Research paper

Comparison of Soil CO_2 Efflux from a Secondary Forest and Tea Plantations in Taiwan

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【Summary】

Soil CO_2 efflux, soil temperatures, and soil water content of 2 stands in a secondary forest, with differing canopy openness, and 2 tea plantations, one actively cropped and the other abandoned for 2 yr, in Taiwan were measured monthly from June 2004 to July 2005. The first objective of this study was to quantify and compare soil CO_2 efflux of the 4 stands. The second objective was to examine the relationship of environmental conditions, specially soil temperature and soil water contents, with soil CO_2 efflux of the forest and tea plantations. Seasonal patterns were found in soil CO_2 efflux and soil temperature but not in soil water content. The magnitude of the soil CO_2 efflux varied from 1 to 3.5 μmol m^{-2} s^{-1} and from 0.5 to 5.0 μmol m^{-2} s^{-1} in the secondary forest and tea plantations, respectively. Within stands, seasonal changes in soil respiration were most highly correlated with soil temperature. The highest Q_{10} value, the factor by which the respiration rate differs for a temperature interval of 10℃, of 2.92 occurred in the actively cropped tea stand, the lowest of 1.83 was calculated for the open forest stand, and intermediate values of 1.94 and 1.98 were found in the dense forest stand and abandoned tea stand, respectively. The results indicate that among the 4 stands, the soil CO_2 efflux of the actively cropped tea stand was most sensitive to changes in soil temperature.

Key words: soil CO_2 efflux, soil temperature, secondary forest, tea plantation, Q_{10}.

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研究報告

台灣低海拔次生林和茶園之土壤二氧化碳通量比較

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摘　要

本文測量台灣宜蘭地區次生林(冠層較密和較開闊區)和茶園(正在耕作和停耕區)在2004年六月到2005年七月間之土壤二氧化碳通量、土壤溫度和土壤含水量的變化。目的在量化和比較這兩種生態系其土壤二氧化碳通量以及檢視二氧化碳通量和環境因子(土壤溫度和土壤含水量)間的關係。測量發現土壤二氧化碳通量和土壤溫度有季節性變化；次生林土壤二氧化碳通量變化從1到3.5 µmol CO$_2$ m^{-2} s^{-1}，茶園則為0.5到5.0 µmol CO$_2$ m^{-2} s^{-1}，此變化和土壤溫度變化有正相關，因此可經由此關係計算溫度每升高10度二氧化碳通量的增加倍率(以Q$_{10}$值表示)；結果發現正在耕作的茶園區其Q$_{10}$值最高(2.92)，而冠層較密的次生林區其Q$_{10}$值最低(1.83)，停耕的茶園區和較開闊的次生林區其Q$_{10}$值介於中間(分別為1.94和1.98)，顯示正在耕作的茶園區其土壤二氧化碳通量變化對溫度變化最敏感。

關鍵詞：土壤二氧化碳通量、土壤溫度、次生林、茶園、Q$_{10}$值。

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INTRODUCTION

Soil is one of the major carbon pools in terrestrial ecosystems (Schlesinger and Andrews 2000). A small change in the soil carbon pool may significantly affect the global carbon cycle. The release of CO$_2$ from the soil (soil respiration) to the atmosphere is one of the most important processes in the carbon cycle of terrestrial ecosystems and the major component of ecosystem respiration (Janssens et al. 2001). In addition, because of the potential for a changing climate to affect net ecosystem productivity and exchange of C between terrestrial ecosystems and the atmosphere (Goulden et al. 1996), it is important to estimate soil CO$_2$ efflux of terrestrial ecosystems and to understand environmental control of the processes.

