Temperature sensitivity of soil respiration is affected by prevailing climatic conditions and soil organic carbon content: A trans-China based case study

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Article info

Understanding the spatial variation of temperature sensitivity (i.e. Q10) of soil respiration (R s) and its controlling factors, is critical to improve the precision of carbon budget estimations at regional scales. In this study, data from 2–3 continuous years of R s measurements over 15 ecosystems of ChinaFLUX were summarized to analyze the response of R s to soil temperature. Moreover, we improved our dataset by collecting previously published Q10 values from 34 ecosystems in China. The ecosystems studied were located in the main climatic zones of China, spanning from alpine via temperate to tropical. Spatial variations of Q10 and its controlling factors were analyzed. The results showed that soil temperature at a 5 cm depth satisfactorily explained the seasonal variations in R s of the 15 ChinaFLUX ecosystems (R 2 varying from 0.37 to 0.83). Based on the overall data, the Q10 values of R s in China ranged from 1.28 to 4.75. The spatial variations in Q10 were primarily determined by soil temperature during measurement periods, soil organic carbon (SOC) content, and ecosystem type. Ecosystems in colder regions and with higher SOC content had relatively higher Q10 values. Moreover, ecosystems of different vegetation types showed different Q10 values. A temperature- and SOC-dependent function for Q10 is suggested, which could be a valuable reference for improving the regional-scale models of R s and ecosystem carbon cycles.

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1. Introduction

Soil respiration (R s), after gross primary productivity, is the second largest carbon flux between terrestrial ecosystems and the atmosphere. As a key factor influencing soil carbon reserves and soil CO 2 flux, the temperature sensitivity of R s has been given considerable attention in the research of the global carbon cycle (Xu and Qi, 2001b; Lenton and Huntingford, 2003; Fierer et al., 2006). However, disagreements among researchers remain, especially regarding whether or not long-term warming will induce acceleration of soil organic carbon (SOC) decomposition and whether root respiration or heterotrophic respiration is more sensitive to long-term temperature changes (Giardina and Ryan, 2000; Knorr et al., 2005; Reichstein et al., 2005a; Davidson and Janssens, 2006; Hartley et al., 2007).

The temperature sensitivity of R s (i.e. the Q10 value), which refers to the factor by which soil CO 2 efflux increases with an increase in temperature of 10°C, is an important ecological parameter in ecosystem carbon cycle models (Reichstein et al., 2005b). Previously, Q10 was commonly treated as a constant in many ecosystem models, for instance, as a constant of 2 in CASA and TEM (Potter et al., 1993; Raich et al., 1991) and as a constant of 2 or 2.5 in the BIOME-BGC model (Running and Hunt, 1993). Many field experiments, however, show that Q10 values vary spatially (Xu and Qi, 2001b; Lenton and Huntingford, 2003), compelling more recent modellers to treat the temperature response of R s differently (Xu and Qi, 2001b; Reichstein et al., 2002, 2003). Several studies suggest that a small deviation of the Q10 value in carbon cycle models may result in significant bias in the estimation of R s (Townsend et al., 1997; Xu and Qi, 2001b). Chen and Tian (2005), for example, found that soil heterotrophic respiration of boreal biome was underestimated by 71% in a model using a constant of 2 as compared to respiration data obtained by a temperature-dependent Q10 model.

To improve the precision of carbon budget estimation at a regional scale, therefore, studying both Q10 values across different ecosystems as well as the spatial variations of Q10 and its controlling factors is critical. In China, scattered R s measurements have
been made for the last 10 years (Wu et al., 1997; Liu et al., 1998), and the number of measurements has increased continuously in recent years (Lou et al., 2004; Cao et al., 2004). By contrast, quantifying the spatial variations of $Q_{10}$ across different ecosystems as well as the response of $Q_{10}$ to environmental factors remains difficult due to differences in measurement methods. The objectives of this study were to examine the temperature response of $R_s$ in 15 terrestrial ecosystems in China by using 2–3 years of $R_s$ data continuously measured at 10 sites of ChinaFLUX (Chinese Terrestrial Ecosystem Flux Research Network) and to analyze the spatial patterns of $Q_{10}$ and quantify the effects of temperature and SOC content on $Q_{10}$ by improving our dataset through previously published $Q_{10}$ data of other terrestrial ecosystems in China. Finally, $Q_{10}$ values in China were compared with those in Europe and North America.

