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Seasonal dynamics of soil CO_2 effluxes with responses to environmental factors in lower subtropical forests of China

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Abstract Seasonal metrics and environmental responses to forestry soil surface CO_2 emission effluxes among three types of lower subtropical forests were consistently monitored over two years with static chamber-gas chromatograph techniques among three types of lower subtropical forests. Results showed that annual CO_2 effluxes (S+L) reached 3942.20, 3422.36 and 2163.02 CO_2 $g\cdot m^{-2}\cdot a^{-1}$, respectively in the monsoon evergreen broadleaf forest, mixed broadleaf-coniferous forest and coniferous forest. All the three types of forests revealed the same characteristics of seasonal changes with the CO_2 effluxes peaking throughout June to August. During this peaking period, the effluxes were 35.9%, 38.1% and 40.2% of the total annual effluxes, respectively. The CO_2 emission process responding to the environmental factors displayed significantly different patterns in forestry soils of the three types of forests. The coniferous forest (CF) was more sensitive to temperature than the other two types. The Q_{10} values were higher, along with greater seasonal variations of the CO_2 efflux, indicating that the structurally unique forestry ecosystem has disadvantage against interferences. All the three types of forestry CO_2 effluxes showed significant correlation with the soil temperature (T_s), soil water content (M_s) and air pressure (P_a). However, stepwise regression analysis indicated no significant correlation between air pressure and the soil CO_2 efflux. With an empirical model to measure soil temperature and water content in 5 cm beneath the soil surface, the CO_2 effluxes accounting for 75.7%, 77.8% and 86.5% of the efflux variability respectively in soils of BF, MF and PF were calculated. This model can be better used to evaluate the CO_2 emission of soils under water stress and arid or semi-arid conditions.

Keywords: forestry soil, CO_2 emission, seasonal dynamic metrics, environmental factors, responses.

Soils are the biggest carbon pool of terrestrial ecosystem[1], in which carbon storage capacity reaches 1500 Pg (1 Pg = 10^{15}g), almost twice more than in atmosphere (750 Pg) and three times of those in terrestrial vegetation[2,3]. Annual CO_2 emission to the atmosphere by soils was about (mainly through soil respiration) 68—75 Pg carbon[4], which was much higher than those C released from burning fuels (5.2 $Pg\cdot a^{-1}$)[5]. Soil respiration is a major component of carbon cycling in terrestrial ecosystem. It is the second biggest efflux in carbon budget in terrestrial ecosystem besides vegetative photosynthesis[4]. Soil respiration plays a very important role in global carbon budgets. The amount of carbons in soils or any slight change in soil respiration will have impact on CO_2 concentration in atmosphere and global carbon balances[6,7].

Soil respirations are complex biological processes which are affected by many factors. These factors cause certain regular and irregular changes of the soil respirations in an unpredictable manner. Of all the factors, temperatures and soil water contents are undoubtedly two key factors affecting soil respirations. In the past several decades, more and more attentions were paid to soil respiration research including total CO_2 emission, root and microbial respirations[8,9], of which the effect of temperature on soil respirations was studied thoroughly. The rising of soil temperature could increase the emission of soil CO_2[10−12]. The correlation between temperature and CO_2 efflux can be expressed using an exponential equation[13,14] or Arrhenius equation[15,16] and sensitivity of soil respiration rate to temperature can be measured with Q_{10} value. The Q_{10} values of global soils differed from 1.3 to 5.6[11,12,17], where the higher the latitude, the higher Q_{10} values would be, representing greater sensitivity of soil respiration to temperatures.

Soil water content (moisture) is the other major factor affecting the soil respiration. Unlike temperature, no convincible and agreeable conclusions have been drawn for the effect of soil water content on soil respiration. The rapid increase of soil respiration rate was observed after raining on arid soil[18]. This result was also demonstrated by Liu *et al.*[19] who studied with a simulated raining experiment. However, some studies showed contradictory results[20] and rainfall did not affect the soil respiration rate[21,22]. Ilstedt *et al.* reported that the CO_2 emission rate reached the maximum values when the soil water content was 50% of the maximum capacity[23]. In general, the soil respiration rate increases with the rising of soil water content when the soil water holding capacity is still in its lower stage, but will slow down or decrease if the water content increases to some degree[24]. Many research models have been proposed to simulate the relationship between soil water content and respiration using linear, logarithmic or quadratic equations[25]. Some models obtained results which were well agreed with the experimental data, while others lacked of common considerations such that the effects of vegetation and vegetation covers, litters and decomposition rate, soil structure, soil organic matter contents and microbial activities, as well as the effects of temperature and water content on the soil respiration rate. Most of these factors are somewhat relied on or constrained by water-heat conditions.

