AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Biogeosciences

RESEARCH ARTICLE
10.1002/2015JG003217

Key Points:
- Temperature sensitivity increased logarithmically with increase in latitude
- Carbon quality-temperature hypothesis is applicable to forest soils on a large scale
- Periodic temperature incubation and continuous measurement offer a new protocol

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3

Correspondence to:
N. He, and Q. Yu,
henp@igsnrr.ac.cn;
turfyu@gmail.com

Citation:
Wang, Q., N. He, G. Yu, Y. Gao, X. Wen, R. Wang, S. E. Koerner, and Q. Yu (2016), Soil microbial respiration rate and temperature sensitivity along a north-south forest transect in eastern China: Patterns and influencing factors, *J. Geophys. Res. Biogeosci.*, *121*, 399–410, doi:10.1002/2015JG003217.

Received 14 SEP 2015
Accepted 13 JAN 2016
Accepted article online 17 JAN 2016
Published online 7 FEB 2016

Soil microbial respiration rate and temperature sensitivity along a north-south forest transect in eastern China: Patterns and influencing factors

Qing Wang[1,2], Nianpeng He[1], Guirui Yu[1], Yang Gao[1], Xuefa Wen[1], Rongfu Wang[2], Sally E. Koerner[3], and Qiang Yu[4,5]

[1]Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China, [2]Anhui Agricultural University, Hefei, China, [3]Nicholas School of the Environment, Duke University, Durham, North Carolina, USA, [4]State Key Laboratory of Forest and Soil Ecology, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang, China, [5]Department of Biology and Graduate Degree Program in Ecology, Colorado State University, Fort Collins, Colorado, USA

Abstract Soil organic matter is one of the most important carbon (C) pools in terrestrial ecosystems, and future warming from climate change will likely alter soil C storage via temperature effects on microbial respiration. In this study, we collected forest soils from eight locations along a 3700 km north-south transect in eastern China (NSTEC). For 8 weeks these soils were incubated under a periodically changing temperature range of 6–30°C while frequently measuring soil microbial respiration rate (*Rs*; each sample about every 20 min). This experimental design allowed us to investigate *Rs* and the temperature sensitivity of *Rs* (Q_{10}) along the NSTEC. Both *Rs* at 20°C (R_{20}) and Q_{10} significantly increased (logarithmically) with increasing latitude along the NSTEC suggesting that the sensitivity of soil microbial respiration to changing temperatures is higher in forest soils from locations with lower temperature. Our findings from an incubation experiment provide support for the hypothesis that temperature sensitivity of soil microbial respiration increases with biochemical recalcitrance (C quality-temperature hypothesis) across forest soils on a large spatial scale. Furthermore, microbial properties primarily controlled the observed patterns of R_{20}, whereas both substrate and microbial properties collectively controlled the observed patterns of Q_{10}. These findings advance our understanding of the driving factors (microbial versus substrate properties) of R_{20} and Q_{10} as well as the general relationships between temperature sensitivity of soil microbial respiration and environmental factors.

1. Introduction

Temperature is one of the key factors that influence soil microbial respiration rate (*Rs*) [*Davidson and Janssens*, 2006; *Fang and Moncrieff*, 2001; *Ise and Moorcroft*, 2006], as such *Rs* is predicted to change in a warmer world. The temperature sensitivity of *Rs* (Q_{10}) is influenced by various factors, in particular, substrate and microbial community properties, and therefore varies across landscapes at both small and large spatial scales [*Davidson and Janssens*, 2006; *Plante et al.*, 2010]. Even slight changes in *Rs* in response to the predicted warmer world might affect the global patterns of soil organic carbon (SOC) storage, with consequential feedbacks on global warming trends [*Jiang et al.*, 2013; *Shibata et al.*, 2005]. Therefore, understanding the mechanisms underlying the global effects of temperature on *Rs* and the patterns of Q_{10} is imperative for predicting carbon sequestration in a warmer world.

Two types of soil factors regulate the response of soil organic matter (SOM) decomposition to temperature—microbial community and abiotic soil properties. Differences in microbial community structure as well as microbial biomass have been shown to influence soil microbial respiration [*Malcolm et al.*, 2008; *Rousk et al.*, 2012]. Moreover, multiple abiotic soil properties, such as oxidation reduction potential (ORP), electrical conductivity (COND), pH [*Shen et al.*, 2013], permeability, hydraulic conductivity [*Gabriel and Kellman*, 2014; *Moyano et al.*, 2013], and substrate for microbial metabolism [*Blagodatskaya et al.*, 2014b; *Zhang et al.*, 2013], might influence soil microbial respiration, as these soil properties regulate microbial activity. Although some studies have focused on these aspects, the dominant factors influencing soil microbial respiration at large spatial scales still remain unclear, particularly the relative contribution of soil microbes and soil substrate properties [*Blagodatskaya et al.*, 2014a; *Briones et al.*, 2014; *Xu et al.*, 2015].

Table 1. Information About the Eight Soil Sampling Sites Along the North-South Transect in Eastern China

Sampling Sites	Longitude (E)	Latitude (N)	MAT[b] (°C)	MAP (mm)	Vegetation Types	Dominant Species	Soil Type
HZ[a]	123°01′12″	51°46′48″	−3.67	472.96	Cold-temperate coniferous forest	*Larix gmelinii* Rupr, *Pinus. Sylvestris* L., *Betula. Platyphylla* Suk.	Grey forest soil
LS	128°53′51″	47°11′06″	0.01	648.34	Temperate conifer broadleaf mixed forest	*L. gmelinii* Rupr, *P. koraiensis* Siebold, *B. platyphylla* Suk.	Dark brown soil
CB	128°05′27″	42°24′16″	2.79	691.00	Temperate conifer broadleaf mixed forest	*L. gmelinii* Rupr, *P. koraiensis* Siebold, *Quercus Mongolica* Fisch.	Dark brown soil
DL	115°25′24″	39°57′27″	6.55	539.07	Warm temperate deciduous broad-leaved forest	*P. tabulaeformis* Carr, *Q. wutaishanica* Mayr, *L. principis-rupprechtii* Mayr	Brown soil
TY	112°04′39″	36°41′43″	5.98	644.38	Warm temperate deciduous broad-leaved forest	*Q. wutaishanica* Mayr, *P. tabulaeformis* Carr, *Populus. davidiana*Dode.	Cinnamon soil
JL	114°26′28″	24°35′05″	18.22	1769.93	Subtropical evergreen broad-leaved forest	*S. superb* Gardn, *Castanopsis. fabri* Hance, *C. carlesii* Hayata.	Red earth
DH	112°32′14″	23°10′25″	21.83	1927.00	South subtropical evergreen broad-leaved forest	*Schima. Superba* Gardn, *Cryptocarya. Chinensis* Hemsl, *P. massoniana* Lamb.	Laterite
JF	108°51′26″	18°44′18″	23.15	2265.80	Tropical mountain rainforest	*Schoepfia. Jasminodora* Sieb, *Ficus. vasculosa* Wall, *Madhuca. Hainanensis* Chun.	Lateritic yellow earth

[a]HZ, Huzhong; LS, Liangshui; CB, Changbai; DL, Dongling; TY, Taiyue; JL, Jiulian; DH, Dinghu; JF, Jianfeng.
[b]MAT, mean annual temperature; MAP, mean annual precipitation.