2. Materials and methods

2.1. Study sites

$R_s$ was measured at 10 sites of ChinaFLUX, including five forest sites (Changbaishan, Qianyanzhou, Dinghushan, Heshan, Xishuangbanna), one grassland site (Haibei), and four cropland sites (Sanjiang, Yucheng, Yanting, Fukang) (Sites 1–10 in Fig. 1). Furthermore, $R_s$ data measured for at least one growing season at 13 other sites in China, including seven forest sites, two grassland sites, and two cropland sites (Sites 11–23 in Fig. 1), were collected from previously published literature. These sites were located in the main climatic zones of China, spanning from alpine via temperate to tropical. Table 1 presents site specific information, including ecosystem types, climates, soil characteristics, and measurement periods for $R_s$.

2.2. Measurements of $R_s$

At the 10 ChinaFLUX sites (15 ecosystems), $R_s$ was measured twice per week (at intervals of two or three days) during the growing season and once per week during the dormancy season by the static chamber/gas chromatography method (Wang and Wang, 2003). In each ecosystem, 4–6 replicate collars of $50 \times 50$ cm$^2$ were randomly inserted to the soil with distance of about 1 m. The CO$_2$ effluxes were measured between 9:00 and 11:00 am (China Standard Time, CST) by fitting the chambers of $50 \times 50 \times 50$ cm$^3$ gas tightly to the collars for 30 min. The four gas samples were taken by 100 ml plastic syringes with intervals of 0, 10, 20 and 30 min after closing the chambers. Air samples were analyzed using 4890D gas chromatography (Agilent Technologies, Palo Alto, CA, USA). $R_s$ rates were determined by changes in measured CO$_2$ concentration with time. While air samples were being collected, air temperatures inside and outside the chambers and soil temperatures at depths of 0 cm and 5 cm were recorded. Detailed information of $R_s$ measurement and data processing are described in Wang and Wang (2003).

The $R_s$ data from the literature survey were measured using either the same method applied at the ChinaFLUX sites or using the dynamic chamber/IRGA method. We only selected $R_s$ data measured with one of these two methods: (1) because these two methods are the most popular methods for $R_s$ measurements in China; and (2) to ensure comparability of $Q_{10}$ values from different measurement methods. (Kou et al. (2007) found the measurement difference was small ($\sim 10\%$) between the static chamber method and the dynamic chamber method with the CO$_2$ concentration measured by the LI-6400 system.) We also found that the difference in measured $R_s$ between these two methods was less than 11\% (unpublished observations), with good comparability of $Q_{10}$ values.

2.3. Data analysis

We used the van’t Hoff equation (Eq. (1); Lloyd and Taylor, 1994) to analyze the response of $R_s$ to temperature at ChinaFLUX sites,

$$R_s = R_0 e^{BT}$$  \hspace{1cm} (1)

where $R_s$ is the soil respiration rate (\mu mol m$^{-2}$ s$^{-1}$), $T$ is the soil temperature at a 5 cm depth (°C), and $R_0$ is the soil respiration rate at a reference temperature of 0°C (\mu mol m$^{-2}$ s$^{-1}$).
Table 1

<table>
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<th>No.</th>
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<th>Longitude</th>
<th>MAT (°C)</th>
<th>MAP (mm)</th>
<th>2003.1–2005.9</th>
<th>Ecosystem type</th>
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<td>Bange</td>
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<td>SOC content(0–20 cm, kg m⁻²) 56 9.0 19 54 27 12.0 0.31 1.93</td>
</tr>
</tbody>
</table>

(continued on next page)
According to the definition of $Q_{10}$, the $Q_{10}$ value for Eq. (1) was calculated as:

$$Q_{10} = \frac{R_{T+10}}{R_T} = e^{10B} \tag{2}$$

where $R_T$ and $R_{T+10}$ are $R_s$ rates at temperature $T$ and $T+10$, respectively. The $Q_{10}$ value is independent of temperature in Eq. (2).

Considering the dramatic difference in soil water status during paddy and dry farming periods in rotation cropland ecosystems, only $R_s$ data measured during dry farming period were selected for analysis at the Yanting site (i.e. $R_s$ data during periods of wheat and rape growing for wheat-paddy rotation cropland and rape-paddy rotation cropland, respectively).