Therefore, understanding the correlations between soil respiration and its factors helps us to precisely estimate and predict the changes of soil respiration in terrestrial ecosystems. Studies of factors affecting the soil respiration provide scientific evidence to explore carbon cycling processes and mechanisms in terrestrial ecosystems, as well as to evaluate the source-sink dynamics of ecosystems. This study analyzed data which were collected by monitoring soil respirations in three types of forests. The objectives of this study were to prove up: i) the correlations between environmental factors and soil respiration, along with the characteristics of their seasonal changes in different lower subtropical forests; ii) in what degree of impacts of temperature, water content and air pressure on soil respiration rate. The results would provide evidence and knowledgeable support for evaluating carbon source-sink dynamics in regional forestry ecosystems.

1 Research sites description

The study was carried out at Dinghushan Mountain National Reserve which is located in central Guangdong Province with the geolocation of 112°30′39″—112°33′41″ E and 23°09′21″—23°11′30″N. The lower subtropical monsoon climate is found at this research site with average annual temperature of 20.8℃, average annual humidity of 80%, total annual precipitation of 1956 mm, and average annual transpiration of 1115 mm. Typically, only two seasons designated as dry and wet seasons are presented in this region. The wet (or rainy) season lasts from April to September accounting for 75% of the total annual precipitations, where the dry season is from October to March. In this paper, the dynamic changes and responses of soil respiration to environmental factors were investigated among three typical forests, monsoon evergreen broadleaf (BF), mixed broadleaf-coniferous (MF) and coniferous forests (CF).

(1) BF is the climax community in lower subtropical region. The forest grows in areas with altitude of 200—400 m, which exists over 400 years. The community shows very complex structures which can be divided vertically into 5 layers, including 3 tree layers, a shrub and a grass layers. There are many ivy species and epiphytes among layers. Total biomass in the community is about 380 $t\cdot ha^{-1}$[26]. The soil is composed of hydrated lateritic red earths decomposed from sandstone parent materials, of which the pH value is approximately 4.0 and the soil layer is 60—90 cm thick[27], with 3%—4% of organic matter (OM) content on surface[28].

(2) MF is a succession community through planting *Schima superba* species into natural growing *Pinus massoniana* species. It is an intermediate forest from CF to BF. Currently MF is the largest forest in Dinghushan Mountain, where it was formed 50 years ago. The vertical distributions of this community can be divided into 4 layers with 2 tree layers occupying 90% of the community and one shrub layer and one grass layer. Total biomass is approximately 260 $t\cdot ha^{-1}$[29]. The soil is composed of lateritic red earths which were aeolian deposited from sandshale rocks. The soil properties showed acidic pH values being about 4.5[27], 30—60 cm thick soil layer with OM content of 3%[28].

(3) CF is a type of relatively simple vegetation community with only pine tree covering 50% of the forest. Shrubs and herbal species consist of *Baeckea frutescens*, *Rhodomyrtus tomentosa*, *Dicranopteris linearis*, and others. Total biomass content is 122 $t\cdot ha^{-1}$[29]. The community is in the early stage of succession and widely seen in southern hilly lands. In recent years, local residents have been rarely collecting shrubs, grass and forestry litters as firewood from forests, due to the improvement of residential fuel structures in the surrounding living areas. Many broadleaf species such as *Schefflera octophylla*, *Castanopsis fissa*, *Schima superba*, and *Evodia lepta*, intrude into the forest and thus accelerate the turnover to the mixed broadleaf forest. The forestry soil property in this community is lateritic red earth and sandshale as its parent material, in which the pH value is between 4.5 and 5.0, and the surface soil organic matter (SOM) content reaches 2%[28]. Table 1 outlines the soil properties under woods of three types of forestry vegetations in the research fields.

2 Research methodology

CO_2 emission effluxes from soil respiration processes were captured by static chamber-gas chromatograph techniques. Sampling chambers which were divided into bottom and upper parts were made of stainless steel. The upper part of the chamber was 1.5 mm steel slab with 500 mm in each edge (length, width and depth) and the top was sealed, where the bottom part was a cubic tube made of 2.5 mm steel slab with 50 mm each in length and width, and 10 mm depth. The groove in the bottom part is 20 mm×25 mm in width and depth which was sealed with rubber sealer. The groove was pushed underground before experiments. The upper part was installed with two axial air-mixing fans, a sampling tube and an air thermal sensor. Sampling chambers were connected by sampling tubes through triple valves (T-valves).

