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Temperature sensitivity of total soil respiration and its heterotrophic and autotrophic components in six vegetation types of subtropical China



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HIGHLIGHTS

GRAPHICAL ABSTRACT

- Soil temperature is not a key driver of seasonal variations in R_a.
- The temperature sensitivity of R_h was significantly affected by vegetation type.
- Vegetation type had minor effects on the temperature sensitivity of R_t and R_b.
- Q_{10} of R_t and its components were related to different environmental variables across six vegetation types.



heterotrophic respiration (R_h) and autotrophic respiration (R_a). Vegetation types included a mixed plantation of 10 tree species (10S), a mixed plantation of 30 tree species (30S), an Acacia crassicarpa monoculture (AC), a Castanopsis hystrix monoculture (CH), a Eucalyptus worphylla monoculture (EU) and a shrub and herb land (SH). Some Q_{10} values were missed for R_a because of the nonsignificant relationship between soil temperature and R_a .

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ABSTRACT

The temperature sensitivity of soil respiration (Q_{10}) is a key parameter for estimating the feedback of soil respiration to global warming. The Q_{10} of total soil respiration (R_t) has been reported to have high variability at both local and global scales, and vegetation type is one of the most important drivers. However, little is known about how vegetation types affect the Q_{10} of soil heterotrophic (R_h) and autotrophic (R_a) respirations, despite their contrasting roles in soil carbon sequestration and ecosystem carbon cycles. In the present study, five typical plantation forests and a naturally developed shrub and herb land in subtropical China were selected for investigation of soil respiration. Trenching was conducted to separate R_h and R_a in each vegetation type. The results showed that both R_t and R_h were significantly correlated with soil temperature in all vegetation types, whereas R_a was significantly correlated with soil temperature in only four vegetation types. Moreover, on average, soil temperature explained only 15.0% of the variation in R_a in the six vegetation types. These results indicate that soil temperature may be not a primary factor affecting R_a . Therefore, modeling of R_a based on its temperature sensitivity may not always be valid. The Q_{10} of R_h was significantly affected by vegetation types, which indicates that the response of the soil carbon pool to climate warming may vary with vegetation type. In contrast, differences in neither the Q_{10} of R_t nor that of R_a among these vegetation types were significant. Additionally, variation in the Q_{10} of R_t among vegetation types was negatively related to fine root biomass,

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http://dx.doi.org/10.1016/j.scitotenv.2017.06.194 0048-9697/© 2017 Elsevier B.V. All rights reserved. whereas the Q_{10} of R_h was mostly related to total soil nitrogen. However, the Q_{10} of R_a was not correlated with any of the environmental variables monitored in this study. These results emphasize the importance of independently studying the temperature sensitivity of R_t and its heterotrophic and autotrophic components.

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1. Introduction

Total soil respiration (R_t) is one of the most important ecological processes, because it is the second largest carbon flux in terrestrial ecosystems (Schlesinger and Andrews, 2000) and has the potential to induce considerable variation in atmospheric carbon dioxide concentration in a world with changing climate (Andrews et al., 1999). The temperature sensitivity of R_t has been widely used to estimate the feedback intensity of R_t to increasing temperature (Reichstein et al., 2003; Davidson and Janssens, 2006). The Q_{10} value, a proportional change in soil respiration with a 10 °C increase in temperature, is one of the most common parameters used to describe the temperature sensitivity of soil respiration.

Most of the previous studies on the temperature sensitivity of soil respiration have focused on Rt. However, Rt is overwhelmingly constituted of heterotrophic (R_h) and autotrophic respiration (R_a) , which could respond differently to different environmental variables (Gaumont-Guay et al., 2008; Savage et al., 2013; Matteucci et al., 2015) and make distinct contributions to soil carbon sequestration (Kuzyakov, 2006). In addition, previous studies have shown that R_h and R_a exhibit different temperature sensitivities (e.g. Boone et al., 1998; Rey et al., 2002), which indicates that they respond differently to global warming, and this consequently increases the uncertainty in attempting to estimate future changes in the soil carbon pool. According to the Arrhenius equation and Michaelis-Menten kinetics, the difference in temperature sensitivity between R_h and R_a may be attributed to differences in substrate availability (Davidson and Janssens, 2006; von Luetzow and Koegel-Knabner, 2009). Additionally, temperature sensitivity estimates based on field monthly measurements include not only the response of soil respiration to soil temperature (ST) but also to other ecological processes such as litter fall and root growth (Davidson et al., 1998; Vargas and Allen, 2008). Consequently, both the different dominant drivers of R_h and R_a and the asynchronous dynamics of these drivers may also contribute to the differences in temperature sensitivity.

Early soil respiration models treated Q_{10} as a spatially invariant value (Aber et al., 1997; Tian et al., 1999; Friedlingstein et al., 2006), which could introduce bias regarding feedback intensity (Zhou et al., 2009). Recent studies have revealed that the Q_{10} of R_t is highly variable at both global and local scales (Lenton and Huntingford, 2003; Peng et al., 2009; Xu et al., 2015). Vegetation type is one of the most common variables related to the variation of Q_{10} (Raich and Tufekcioglu, 2000; Song et al., 2013; Diaz-Pines et al., 2014). The Q_{10} of R_t is affected by both soil and plant attributes, including soil water content (SWC) (Wen et al., 2006; Yan et al., 2013), ST (Wen et al., 2006), soil organic matter (Zheng et al., 2009), plant photosynthesis and productivity (Boone et al., 1998; Wan and Luo, 2003; Subke and Bahn, 2010), and plant phenology (Yuste et al., 2004; DeForest et al., 2006).