Temporal and spatial variations in soil CO$_2$ efflux have been found in various ecosystems. Temporal variations in soil CO$_2$ efflux were associated with changes in soil temperature (Fang et al. 1998, Longdoz et al. 2000, Fang and Moncrieff 2001), and changes in soil temperature and soil water content (Davidson et al. 1998, Epron et al. 1999, Xu and Qi 2001). The temperature effect is commonly described as an exponential function. Many studies applied Q$_{10}$ functions to represent the effect of soil temperature on soil respiration (Boone et al. 1998, Davidson et al. 1998, Epron et al. 1999, Janssens and Pilegaad 2003, Xu and Qi 2001). The value of Q$_{10}$ is the factor by which the respiration rate differs over a temperature interval of 10℃, and is defined as: $Q_{10} = R_{T+10} / R_T$, where R_T and R_{T+10} are respiration rates at temperatures of T and T+10, respectively (Winkler et al. 1996). In contrast, there is little consensus in representing the functional relationship between the soil water content and soil efflux of CO$_2$.

The effect of the soil water content on the efflux of CO_2 from soils has been described by linear, logarithmic, quadratic, and parabolic functions of the soil water content.

In addition to variations in soil CO_2 flux caused by environmental factors, human disturbances and agricultural activities also affect soil respiration. Soil respiration varies with vegetation, and comparisons of adjacent, different plant communities frequently demonstrate differences in soil CO_2 efflux (Tufekcioglu et al. 2001). In addition, soil CO_2 efflux can also vary with stand structure (Buchmann et al. 1996). Many natural forests have been converted to managed agricultural systems by humans. The transformation not only changes the above-ground vegetation types but also biotic and abiotic components below ground. It is hence expected that the amount and factors controlling soil CO_2 efflux may differ between natural forest ecosystems and agricultural systems. Soil CO_2 efflux in forests has been reported to be a significant component of global carbon cycling (Woodwell et al. 1983). With forests increasingly being transformed into agricultural systems, it is necessary to have a better understanding of the global carbon cycle by studying the soil efflux CO_2 from agricultural systems and forest ecosystems as well as and the relationship between environmental factors and the efflux of soil CO_2 of both systems.

Many forests at low and mid elevations of Taiwan have been cleared for tea plantations. The effect of this type of land transformation on the soil carbon balance has not been studied. Hence, the first objective of this study was to quantify and compare soil CO_2 effluxes of a secondary forest and adjacent tea plantations. The second objective was to examine the relationship between environmental conditions, in particular, soil temperature and soil water contents, and soil CO_2 efflux of the forest and tea plantations and to investigate if the relationship differs between these 2 ecosystems.

MATERIALS AND METHODS

Study site

Both study sites, at an elevation of 600 m, are located in the northwestern part of Ilan County, northeasternTaiwan (Fig. 1). The monthly mean air temperature of the area ranges from 15 to 30℃, and the mean annual rainfall is ca. 3000 mm (Central Weather Bureau, Taiwan). The secondary forest (24°35’19.3”N 121°28’59.0”E) was about 10 km away from the tea plantations (24°40’24.2”N 121°35’01.2”E). The canopy of the secondary forest, of ca. 20 ha, is dominated by the Lauraceae and Fagaceae. To investigate if canopy openness affects soil respiration, 2 stands in the secondary forest with different extents of overstory canopy openness were selected for the study. The leaf area index (LAI), estimated with a plant canopy analyzer (LI-2000, Li-Cor, Lincoln, NE, USA), for the open and dense forest stands were 1.61 ± 0.05 (mean ±

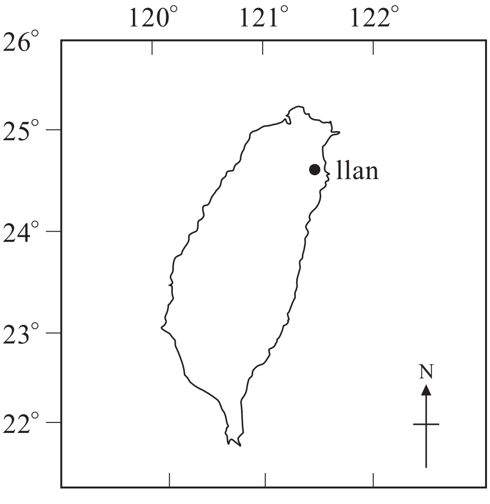

Fig. 1. Map of Taiwan showing the location of the study site.

standard error, $n = 3$) and 3.42±0.23, respectively. Two tea plantations were chosen for comparison; one was actively cropped (LAI = 1.66±0.05) while the other (LAI = 3.84 ±0.26) had been abandoned for 2 yr. The tea plantations consisted of a monoculture of *Camellia sinensis* L. The average tree heights were 0.8 and 2 m for the cropped and abandoned tea plantations, respectively.