In addition, the reasons for observed global patterns of Q_{10}, a representation of soil microbial respiration response to changing temperature [*Davidson and Janssens*, 2006], are also still debated. Two important hypotheses addressing the global patterns of Q_{10} have been developed in the past decades. First, *Kirschbaum* [1995] hypothesized that *Rs* is more sensitive to temperature in regions with historically low temperature climate than in regions with a high temperature climate (i.e., Q_{10} is stronger in low temperature regions compared to that in high temperature regions). Overall, large spatial scale experimental evidence for a latitudinal gradient is scarce, although support for this hypothesis has been obtained from incubation experiments [*Conant et al.*, 2011; *Kirschbaum*, 1995] as well as small spatial scale regional studies performed using elevation gradients [*Whitby and Michael*, 2013]. Second, the carbon (C) quality-temperature (CQT) hypothesis [*Bosatta and Ågren*, 1999] predicts that *Rs* of low-quality substrates will have a stronger temperature dependency than high-quality substrates. *Rs* is regulated by microbial enzyme kinetics, and soil microbial respiration increases with a decrease in SOM quality. Differences in definitions and measurements of C quality in SOM [*Li et al.*, 2015; *Plante et al.*, 2010; *Wagai et al.*, 2013] have resulted in inconsistent support for the CQT hypothesis, with studies finding that Q_{10} increases [*Craine et al.*, 2010; *Gershenson et al.*, 2009], has no relationship [*Conen et al.*, 2006; *Fang et al.*, 2005], or decreases with the carbon quality of the substrate [*Liski et al.*, 1999; *Sierra*, 2012]. The discrepancies in these studies might possibly be a virtue of the different definitions of C quality by physical or chemical methods [*Bosatta and Ågren*, 1999; *Plante et al.*, 2010; *Wagai et al.*, 2013]. *Min et al.* [2014] and *Sierra* [2012] reported the temperature sensitivity of soil organic matter decomposition using the Arrhenius equation, which implied that a substrate of low quality requires high amounts of energy to be degraded, and its decomposition rate is slow. In other word, the decomposition rate was positively related to SOM quality, or the higher decomposition rate indicated higher qual-

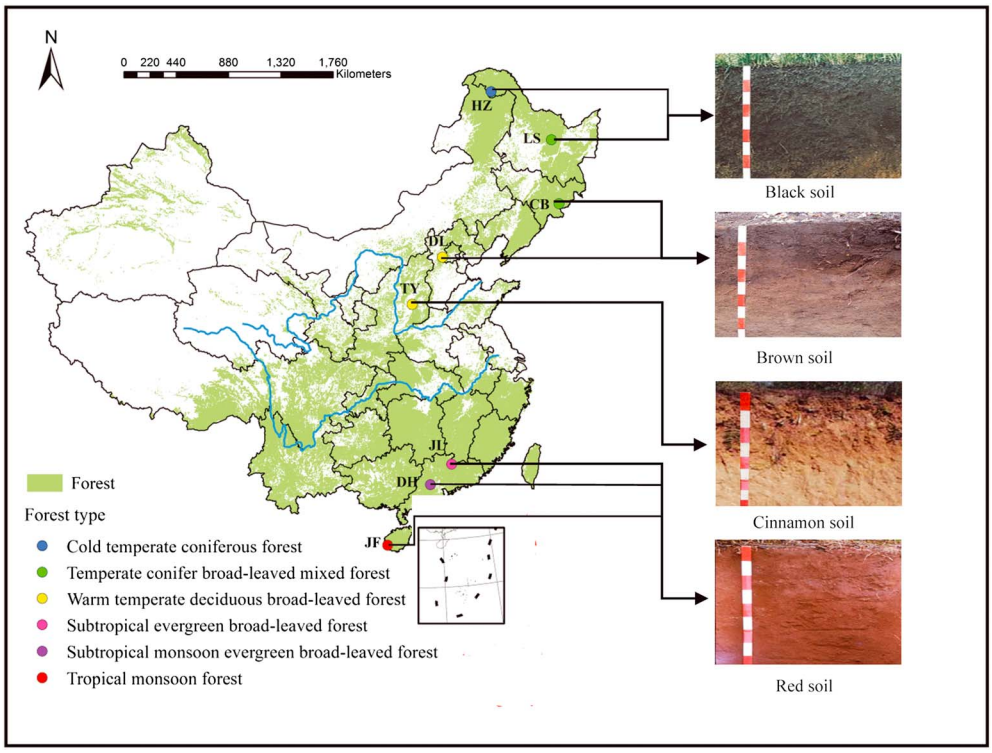

Figure 1. Site locations along the north-south transect of eastern China. The eight sites were located in forests which were typical representations of that forest type. HZ, Huzhong; LS, Liangshui; CB, Changbai; DL, Dongling; TY, Taiyue; JL, Jiulian; DH, Dinghu; JF, Jianfeng. The eight sampling sites were categorized as black soil (HZ and LS), brown soil (CB and DL), cinnamon soil (TY), and red soil (JL, DH, and JF) according to the genetic type of soils in China. The colored illustrations are inserted according to soil types in the right.

ity of substrate. Referring to the result of *Min et al.* [2014] and *Sierra* [2012], we assumed that SOM quality may be defined as the relative rate of *Rs* ($\mu gC\, g^{-1}\, d^{-1}$), which was the overall quality (availability and lability) of substrates that were catabolized by decomposer organisms at a given time; then, we may compare different research results without considering their different classifications of C quality. Therefore, a clear uniform definition of C quality is needed as a method to distinguish microbial accessible parts from bulk SOM and to assess the temperature effects on the decomposition of easily soluble C pools and microbial properties. In addition, further studies, especially at large spatial scales, are required to investigate both the related hypotheses.

The north-south transect of eastern China (NSTEC), which includes a range of forest types from tropical to cold temperate. There are big differences in mean annual precipitation, in soil C, N concentrations, in vegetation type and so on (Table 1 and Table S1 in the supporting information), and consequently associated magnitudes of elemental/resource fluxes. There must be huge differences in the magnitude of annual organic matter input and decomposition, which provides an optimal gradient for investigating the spatial patterns of *Rs* and Q_{10} and for studying the above hypotheses (higher Q_{10} in colder zones and CQT). In this study, we collected forest soils from eight locations along the NSTEC. By conducting an 8 week incubation experiment with periodically changing temperature, we investigated *Rs* and Q_{10} with two main objectives: (1) to determine the spatial patterns of *Rs* and Q_{10} across large spatial scales and provide incubation experiment for the two above mentioned hypotheses and (2) to explore the relative importance of microbial and abiotic soil properties on the spatial variation of *Rs* and Q_{10}.