There have, however, only been a few studies that have focused on the effects of vegetation type on the temperature sensitivity of R_h and/ or R_a in the field. Currently, there is no consensus on whether vegetation type affects the temperature sensitivity of R_h and R_a . Some studies have reported a positive effect of vegetation type on the Q_{10} of R_h (Lee et al., 2010; Uchida et al., 2010), whereas other studies have shown that vegetation type has a neutral effect on the Q_{10} of R_h (Vesterdal et al., 2012; Shi et al., 2015). There have been few studies that have explored the effect of vegetation type on the temperature sensitivity of R_a , and these have reported different results (Luan et al., 2011; Yan et al., 2015). It is still not clear why these discrepancies exist. Additionally, there is currently little information on how temperature sensitivity of R_h and R_a vary with vegetation types, and those studies that have been conducted have reported conflicting results. For example, Lee et al. (2010) found that the Q₁₀ values of R_t, R_h, and R_a for a coniferous plantation were higher than those in a *Quercus*-dominated forest, which indicated that the Q₁₀ values of R_t, R_h, and R_a varied similarly with vegetations types. However, Wang et al. (2013) showed that the Q₁₀ of R_a was significantly different between a pine plantation and a larch plantation, but that the Q₁₀ of R_t and R_h was similar.

In the present study, our main objectives were (i) to separate R_t into R_h and R_a , thereby enabling us to independently quantify their temperature sensitivity in six typical vegetation types in subtropical China, and (ii) to examine how the Q_{10} values of R_t , R_h , and R_a vary according to vegetation type.

2. Materials and methods

2.1. Site description and trenching

The study site is located at Heshan National Field Research Station of Forest Ecosystem (Heshan station), Heshan County, in the central part of Guangdong Province, south China (112°54′E, 22°41′N; 80 m above sea level). This area is characterized by a typical south subtropical monsoon climate. The mean annual temperature is 21.7 °C and the highest and lowest mean monthly temperatures are 28.7 °C (in July) and 13.1°C (in January), respectively. The mean annual effective accumulated temperature (\geq 10 °C) is 7597.2 °C. The mean rainfall is 1700 mm and the mean evaporation is 1600 mm. The soil is classified as a Ultisol developed from sandstone (FAO, 2006).

In the present study, six vegetation types, five plantations and a naturally recovered shrub and herb land (SH), were selected. The five plantations were as follows: a mixed species plantation containing 10 tree species (10S), a mixed species plantation containing 30 tree species (30S), an Acacia crassicarpa monoculture (AC), a Castanopsis hystrix monoculture (CH), and a Eucalyptus urophylla monoculture (EU). The trees planted in 10S comprised seven native species (Castanopsis hystrix, Liquidambar formosana, Machilus chinensis, Cinnamomum burmannii, Tsoongiodendron odorum, Bischofia javanica, and Schima superba) and three exotic species (Magnoliaceae glanca, Jacaranda acutifolia, and Dillenia indica). The 30S plantation contained all the species planted in 10S and a further 17 native species (Michelia macclurei, Ormosia pinnata, Sterculia lanceolata, Garcinia oblongifolia, Garcinia cowa, Dracontomelon dao, Elaeocarpus japonicus, Cinnamomum parthenoxylon, Radermachera sinica, Maesa japonica, Dolichandrone caudafelina, Michelia chapensis, Syzygium cumini, Elaeocarpus apiculatus, Castanopsis fissa, Acronychia pedunculata, Schefflera octophylla) and three exotic species (Delonix regia, Grevillea robusta, and Pterocarpus indicus) The plantations were established in May 2005, and a complete randomized design was employed for plantation configuration. There were three replications for each vegetation type. The trees were planted with a spacing of 3×2 m and the area used for each replication was 1 ha.

Four subplots in SH and Six subplots $(1 \text{ m} \times 1 \text{ m})$ in other vegetation types between the trees and 8–10 m apart from each other were established. Half of these subplots were trenched in the early spring of 2007, and the other three untrenched plots served as controls. For the trenched treatments, a trench of width 0.2 m wide and depth 1 m was dug around each subplot. After lining the trench with polyvinyl chloride (PVC), soil was refilled back into the trench according to the original soil profile, and was subsequently kept free of seedlings and herbs by

manual removal. At the end of 2012, the trenched subplots were retrenched using the same procedure to sever roots growing into the subplot.

2.2. Soil respiration, temperature, and moisture measurement

Soil respiration was measured using a soil CO_2 Flux system (Li-8100, LI-COR Ltd., Lincoln, NE, USA) during the period from March 2013 to February 2014. A PVC collar (20 cm internal diameter, 5 cm height), was positioned and inserted 3 cm into the soil in each subplot. PVC collars were left in the same locations throughout the experiment in which soil respiration was measured in situ. Measurements were conducted once a month during the period 09:00–11:30 AM, the exception being June because of heavy rain. R_t and R_h values were obtained from the control and trenched plots, whereas R_a was calculated as the difference between R_t and R_h .

ST and SWC at 5 cm were recorded simultaneously using the LI-8100 system when the soil respiration was measured. The average value of three measurements was used for data analysis. No measurement of SWC was obtained in February 2014 owing to equipment malfunction. In studies of soil respiration, soil temperature has been measured at different depths at different sites; for example, at depths of 2.5 cm (Akinremi et al., 1999), 5 cm (Rayment and Jarvis, 1997), and 10 cm (Rey et al., 2002). We decided to measure ST at 5 cm because (i) the R² of the soil respiration–ST relationship may be higher at this depth (Pavelka et al., 2007), and (ii) this depth is widely adopted, and thus facilitates comparison with other studies (Xu et al., 2015).

2.3. Q₁₀ value

Numerous equations have been developed to express the temperature sensitivity of soil respiration (Davidson et al., 2006). In the present study, the Q_{10} values were estimated using a first-order exponential equation of the Van't Hoff type (Lloyd and Taylor, 1994; Davidson et al., 2006), which is the most commonly used expression (Xu et al., 2015):

$$\mathbf{R}_{\mathbf{t}}(\text{or }\mathbf{R}_{\mathbf{h}},\mathbf{R}_{\mathbf{a}})=ae^{b\mathbf{T}},$$

where R_t , R_h , and R_a represent the soil respiration efflux (µmol m⁻² s⁻¹), T is ST (°C) at 5 cm depth, and a and b are fitted parameters. The b values were used to calculate the Q_{10} value to describe the temperature sensitivity of soil respiration according to the following equation:

 $Q_{10} = e^{10b}$.