Sampling design and procedure

In each of the 4 stands, 6 locations were randomly chosen for making measurements. Permanently installed PVC rings, 10 cm tall and 25 cm in diameter, inserted about 1 cm into the soil were used to measure soil CO_2 efflux. Soil CO_2 efflux was quantified via the dynamic method using a LI-COR 6200 (Li-Cor) coupled to a LI-COR 6000-09 chamber (with a volume of 1100 cm^3). During the measurement, the CO_2 concentration was first drawn down, then changes in the CO_2 concentration inside the chamber for 6 consecutive 5-s observations were recorded. Soil temperatures were automatically logged during the CO_2 flux measurements with a temperature probe, a chromel-constanan thermocouple wired directly to the LI-6200 sensor housing, inserted into the soil adjacent to each PVC chamber ring to a depth of 10 cm. Measurements were taken approximately monthly, 1 d close to the end of each month, from June 2004 to July 2005. Because of a typhoon, we were unable to access the sites in July 2004. Hence, no data are available for that month. During each measuring period, measurements were normally conducted twice over 2 time intervals, morning (between 0830 and 1000 h) and afternoon (between 1430 and 1600 h), except sometimes during the sampling period, the measurement was interrupted by a rain event.

Six soil samples, from the top 10 cm of soil, each adjacent to the PVC chamber ring were also collected and pooled for each stand. These samples were sealed and kept in a cooler until they were brought back to the laboratory to measure soil water content. The collected soil samples were dried at 70℃ to a constant weight (W_{dry}) after the wet soil sample had been weighed (W_{wet}). The gravimetric soil moisture content (SWC, percent dry weight) was then calculated as follows: $SWC (\%) = [(W_{wet} - W_{dry}) / W_{dry}] \times 100$.

Statistical analyses

The difference in soil CO_2 efflux measured in the morning and afternoon and that of soil water content of the 2 vegetation types were compared using Student's *t*-test. Significance levels are reported as $p < 0.05$.

An exponential equation was used to describe the relationship between soil CO_2 efflux (Rs) and soil temperature (Ts):

$Rs = R_{10} \times Q_{10}^{(Ts-10) / 10}$;

where R_{10} is a parameter. Q_{10} values were log-transformed and compared by Duncan's test (SigmaStat, Systat Software). Significance levels are reported as $p < 0.05$.

RESULTS

Temporal trends

In all 4 study stands, soil CO_2 efflux showed a clear seasonal pattern, with minimum values measured in winter and peak values in summer months (Figs. 2, 3). In the secondary forest, the lowest soil CO_2 efflux was 1 μmol m^{-2} s^{-1}, and the highest was 3.5 μmol m^{-2} s^{-1} (Fig. 2). In the tea plantations, soil CO_2 efflux ranged 0.5 to 5.0 μmol m^{-2} s^{-1} (Fig. 3). The active tea plantation showed the greatest variation in the magnitude of the soil CO_2 efflux. Seasonal patterns of soil CO_2 efflux of the 4 stands followed the general patterns of soil temperature.