2. Materials and Methods

2.1. Site Description

NSTEC (108°51′26″–123°01′12″W, 18°44′18″–51°46′48″N) is a unique forest belt, along the thermal gradient spanning cold-temperate, temperate, subtropical, and tropical forests [*Zhang and Yang*, 1995]. Eight sampling

sites were established in typical forests along the NSTEC (Figure 1). The mean annual temperature at these sites ranged from −3.67°C to 23.15°C; the mean annual precipitation ranged from 473.0 mm to 2265.8 mm (Table 1). Anthropogenic disturbances were reduced by establishing the sampling plots within well-protected national nature reserves in China at each site, where the vegetation is relatively homogenous and strongly representative of the given forest type. Besides, soil properties from the eight sites along the NSTEC were significant different among each other (Table S1).

2.2. Field Sampling and Pretreatment

Field sampling was conducted between July and August 2013. Four experimental plots (30 × 40 m) were established in each forest site. Soil samples (0–10 cm depth) were collected from four randomly chosen locations in each plot and combined to form one composite sample per plot. Soil samples were sieved (2 mm diameter), and roots and visible organic debris were removed manually. For each plot, homogenized soil was divided into three subsamples for testing: (1) approximately 200 g of fresh soil frozen at −80°C to test basic soil microbial properties, (2) approximately 100 g air-dried soil to test soil biochemistry and physical properties, and (3) 5 kg fresh soil stored at 4°C for incubation experiments. Soil and microbial properties were measured to investigate how they influenced *R*s or Q_{10} among the NSTEC.

In the laboratory, soil water content, soil water holding capacity (WHC, %), and other properties were measured. The contents of SOC and total nitrogen were measured using an elemental analyzer (Elementar Vario Max, Germany). Phospholipid fatty acid content was measured using the mild alkaline methyl esterification method and gas chromatography and mass spectrometry (Thermo ISQ TRACE GC system Ultra ISQ, Germany) [*Xu et al.*, 2015] (self-communicated data from Dr. Xu Zhiwei) (Tables 1 and S1). The details of measurement of soil pH, ORP, COND, dissolved organic C (DOC), and dissolved organic nitrogen (DON) could be seen in section 2.4.2.

2.3. Design of Incubation Experiment

2.3.1. Incubation With Periodically Changing Temperature

Most incubation experiments are conducted with a single constant incubation temperature [*Fierer et al.*, 2005; *Gershenson et al.*, 2009; *Rousk et al.*, 2012; *Wagai et al.*, 2013] or by placing different soil samples at different constant temperatures along a temperature gradient [*Weedon et al.*, 2013; *Xu et al.*, 2012], which had relative few data to calculate Q_{10} and might influence the accuracy of Q_{10}. In addition, soils incubated at an appropriate temperature might consume more substrate than at higher or lower temperatures. The disadvantages of traditional incubation experiments were overcome here by developing a new experimental design where soil samples were incubated under continuously and periodically changing temperature conditions from 6°C to 30°C (we assumed all soils would experience the temperature range 6 (in the cold middle night) to 30°C (in the hot afternoon) under future global warming scenarios) daily during the 56 days of incubation. Simultaneously, *R*s and soil temperature were continuously measured under a model of varying temperature in 12 h according to the designated program (for details see Figures S1 and S2) [*He et al.*, 2013]. Measuring *Rs* more frequently at intervals of several minutes allows better exploration of the relationship between *R*s and changing temperatures as well as a more accurate Q_{10}. Soil chemistry, microbial community, and substrate properties were measured by conducting destructive sampling at different incubation times in order to determine their influence on R_{20} and Q_{10}.

2.3.2. Incubation Experiment

For each treatment, 40 g of fresh soil and 10 g quartz sand were mixed together (preventing soil from caking), adjusted to 55% WHC, and placed in 150 mL polyethylene plastic bottle. Each forest soil had 15 replicates, 3 replicates for the repeated measurements of *Rs* throughout the incubation period and 12 replicates for four separate destructive sampling times to measure soil chemistry, microbial community, and substrate properties. In all, 120 incubation soil samples were used for the eight forest soils. All soil samples were first preincubated at 20°C for 1 week and then placed in an incubator with automatic temperature regulation. Considering the diurnal dynamics of air temperature and limit of the device, four incubation temperatures (6, 14, 22, and 30°C) were established, and each temperature was maintained for 6 h within a day (Figure S1). In order to maintain constant soil moisture levels, water loss was checked, and soil water content was adjusted on the basis of weight at intervals of 3–4 days. Repeated *Rs* measurements were conducted after 0, 7, 14, 21, 42, and 56 days of incubation. Soil substrate (DON and DOC), microbial (microbial biomass carbon (MBC), microbial biomass nitrogen (MBN)), and chemical properties (pH, ORP, and COND) were measured after 0, 14, 42, and 56 days of incubation.