Experiments were set up in two treatments: (i) eliminating soil surface litters and tiny plants (S); (ii) eliminating only tiny plants, but leave litters intact (S + L). Each treatment was repeated 6 times with weekly sampling time at 9:00 to 11:30 AM. Samples of 90 mL volume were collected by inserting medical syringe into the chamber each time after the upper part was covered to the durations of 0, 10, 20 and 30 min. The sampling time was precisely clocked by a digital

Table 1 Overviews of the three vegetation types and their soil properties in the research fields

Vegetation type[a)]	Coverage	Leaf area index (LAI)	Biomass ($t\cdot hm^{-2}$)	Litter mass ($t\cdot hm^{-2}\cdot a^{-1}$)	Soil type	Soil density (0—10 cm)/$g\cdot cm^{-3}$	SOM(0—10 cm) ($g\cdot kg^{-1}$)
BF	>95%	6.2	380	8.28±0.64	lateritic red earths	0.86±0.06	38.9±1.6
MF	>90%	4.8	260	8.50±0.62	lateritic red earths	1.10±0.08	26.8±1.3
CF	approx. 50%	3.6	122	3.31±0.57	lateritic red earths	1.32±0.04	23.3±1.1

a) BF, MF and CF represent broadleaf, mixed coniferous and broadleaf, and coniferous forests, respectively.

timer. The CO_2 concentrations of the samples were then tested with HP4890D Gas Chromatographer within the same sampling day. The soil CO_2 efflux was then calculated from the differences of CO_2 concentrations between sample times. The gas sample was fed into the sample counter by the sample feeder manufactured by Institute of Atmospheric Physics, CAS (Patent protected), then entered the chromatographic column to the isolation process. After transformed by the nickel-mediated transformer, the sample CO_2 was detected by a flame ionization detector (FID). The temperatures in the detector and transformer column were 200 and 375.55 ℃, respectively, filled with highly pure nitrogen with flowing rate at 30 $mL\cdot min^{-1}$. Environmental factors such as soil surface temperature, soil temperature of 5 cm beneath surface (T_s), air temperature (T) and soil water content 10 cm beneath soil surface (M_s), and atmospheric pressure (P_a) were also recorded at the same time of sampling. Temperatures were measured with three-head digital thermometer, while the soil water content was measured by a hand-hold MPKit Moisture Probe Meter. The measurement of air pressure at MF filed sites was carried out by a CS105 atmospheric pressure sensor made by Vaisala, Inc. of Finland which was installed on the efflux monitor tower. The air pressures of BF and CF were calculated by an atmospheric pressure-altitude equation as

$$\log\frac{P_1}{P_2}=\frac{h}{1800(1+\alpha t_m)},$$

where P_1 and P_2 are the pressures of low and high altitudes, respectively; h is the altitude between low and high; t_m is the average temperature and α is a constant with value of 1/273. Soil CO_2 efflux was computed with an equation described as

$$F=\rho\frac{V}{A}\frac{P}{P_0}\frac{T_0}{T}\frac{dC_t}{dt},$$

where F is CO_2 efflux ($mg\cdot m^{-2}\cdot h^{-1}$); V is the chamber volume; C_t is the concentration of gas to be measured at the mixed volume at time t; ρ is the gas density at the standard conditions; T_0 and P_0 are absolute temperature and air pressure in the standard conditions; P and T are air pressure and temperature at the time of sampling. All data were handled and analyzed by the software program SAS version 8.2.

3 Results and analysis

3.1 Seasonal changes of CO_2 effluxes in forestry soils

Soil CO_2 emission effluxes in lower subtropical forests displayed seasonal characteristics with emission peaked in June to August and the minimum emission from December to February (Fig. 1). These seasonal changes were corresponding to the climate change, wet-dry seasonal changes as well as the plant

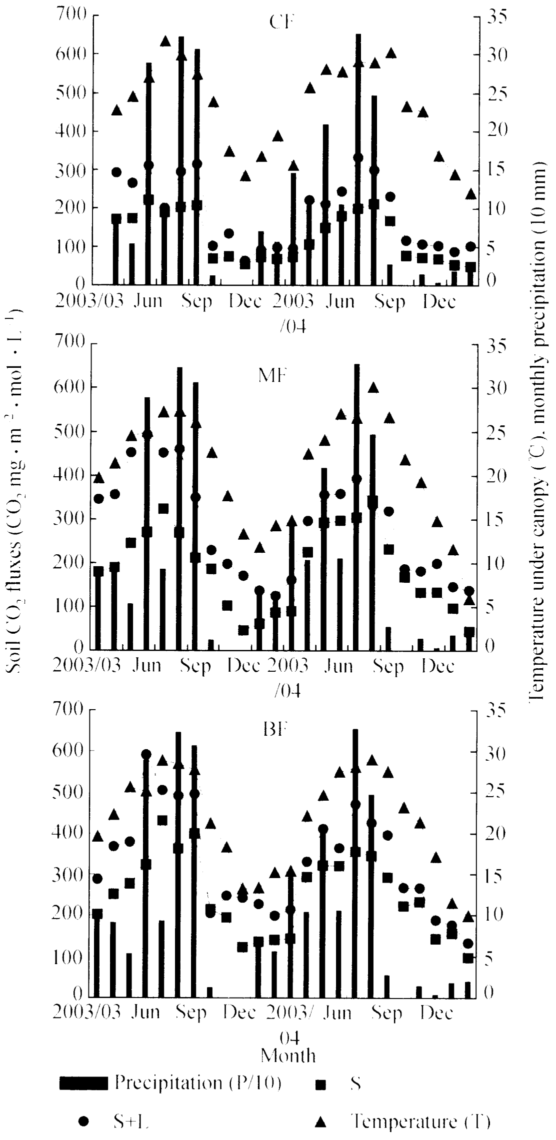

Fig. 1. Seasonal dynamics of soil CO_2 effluxes in different forests. BF, MF and CF represent monsoon broadleaf forest, mixed coniferous and broadleaf forest, and coniferous forest, respectively. The precipation is 1 : 10 of the actual values.