For the $Q_{10}$ values of terrestrial ecosystems in China collected from published literature only the datasets that satisfied the following requirements were used: (1) the $Q_{10}$ value was derived from measurements lasting for at least one growing season; (2) the $Q_{10}$ value was derived from Eqs. (1) and (2); (3) the temperature index was soil temperature at a depth of 5 ± 5 cm; and (4) the determination coefficient ($R^2$) between $R_s$ and soil temperature was higher than 0.50. If the $Q_{10}$ value was not directly given in the literature, we calculated the $Q_{10}$ value using Eq. (2) with the given parameters of Eq. (1). Thus, we obtained 34 $Q_{10}$ values from 23 sites (Table 1).

To compare $Q_{10}$ values in China with other regions, $Q_{10}$ values were collected from published literature for forest ecosystems in Europe and North America using the same data collection requirements as used for China.

An exponential equation (Eq. (3)) was used to analyze the relationship between temperature and $Q_{10}$.

$$Q_{10} = a e^{-kT_{ave}} \tag{3}$$

where $T_{ave}$ is the average soil temperature at a depth of 5 ± 5 cm during the measurement periods, $k$ is the constant indicating how fast $Q_{10}$ is changing with temperature, and $a$ is the $Q_{10}$ value when $T_{ave}$ is 0°C.

All statistical analyses were performed by SPSS 13.0 (SPSS for Windows, Version 13.0, Chicago, IL, USA), and significant differences for all statistical tests were evaluated at the level of $\alpha = 0.05$.

### 3. Results

#### 3.1. The response of $R_s$ to temperature

The relationship between $R_s$ and soil temperature at a depth of 5 cm for 15 different ecosystems in China could be described satisfactorily using the van’t Hoff equation (Fig. 2), and from 37% to 83% of seasonal variations in $R_s$ could be explained by soil temperature (Table 2). The correlations between $R_s$ and soil temperature were lower for artificial ecosystems (i.e. cropland) than natural ecosystems (i.e. forest and grassland).

The temperature sensitivity of $R_s$ varied among different ecosystem types (Table 2). The $Q_{10}$ value in the Changbaishan temperate forest was highest among the six forest ecosystems, but still within the range (2.0–6.3) reported for temperate forest ecosystems (Davidson et al., 1998). Among the three subtropical forests with similar temperature condition (i.e. Qianyazhou, Dinghushan, and Heshan), the $Q_{10}$ value of Dinghushan evergreen broadleaved forest (about 400 years old) was lower than those of both the Qianyazhou and Heshan planted forest ecosystems (about 20 years old). The $Q_{10}$ values at two alpine grassland ecosystems (i.e. alpine meadow and alpine shrub at Haibei) were near to or higher than the average $Q_{10}$ value of temperate and tropical grassland ecosystems on global scales (2.1, Wang and Fang, 2000).
2007) and higher than those of temperate grassland ecosystems in China (1.60–1.81, Liu et al., 2007). The fluctuation of $Q_{10}$ in cropland ecosystems was small (1.67–2.14), and $Q_{10}$ varied with the change in crop systems at the same site.

3.2. The spatial variations of $Q_{10}$ values in China

Synthesizing ChinaFLUX data and collected data, the results showed that the frequency distribution of $Q_{10}$ values in China was partial normal, with skewness and kurtosis at 1.45 and 2.61, respectively (Fig. 3a). $Q_{10}$ values of diverse terrestrial ecosystems in China changed from 1.28 to 4.75 ($n = 49$), within the range of previously reported values (1–8) (Lenton and Huntingford, 2003).

The average $Q_{10}$ values showed an order of forest ($2.51 \pm 0.78$) > grassland ($2.15 \pm 0.44$) > cropland ($1.99 \pm 0.24$) ecosystems, with significant difference among these three ecosystem types ($P < 0.05$). The $Q_{10}$ of deciduous forest was significantly higher than that of evergreen forest ($P < 0.05$), and the $Q_{10}$ of evergreen needle-leaf forest was significantly higher than that of evergreen broadleafed forest ($P < 0.05$) (Fig. 3b). The average $Q_{10}$ values of alpine, temperate, warm temperature, subtropical, and tropical ecosystems were 2.69, 2.66, 2.22, 1.94, and 2.31, respectively (Fig. 3c), and generally the colder the climate, the higher the $Q_{10}$ value.