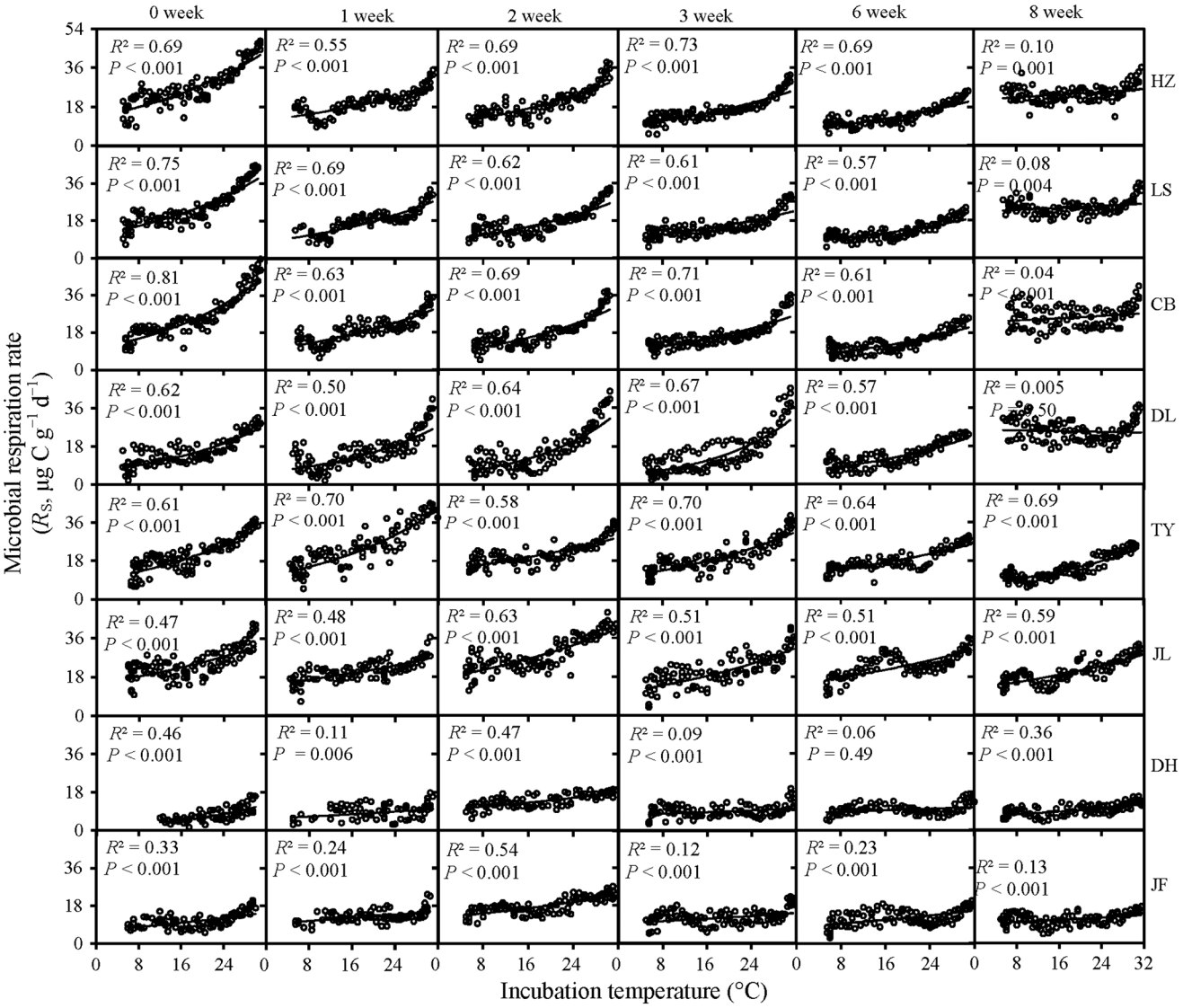

Figure 2. Changes in soil microbial respiration rate (R_S, μgC g^{-1} d^{-1}) with incubation temperature. HZ, Huzhong; LS, Liangshui; CB, Changbai; DL, Dongling; TY, Taiyue; JL, Jiulian; DH, Dinghu; JF, Jianfeng.

2.4. Measurements of *Rs*, Soil Microbial Content, and Chemical Properties

2.4.1. Measurements of *Rs*

Traditionally, scientists establish 3–6 specific temperature gradients to determine *Rs* and then calculate Q_{10} [*Craine et al.*, 2010; *He et al.*, 2013; *Wang et al.*, 2015; *Wetterstedt et al.*, 2010]. In this study, a continuous measurement apparatus was used to measure (at intervals of 20 min for each sample) the dynamics of *Rs* over 12 h at each incubation time point by using an automatic poikilothermia system and raising the temperature from 6 to 30°C at four incremental temperatures in this 12 h period; this method was modified from *He et al.* [2013] by involving an automatic temperature regulator (Julabo, Germany; Figure S2). Further, a button thermometer (DS1922L; DALLAS, USA) was used to measure the actual soil temperature while measuring *Rs*, providing accurate paired data for *Rs* and soil temperature to calculate Q_{10}.

Rs was first calculated from the slope of the CO_2 concentration and conversion factors as follows [*He et al.*, 2013]:

$$Rs = \frac{C \times V \times \alpha \times \beta}{m} \quad (1)$$

Table 2. Two-Way Analysis of Variance for the Changes in Soil Microbial Respiration Rate at 20°C (R_{20}), Temperature Sensitivity (Q_{10}), R^2 (The Goodness of the Fitted Exponential Equation to Depict the Sensitivity of Soil Microbial Respiration Rate to Changing Temperature) With Latitude and Incubation Time

	R_{20}		Q_{10}		R^2	
Factors	*F*	*P*	*F*	*P*	*F*	*P*
Latitude (*L*)	319.88	<0.001	184.77	<0.001	19.81	<0.001
Incubation time (*T*)	119.82	<0.001	186.27	<0.001	2.30	0.084
$L \times T$	50.71	<0.001	43.82	<0.001	1.64	0.045

where *Rs* is the soil microbial respiration rate ($\mu gC\, g^{-1}\, h^{-1}$); *C* is the slope of the change in CO_2 concentration; *V* is the volume of the incubation bottle and gas tube; *m* is the soil weight (g); α (12/44, from CO_2 to C) is the conversion coefficient for CO_2 mass; and β (3600, from second to hour) is a conversion coefficient for time. The value of *Rs* ($\mu gC\, g^{-1}\, h^{-1}$) was obtained using the conversion coefficient of α and β, since the original measurement from the equipment was CO_2 concentration.

Changes in *Rs* with temperature were well fit by exponential models (Figure 2); therefore, the Q_{10} values were calculated using the following exponential equations [*Lloyd and Taylor*, 1994]:

$$Rs = A \times e^{b \times T} \tag{2}$$

$$Q_{10} = e^{10 \times b} \tag{3}$$

where *Rs* is the microbial respiration rate ($\mu gC\, g^{-1}\, d^{-1}$), *T* is temperature (°C), and *A* and *b* are the exponential parameters that describe the intercept and slope of the line, respectively.

All CO_2 concentration values which were used to calculate *Rs* and Q_{10} were collected under experimental rising temperature. Besides, we calculated R_{20} by fitting exponential equations at 20°C.

Min et al. [2014] and *Sierra* [2012] theoretically and empirically reported the temperature sensitivity of organic matter decomposition in the Arrhenius equation, which implied that a substrate of low quality requires high amounts of energy to be degraded, and its rate of decomposition is slow. That is, the decomposition rate was positively proportional to SOM quality; the higher decomposition rate indicated higher quality of substrate. So in this study, SOM quality was defined as the relative rate of *Rs*. In other words, the C quality of soil microbial respiration was equal to *A* ($\mu gC\, g^{-1}\, d^{-1}$) in equation (2), which was the *y* intercept of the first-order exponential equation relating decomposition rate to temperature, i.e., the overall quality (availability and lability) of substrates that were catabolized by decomposer organisms at a given time. Other studies have described substrate C quality in a similar manner [*Bosatta and Ågren*, 1999; *Fierer et al.*, 2005; *Xu et al.*, 2012].

2.4.2. Measurements of Soil Microbial Biomass and Chemical Properties

Soil substrate, microbial community, and chemical properties (DON, DOC, microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), pH, ORP, and COND) were measured at 0, 14, 42, and 56 days after incubation. The chloroform-fumigation method was used to estimate the MBN ((*Kn* = 1.85)) [*Brookes et al.*, 1985], and the extractable N of nonfumigated samples was treated as soil DON. A modified fumigation-extraction method was used to measure soil MBC ((*Kc* = 2.22)) [*Baumann et al.*, 1996] and DOC. In detail, both the fumigation and nonfumigation soil samples were extracted with 50 mL K_2SO_4 solution and shaken simultaneously for 1 h. After shaking, the suspensions were allowed to settle for 10 min, and the supernatants were filtered through a membrane having a pore size of 0.45 μm. The supernatants of C and N were measured using a total organic carbon (TOC) instrument (liquid TOC II; USA) and continuous flow analyzer (Futura, France), respectively. Furthermore, the samples for pH, ORP, and COND were extracted with 25 mL ultrapure water (slurry of soil and ultrapure water, 1:2.5) and shaken simultaneously for 1 h. After shaking, the suspensions were allowed to settle for 10 min, and the supernatants were poured into two slots of "Ultrameter II" (Myron L Company, USA) to measure pH, ORP, and COND (Tables S1 and S2).

