>Bt2</td>
<td>130</td>
<td>3.59</td>
<td>0.35</td>
<td>10.4</td>
<td>6.38</td>
<td>5.42</td>
<td>12.38</td>
<td>1.28</td>
<td>0.38</td>
<td>0.20</td>
<td>0.26</td>
<td>17.1</td>
<td>L</td>
</tr>
<tr>
<td>BC</td>
<td>160</td>
<td>3.08</td>
<td>0.32</td>
<td>9.8</td>
<td>n.d.</td>
<td>n.d.</td>
<td>5.83</td>
<td>1.42</td>
<td>0.35</td>
<td>0.26</td>
<td>0.95</td>
<td>51.1</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

1): Percentage of base saturation.
2): Not determined.
Soil Respiration in Different Ages of Teak Plantations in Thailand

3. Soil respiration rate

In T-Y, we estimated the contribution of CO₂ sources, i.e., soil, roots and organic layer, to total soil respiration. Estimation was done by comparing total soil respiration and respiration whereby CO₂ from the organic layer and roots was eliminated. The calculation method is shown below.

Soil respiration rate was measured using the closed chamber method. The size of the steel chamber used was 30 cm in diameter and 30 cm in height. The bottom rim of the chamber was inserted 3–5 cm into the surface soil. About 20 min after the cover was sealed, CO₂ concentration in the headspace of the chamber was determined using an IRGA (ZFP5, Fuji Electronics Co., Ltd., Japan). Soil respiration rate was calculated using a linear model of increasing CO₂ concentration. Temperature correction was applied.

4. Separation of CO₂ sources

One chamber (Chamber A) was set on the forest floor for measuring total soil respiration as described above. Another chamber (Chamber B), in which the surface organic layer was removed from the soil in the chamber, was installed a meter away from Chamber A, and was expected to have no CO₂ emissions from organic layers. A third chamber, Chamber C, was installed 1.5 m away from Chamber A, in the opposite direction to Chamber B. A 60 cm square trench was dug 30 cm deep around Chamber C to cut the roots in the soil. Plastic boards were vertically inserted into the trench to prevent root invasion, and then the soil was replaced. The organic layer was also removed from Chamber C. This treatment was expected to eliminate both root respiration and organic layer respiration. At the study sites, there were no roots in the organic layers. This treatment was performed one month before measurement.

Total soil respiration (Rt) was determined by the CO₂ flux in Chamber A (RA), which consisted of CO₂ respired from the soil (Rs), from the organic layer (Ro), and from the roots (Rr). Thus,

\[ RA = Rt = Rs + Ro + Rr \]  (1)

Respiration in Chamber B (RB) is given by:

\[ RB = Rs + Rr = Rs + Rr_1 + Rr_2 \]  (2)

where \( Rr_1 \) is respiration from the roots in the 0–30 cm soil layer in the trench and \( Rr_2 \) is respiration from roots more than 30 cm deep. Respiration in Chamber C (RC) is

\[ RC = Rs + Rr_2 \]  (3)

Organic layer respiration is given by:

\[ Ro = RA – RB = Rt – (Rs + Rr_1 + Rr_2) \]  (4)

Root respiration is given by:

\[ Rr = Rt – (Rs + Ro + Rr_1 + Rr_2) \]  (5)

If we assumed that root respiration per unit of root biomass was constant throughout the soil layer, the following formula is derived:

\[ Rr = Rr_1 + Rr_2 = aB_1 + aB_2 \]  (6)

where \( B_1 \) is root biomass 0–30 cm in depth, \( B_2 \) is root biomass more than 30 cm deep up to the rooting zone and “a” is a specific root respiration rate per unit root biomass.

\[ Rr_1 = RB – RC = aB_1 \]  (7)

\[ Rr = (RB – RC)(1 + B_2/B_1) \]  (8)

In this study, we assumed that the rooting zone was 1.2 m deep and that the root biomass contributing to root respiration was limited to fine roots with a diameter smaller than 3 mm.

For replication, four sets of Chambers A, B and C were installed in T-Y. In T-S and T-M, four units of Chamber A were installed for measuring total soil respiration only.