3.3. The controlling factors and functions of the spatial variations in $Q_{10}$

This study suggested that $Q_{10}$ in cold regions was higher than that in warm regions (Fig. 3c), which was consistent with the earlier studies (Tjoelker et al., 2001; Chen and Tian, 2005). The result of exponential regression between $Q_{10}$ and temperature (Eq. (3)) showed that soil temperature at a depth of 5 ± 5 cm during the measurement periods explained 27% of the spatial variation of $Q_{10}$ in China (Fig. 4), and a 1°C increase in average soil temperature would lead to a 3.3% decrease in $Q_{10}$ in China.
The labile pool of SOC provides important substrate for microbial respiration. Therefore, the change of SOC content, especially in the topsoil, affects soil microbial activities (Atkin et al., 2000), causing the temperature response of $R_t$ to vary among soils with different SOC contents. There was a strong positive correlation between $Q_{10}$ and SOC content at a depth of 20 cm, accounting for 44% of the spatial variation of $Q_{10}$ ($P < 0.001$) (Fig. 5a). The outlying data of SOC content at the Miyaluo site (36.9 kg m$^{-2}$), however, exhibited a high weighing on the regression analysis (Fig. 5a), which may have influenced the analysis result. After further analysis that excluded data from the Miyaluo site, the correlation coefficient between $Q_{10}$ and SOC content remained significantly ($R^2 = 0.26$, $P < 0.001$, Fig. 5b). Moreover, setting $T_{\text{ave}}$ (i.e. the average soil temperature at a depth of $5 \pm 5$ cm during the measurement periods, Eq. (3)) as a controlling factor, the partial correlation analysis showed that the partial correlation between SOC content and $Q_{10}$ remained significantly (correlation coefficient 0.37, $P < 0.05$). This result further indicates the direct influence of SOC content on $Q_{10}$.

The above results (Figs. 2–4) suggested that the spatial variations in $Q_{10}$ of $R_t$ in China were primarily determined by soil temperature during the measurement periods, SOC content, and ecosystem type. In this study, by analyzing the relationship between $Q_{10}$ and the average soil temperature during the measurement periods ($T_{\text{ave}}$) and SOC content (0–20 cm), two statistical functions were obtained:

$$Q_{10} = 3.67e^{-0.033T_{\text{ave}}}, R^2 = 0.27, P < 0.001$$

$$Q_{10} = 0.09 \text{SOC} + 1.79, R^2 = 0.26, P < 0.001$$

A multi-variable function was also obtained by further regression analysis:

$$Q_{10} = 0.56e^{-0.018T_{\text{ave}}(0.13 \text{SOC} + 4.77)}, R^2 = 0.32, P < 0.001$$

These functions therefore represent the best estimates of the attendant parameters with currently available data. Although they are not completely precise, they are arguably appropriately representative, and are valuable for application in the modification of regional-scale models of $R_t$ in China.

### 3.4. Comparison of $Q_{10}$ between China and other regions

Taking forest ecosystems as an example, the linear regressions were performed between latitude, mean annual air temperature, SOC content at a depth of 100 cm and $Q_{10}$ values in China, as well as in other regions (Europe and North America; Fig. 6). Then, the significance test of difference in curve slopes of regression functions was made.
The spatial variations of $Q_{10}$ in other regions were also affected by temperature and SOC content to a certain degree (Fig. 6b,c). Within a similar latitudinal range, mean annual air temperature, and SOC content, the differences among the curve slopes for $Q_{10}$ with the above three factors between China and other regions were not significant (significance test of difference in curve slopes: $P = 0.46, 0.054, \text{and } 0.58$).

**Fig. 4.** The relationship between $Q_{10}$ and average soil temperature at a 5 ± 5 cm depth during measurement periods ($T_{\text{ave}}$ °C).

**Fig. 5.** The relationship between $Q_{10}$ and SOC content (0–20 cm, kg m$^{-2}$). Data of Miyaluo alpine forest (Site 14 in Table 1) was excluded in Fig. 5b.