growth seasons. In the seasons where plants grow aggressively, the growth of roots was very active along with highly active microbial growth resulting from higher temperature and wet climate which happened to be raining and heat at the same season. From June to August, the forestry soil CO_2 effluxes were 35.9% (BF), 38.1% (MF) and 40.2% (CF) of the total annual effluxes, while only 14.0%, 13.4% and 12.6%, respectively from December to February. The CO_2 effluxes in forestry soils (S+L) in the wet season (April to September) were 66.36% (BF), 67.52% (MF) and 74.53% (CF) of the total annual effluxes. The results of the seasonal CO_2 emission in these three forests indicated that BF and MF showed better functionalities of the forest microclimate environment due to their higher vegetation coverage and complex vegetation distributions. These forests can be a buffer zone to outer environmental changes and also maintain little climate change inside the forest, which result in marginal soil CO_2 emission in all seasons. The results demonstrated the vegetation or soil surface coverage contribute to the differences of soil respiration in responding to the environmental changes.

3.2 Comparisons of CO_2 effluxes among varieties of forestry soils

Fig. 2 shows that the forestry soil CO_2 effluxes increased substantially in the direction of positive succession, using experiment setups with and without forestry litter coverage. The CO_2 effluxes (CO_2 $g{\cdot}m^{-2}{\cdot}a^{-1}$) without forestry litters were 2987.32(±92.3), 2271.68(±131.2), 1460.3(±68.5), respectively in BF, MF and CF, while the effluxes with litter coverage were recorded with 3942.2(±421.1), 3422.36(±496.0), 2163.02(±10.4), respectively. The soil surface CO_2 effluxes in BF and MF (S+L) appeared to be much higher than the temperate mountain forests in Beijing (143—1132 gCO_2 $m^{-2}{\cdot}a^{-1}$)[30], but only slightly higher than natural sharp-tooth oak forests in Qinglin Mountains (2232 gCO_2 $m^{-2}{\cdot}a^{-1}$)[31] and central subtropical evergreen broadleaf forest in Zhejiang Province (2412 gCO_2 $m^{-2}a^{-1}$)[32], and close to the tropical forests in Jianfenglin Mountain in Hainan Province (3316 gCO_2 $m^{-2}{\cdot}a^{-1}$)[33]. The differences of soil CO_2 effluxes in forests were mainly caused by the hot and humid conditions and the soil quality differed among forests. Additionally, factors such as structure of the vegetation community, productivity performance and microbial activities in the forestry soils in the same region also led to the differences of the forest soil CO_2 emission. Raich *et al.*[144] assumed that the effect of surface vegetation on soil respiration was determined by means of biomass and distribution of roots, soil properties and micro environment, and litters with different quantity and quality to soils. They also confirmed that vegetations played a significant role in effect of soil respiration in the same type of forestry soil[34].

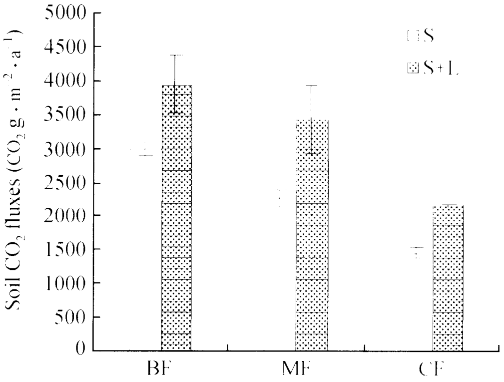

Fig. 2. Annual soil CO_2 effluxes in different lower subtropical forests.

For forests where the CO_2 efflux of soils with litter coverage was higher than that without litters coverage, the contributions of BF, MF and CF litters to the soil respiration respectively were 20.06(±23.13)%, 32.93 (±22.86)% and 30.87(±15.03)%, assuming that the differences of soil respirations with and without litters were viewed as contributions. The forestry litters released CO_2 through decomposition and were also a large carbon source for soil microbial activities. A survey in 2002 showed that the litter masses of BF, MF and CF in Dinghushan Mountain were 328±71, 497±103 and 436±146 $g{\cdot}m^{-2}$, respectively[35], indicating that the level of contributions of forestry litters to the soil respiration relied on the quantity of litter masses.