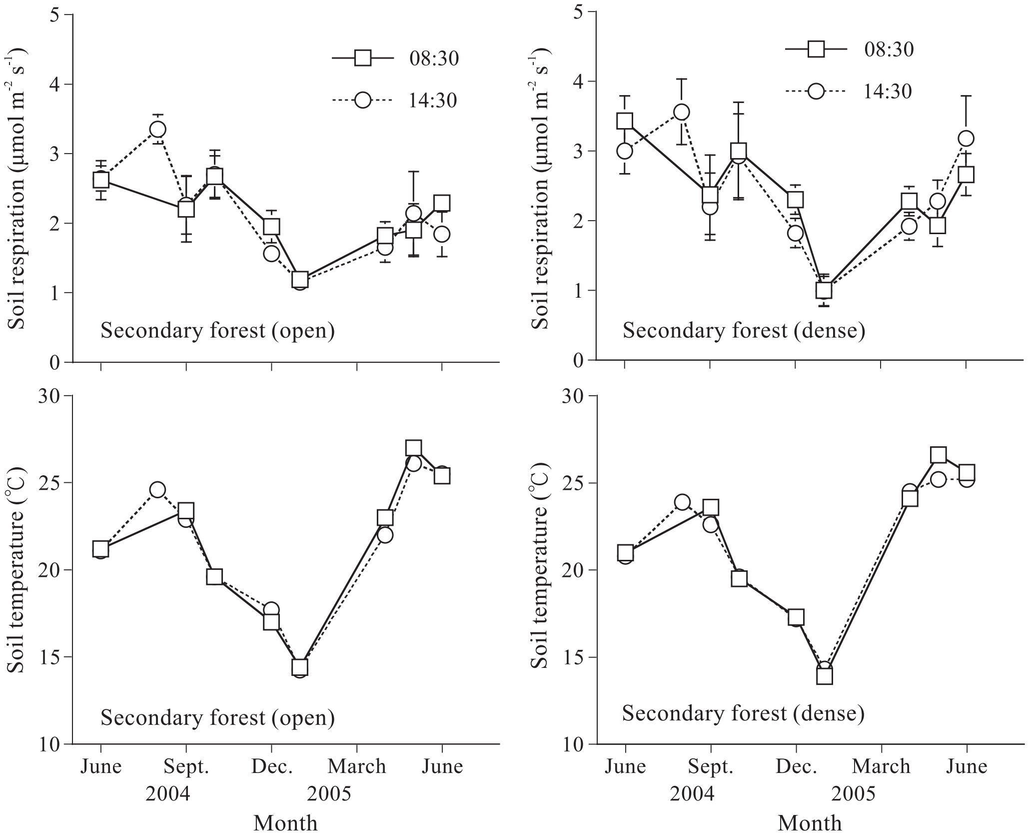

Fig. 2. Patterns of soil CO_2 efflux and soil temperature at 10-cm depth measured at 08:30 and 14:30 for the secondary forest (open and dense stands). Standard errors of the mean are plotted as error bars.

Within the same stand, no significant difference was found in soil CO_2 efflux measured in the morning and afternoon hours.

No seasonal pattern was found in the relative soil water content. The soil water content was higher in the secondary forest stands, at 36~80%, than in the tea plantations, at 30~60%, (Fig. 4). In a comparison between the 2 tea plantations, soil of the abandoned site had a significantly higher water content than that of the actively cropped one.

Relationship between soil respiration and soil temperature

When data from soil respiration measurements within the year were pooled and regressed against temperature, the Rs was strongly correlated with soil temperature (Figs. 5, 6). The exponential equation best described the Rs vs. Ts relation. Soil temperature explained 50 (for the forest stands) to 80% (for the tea plantations) of the seasonal variability in soil respiration.

Fitting the data for each of the 4 study stands independently, the Q_{10} values differed among the 4 stands. The highest Q_{10} value of 2.92 occurred in the managed tea plantation, the lowest of 1.83 was calculated for the open forest stand, and intermediate values of 1.94 and 1.98 were found in the dense forest stand and abandoned tea plantation stand, respectively.