2.5. Statistical Analysis

Two-way analysis of variance (ANOVA) was used to analyze the differences in R_{20}, Q_{10}, R^2 (the goodness of the fitted exponential equation to the experimental data, which was calculated sensitivity of *Rs* to temperature) among different forest soil samples and incubation times. The correlations between R_{20}, Q_{10}, microbial,

Table 3. Correlations Between Soil Microbial Respiration Rate at 20°C (R_{20}) and Temperature Sensitivity (Q_{10}) Related to Soil Substrate, Microbial, and Chemical Properties

		R_{20}		Q_{10}	
	Properties	R^2	P	R^2	P
Substrate	DOC[a]	0.16	<0.05	0.06	0.19
	DON	0.02	0.71	0.12	0.18
Microbe	MBC	0.03	0.33	0.005	0.71
	MBC/DOC	0.04	0.53	0.01	0.57
	MBN	0.51	<0.001	0.08	0.13
	MBN/DON	0.02	0.46	0.16	<0.05
Chemistry	pH	0.22	<0.05	0.39	<0.01
	ORP	0.11	0.59	0.28	0.01
	COND	0.24	<0.01	0.07	0.34

[a]DOC, MBC, DON, MBN, ORP, and COND are abbreviations for soil organic carbon, microbial biomass carbon, dissolved organic nitrogen, microbial biomass nitrogen, oxidation reduction potential, and conductivity, respectively.

substrate, and chemical properties were analyzed using regression analysis. Structural equation modeling (SEM) was used to explicitly evaluate the causal relationships among multiple interacting variables and to determine the relative roles of microbial, substrate, and chemical properties in influencing R_{20} and Q_{10}. The SEM was conducted using the procedure of Amos 17 for Windows. Statistical analysis was conducted using SPSS 18.0 for Windows (SPSS Inc., Chicago, IL, USA). The significance level was set at $P = 0.05$ level.

3. Results

3.1. Changes in R_{20} Along the Transect

Temperature significantly influenced *Rs*, with the relationship being well depicted by exponential equations (Figure 2). At the same time, when compared the R^2 estimates from Figure 2 by one-way ANOVA, we found no significant difference among incubation times (Table 2). Forest type and incubation time had a significant impact on R_{20} ($P < 0.001$ for forest type; $P < 0.001$ for incubation time), with a significant interaction ($P < 0.001$; Table 3). R_{20} increased logarithmically with increase in latitudes ($R^2 = 0.34$, $P < 0.001$; Figure 3a). Furthermore, the observed R_{20} significantly decreased with forest type in the following order: temperate forest (15.08 $\mu g C\, g^{-1}\, d^{-1}$) > subtropical forest (10.76 $\mu g C\, g^{-1}\, d^{-1}$) > tropical forest (9.97 $\mu g C\, g^{-1}\, d^{-1}$). R_{20} differed significantly among different soil types, in the following order: black soil > cinnamon soil > brown soil > red soil (data not shown). When R_{20} was calculated based on MBC, R_{20} ($\mu g\, g_{MBC}^{-1}\, d^{-1}$) also significantly increased with latitude (Figure S3).

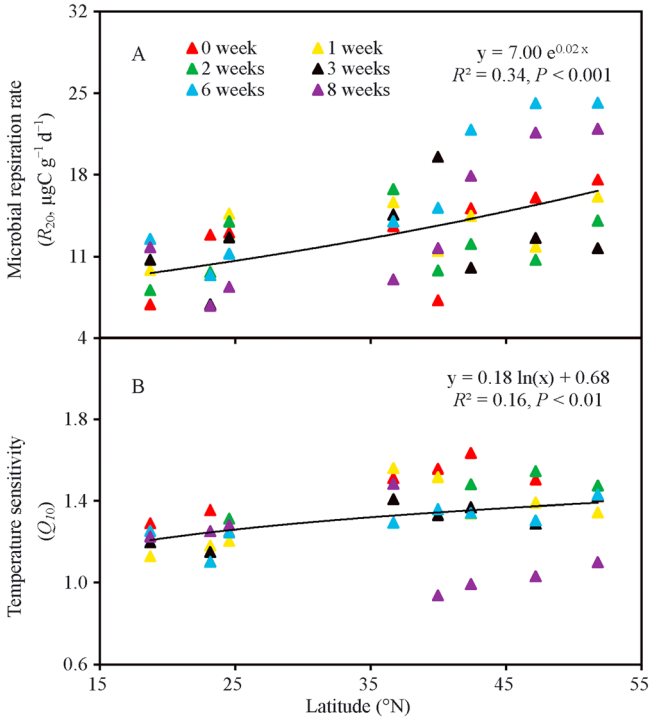

Figure 3. Changes in soil (a) microbial respiration rates at 20°C (R_{20}, $\mu g C\, g^{-1}\, d^{-1}$) and (b) temperature sensitivity (Q_{10}) of six-time incubations with latitude. Six different colors represents six different incubation times. The regression curve was used to depict the relationship between mean R_{20} or Q_{10} and latitude irrespective of incubation time.

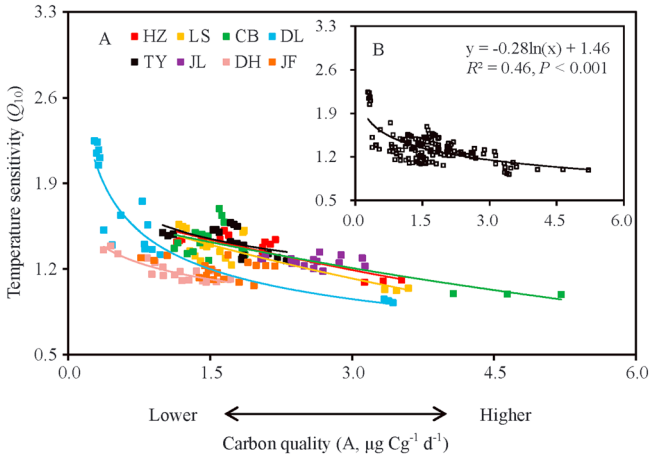

Figure 4. Relationship between temperature sensitivity (Q_{10}) and carbon quality (A). (a) The different sampling locations with each point being a different incubation time. And just significant fitted curve was displayed. (b) All the data of Q_{10} and carbon quality without regard for sampling locations.

3.2. Changes in Q_{10} Along the Transect

Q_{10} was significantly affected by incubation time ($P < 0.001$) and forest type ($P < 0.001$), with a significant interaction ($P < 0.001$). That is, Q_{10} decreased with incubation time and varied from 1.19 ± 0.1 to 1.61 ± 0.48 along the NSTEC increasing logarithmically with increasing latitude ($R^2 = 0.16$, $P < 0.01$; Figure 3b). The Q_{10} values were the maximum (1.42 ± 0.05) in the temperate zone and the minimum in the tropical zone (1.20 ± 0.4). Q_{10} varied with soil type: cinnamon soil (1.49) > brown soil (1.43) > black soil (1.36) > red soil (1.22). Higher latitudes showed greater variation of C quality (A) with incubation time than lower latitude. The relationship between Q_{10} and A was significant in higher latitudes and weaken with increasing latitudes except the sample site DH (Figure 4a). Without considering sample sites, Q_{10} (across incubation times) was significantly negatively correlated with A ($R^2 = 0.46$, $P < 0.001$; Figure 4b).