3.3 Environmental responses of CO_2 effluxes in forestry soils

(1) Effects of temperature on CO_2 emission in forestry soils. Temperature showed to be a strong factor influencing soil respiration. The analysis results

showed that atmospheric temperature, soil surface temperature, and soil temperature 5 cm beneath surface had statistically significant impacts on soil CO_2 effluxes ($P < 0.0001$), where the temperature of soil 5 cm beneath surface showed the greatest impact (Fig. 3). Apparently, the CO_2 in soil respirations resulted from activities of soil microorganisms and root metabolism of plant species. Hence, the soil CO_2 effluxes were very sensitive in response to the temperatures. The soil temperature dependency is often described by Q_{10} value. The Q_{10} value is generally calculated with an exponential function measuring respiration rates at certain temperature intervals. The Q_{10} values of soil respiration rates in BF, MF and CF (S+L) were 1.79, 2.00 and 2.38, respectively. Soil respiration in CF was more sensitive to the temperature because of easy penetration of sunlight to the canopy of the forest, since the canopy was sparse.

(2) The correlation of forestry soil CO_2 emission with soil water content. Many studies have shown that soil respiration was strongly affected by water content[25,36–38]. Our results and data analysis indicated that the correlation of the soil CO_2 efflux and water content was apparently linear in all Dinghushan Mountain forests (Fig. 4). These results did not agree with those in Xishuangbanna tropical forests which showed a parabolic correlation[39]. The annual precipitation was 1298 and 1297 mm in years 2003 and 2004 when this research was conducted, which was far lower than historical average annual precipitation of 1956 mm. During this period, the long term water stress attributed to the linear correlation in this study which was in agreement with previous statement that "the higher soil respiration rates were strongly correlated with the greater water content when the water holding capacity was low in soils"[24]. Soil water contents were closely related to plat root growth and microbial growth and activity, especially in the dry season. Yu *et al.*[40] found in a research of ecosystem respiration in subtropical and temperate forests, that temperature together with moisture was factors driving seasonal variation in ecosystem respiration while temperature was in the most decisive role. Once stressed by drought conditions, moisture could be turned into a decisive role in ecosystem respiration[40].

(3) Effects of air pressure on CO_2 emission in forestry soils. It seems no much attention to be paid to the influence of air pressure on soil CO_2 emission. Our study could draw a meaningful conclusion of the correlation of air pressure with the soil CO_2 efflux due to the fact that all field sites in this study were located at different altitudes (200 m for BF, 300 m for MF and 50 m for CF), as well as the seasonal changes to air pressures. The results showed that air pressure correlated negatively with forestry soil CO_2 efflux (Fig. 5). The impact of air pressure on soil CO_2 emission is merely a physical process. The soil CO_2 emission was apparently benefited from low air pressure. Hence, the

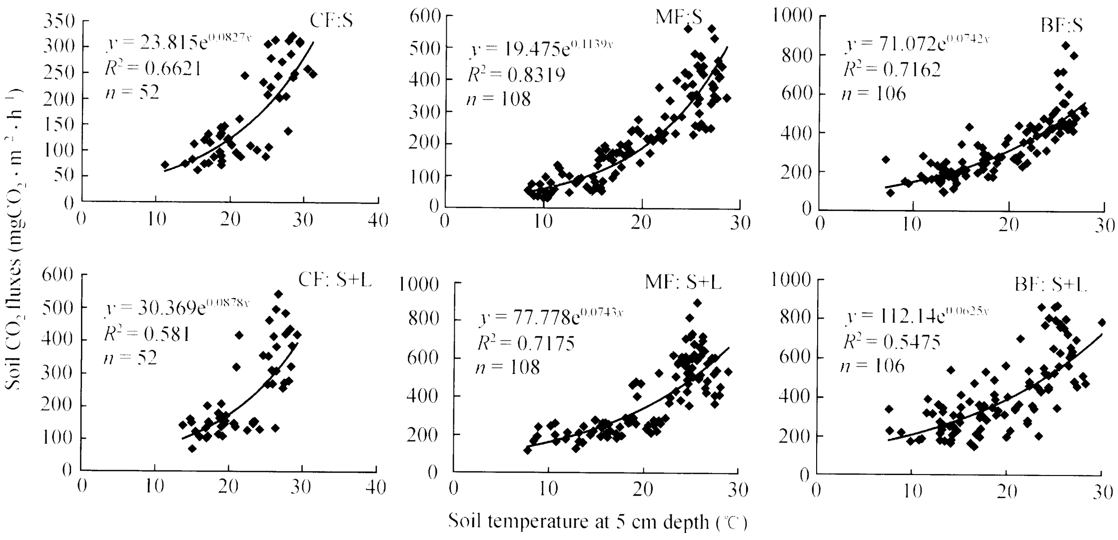

Fig. 3. The relationship between CO_2 effluxes and soil temperatures in different forests.