2.4. Soil and vegetation sampling and analysis

Three mixed soil samples were taken from a depth of 0-10 cm in each plot in August 2013. SOC was measured using the H_2SO_4 -

Table	1
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Soil characteristics associated	l with the six	vegetation	types.
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K₂Cr₂O₇ oxidation method (Wang et al., 2010). Soil total nitrogen (TN) was determined using the Kjeldahl acid digestion method with an Alpkem autoanalyzer (Kjeltec System 1026 Distilling Unit, Sweden) (Mo et al., 2016). Leaf area index (LAI) was measured in August 2013 using a Plant Canopy Analyzer (LAI 2000, LI-COR Ltd., Lincoln, NE, USA). At the beginning of measurements, five measurements were taken above the canopy level in an open field, and then at least 10 measurements were taken below the canopy level around each subplot. The mean of the 10 measurements was treated as the value of the subplot. Aboveground litter input (ALI) was estimated using litter traps. Three litter traps of area 1 m \times 1 m and height 1.2 m were randomly installed in each plot. Litter falling into the traps was collected once a month. The collected leaf litter was taken back to the laboratory and dried at 65 °C to a constant mass and then weighed. We were unable to quantify the LAI and ALI for the SH plot because of the absence of a tree layer. Fine root biomass (FRB) was quantified in September 2013, when the FRB might have reached a maximum value (Xu et al., 2013). We used soil cores of 2.4-cm diameter \times 10-cm depth to sample fine roots. Twelve soil cores collected from each plot were taken to the laboratory, and then carefully washed through a 0.5-mm mesh sieve to identify live roots. Root samples were oven-dried at 65 °C to a constant mass and then weighed.

2.5. Statistical analysis

Differences in soil and vegetation characteristic and soil respiration among the different vegetation types were analyzed using a one-way ANOVA. Pairwise comparison was conducted using Tukey's studentized range test. Pearson's correlation analysis was used to quantify the relationship between soil and vegetation characteristics and Q_{10} across the six vegetation types. All data were analyzed using the SPSS 16.0 package (SPSS, Chicago, IL, USA). The significance of differences obtained with all the statistical tests was evaluated at P = 0.05.

3. Results

3.1. The effects of vegetation type on soil and plant characteristics

There were only slight effects of vegetation type on soil and plant characteristics (Tables 1, 2). The effects of vegetation type on mean soil temperature (MST, P = 0.691), mean soil water content (MSWC, P = 0.136), SOC (P = 0.693), TN (P = 0.482), and LAI (P = 0.251) were not significant. However, some of the trends are worthy of mention. We found that MSWC for the SH plot was the highest, being 15.7% higher than the mean of the five plantations. Both SOC and TN were extremely low in the EU plot, which were respectively 26.5% and 26.9% lower than the means for the other vegetation types. Vegetation type had significant effects on soil pH (P = 0.040). The 10S plot had the highest pH and this was significantly higher than that of the AC plot (P = 0.027). ALI was significantly different among the five plantation types (P = 0.006). ALI in the AC plot was approximately

	8 91				
Vegetation type	MST (°C)	MSWC (%)	рН	SOC (g kg ^{-1})	$TN (g kg^{-1})$
10S	$21.58\pm0.40a$	$25.41 \pm 1.25a$	$3.92\pm0.01a$	$44.89\pm3.42a$	$1.86\pm0.18a$
30S	$21.03 \pm 0.21a$	$22.86 \pm 1.48 a$	$3.85\pm0.03ab$	$40.18 \pm 3.71a$	$1.71\pm0.08a$
AC	$21.23\pm0.15a$	$26.59 \pm 1.44 a$	$3.80\pm0.01b$	$43.98 \pm 8.85 a$	$1.80\pm0.17a$
СН	$21.58\pm0.41a$	$20.69\pm0.83a$	$3.85\pm0.03ab$	$40.10\pm5.93a$	$1.71\pm0.29a$
EU	$21.19 \pm 0.16a$	$24.23 \pm 1.36 a$	3.89 ± 0.01 ab	$30.79\pm8.28a$	1.27 ± 0.30 a
SH	$21.53\pm0.61a$	$27.72\pm0.82a$	$3.84\pm0.03ab$	$40.22\pm6.09a$	$1.61\pm0.17a$
P value	0.691	0.136	0.040	0.693	0.482

MST, MSWC, pH, SOC, and TN are the mean soil temperature at 5 cm during the experimental period, annual mean soil water content at 0–5 cm during the experimental period, soil pH at 0–10 cm, soil organic content at 0–10 cm, and total soil nitrogen at 0–10 cm, respectively. 10S, 30S, AC, CH, EU, and SH are the mixed species plantation containing 10 tree species, mixed species plantation containing 30 tree species, *Acacia crassicarpa* monoculture, *Castanopsis hystrix* monoculture, *Eucalyptus urophylla* monoculture, and a shrub and herb land. Values are the means \pm SE, n = 3. One-way ANOVA and Tukey's test were used to compare soil characteristics among the vegetation types. Different letters indicate significant differences among the different vegetation types at the P = 0.05 level.

Table 2Plant characteristic for the six vegetation types.

Vegetation type	LAI	$ALI (g m^{-2} yr^{-1})$	$FRB (g m^{-2})$
10S	$1.89\pm0.67a$	$324.1 \pm 67.2b$	$141.91\pm22.90 \mathrm{ab}$
30S	$2.13 \pm 0.54a$	$256.5 \pm 31.7b$	$187.99 \pm 33.19a$
AC	$2.33\pm0.37a$	$556.1 \pm 36.9a$	$134.54\pm5.92ab$
CH	$1.10\pm0.26a$	362.7 ± 31.7ab	$113.04\pm16.29 \mathrm{ab}$
EU	$1.08\pm0.34a$	377.7 ± 32.7ab	117.95 ± 17.12 ab
SH	-	-	$90.31 \pm 4.26b$
P value	0.251	0.006	0.057

LAI, ALI, and FRB are the leaf area index during the wet season, aboveground litter input during the experimental period, and fine root biomass during the wet season, respectively. Values are the means \pm SE, n = 3. One-way ANOVA and Tukey's test were used to compare vegetation characteristics among the vegetation types. Different letters indicate significant differences among vegetation types at the P = 0.05 level.

two times greater than that for the other plantations, and was significantly higher than that in the 10S (P = 0.019) and 30S (P = 0.003) plots. FRB was slightly affected by the vegetation type (P = 0.057). Tukey's test showed that FRB in the 30S plot was significantly higher than that in the SH plot (P = 0.035).