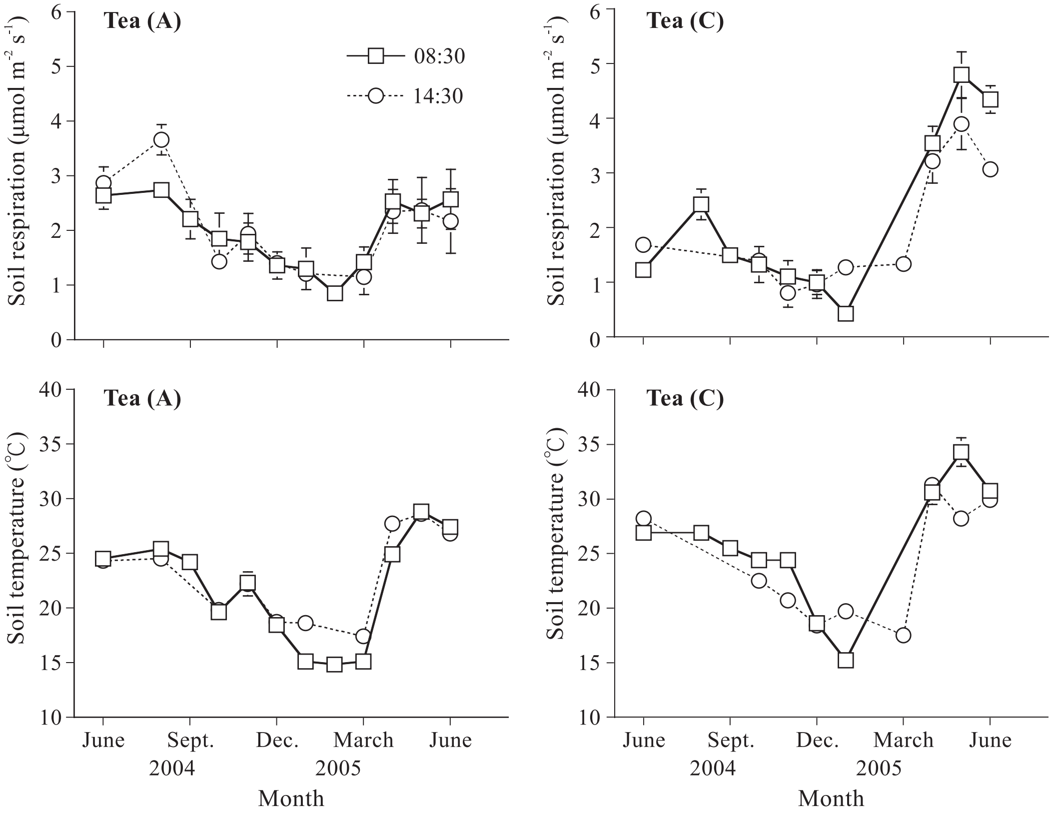

Fig. 3. Patterns of soil CO_2 efflux and soil temperature at 10-cm depth measured at 08:30 and 14:30 for a cropped (C) and an abandoned (A) tea plantation. Standard errors of the mean are plotted as error bars.

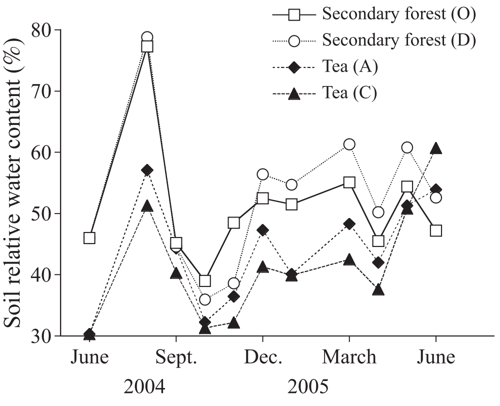

Fig. 4. Patterns of soil water content of the secondary forest, measured at open (O) and dense (D) sites, and in a cropped (C) and abandoned (A) tea plantations.

Effect of soil moisture

A significant, positive linear relationship between Rs and the soil water content was found in the actively cropped tea stand (Fig. 7). Soil water content explained ca. 40% of seasonal variability in soil respiration. In contrast, no such correlation was found in other studied stands (data not shown).