When soil respiration was measured, soil (0–5 cm) and organic layer samples around the chambers were collected to determine moisture content. The samples were oven-dried at 105°C. Soil moisture in the 0–15 and 15–30 cm layers was monitored using TDR sensors (Moisture Point™ Model MP-917, Environmental Sensors, Canada) during the period of soil respiration measurement. The measurement interval was one to three days in 1997 and 1998, but the equipment frequently broke down for long periods in 1999.

5. Root biomass and carbon stock in soil and organic layer

Root biomass (< 10 mm) was measured using a soil column with an area of 15 × 15 cm at a depth of 0–15,
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15–30, 30–60, 60–90, and 90–120 cm. Triplicate sampling was done in November 1998. Dead roots were eliminated by visible inspection. Roots were separated according to their diameter, and washed and weighed after being oven-dried at 70°C. Carbon stock in the soil in T-Y and T-M was determined from bulk fine soil (≤2 mm) density measured by soil cylinder core (400 mL, 100 cm² × 4 cm) and carbon content in fine soil. Carbon content was analyzed using an NC analyzer (Shimadzu Co., Kyoto, Japan). We did not measure soil carbon stock in T-S. Dry weight of organic layer, mostly relatively fresh litter, was measured in T-Y in December 1998.

6. Statistics

Differences in soil respiration and related parameters among plots were tested by repeated-measures ANOVA. All statistics were calculated using STATISTICA software (StatSoft Japan Inc.).

Results

1. Soil respiration at different stand ages of teak plantations

The seasonal patterns of total soil respiration in teak plantations were similar among plots of different stand ages (Fig. 3). In 1997, soil respiration was quite low during the middle of the dry season from January to March and then increased from April with the highest peaks in September. In 1998, a similar seasonal pattern of low respiration in the dry season and high in the rainy season with a peak in the late rainy season was observed in the T-Y. The T-S plot showed the highest soil temperature but the lowest water content, while the T-M plot showed the lowest soil temperature and highest soil water content (Table 2). Although tree biomass and site environment differed greatly among plots, total soil respiration rates did not differ significantly among the plots (ANOVA, p = 0.698).

Soil carbon stock (kgC m⁻²) was larger in the T-M plots than in the T-Y plots for surface (0–0.3 m) and all soil layers (0–1.2 m) (Table 3). Mass of organic layer measured in T-Y was 0.247 kg m⁻² in December 1998.

2. Separation of CO₂ sources

In T-Y, mean biomass (s.e. n = 3) of total roots (< 2 cm) was 2.34 (1.20) kg m⁻² and that of fine roots (< 3 mm) was 0.27 (0.03) kg m⁻² at a depth of 0–1.2 m. In the 0–0.3 m surface soil layer, fine root biomass was 0.07 (0.01) kg

Fig. 3. CO₂ effluxes from the forest floor in 1 year-old (T-S), 6 year-old (T-Y) and 21 year-old (T-M) teak plantations

In the T-Y plot, the effluxes in Chambers A (dot, total soil respiration), B (open triangle, soil respiration without organic layer) and C (circle, soil respiration without organic layer and roots) are depicted. Mean efflux and standard error (vertical bar, n = 4) are shown.
Table 2. Comparison of mean soil temperature, soil water content, organic layer moisture, and total soil respiration in teak plantations by ANOVA

<table>
<thead>
<tr>
<th>Plots</th>
<th>T-S</th>
<th>T-Y</th>
<th>T-M</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil temperature (°C)</td>
<td>26.9</td>
<td>25.7</td>
<td>24.5</td>
<td>0.040</td>
</tr>
<tr>
<td>Soil water content (v/v)</td>
<td>0.174</td>
<td>0.182</td>
<td>0.280</td>
<td>0.056</td>
</tr>
<tr>
<td>Organic layer moisture (w/w)</td>
<td>0.228</td>
<td>0.222</td>
<td>0.241</td>
<td>0.982</td>
</tr>
<tr>
<td>Soil respiration rate (gC m⁻² d⁻¹)</td>
<td>3.002</td>
<td>2.618</td>
<td>2.770</td>
<td>0.698</td>
</tr>
</tbody>
</table>

1): Temperature at 10 cm in depth.  
2): Volumetric water content of soil in the 0–15 cm layer measured by TDR sensor.