3.2. The response of R_t , R_h , and R_a to ST in the six vegetation types

R_t in the 10S, 30S, AC, CH, EU, and SH plots was significantly exponentially to ST (P < 0.001) (Fig. 1). Similarly, there were exponential regression relationships between R_h and ST in plots 10S, 30S, AC, CH, EU, and SH (P < 0.001) (Fig. 2). However, only in plots 10S, AC, CH, and SH did R_a show a significant exponential regression relationship with ST (P < 0.01). In plots 30S and EU, R_a was not significantly exponentially related to ST (P > 0.05) (Fig. 3). On average, ST explained 40.9% of the variation in R_t in the six vegetation types (Fig. 1), and 56.8% of R_h (Fig. 2). In contrast, ST explained only 15.0% of the variation in R_a (Fig. 3). Moreover, in each vegetation type, the degree of correlation between ST and R_a was the lowest among the different respirations.

3.3. The effects of vegetation type on the temperature sensitivity of R_t , R_h , and R_a

The Q_{10} values for R_t in vegetation types 10S, 30S, AC, CH, EU, and SH were 1.82 \pm 0.14, 1.48 \pm 0.08, 1.82 \pm 0.24, 1.96 \pm 0.19, 1.85 \pm 0.32, and 2.28 \pm 0.13, respectively (Fig. 4). The Q_{10} of R_t in plot SH tended

to be higher than that in the plantations, being 27.7% higher than the mean of the Q₁₀ of R_t in the five plantations and 54.1% higher than the lowest Q₁₀ of R_t in plot 30S (P = 0.119). Overall, however, the effect of vegetation type on the Q₁₀ of R_t was not significant (P = 0.216). The Q₁₀ values for R_h in vegetation types 10S, 30S, AC, CH, EU, and SH were 1.94 \pm 0.07, 1.65 \pm 0.04, 1.57 \pm 0.12, 1.73 \pm 0.07, 2.2 \pm 0.10, and 1.91 \pm 0.19, respectively, which were significantly affected by the vegetation type (P = 0.017) (Fig. 4). The Q₁₀ of R_h in plot EU was the highest, and was significantly higher than the Q₁₀ of R_h in plots 30S (P = 0.038) and AC (P = 0.016). The Q₁₀ values for R_a in plots 10S, AC, CH, and SH were 1.76 \pm 0.44, 1.96 \pm 0.31, 1.66 \pm 0.17, 2.59 \pm 0.52, respectively (Fig. 4). The vegetation type did not significantly affect the Q₁₀ of R_a in these vegetation types (P = 0.250).

3.4. The relationship between Q_{10} and environmental variables

The Q₁₀ of R_t was negatively related to FRB (r = -0.954, P = 0.003) across the six vegetation types (Table 3). No other significant relationship was found between the Q₁₀ of R_t and environmental variables. TN showed the strongest relationship with the Q₁₀ of R_h (r = -0.733, P = 0.098). In contrast to the other environmental variables examined, SOC was also closely related to the Q₁₀ of R_h (r = -0.683, P = 0.135). Since both TN and SOC are widely accepted as indicators of soil organic matter, our results may indicate that the Q₁₀ of R_h is regulated by soil organic matter across six vegetation types. In contrast, the Q₁₀ of R_a was not closely related to any of the environmental variables examined in this study. Notably, although not significant, some of the environmental variables could affect Q₁₀ in contrary ways for different types of Q₁₀. For example, LAI was negatively related to the Q₁₀ of R_t and R_h, but was positively related to the Q₁₀ of R_a.

4. Discussion

4.1. Vegetation type has minor effects on the Q_{10} of R_t .

At a local scale, the Q_{10} of R_t has generally been found to be related to SWC across different vegetation types. For example, J. Luan et al. (2013) showed that the Q_{10} of R_t in a pine plantation was higher than that in a nearby oak forest, which was attributed to the higher SWC at the former site. Similarly, Wang et al. (2006) found that the Q_{10} of R_t in six temperate forests varied significantly and was related to SWC. In the present



Fig. 1. The response of Rt (total soil respiration) to soil temperature (ST) in six vegetation types. See Table 1 for the abbreviations of vegetation types.



Fig. 2. The response of R_h (heterotrophic respiration) to soil temperature (ST) in six vegetation types. See Table 1 for the abbreviations of vegetation types.

study, R_t in the natural developed shrub and herb land tended to be more sensitive to soil temperature than that in the plantations, which may due to the higher SWC of this vegetation.

Overall, however, our results indicate that vegetation type did not affect the Q₁₀ of R_t, which contrasts with the findings of many previous studies (Jenkins and Adams, 2011; Song et al., 2013; e.g. Diaz-Pines et al., 2014). Nevertheless, the findings of some previous studies are consistent with those of the present study. For example, Kim et al. (2010) found that there were no significant differences in the Q_{10} of R_t among adjacent deciduous, coniferous, and mixed forests in Korea. Moreover, Yan et al. (2013) found no significant difference in the Q₁₀ of Rt between a forest and a grassland at a small scale in the eastern Loess Plateau of China. The former authors suggested that the nonsignificant differences could be attributable to the only slight variation in soil and plant variables among the different vegetation types, whereas the latter authors suggested that any differences could be offset by different environmental factors. In the present study, the differences in soil and plant characteristics among the different vegetation types were small, most of which were not significant. Additionally, the Q₁₀ of R_t was positively related to some environmental variables but negatively related to others. Consequently, both of these factors could be the potential reason for the non-significant effects of vegetation type. It should also be noted that the temperature sensitivity of R_t is, in fact, the integrative response of R_h and R_a to soil temperature. Accordingly, the effect of vegetation type could be confounded by the different responses of the Q_{10} of R_h and Q_{10} of R_a to the different vegetation types.