3.3. Dominant Factors Affecting R_{20} and Q_{10}

Regression analysis revealed that R_{20} was significantly correlated with MBN ($P < 0.001$), DOC ($P < 0.05$), COND ($P < 0.01$), and pH ($P < 0.05$; Table 3). However, when all the factors were classified into microbial characteristics, soil chemical properties, and substrate properties by using SEM, all three factors could explain 47% variation of R_{20} (Figure 5a); the decisive factors were microbial characteristics ($R = 0.46$, R: correlation coefficient, when a correlation coefficient is positive this indicates a positive relationship between R_{20} (or Q_{10})

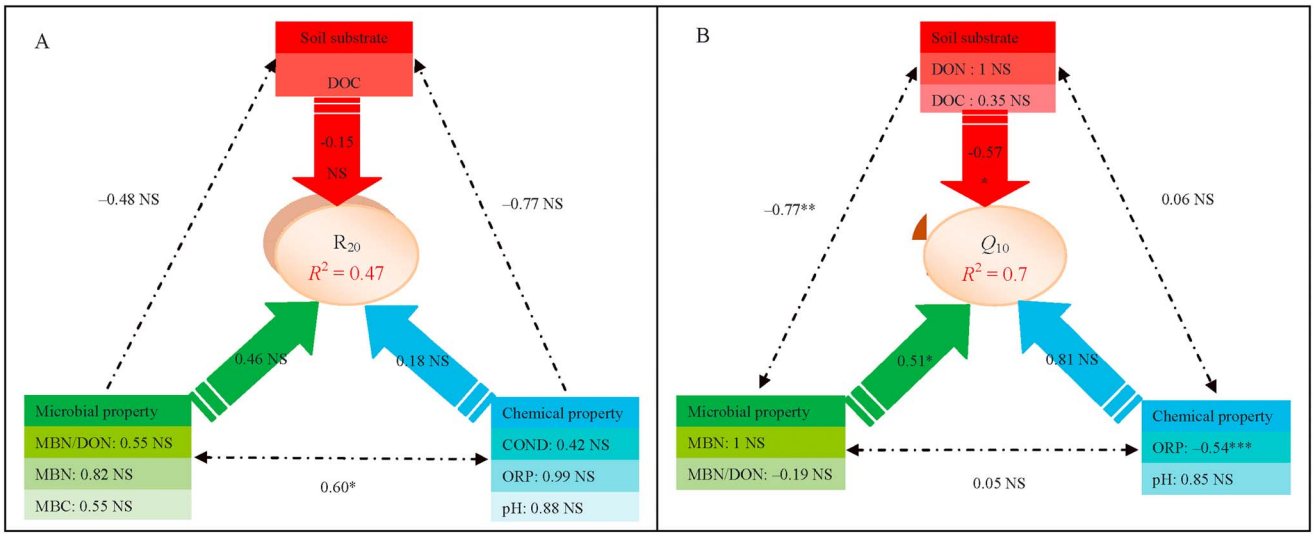

Figure 5. The effects of substrate, microbial, and chemical properties on (a) soil microbial respiration rate (R_{20}) and (b) temperature sensitivity (Q_{10}) were estimated using structural equation models. NS represents no significant difference; *, **, and *** represent significant differences at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. DOC, dissolved organic carbon; DON, dissolved organic nitrogen; MBN/DON, ratio of microbial biomass nitrogen to dissolved organic nitrogen; MBN, microbial biomass nitrogen; MBC, microbial biomass carbon; COND, electrical conductivity; ORP, oxidation-reduction potential.

and an environmental factor, e.g., substrate property, microbial property, chemistry property. When a correlation coefficient is negative this indicates a negative relationship between the two), soil chemical properties ($R = 0.18$), and substrate properties ($R = -0.15$). Similar to R_{20}, Q_{10} values were significantly correlated with MBN/DON ($P < 0.05$), ORP ($P = 0.01$), and pH ($P < 0.01$; Table 3). The three factors could explain 70% variation of Q_{10} (Figure 5b) and primarily driven by substrate ($R = -0.57$, $P = 0.039$) and microbial ($R = -0.51$, $P = 0.049$) properties.

4. Discussion

4.1. Q_{10} Increased in Forest Soils With Increasing Latitude

The Q_{10} values increased logarithmically with increasing latitude, and the maximum and minimum Q_{10} values were observed in the temperate and tropical zones, respectively. The significant positive correlation between Q_{10} and latitude suggests that the temperature sensitivity of soil microbial respiration might decline under continued global warming; further, the temperature sensitivity of soil microbial respiration is greater in cold, high-latitude ecosystems than in warm, temperate areas, supporting previous findings [*Peng et al.*, 2009; *Piao et al.*, 2003]. It was important to speculate a temperature dependence of microbial carbon use efficiency, which implied that microbial carbon use efficiency decreased with increasing temperature, although we did not measure the data of microbial growth rates, exudation rates or their carbon use efficiency. A theoretical framework [*Gillooly et al.*, 2001] and an empirical data [*Tucker et al.*, 2013] have been developed to explain the temperature dependence of microbial carbon use efficiency although the temperature dependence is not always measurable [*Dijkstra et al.*, 2011]. *Hagerty et al.* [2014], using metabolic tracer probing to determine microbial growth efficiency, found that microbial turnover accelerates with warming and determines the response of microbial respiration to temperature change as the principles of enzyme kinetics. Some studies provided some plausible explanations for the increasing Q_{10} with decreasing temperature. For example, *Wang et al.* [2013] conducted an incubation experiment along the elevation gradient in the Wuyi Mountains, China, and showed that Q_{10} linearly increased with elevation. Based on China FLUX data and Q_{10} data in public literatures, *Zheng et al.* [2009] found that ecosystems in colder regions have potentially relatively higher Q_{10} values. Other studies also provided experimental evidences for the similar results [*German et al.*, 2011; *Gershenson et al.*, 2009; *Wang et al.*, 2013; *Whitby and Michael*, 2013; *Xu et al.*, 2013]. Taken together, these findings suggest that soils from low native temperatures have a greater potential to release C in response to climate warming.

In this study, Q_{10} values ranged from 1.2 to 1.6 for the NSTEC soils under periodic incubation temperatures. These values are slightly lower on average than those previously reported (e.g., *Hopkins et al.* [2012] $Q_{10} = 1.5–1.9$ and $Q_{10} = 2.9–3.1$ for two different North American temperate forests; *Zimmermann and Bird* [2012] $Q_{10} = 1.43–1.58$ for short-term incubation and $Q_{10} = 2.02–2.21$ for long-term (1 year) incubation). This difference may owe to the different incubation temperature conditions. As mentioned above, most incubation experiments have been conducted at a constant incubation temperature. *Zhu and Cheng* [2011], who incubated two soils (a farm soil and grassland soil) under two temperature regimes (constant versus diurnally varying), found that Q_{10} values under constant temperature regime were consistently and significantly higher than those under diurnally varying temperature regime. The varying temperature regime should be paid certain attention when compared Q_{10} from different researches.