DISCUSSION

Seasonal patterns of soil CO_2 efflux and soil temperatures were found in the 4 study stands. The seasonal patterns and magnitudes of soil CO_2 efflux (Figs. 2, 3) were similar to those of riparian buffers and corn and soybean

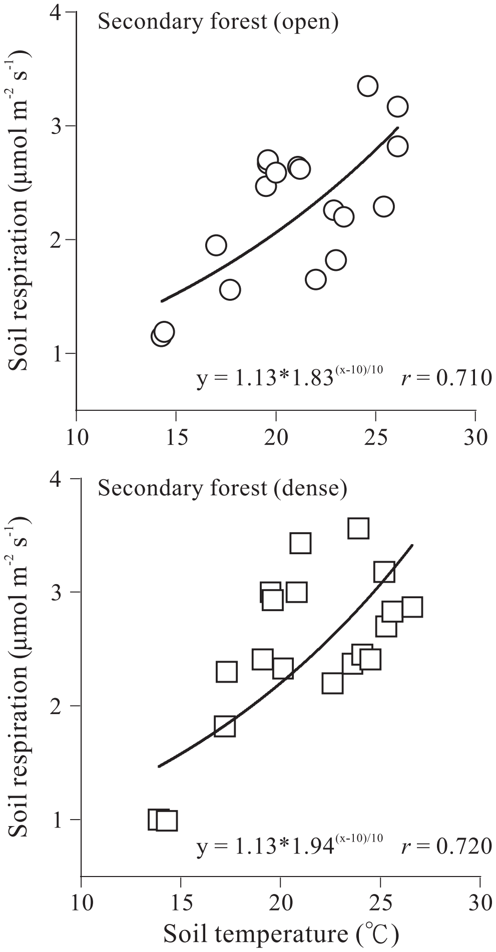

Fig. 5. Relationship between soil CO_2 efflux and soil temperature of open and dense sites in the secondary forest. Solid lines are exponential fits.

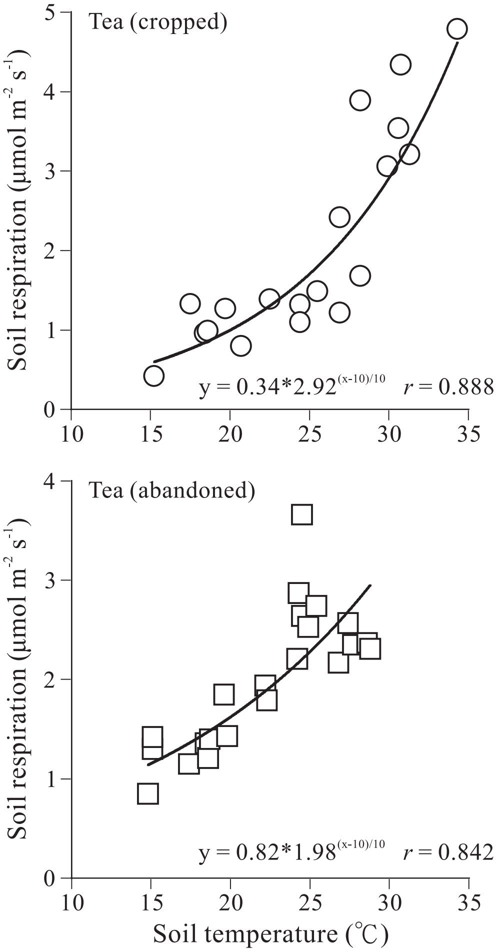

Fig. 6. Relationship between soil CO_2 efflux and soil temperature of a cropped (C) and abandoned (A) tea plantation. Solid lines are exponential fits.

fields in central Iowa, USA (Tufekcioglu et al. 2001). The seasonal variation was largely explained by soil temperature (Figs. 5, 6). Soil temperature was also found to exert a strong influence on soil respiration in natural forests and in human managed plantations; for example, in a temperate mixed hardwood forest in Massachusetts (Davidson et al. 1998), in tropical pine plantations in Florida (Ewel et al. 1987, Fang et al. 1998), in an oil palm plantation in Benin (Lamade et al. 1996), and in mixed pine forests in Georgia (Dilustro et al. 2005). An exponential increase in soil respiration with respect to temperature is often observed in many different types of ecosystem. The Q_{10} value is commonly used to compare the temperature dependence or sensitivity to temperature variations of soil respiration in different ecosystems. Raich and Schlesinger (1992) after reviewing the literature of soil respiration studies reported a median Q_{10} value of 2.4 (range 1.3~3.3). Our estimated Q_{10} values for the secondary forest (1.83 and 1.94) and tea plantations (1.98 and