The Q_{10} values for R_t were negatively related to FRB in the six vegetation types examined in this study. Roots have been found to increase (Boone et al., 1998; Lee et al., 2010) or decrease (Lin et al., 1999) the temperature sensitivity of R_t , whereas other studies have found no significant relationship between FRB and the Q_{10} of R_t (Wang et al., 2016). Even in the same study, FRB was positively related to the Q_{10} of R_t in an adjacent oak plantation (J.W. Luan et al., 2013). Additionally, the findings of this study indicate that, as a consequence of having higher fine root biomass, the oak plantation had a lower Q_{10} of R_t compared to the pine plantation. These contradictions serve to complicate the issue of how roots affect the temperature sensitivity of R_t . The partition of R_t into R_h



Fig. 3. The response of R_a (autotrophic respiration) to soil temperature (ST) at six vegetation types. See Table 1 for the abbreviations of vegetation types.



Fig. 4. Q_{10} values for R_t (total soil respiration), R_h (heterotrophic respiration), and R_a (autotrophic respiration) in six vegetation types. Q_{10} is the temperature sensitivity of soil respiration ($Q_{10} = e^{10b}$). The error bars represent the standard error of the mean (n = 3). A one-way ANOVA and Tukey's test were used to compare the Q_{10} of R_t , R_h , and R_a among the six vegetation types. Different letters indicate significant differences (P = 0.05) among the vegetation types. See Table 1 for the abbreviations of vegetation types.

and R_a may provide a more detailed mechanistic insight on the drivers of the Q_{10} of R_t . However, neither the Q_{10} of R_h nor R_a alone was significantly related to FRB, and it remains unclear which factors contribute to the negative correlation between FRB and the Q_{10} of R_t .

4.2. Vegetation type significantly affect the Q_{10} of R_h

There have been only a few studies on the Q_{10} of R_{h} , and at present, there is no consensus on whether vegetation type has an effect on this parameter (e.g. Lee et al., 2010; Vesterdal et al., 2012). The present study provides evidence indicating that vegetation type could affect the Q₁₀ of R_h in plantations in subtropical China. Afforestation, combined with shrub recovery since the 1980s has accounted for >65% of the carbon sink in China's terrestrial ecosystems (Piao et al., 2009). As one of the most widely cultivated plantation types in this region, eucalyptus plantations have the highest Q₁₀ of R_b among the vegetation types examined in the present study. A previous study has shown that eucalyptus plantations have a large carbon sink in this site (Chen et al., 2011). However, compared to other vegetation types, the soil carbon sequestration capacity of eucalyptus plantations may be compromised by the high Q₁₀ of R_h. In contrast, AC, another typically fastgrowing plantation in south China, had the lowest Q₁₀ of R_h. Additionally, the 30S plantation tended to have the lowest Q_{10} value of R_{h} , which may suggest that higher species numbers would alleviate the feedback intensity of R_h to warming. It is still not known what contributes to

Table 3

The relationship between Q₁₀ and soil and plant characteristics across six vegetation types.

	Q_{10} of R_t	Q ₁₀ of R _h	Q_{10} of R_a
	P = 0.190	P = 0.243	P = 0.655
	n = 6	n = 6	n = 4
SWC	r = 0.569	r = 0.085	r = 0.748
	P = 0.239	P = 0.872	P = 0.252
	n = 6	n = 6	n = 4
pH	r = -0.108	r = 0.719	r = -0.330
	P = 0.839	P = 0.107	P = 0.670
	n = 6	n = 6	n = 4
SOC	r = -0.036	r = -0.683	r = -0.374
	P = 0.947	P = 0.135	P = 0.626
	n = 6	n = 6	n = 4
TN	r = -0.165	r = -0.733	r = -0.714
	P = 0.754	P = 0.098	P = 0.286
	n = 6	n = 6	n = 4
LAI	r = -0.588	r = -0.656	r = 0.938
	P = 0.297	P = 0.229	P = 0.225
	n = 5	n = 5	n = 3
ALI	r = 0.482	r = -0.257	r = 0.883
	P = 0.411	P = 0.676	P = 0.312
	n = 5	n = 5	n = 3
FRB	r = -0.954	r = -0.425	r = -0.721
	P = 0.003	P = 0.401	P = 0.279
	n = 6	n = 6	n = 4

See Table 1 and Fig. 1 for the abbreviations.

this variation of the Q_{10} of $R_{\rm h}$. However, it is clear that the selection of vegetation type for afforestation may influence the feedback of soil carbon pool to future global warming.

The Q₁₀ of R_b could be directly affected by substrate quality, and indirectly affected by substrates accessibility, pH, moisture, and oxygen and nutrient supply (Davidson and Janssens, 2006; von Luetzow and Koegel-Knabner, 2009), all of which could be influenced by vegetation type (Baldocchi et al., 2004; Russell et al., 2007; Ceccon et al., 2015). Using organic soils from three sub-alpine communities, Jenkins and Adams (2011) found that variation in the Q_{10} of $R_{\rm b}$ reflected the various productivity among three vegetation types in sub-alpine Australia. In a soil incubation experiment, Nianpeng et al. (2013) found that Q₁₀ varied with the stoichiometry of newly input substrate among four vegetation types. These findings indicate that substrate availability could exert a strong influence on the Q₁₀ of R_h and emphasize the key role of substrate availability in regulating the Q₁₀ of R_b across different vegetation types. Our results may support the previous viewpoint that soil TN is the most relevant variable related to variation of the Q10 of Rh across different vegetation types in this study, and that SOC is also closely correlated with the Q₁₀ of R_h.