Table 3. Carbon stocks (kgC m⁻²) in soil in 0-0.3 m, and soil in 0-1.2 m in T-Y and T-M plots

<table>
<thead>
<tr>
<th>Plot</th>
<th>Surface soil (0-0.3 m)</th>
<th>Soil (0-1.2 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-Y</td>
<td>5.05</td>
<td>11.74</td>
</tr>
<tr>
<td>T-M</td>
<td>5.60</td>
<td>13.82</td>
</tr>
</tbody>
</table>

m⁻². The teak plantation (T-Y) had a low proportion of fine root biomass to total roots, and fine roots were sparse in the surface layer.

Total soil respiration (Chamber A) was usually highest, followed by that from the chamber without organic layer (Chamber B), and then that from the chamber without organic layer and root respiration (Chamber C). However, the difference was small in T-Y in the teak plantation (Fig. 3). Although poor separation of CO₂ sources occurred in some measurements, the average contribution of CO₂ sources was calculated. In the teak plantation, the contribution of root respiration was 14.6% and that of organic matter was 17.2%; therefore, that of soil respiration was 68.2%.

3. Factors controlling soil respiration and estimation of annual CO₂ efflux from forest floor

We examined the relationship between total soil respiration rate and soil temperature at a depth of 10 cm, water content in organic layer, and water content in 0–30 cm soil layer, which was the average of 0–15 and 15–30 cm layers determined by TDR sensor (Table 4). Variation in soil temperature was largest in T-S, ranging from 22.8 to 31.9°C. Water content of organic layer varied largely even in the rainy season. Accordingly, these parameters had a low correlation with soil respiration, except for the T-Y plot. The only factor strongly correlated with total soil respiration was water content in the 0–30 cm soil layer.

For estimating the annual CO₂ efflux from the forest floor in the plots, i.e. annual amount of CO₂ emitted by total soil respiration, the following equation was used: Rt = a × WC⁻¹, where Rt is total soil respiration (gC m⁻² d⁻¹), WC is water content at 0–30 cm (v/v), and a and b are constants, at each site (Fig. 4). The coefficient of determination, R², ranged from 0.497 to 0.701. The response of total soil respiration to soil water content was relatively weak in the T-M plot. Using the monitoring data on soil water content measured by TDR and the above equations, annual CO₂ efflux by soil respiration was estimated (Table 5). The teak plantation released 1,062–1,154 gCO₂-C by soil respiration in 1997. Although stand age ranged from 1 to 21 years old, annual CO₂ efflux was similar. For interannual variation in the T-Y plot, annual CO₂ efflux in 1998 was reduced to 79.6% of the efflux in 1997.

Discussion

We assumed that varying tree biomass in different
Detailed monitoring of carbon balance, including the efflux to some ex-522
soil carbon is often found in shifting cultivation systems of northern Thailand.  As Hashimoto found that forest soils in Thailand responded to soil temperature by soil incubation experiments, a temperature parameter also may improve the estimation of annual CO$_2$ efflux to some extent. Moreover, seasonal variation in CO$_2$ sources should be studied in future because respiration of soil microbes and that of plant roots respond differently to seasonal environment.

In conclusion, carbon dynamics in the soil under teak plantations in western Thailand were determined by the soil moisture regime, which is controlled by seasonal rainfall pattern and annual rainfall. Temperature did not significantly influence soil respiration due to small variation. Soil respiration in teak plantations had no clear difference between different stand ages. Annual CO$_2$ efflux from the forest floor in the Mae Klong watershed ranged from 919 to 1,154 gC m$^{-2}$ y$^{-1}$ in 1997 and 1998. The CO$_2$ efflux fluctuated probably due to changes in soil moisture controlled by rainfall events.

Acknowledgments

We thank Drs. U. Kutintara and C. Yarwudhi from Kasetsart University, Ms. V. Sunantapongsuk and Ms. P. Tummakate from Land Development Department, and Drs. K. Ishizuka, S. Kobayashi, N. Tanaka, H. Tanaka, and A. Ishida from Forestry and Forest Product Research Institute for their valuable suggestions and cooperation. This study was partly funded by grants-in-aid from the Japan Society for the Promotion of Science (18255011).

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