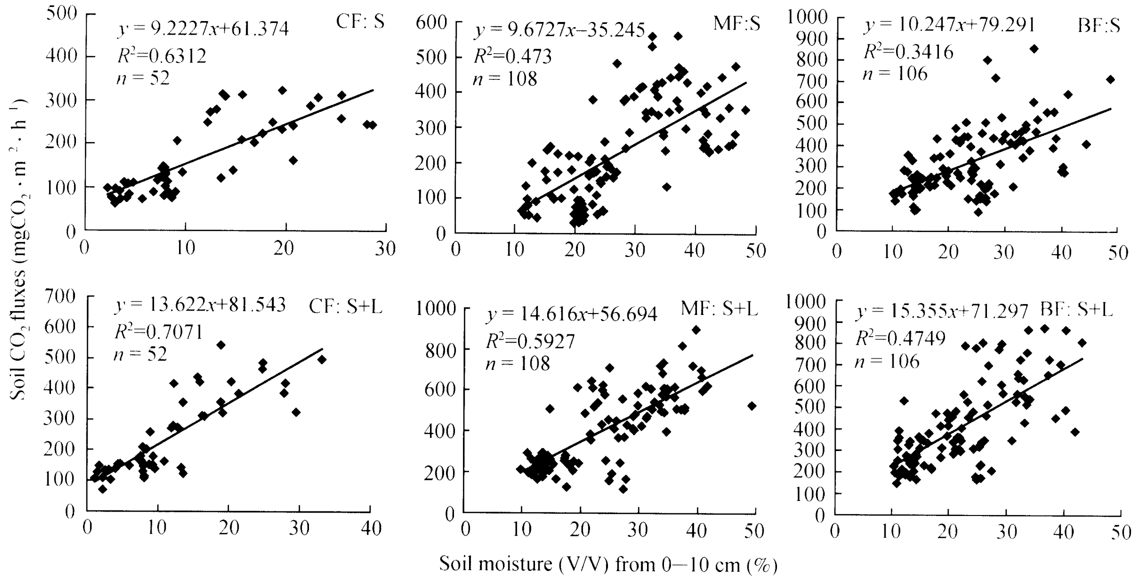

Fig. 4. The relationship between soil CO$_2$ effluxes and soil (0—10 cm) water content.

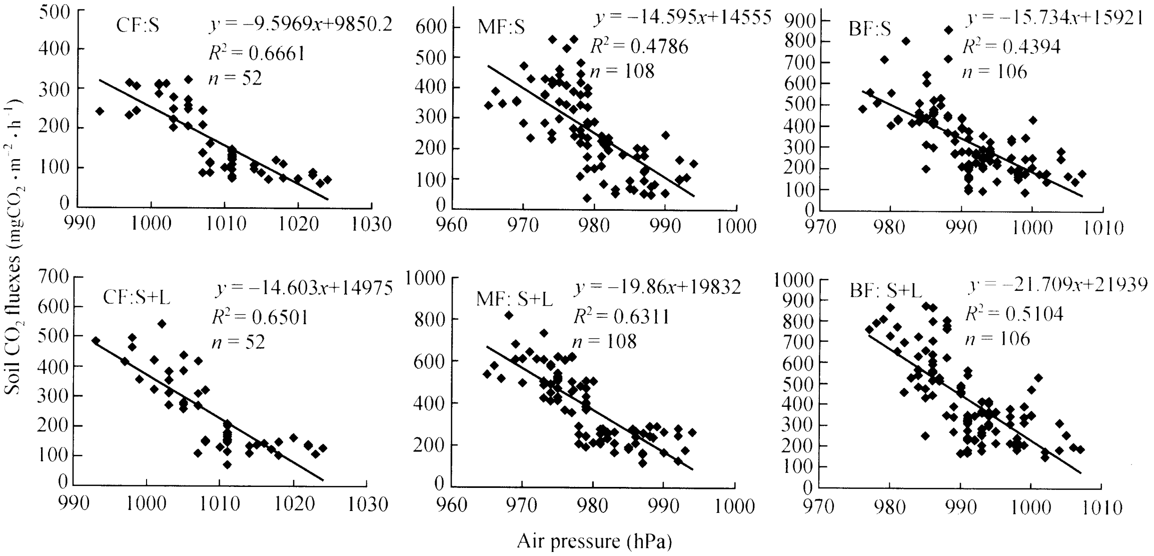

Fig. 5. The relationship between soil CO$_2$ efflux and atmospheric pressure.

differences of altitudes of our field sites would drive greater variation in forestry soil CO$_2$ efflux when the same model prediction was used in the same region.