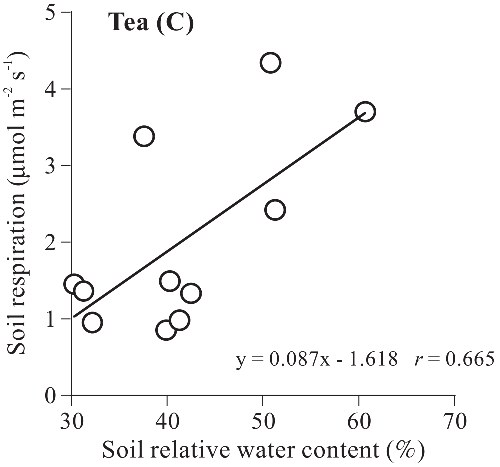

Fig. 7. Relationship between soil CO_2 efflux (the average of measurements taken at 08:30 and 14:30) and soil relative water content of a cropped tea plantation.

2.92) are within the range of reported values. The actively cropped tea stand had significantly higher Q_{10} values than the others. The result indicates that among the 4 stands, the soil CO_2 efflux of the actively cropped tea stand was most sensitive to changes in soil temperature.

Respiration by roots and their associated microbial components represent a significant part of soil respiration in most ecosystems (Bowden et al. 1993, Kelting et al. 1998). Different plant communities host different microbial compositions. It is thus expected that soil respiration varies with vegetation. Comparisons of adjacent, different plant communities frequently demonstrate differences in soil respiration rates (Tufekcioglu et al. 2001). In this study we also found that an actively cropped tea plantation stand released less CO_2 per ground soil area per year than did the secondary forest. In addition, a sharp increase in soil respiration with increasing temperature from December 2004 to July 2005 was found in the actively cropped tea stand, and this could account for the highest Q_{10} value for the stand. Thus, changes in vegetation have the potential to alter the global C cycle. Therefore, it is important to evaluate the effects of vegetation type on soil CO_2 efflux.

Rochette et al. (1997) observed that soil respiration in moist soils was 2~3 times higher than that in drier soil. Seasonal variations in soil respiration are thought to be largely explained by soil temperature and water content in sites exhibiting a dry season as in some temperate areas or under a Mediterranean climate (Hanson et al. 1993, Davidson et al. 1998, Epron et al. 1999, Qi and Xu 2001, Rey et al. 2002, Dilustro et al. 2005). Linear relationships have often been used to describe the relationship between soil respiration and soil water content (Holt et al. 1990, Epron et al. 1999, Rey et al. 2002). In this study, a positive, linear relationship was found only in the actively cropped tea stand (Fig. 7) which had the least soil water content (Fig. 4) among the 4 study stands. It has been reported that low soil moisture limits microbial and root respiration (Yuste et al. 2003). Thus, it is possible that the existing relationship between soil water content and soil CO_2 efflux in the actively cropped tea stand may have resulted from the altering of soil moisture by tea cropping activities (Chang et al. 2008).

In conclusion, we found differences in the magnitudes of seasonal variations in soil CO_2 efflux, in Q_{10} values, and in the relationship between the soil water content and soil CO_2 efflux between tea plantations and an adjacent forest. However, the data collected in this study do not provide a mechanism to explain the differences observed. Differences in C allocation patterns, litter production rates, litter quality, or root respiration are all possible factors contributing to the differences. Physiological and structural differences between tea plantations and forests are likely also involved. In addition, the observed differences in soil respiration may also have been due to differences in soil characteristics of the secondary forest and tea plantations. Further studies are needed to understand the underlying mechanisms causing soil respiration rates to change in response to changes in vegetation.

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