4.3. R_a had a weak relationship with ST

Many previous studies have found that both R_t and its two components are significantly exponentially related to ST (e.g. Boone et al., 1998; Gaumont-Guay et al., 2008; Yan et al., 2015). In the present studies, both R_t and R_h were significantly related to ST. However, ST did not explain much of the variation of R_a . R_a includes root respiration and rhizomicrobial respiration by rhizospheric microbes utilizing rhizospheric organic matter or/and materials released from live roots (Kuzyakov and Larionova, 2005; Kuzyakov, 2006). R_a is closely associated with the aboveground C supply (Tang et al., 2005; Gaumont-Guay et al., 2008; Kuzyakov and Gavrichkova, 2010), and this supply may have a time lag lasting from minutes to days (Kuzyakov and Gavrichkova, 2010). Additionally, root–soil interactions could influence the temperature sensitivity of SOM decomposition in the rhizosphere (Zhu and Cheng, 2011). All these mechanisms only serve to complicate estimations of the temperature sensitivity of R_a .

Some studies have shown that the apparent close relationship between R_a and ST may include the response of R_a to environmental factors other than ST, but covariant with ST (Subke and Bahn, 2010; Gomez-Casanovas et al., 2012; Savage et al., 2013). Conversely, the decoupling of ST and other environmental variables may weaken the relationship between R_a and ST. For example, in Mediterranean-type ecosystems, where fine root growth does not fluctuate with soil temperature (Burton et al., 1998; Rey et al., 2002), Hinko-Najera et al. (2015) found that the R_a of a broadleaf forest did not response significantly to soil temperature. At this site, a previous study has also shown that considerable root growth commences in May and reaches a maximum value in September (Xu et al., 2013). These observations are, nevertheless, inconsistent with the fluctuation in soil temperature recorded in the present study (data not shown). This may be a potential reason explaining the weak relationship between R_a and ST in this study.

5. Conclusions

In this study, we separated R_t into its components R_h and R_a by means of trenching in six vegetation types of subtropical China. Soil respiration rate and ST were measured monthly, and the relationships between ST and R_t , R_h , and R_a were subsequently estimated. The temperature sensitivity of R_t , R_h , and R_a was calculated and described in terms of the Q_{10} value. We examined the effects of vegetation type on the Q_{10} of R_t , R_h , and R_a separately, and attempted to explore how they varied with soil and plant attributes across the six vegetation types. The main findings of the study are as follows:

ST is a key driver of R_t and R_h , although other environmental factors exert important effects on R_a . Consequently, the estimated feedback intensity of R_a to global warming based on its temperature sensitivity may not be accurate for these vegetation types.

The Q_{10} of R_h was significantly affected by vegetation type, which suggests that the selection of vegetation type for afforestation may influence the feedback of the soil carbon pool in response to global warming.

The Q_{10} of R_h was significantly affected by vegetation type, whereas the Q_{10} values of R_t and R_a were not. The results may contribute to the difficulty in evaluating soil respiration feedback in response to global warming, and confirm the necessity of treating R_t and its components differently in studying the effect of vegetation type on soil respiration temperature sensitivity.

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References

- Aber, J.D., Ollinger, S.V., Driscoll, C.T., 1997. Modeling nitrogen saturation in forest ecosystems in response to land use and atmospheric deposition. Ecol. Model. 101, 61–78. Akinremi, O.O., McGinn, S.M., McLean, H.D.J., 1999. Effects of soil temperature and mois-
- ture on soil respiration in barley and fallow plots. Can. J. Soil Sci. 79, 5–13.
- Andrews, J.A., Harrison, K.G., Matamala, R., Schlesinger, W.H., 1999. Separation of root respiration from total soil respiration using carbon-13 labeling during Free-Air Carbon dioxide Enrichment (FACE). America Journal]–>Soil Sci. Soc. Am. J. 63, 1429–1435.
- Baldocchi, D.D., Xu, L.K., Kiang, N., 2004. How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak-grass savanna and an annual grassland. Agric. For. Meteorol. 123, 13–39.
- Boone, R.D., Nadelhoffer, K.J., Canary, J.D., Kaye, J.P., 1998. Roots exert a strong influence on the temperature sensitivity of soil respiration. Nature 396, 570–572.
- Burton, A.J., Pregitzer, K.S., Zogg, G.P., Zak, D.R., 1998. Drought reduces root respiration in sugar maple forests. Ecol. Appl. 8, 771–778.
- Ceccon, E., Sanchez, I., Powers, J.S., 2015. Biological potential of four indigenous tree species from seasonally dry tropical forest for soil restoration. Agrofor. Syst. 89, 455–467.
- Chen, D., Zhang, C., Wu, J., Zhou, L., Lin, Y., Fu, S., 2011. Subtropical plantations are large carbon sinks: evidence from two monoculture plantations in South China. Agric. For. Meteorol. 151, 1214–1225.
- Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173.
- Davidson, E.A., Belk, E., Boone, R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Glob. Chang. Biol. 4, 217–227.
- Davidson, E.A., Janssens, I.A., Luo, Y.Q., 2006. On the variability of respiration in terrestrial ecosystems: moving beyond Q(10). Glob. Chang. Biol. 12, 154–164.
- DeForest, J.L., Noormets, A., McNulty, S.G., Sun, G., Tenney, G., Chen, J., 2006. Phenophases alter the soil respiration-temperature relationship in an oak-dominated forest. Int. J. Biometeorol. 51, 135–144.