**Fig. 6.** The relationship between $Q_{10}$ (●: China; ○: Europe; △: North America) and (a) latitude, (b) mean annual air temperature and (c) SOC content (0–100 cm, kg m$^{-2}$). SOC content data of China was derived from Data-sharing Network of Earth System Science (http://www.geodata.cn). SOC content data of non-China regions was derived from IGBP-DIS (ftp://www.daac.ornl.gov/data/global_soil/IGBP-SurfaceProducts/data/soilcarb.dat). The bold line in each plot presents the best fit for data from China, and the thin line presents the best fit for data from other regions. $Q_{10}$ values of non-China regions were derived from: Buchmann (2000) ($Q_{10} = 2.41, 3.22, 2.87, 2.39$); Granier et al. (2000) ($Q_{10} = 1.72$); Janssens and Pilegaard (2003) ($Q_{10} = 4.21$); Epron et al. (2004) ($Q_{10} = 3.35$); Davidson et al. (1998) ($Q_{10} = 3.9$); Xu and Qi (2001a) ($Q_{10} = 1.72$); Southern et al. (2002) ($Q_{10} = 2.86$); Samuelson et al. (2004) ($Q_{10} = 1.43, 1.81, 1.83, 1.91$); Falk et al. (2005) ($Q_{10} = 2.93$); Happer et al. (2005) ($Q_{10} = 2.22$); Khomik et al. (2006) ($Q_{10} = 5.6$, averaged in this study); McCulley et al. (2007) ($Q_{10} = 1.78$).
4. Discussion

4.1. The influences of prevailing climatic conditions on $Q_{10}$

Previous studies have suggested a negative correlation between $Q_{10}$ and temperature during measurement periods (Tjoelker et al., 2001; Chen and Tian, 2005; Kirschbaum, 2006). Our study also found a 1°C increase in average soil temperature during measurement periods would lead to a 3.3% decrease in $Q_{10}$ in China (Fig. 4), which is lower than the value of 8% at global scale (Chen and Tian, 2005). Furthermore, the $Q_{10}$ value was higher for the temperate forest ecosystem than subtropical and tropical forest ecosystems (Table 2). The major reason for the strong effect of temperature on $Q_{10}$ is the varying dependence of $R_5$ processes (i.e. the decomposition of soil carbon matter by soil microbial activities and root respiration with root growth) on temperature across ecosystems within different climatic zones. The low temperature condition is the major limiting factor for root growth and soil microbial activities of ecosystems in cold regions, such as the Changbai mountain temperate forest and the Haibei alpine grassland. The soil microbial activities and root growth in cold ecosystems are low under the long-term cold environment and the soil $CO_2$ flux is low. Furthermore, soil warming, especially during the short summer, can enhance the soil microbial activities and root growth sharply, which leads to an active decomposition of soil carbon matter and the enhancement of plant-derived $CO_2$ release from root respiration, and results in a quick increase in the soil $CO_2$ efflux rate. However, the temperature condition is usually conducive for root growth and soil microbial activities in tropical and subtropical ecosystems, temperature limitations on biologic activities being low in such ecosystems.

Moreover, a strong dependence of $Q_{10}$ on soil moisture has been quantified in many studies (Xu and Qi, 2001b; Reichstein et al., 2002; Janssens and Pilegaard, 2003; Gaumont-Guay et al., 2006). As a whole, the interpretations of the influence of soil moisture on $Q_{10}$ are complicated. Reichstein et al. (2002) speculates that the reduction of $Q_{10}$ with increasing drought severity could be due to a switch in the carbon pool being respired; however, recent study has found that the $Q_{10}$ value of forest ecosystems in China was significantly and negatively correlated with mean annual precipitation (Peng et al., 2009), indicating the temperature sensitivity of $R_5$ declined when the soil moisture saturated, leading to limited oxygen diffusion (Wang et al., 2006). Moreover, a controlled-environment laboratory experiment on undisturbed organic and mineral soil cores found the $Q_{10}$ was stable and decreased only slightly when the soil dried (Reichstein et al., 2005b), which implies the moisture effects on temperature sensitivity $R_5$ are confounded. Although we did not find significant correlation between mean annual precipitation and $Q_{10}$ based on our studied data, and did not take soil moisture into account considering that most ecosystems in this study were in relatively humid regions, precipitation or soil moisture should be considered as important environmental factors in further $R_5$ measurements, especially in with respect to arid regions.

4.2. The influence of SOC content on $Q_{10}$

Our study concluded that ecosystems with higher SOC content had higher $Q_{10}$ values (Fig. 5). This conclusion was partially because the labile pool of SOC is an important substrate for $R_5$. Ecosystems with higher SOC content generally have greater potential for soil $CO_2$ efflux. Thus, with other environmental factors are fixed, the increase rate of $R_5$ in ecosystems with higher SOC content tends to be higher than that with lower SOC content. Moreover, several experiments suggest that SOC characteristics (e.g. SOC quantity/quality) could affect the temperature sensitivity of soil organic matter composition (Fierer et al., 2005; Knorr et al., 2005). The composition of microbial community and quantity/quality of SOC are linked such that the temperature response of soil organic matter decomposition decreases with a decrease in SOC content (Zogg et al., 1997; Atkin et al., 2000; Fierer et al., 2005; Knorr et al., 2005), indicating that the acclimation of $R_5$ to warming may also induce the lower temperature sensitivity of $R_5$ with lower SOC content (Luo et al., 2001).