(4) Comprehensive effects of environmental factors on soil CO$_2$ emission. Soil CO$_2$ emission is a complex biological process influenced by many factors. Environmental factors previously discussed in this study displayed significant individual correlations with soil CO$_2$ efflux, but stepwise regression analysis showed that air pressure was an insignificant factor in terms of influencing soil CO$_2$ efflux. It clearly states that the influence of environmental factors on the soil CO$_2$ efflux was an interactive event, not an individual event with simple adding together, implicating the complexity of soil CO$_2$ emission processes. Because of the small seasonal variation in air pressures, as well as the plant root and microbial metabolic activities relying only on temperature and water, the air pressure has much smaller impact on the efflux than temperatures and water contents. Taking soil temperature, water content and atmospheric pressure into accounts, using stepwise regression analysis, approximately

75.7% (BF), 77.8% (MF) and 86.5% (CF) of soil CO_2 effluxes could be determined by the first two factors, i.e. soil temperature and water content in lower subtropical forests (S+L). The derived regression equations are

$\ln F=0.0634T_s+0.1930\ln M_s+3.8638$ (BF, $P<0.0001$),
$\ln F=0.0549T_s+0.3737\ln M_s+3.5689$ (MF, $P<0.0001$),
$\ln F=0.0597T_s+0.3371\ln M_s+3.3021$ (CF,$P<0.0001$),

where F is expressed as $F = e^{aT_s} \times Ms^{b \times c}$, letters a, b and c are constants, T_s is soil temperature, M_s is soil gravimetric water content. This equation is similar to the factorization model[40,41] which used the same temperature and soil water content as driving variables, but showed different in linear correlation of soil respiration and water content, rather than quadratic equation. The prediction results well matched with the empirical data (Fig. 6).

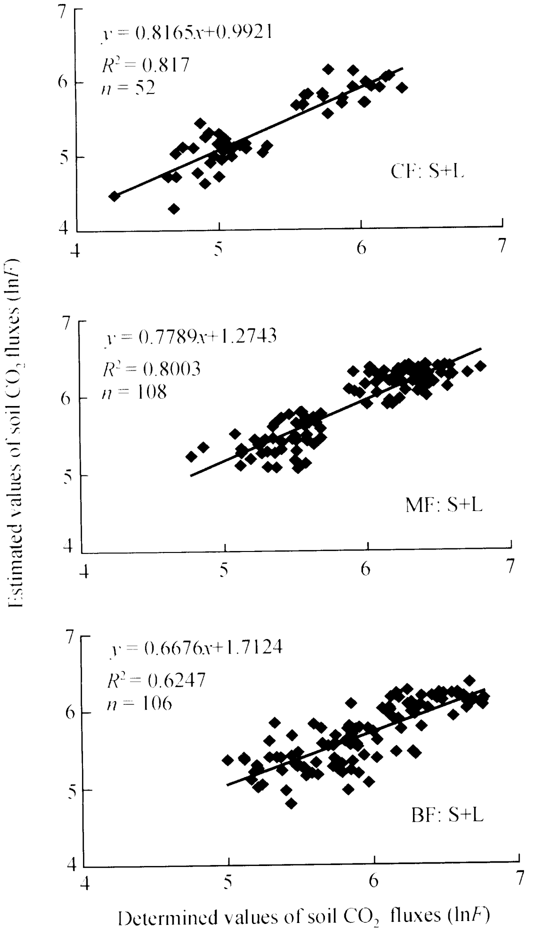

Fig. 6. Curve-fitting of forestry soil CO_2 effluxes using estimated and empirical values.

Based on the values of determinant coefficient (r^2), the variation of soil respiration correlated with soil temperature and water content in the coniferous forest was relatively greater than in broadleaf and mixed broadleaf and coniferous forests (Table 2). Relatively simple structure, interior water holding capacity and lower soil water content in the coniferous forest explained this greater variation in soil respiration. In summary, this equation can be used meaningfully for those in arid and semi-arid regions.

4 Discussion

Soil CO_2 emission process was also influenced by many other factors, such as surface vegetation types and coverage, soil substrate and organic matter content, and soil microbial growth and activity, except those mentioned in previous context.

Different vegetation types presented in the three experiment locations in this study, in which the coverage, LAI (leaf area index), biomass and litter mass also varied from each forest type (Table 1), led to the differences of soil CO_2 emission process and efflux in responding the environmental changes. Wen *et al.*[42] reported that biomasses of BF and MF in Dinghushan Mountain on the surface soil (0—40 cm depth) fine roots (≤5 mm) were 11.40 and 9.59 $t \cdot ha^{-1}$ with net productivity of 3.90 and 3.63 $t \cdot ha^{-1}$, respectively; and the turnover rate of approximately 0.57 and 0.69 times/a on fine roots (≤2 mm). Yi *et al.*[43] also confirmed that there were significant differences of soil microbial biomass in BF, MF and CF of Dinghushan Mountain, having 82.2, 58.8 and 53.0 g $C_{mic} \cdot 100^{-1}$dry soil, and the soil microbial metabolic entropies were 0.58, 0.95 and 1.32 (CO_2-C g^{-1} $C_{mic} \cdot h^{-1}$), respectively in these three types of forests. Clearly, the biomass and productivity of plant roots, and microbial metabolic activity are the main reasons driving the soil CO_2 efflux to higher in BF than in MF and CF. The soil properties of BF were lower in density resulting in easy gas distribution and emission, and higher in organic matter content contributing to rich carbon sources as usage for soil microbial activity. Raich *et al.* indicated that forestry soil respiration rates displayed significant linear correlation with litter mass[44]. Our results in this study showed the similar pattern. Litter