4.2. CQT Hypothesis in Forest Soils at a Large Spatial Scale

The Q_{10} values showed significant negative correlation with C quality in forest soils; this provided experimental support for the CQT hypothesis. *Xu et al.* [2012], who incubated samples with changing temperature (low-high-low at ±5°C), also found that soils with lower C quality had higher Q_{10}, as have others [*Hartley and Ineson*, 2008; *Liski et al.*, 1999]. In this study, greater variation of C quality (A) with prolonged incubation time was found at higher latitude than at lower latitude. *Briones et al.* [2014] used ^{14}C isotope technology and found higher Q_{10} values than those reported here in boreal forests possibly due to the positive controlling effects of substrate availability on Q_{10} in long-term incubation experiments. Additionally, this difference might be due to the lower C quality in the soils used in this study before incubation as well as the shorter preincubation time, leading to poor initial soil condition in this study. With the prolongation of incubation, the formation rates of labile SOM exceeded the soil microbial respiration rate. While our findings as well as those of many others support the CQT hypothesis, many studies also show contradictory

evidence (e.g., *Lefevre et al.* [2014] used bare fallow soils with different treatments and found that the Q_{10} values were higher in soils with stable C than in those with labile C). Because of the large amount of contradictory findings, the CQT hypothesis still requires further testing. As proposed by *Wagai et al.* [2013], some issues for better understanding the CQT hypothesis need to be addressed in the future by (1) providing a better definition of "C quality" based on the actual molecular structure of organic compounds in soil; (2) distinguishing the active or microbial accessible fraction from bulk SOM; and (3) simultaneously assessing the temperature effect on easily soluble C pools and microbial biomass C in addition to microbial respiration.

4.3. Soil Microbial Properties Control R_{20}

Microbial communities play a more important role in soil microbial respiration than the substrate and soil chemical properties, even though R_{20} was significantly correlated with DOC, COND, and pH. Some studies have shown that factors such as chemical properties (e.g., pH and ORP) and substrate properties (e.g., SOC and DON) affect R_{20} mainly by regulating microbial activity or community structure [*Boberg et al.*, 2014; *Bradford et al.*, 2008; *Entry*, 2000; *Shen et al.*, 2013; *Wei et al.*, 2014]. Further, significant relationships were found between microbial community properties and soil properties (DOC, DON, COND, ORP, and pH). Thus, we conclude that DOC, DON, COND, ORP, and pH have no direct effects on R_{20} but primarily impact R_{20} by regulating microbial properties. In addition, the tendency of C:N to decrease with latitude along the NESTC could partly explain why R_{20} increased logarithmically with latitude. *Leifeld and von Lutzow* [2014] found that, with declining C:N ratios, respiration rates increased. N may be a limiting factor for soil microbial metabolism (or microbial physiology) since organic soils have a wide range of C:N; however, C:N is inherently intertwined with soil pH, making it difficult to separate their effects. *Min et al.* [2014] used a controlled experiment with different pH treatments and found that pH can induce differential effects on reaction rates and temperature sensitivity of organic C and N liberation, leading to changes in the relative availabilities of C and N for microbial assimilation. Moreover, *Sinsabaugh et al.* [2008] showed that soil pH is strongly related to the recalcitrant fractions of SOM, an observation not seen in this study possibly because labile SOM was considerably higher at the preliminary stage of incubation.

4.4. Substrates and Microbial Content Collectively Control Q_{10}

Substrate (DOC and DON) and microbial properties (MBN and MBN/DON) were both important for explaining the variation of Q_{10} along the NSTEC transect. Other studies have also reported that increased substrate availability has a significant positive effect on Q_{10}, and this effect is inversely proportional to the original substrate availability [*Davidson and Janssens*, 2006; *Gershenson et al.*, 2009; *He et al.*, 2013; *Zhou et al.*, 2013]. Changes in microbial community structure and quantity exert important impacts on Q_{10}; however, adaptation in the high-temperature region might be responsible for the lower sensitivity to temperature and declining effects on Q_{10} [*Malcolm et al.*, 2008; *Rousk et al.*, 2012; *Wei et al.*, 2014]. *Hagerty et al.* [2014] used metabolic tracer probing to determine microbial growth efficiency and found that microbial turnover accelerates with warming and determines the response of microbial respiration to temperature change to some extent. Changes in the availability of C and N in SOM might affect the microbial resource strategies, which in turn might influence the response of soil microbial respiration to temperature [*Weedon et al.*, 2013; *Zhou et al.*, 2013]. In this study, the result that MBN plays a more important role in Q_{10} might be attributed to the lower ratio of soil C:N (approximately 10–20) along the transect.

Kinetic theory and empirical studies have predicted that soils from cooler climates might be more sensitive to projected warming with a bigger increase in decomposition rates than those seen in soils from warmer climates [*Davidson and Janssens*, 2006]. Similarly, we found that both R_{20} and Q_{10} increased with latitude. Therefore, our findings gave an experiment support that soils from cooler zones might decompose faster than soils from warmer zones under projected warming because microbes from the warmer zone might already be acclimated to the warm climate.

5. Conclusions

The new experimental design for incubation experiments presented in this study combines periodic changing incubation temperature with continuous measurement eliminating microbial community adaptation to a specific temperature. This method might improve our ability to more accurately explore the response

of soil microbial respiration to temperature in the future. In addition, the results of this study showed that temperature sensitivity of soil microbial respiration differed significantly among different forest soils and increased logarithmically with increasing latitude, providing experimental support for the hypothesis that the sensitivity of soil microbial respiration to temperature is higher at lower temperatures, which indirectly implied that the carbon use efficiency decreased with increasing temperature. Further, these findings also provide experimental support for the CQT hypothesis; low-quality C has greater sensitivity to temperature. In addition, according to the SEM analysis, the controlling factors (microbial versus substrate properties) were found to be different for the spatial patterns of R_{20} and Q_{10}; the spatial patterns of R_{20} were mainly controlled by microbial properties, and the spatial patterns of Q_{10} were collectively controlled by microbial and substrate properties. Soil microbial respiration is being altered by global climate change, and the response of SOM decomposition to changes in temperature might be more sensitive in the cold-temperate zone than in the tropical zone. These findings advance our understanding of the driving factors (microbial versus substrate properties) of R_{20} and Q_{10}.

Acknowledgments
We gratefully acknowledge the staff in eight forest research stations for access and permission. This work was partially supported by the Major Program of the National Natural Science Foundation of China (31290221, 31470506), the Program for Kezhen Distinguished Talents in Institute of Geographic Sciences and Natural Resources Research, CAS (2013RC102), and the program of Youth Innovation Promotion Association CAS. Requests for data sharing should be directed to Nianpeng He (henp@igsnrr.ac.cn).