- Diaz-Pines, E., Schindlbacher, A., Godino, M., Kitzler, B., Jandl, R., Zechmeister-Boltenstern, S., Rubio, A., 2014. Effects of tree species composition on the CO₂ and N₂O efflux of a Mediterranean mountain forest soil. Plant Soil 384, 243–257.
- FAO, 2006. World reference base for soil resources 2006. World Soil Resources Report 103. FAO, Rome.
- Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K.G., Schnur, R., Strassmann, K., Weaver, A.J., Yoshikawa, C., Zeng, N., 2006. Climatecarbon cycle feedback analysis: results from the (CMIP)-M-4 model intercomparison. J. Clim. 19, 3337–3353.
- Gaumont-Guay, D., Black, T.A., Barr, A.G., Jassal, R.S., Nesic, Z., 2008. Biophysical controls on rhizospheric and heterotrophic components of soil respiration in a boreal black spruce stand. Tree Physiol. 28, 161–171.
- Gomez-Casanovas, N., Matamala, R., Cook, D.R., Gonzalez-Meler, M.A., 2012. Net ecosystem exchange modifies the relationship between the autotrophic and heterotrophic components of soil respiration with abiotic factors in prairie grasslands. Glob. Chang. Biol. 18, 2532–2545.
- Hinko-Najera, N., Fest, B., Livesley, S.J., Arndt, S.K., 2015. Reduced throughfall decreases autotrophic respiration, but not heterotrophic respiration in a dry temperate broadleaved evergreen forest. Agric. For. Meteorol. 200, 66–77.
- Jenkins, M.E., Adams, M.A., 2011. Respiratory quotients and Q(10) of soil respiration in sub-alpine Australia reflect influences of vegetation types. Soil Biol. Biochem. 43, 1266–1274.
- Kim, D.G., Mu, S., Kang, S., Lee, D., 2010. Factors controlling soil CO₂ effluxes and the effects of rewetting on effluxes in adjacent deciduous, coniferous, and mixed forests in Korea. Soil Biol. Biochem. 42, 576–585.
- Kuzyakov, Y., 2006. Sources of CO₂ efflux from soil and review of partitioning methods. Soil Biol. Biochem. 38, 425–448.
- Kuzyakov, Y., Gavrichkova, O., 2010. REVIEW: time lag between photosynthesis and carbon dioxide efflux from soil: a review of mechanisms and controls. Glob. Chang. Biol. 16, 3386–3406.
- Kuzyakov, Y., Larionova, A.A., 2005. Root and rhizomicrobial respiration: a review of approaches to estimate respiration by autotrophic and heterotrophic organisms in soil. J. Plant Nutr. Soil Sci. 168, 503–520.
- Lee, N.-Y., Koo, J.-W., Noh, N.J., Kim, J., Son, Y., 2010. Autotrophic and heterotrophic respiration in needle fir and Quercus-dominated stands in a cool-temperate forest, central Korea. J. Plant Res. 123, 485–495.
- Lenton, T.M., Huntingford, C., 2003. Global terrestrial carbon storage and uncertainties in its temperature sensitivity examined with a simple model. Glob. Chang. Biol. 9, 1333–1352.
- Lin, G.H., Ehleringer, J.R., Rygiewicz, P.T., Johnson, M.G., Tingey, D.T., 1999. Elevated CO₂ and temperature impacts on different components of soil CO₂ efflux in Douglas-fir terracosms. Glob. Chang. Biol. 5, 157–168.
- Lloyd, J., Taylor, J.A., 1994. On the temperature-dependence of soil respiration. Funct. Ecol. 8, 315–323.
- Luan, J., Liu, S., Wang, J., Zhu, X., Shi, Z., 2011. Rhizospheric and heterotrophic respiration of a warm-temperate oak chronosequence in China. Soil Biol. Biochem. 43, 503–512.
- Luan, J., Liu, S., Wang, J., Zhu, X., 2013. Factors affecting spatial variation of annual apparent Q(10) of soil respiration in two warm temperate forests. PLoS One 8.
- Luan, J.W., Liu, S.R., Wang, J.X., Zhu, X.L., 2013. Factors affecting spatial variation of annual apparent Q(10) of soil respiration in two warm temperate forests. PLoS One 8.
- von Luetzow, M., Koegel-Knabner, I., 2009. Temperature sensitivity of soil organic matter decomposition-what do we know? Biol. Fertil. Soils 46, 1–15.
- Matteucci, M., Gruening, C., Ballarin, I.G., Seufert, G., Cescatti, A., 2015. Components, drivers and temporal dynamics of ecosystem respiration in a Mediterranean pine forest. Soil Biol. Biochem. 88, 224–235.
- Mo, Q., Li, Z.a., Zhu, W., Zou, B., Li, Y., Yu, S., Ding, Y., Chen, Y., Li, X., Wang, F., 2016. Reforestation in southern China: revisiting soil N mineralization and nitrification after 8 years restoration. Sci Rep 6.
- Nianpeng, H., Ruomeng, W., Yang, G., Jingzhong, D., Xuefa, W., Guirui, Y., 2013. Changes in the temperature sensitivity of SOM decomposition with grassland succession: implications for soil C sequestration. Ecol. Evol. 3, 5045–5054.
- Pavelka, M., Acosta, M., Marek, M.V., Kutsch, W., Janous, D., 2007. Dependence of the Q10 values on the depth of the soil temperature measuring point. Plant Soil 292, 171–179.
- Peng, S.S., Piao, S.L., Wang, T., Sun, J.Y., Shen, Z.H., 2009. Temperature sensitivity of soil respiration in different ecosystems in China. Soil Biol. Biochem. 41, 1008–1014.
- Piao, S., Fang, J., Ciais, P., Peylin, P., Huang, Y., Sitch, S., Wang, T., 2009. The carbon balance of terrestrial ecosystems in China. Nature 458, 1009–U1082.
- Raich, J.W., Tufekcioglu, A., 2000. Vegetation and soil respiration: correlations and controls. Biogeochemistry 48, 71–90.
- Rayment, M.B., Jarvis, P.G., 1997. An improved open chamber system for measuring soil CO₂ effluxes in the field. J. Geophys. Res.-Atmos. 102, 28779–28784.
- Reichstein, M., Rey, A., Freibauer, A., Tenhunen, J., Valentini, R., Banza, J., Casals, P., Cheng, Y.F., Grunzweig, J.M., Irvine, J., Joffre, R., Law, B.E., Loustau, D., Miglietta, F., Oechel, W., Ourcival, J.M., Pereira, J.S., Peressotti, A., Ponti, F., Qi, Y., Rambal, S., Rayment, M., Romanya, J., Rossi, F., Tedeschi, V., Tirone, G., Xu, M., Yakir, D., 2003. Modeling temporal and large-scale spatial variability of soil respiration from soil water availability, temperature and vegetation productivity indices. Glob. Biogeochem. Cycles 17.
- Rey, A., Pegoraro, E., Tedeschi, V., De Parri, I., Jarvis, P.G., Valentini, R., 2002. Annual variation in soil respiration and its components in a coppice oak forest in Central Italy. Glob. Chang. Biol. 8, 851–866.
- Russell, A.E., Raich, J.W., Valverde-Barrantes, O.J., Fisher, R.F., 2007. Tree species effects on soil properties in experimental plantations in tropical moist forest. America Journal]– >Soil Sci. Soc. Am. J. 71, 1389–1397.