Table 2 Comparative analysis of air temperature, soil water content and temperature in the three types of forests of Dinghushan Mountain

	Season	Treatment	BF	MF	CF
Soil gravimetric water content (M_s) (%)	dry	S	18.56 (6.76)$^{a)}$	21.62 (6.07)$^{b)}$	5.74 (2.89)$^{c)}$
	wet	S	31.33 (6.70)$^{a)}$	35.81 (5.32)$^{b)}$	18.22 (6.36)$^{c)}$
	dry	S+L	16.94 (6.85)$^{a)}$	16.31 (5.15)$^{a)}$	5.61 (4.09)$^{b)}$
	wet	S+L	29.78 (5.74)$^{a)}$	28.68 (6.58)$^{a)}$	17.97 (7.00)$^{b)}$
Soil temperature (0—5 cm depth) (T_s) (℃)	dry	S	16.21 (4.24)$^{a)}$	16.52 (4.25)$^{a,c)}$	18.58 (3.73)$^{b,c)}$
	wet	S	24.57 (2.23)$^{a)}$	25.36 (2.33)$^{a,c)}$	26.08 (3.53)$^{b,c)}$
	dry	S+L	16.21 (4.23)$^{a)}$	16.37 (4.38)$^{a)}$	18.98 (3.71)$^{b)}$
	wet	S+L	24.99 (2.28)$^{a)}$	24.27 (3.45)$^{a)}$	25.55 (2.32)$^{a)}$
Temperature under forest canopy (T) (℃)	dry	/	16.36(3.35)$^{a)}$	15.58(2.79)$^{a)}$	18.18(3.22)$^{c)}$
	wet	/	25.87(4.39)$^{a)}$	26.73(3.96)$^{a)}$	28.10(4.12)$^{c)}$

Numbers in the parentheses are standard deviation, where the same letter (a, b, c) means no significant difference, and different letters represent significant difference at 95% confident level.

coverage provides sufficient carbon source and nutrients for microbial biomass and plant roots, which benefits the growth and activity of roots and microorganisms.

In additions, structural differences of forests likely lead to a serial of variations in environmental factors. Monitoring environmental factors simultaneously in BF and MF showed that forestry air temperature, soil temperature and water content were no significant different among the two forest types whenever in wet or dry seasons. However, those environment factors of CF were shown to be significantly different from the other two types of forests, especially most significant difference in soil water content (Table 2). BF and MF have complex structures and shady environment under forest, which leads to a strong-regulated micro climate. The inner temperature is lower than outer temperature in hot summer, while higher in dry and cold winter. This type of forestry micro climate results ecologically in little change inside the forest and relatively stable environment is suitable for growth and metabolic activities of plant, soil animals and microorganisms. CF has low vegetation coverage leading to easy sunlight penetration, soil evaporation increase and higher radiation. All these would cause greater temperature changes in the forest than outside environment. Dramatically changing of temperature and humidity has negative impact on microbial metabolic activities and thus causes the CF soil CO_2 emission process to be more sensitive in responding to environmental changes.

5 Conclusion

(1) Forestry soil CO_2 effluxes showed greater responses to the seasonal changes. The effluxes were peaked in June to August. During the period, the soil effluxes of BF, MF and CF accounted for 35.9%, 38.1% and 40.2% of total annual effluxes, respectively. The whole wet season (April to September) accounted for 66.36%, 67.52% and 74.53% of total annual effluxes (S+L).

(2) Total annual forestry soil CO_2 effluxes (CO_2 $g \cdot m^{-2} \cdot a^{-1}$) of BF, MF and CF with litter coverage (S+L) were 3942.2±421.1, 3422.36±496.0 and 2163.02±10.4, respectively; while without litters (S) were 2987.32±92.3, 2271.68±131.2 and 1460.3±68.5, respectively. The contributions (%) of forestry litters were 20.06±23.13, 32.93±22.86 and 30.87±15.03 with respecting to BF, MF and CF in Dinghushan Mountain.

(3) CF possessed relatively simpler forestry structure and lower shady area than BF and MF, which led to poor functionality in terms of regulating microclimate. Temperatures inside the forest especially the soil temperature was easily influenced by outside environment conditions resulting in greater sensitivity and seasonal variations in soil CO_2 emission process in responding to the environmental changes. These results well agreed with the corresponding Q_{10} values.

(4) Empirical prediction model based on the data collected in this study showed that 75.7%, 77.8% and 86.5% of the soil CO_2 effluxes (S+L), with respect to those of BF, MF and CF in Dinghushan Mountain lower subtropical region, were determined by this model with soil temperature and water content as variables. This model could better predict the variations in soil respiration rates and characteristics for arid or semi-arid regions with water-stressed or low water content soils.

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