4.3. The influence of ecosystem types on $Q_{10}$

The result indicating that the $Q_{10}$ of deciduous forest was significantly higher than that of evergreen forest and that the $Q_{10}$ of evergreen needle-leaf forest was significantly higher than that of evergreen broadleaved forest (Fig. 3b) suggests that ecosystem type also influences the spatial variation of $Q_{10}$. One reason is the different phenological patterns of belowground biologic activities within different ecosystems. In general, plant phenological variabilities of deciduous forests in cold regions are more obvious than those of evergreen forests in warm regions, with the increasing range of root activity of deciduous forests in spring being more significant than in evergreen forests. Therefore, $R_5$ of deciduous forests transfer from heterotrophic-dominated activity to heterotrophic- and autotrophic-dominated activities (Griffis et al., 2004). The abrupt change of the $R_5$ component in deciduous forests resulted in higher $Q_{10}$ than in evergreen forests on an annual scale (Table 2, Fig. 3). Curiel Yuste et al. (2004) also found that $Q_{10}$ in deciduous forests was significantly higher than that in needle-leaf forests with similar climate and soil conditions in a mixed forest in Belgium due to the more seasonal variations of plant activity and phenology in deciduous forests than in evergreen forests.

Another reason for the influence of ecosystem type on $Q_{10}$ is possibly attributed to the varying microbial communities and SOC component among different ecosystem types (Zhou et al., 2002), which would affect the response of $R_5$ to temperature. A SOC mineralization experiment on the Dinghushan ecosystem (Ouyang et al., 2007) suggests that when the early and mid-succession forests are replaced by the advanced-succession forests, the SOC content and stable carbon reserves in later forests increase as a way of accumulating more stable carbon into the soil. If the stable carbon is really less sensitive to temperature than labile carbon (Giardina and Ryan, 2000; Thornley and Cannell, 2001), this could be a further explanation for the lower $Q_{10}$ in evergreen broadleaved forests than in evergreen needle-leaf forests. Moreover, lower correlations between soil temperature and $R_5$ of artificial ecosystems (i.e. cropland) than natural ecosystems (i.e. grassland and forest) may partly be ascribed to the two ecosystem types are under different soil managements. In this study, the cropland ecosystems were tilled annually, mixing organic matter with the soil and causing transitional changes in soil porosity or moisture, which could cause extra variability in $R_5$, partly hampering the effect of temperature in contrast to the soil under grassland and forest ecosystems.

5. Conclusions

This study identified the environmental influences on temperature sensitivity ($Q_{10}$) of soil respiration ($R_5$) across major terrestrial ecosystems in China. Ecosystems in colder regions and with higher SOC content had relatively higher $Q_{10}$ values and ecosystems of different types showed different $Q_{10}$ values. The spatial variations in $Q_{10}$ are primarily determined by soil temperature during measurement periods, SOC content, and ecosystem type across China. The negative correlation between $Q_{10}$ and temperature resulted from the varying dependence of $R_5$ processes on
temperatures across ecosystems within different climatic zones. The dependence of $Q_{10}$ on SOC content indicated the labile organic carbon pool as substrate for microbial respiration and the acclimatisation of $R_{t}$ to warming. Ecosystem type also influenced the spatial variation of $Q_{10}$ partly due to different phenological patterns of biologic activities belowground and partly due to different microbial communities and SOC components among different ecosystem types. And partly due to ecosystems of artificial and natural types under different soil managements, the correlation between soil temperature and $R_{t}$ of cropland ecosystems was lower than forest and grassland ecosystems. A temperature- and SOC-dependent function for $Q_{10}$ is suggested for the improvement of $R_{t}$ and ecosystem carbon cycle modelling in China. The spatial variation of $Q_{10}$ implies that regional-scale $R_{t}$ derived from carbon cycle models with fixed $Q_{10}$ value should be used with due caution. It also implies that further studies on the spatial pattern of $Q_{10}$ and its controlling factors, as well as the function for describing such spatial pattern, are required in order to improve the precision of carbon budget estimations on regional scales.

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