- Savage, K., Davidson, E.A., Tang, J., 2013. Diel patterns of autotrophic and heterotrophic respiration among phenological stages. Glob. Chang. Biol. 19, 1151–1159.
- Schlesinger, W.H., Andrews, J.A., 2000. Soil respiration and the global carbon cycle. Biogeochemistry 48, 7–20.
- Shi, B.K., Gao, W.F., Jin, G.Z., 2015. Effects on rhizospheric and heterotrophic respiration of conversion from primary forest to secondary forest and plantations in northeast China. European Journal of Soil Biology]->Eur. J. Soil Biol. 66, 11–18.
- Song, X., Yuan, H., Kimberley, M.O., Jiang, H., Zhou, G., Wang, H., 2013. Soil CO₂ flux dynamics in the two main plantation forest types in subtropical China. Sci. Total Environ. 444, 363–368.
- Subke, J.-A., Bahn, M., 2010. On the 'temperature sensitivity' of soil respiration: can we use the immeasurable to predict the unknown? Soil Biol. Biochem. 42, 1653–1656.
- Tang, J.W., Baldocchi, D.D., Xu, L., 2005. Tree photosynthesis modulates soil respiration on a diurnal time scale. Glob. Chang. Biol. 11, 1298–1304.
- Tian, H., Melillo, J.M., Kicklighter, D.W., McGuire, A.D., Helfrich, J., 1999. The sensitivity of terrestrial carbon storage to historical climate variability and atmospheric CO₂ in the United States. Tellus Ser. B-Chem. Phys. Meteorol. 51, 414–452.
- Uchida, Y., Hunt, J.E., Barbour, M.M., Clough, T.J., Kelliher, F.M., Sherlock, R.R., 2010. Soil properties and presence of plants affect the temperature sensitivity of carbon dioxide production by soils. Plant Soil 337, 375–387.
- Vargas, R., Allen, M.F., 2008. Environmental controls and the influence of vegetation type, fine roots and rhizomorphs on diel and seasonal variation in soil respiration. New Phytol. 179, 460–471.
- Vesterdal, L., Elberling, B., Christiansen, J.R., Callesen, I., Schmidt, I.K., 2012. Soil respiration and rates of soil carbon turnover differ among six common European tree species. For. Ecol. Manag. 264, 185–196.
- Wan, S.Q., Luo, Y.Q., 2003. Substrate regulation of soil respiration in a tallgrass prairie: results of a clipping and shading experiment. Glob. Biogeochem. Cycles 17.
- Wang, C., Yang, J., Zhang, Q., 2006. Soil respiration in six temperate forests in China. Glob. Chang. Biol. 12, 2103–2114.
- Wang, F., Zhu, W., Xia, H., Fu, S., Li, Z., 2010. Nitrogen mineralization and leaching in the early stages of a subtropical reforestation in southern China. Restor. Ecol. 18, 313–322.
- Wang, W., Zeng, W.J., Chen, W.L., Yang, Y.H., Zeng, H., 2013. Effects of forest age on soil autotrophic and heterotrophic respiration differ between evergreen and deciduous forests. PLoS One 8.

- Wang, R., Wang, Z., Sun, Q., Zhao, M., Du, L., Wu, D., Li, R., Gao, X., Guo, S., 2016. Effects of crop types and nitrogen fertilization on temperature sensitivity of soil respiration in the semi-arid Loess Plateau. Soil Tillage Res. 163, 1–9.
- Wen, X.-F., Yu, G.-R., Sun, X.-M., Li, Q.-K., Liu, Y.-F., Zhang, L.-M., Ren, C.-Y., Fu, Y.-L., Li, Z.-Q, 2006. Soil moisture effect on the temperature dependence of ecosystem respiration in a subtropical Pinus plantation of southeastern China. Agric. For. Meteorol. 137, 166–175.
- Xu, W., Liu, J., Liu, X., Li, K., Zhang, D., Yan, J., 2013. Fine root production, turnover, and decomposition in a fast-growth *Eucalyptus urophylla* plantation in southern China. J. Soils Sediments 13, 1150–1160.
- Xu, Z., Tang, S., Xiong, L., Yang, W., Yin, H., Tu, L., Wu, F., Chen, L., Tan, B., 2015. Temperature sensitivity of soil respiration in China's forest ecosystems: patterns and controls. Appl. Soil Ecol. 93, 105–110.
- Yan, J.X., Chen, L.F., Li, J.J., Li, H.J., 2013. Five-year soil respiration reflected soil quality evolution in different forest and grassland vegetation types in the eastern loess plateau of China. Clean-Soil Air Water 41, 680–689.
- Yan, M., Guo, N., Ren, H., Zhang, X., Zhou, G., 2015. Autotrophic and heterotrophic respiration of a poplar plantation chronosequence in northwest China. For. Ecol. Manag. 337, 119–125.
- Yuste, J.C., Janssens, I.A., Carrara, A., Ceulemans, R., 2004. Annual Q(10) of soil respiration reflects plant phenological patterns as well as temperature sensitivity. Glob. Chang. Biol. 10, 161–169.
- Zheng, Z.-M., Yu, G.-R., Fu, Y.-L., Wang, Y.-S., Sun, X.-M., Wang, Y.-H., 2009. Temperature sensitivity of soil respiration is affected by prevailing climatic conditions and soil organic carbon content: a trans-China based case study. Soil Biol. Biochem. 41, 1531–1540.
- Zhou, T., Shi, P., Hui, D., Luo, Y., 2009. Global pattern of temperature sensitivity of soil heterotrophic respiration (Q(10)) and its implications for carbon-climate feedback. J. Geophys. Res.-Biogeosci. 114.
- Zhu, B., Cheng, W., 2011. Rhizosphere priming effect increases the temperature sensitivity of soil organic matter decomposition. Glob. Chang. Biol. 17, 2172–2183.