References

Baumann, A., W. Schimmack, H. Steindl, and K. Bunzl (1996), Association of fallout radiocesium with soil constituents: Effect of sterilization of forest soils by fumigation with chloroform, *Radiat. Environ. Biophys.*, *35*, 229–233.
Blagodatskaya, E., S. Blagodatsky, T. H. Anderson, and Y. Kuzyakov (2014a), Microbial growth and carbon use efficiency in the rhizosphere and root-free Soil, *Plos One*, *9*, e93282, doi:10.91371/journal.pone.0093282.
Blagodatskaya, E., X. Zheng, S. Blagodatsky, R. Wiegl, M. Dannenmann, and K. Butterbach-Bahl (2014b), Oxygen and substrate availability interactively control the temperature sensitivity of CO_2 and N_2O emission from soil, *Biol. Fert. Soils*, *50*, 775–783.
Boberg, J. B., R. D. Finlay, J. Stenlid, A. Ekblad, and B. D. Lindahl (2014), Nitrogen and carbon reallocation in fungal mycelia during decomposition of boreal forest litter, *Plos One*, *9*, e92897, doi:10.91371/journal.pone.0092897.
Bosatta, E., and G. I. Ågren (1999), Soil organic matter quality interpreted thermodynamically, *Soil Biol. Biochem.*, *31*, 1889–1891.
Bradford, M. A., C. A. Davies, S. D. Frey, T. R. Maddox, J. M. Melillo, J. E. Mohan, J. F. Reynolds, K. K. Treseder, and M. D. Wallenstein (2008), Thermal adaptation of soil microbial respiration to elevated temperature, *Ecol. Lett.*, *11*, 1316–1327.
Briones, M. J. I., N. P. McNamara, J. Poskitt, S. E. Crow, and N. J. Ostle (2014), Interactive biotic and abiotic regulators of soil carbon cycling: Evidence from controlled climate experiments on peatland and boreal soils, *Global Change Biol.*, *20*, 2971–2982.
Brookes, P. C., J. F. Kragt, D. S. Powlson, and D. S. Jenkinson (1985), Chloroform fumigation and the release of soil nitrogen: The effects of fumigation time and temperature, *Soil Biol. Biochem.*, *17*, 831–835.
Conant, R. T., et al. (2011), Temperature and soil organic matter decomposition rates—Synthesis of current knowledge and a way forward, *Global Change Biol.*, *17*, 3392–3404.
Conen, F., J. Leifeld, B. Seth, and C. Alewell (2006), Warming mineralises young and old soil carbon equally, *Biogeosciences*, *3*, 515–519.
Craine, J. M., N. Fierer, and K. K. McLauchlan (2010), Widespread coupling between the rate and temperature sensitivity of organic matter decay, *Nat. Geosci.*, *3*, 854–857.
Davidson, E. A., and I. A. Janssens (2006), Temperature sensitivity of soil carbon decomposition and feedbacks to climate change, *Nature*, *440*, 165–173.
Dijkstra, P., S. C. Thomas, P. L. Heinrich, G. W. Koch, E. Schwartz, and B. A. Hungate (2011), Effect of temperature on metabolic activity of intact microbial communities: Evidence for altered metabolic pathway activity but not for increased maintenance respiration and reduced carbon use efficiency, *Soil Biol. Biochem.*, *43*, 2023–2031.
Entry, J. A. (2000), Influence of nitrogen on cellulose and lignin mineralization in blackwater and redwater forested wetland soils, *Biol. Fert. Soils*, *31*, 436–440.
Fang, C., and J. B. Moncrieff (2001), The dependence of soil CO_2 efflux on temperature, *Soil Biol. Biochem.*, *33*, 155–165.
Fang, C. G., P. Smith, J. B. Moncrieff, and J. U. Smith (2005), Similar response of labile and resistant soil organic matter pools to changes in temperature, *Nature*, *433*, 57–59.
Fierer, N., J. M. Craine, K. McLauchlan, and J. P. Schimel (2005), Litter quality and the temperature sensitivity of decomposition, *Ecology*, *86*, 320–326.
Gabriel, C. E., and L. Kellman (2014), Investigating the role of moisture as an environmental constraint in the decomposition of shallow and deep mineral soil organic matter of a temperate coniferous soil, *Soil Biol. Biochem.*, *68*, 373–384.
German, D. P., S. S. Chacon, and S. D. Allison (2011), Substrate concentration and enzyme allocation can affect rates of microbial decomposition, *Ecology*, *92*, 1471–1480.
Gershenson, A., N. E. Bader, and W. X. Cheng (2009), Effects of substrate availability on the temperature sensitivity of soil organic matter decomposition, *Global Change Biol.*, *15*, 176–183.
Gillooly, J. F., J. H. Brown, G. B. West, V. M. Savage, and E. L. Charnov (2001), Effects of size and temperature on metabolic rate, *Science*, *293*, 2248–2251.
Hagerty, S. B., K. J. van Groenigen, S. D. Allison, B. A. Hungate, E. Schwartz, G. W. Koch, R. K. Kolka, and P. Dijkstra (2014), Accelerated microbial turnover but constant growth efficiency with warming in soil, *Nat. Clim. Change*, *4*, 903–906.
Hartley, I. P., and P. Ineson (2008), Substrate quality and the temperature sensitivity of soil organic matter decomposition, *Soil Biol. Biochem.*, *40*, 1567–1574.
He, N. P., R. M. Wang, Y. Gao, J. Z. Dai, X. F. Wen, and G. R. Yu (2013), Changes in the temperature sensitivity of SOM decomposition with grassland succession: Implications for soil C sequestration, *Ecol. Evol.*, *3*, 5045–5054.
Hopkins, F. M., M. S. Torn, and S. E. Trumbore (2012), Warming accelerates decomposition of decades-old carbon in forest soils, *Proc. Natl. Acad. Sci. U.S.A.*, *109*, E1753–E1761.
Ise, T., and P. R. Moorcroft (2006), The global-scale temperature and moisture dependencies of soil organic carbon decomposition: An analysis using a mechanistic decomposition model, *Biogeochemistry*, *80*, 217–231.

Jiang, H., Q. Deng, G. Zhou, D. Hui, D. Zhang, S. Liu, G. Chu, and J. Li (2013), Responses of soil respiration and its temperature/moisture sensitivity to precipitation in three subtropical forests in southern China, *Biogeosciences*, *10*, 3963–3982.
Kirschbaum, M. U. F. (1995), The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage, *Soil Biol. Biochem.*, *27*, 753–760.
Lefevre, R., et al. (2014), Higher temperature sensitivity for stable than for labile soil organic carbon—Evidence from incubations of long-term bare fallow soils, *Global Change Biol.*, *20*, 633–640.
Leifeld, J., and M. von Lutzow (2014), Chemical and microbial activation energies of soil organic matter decomposition, *Biol. Fert. Soils*, *50*, 147–153.
Li, J., N. P. He, X. H. Wei, H. Chai, X. F. Wen, J. Y. Xue, and Y. Zuo (2015), Changes in temperature sensitivity and activation energy of soil organic matter decomposition in different Qinghai-Tibet Plateau grasslands, *Plos One*, *10*, e0132795, doi:10.1371/journal.pone.0132795.
Liski, J., I. Hannu, M. Annikki, and J. W. Carl (1999), CO_2 emissions from soil in response to climatic warming are overestimated: The decomposition of old soil organic matter is tolerant of temperature, *Ambio*, *28*, 171–174.
Lloyd, J., and J. A. Taylor (1994), On the temperature dependence of soil respiration, *Funct. Ecol.*, *8*, 315–323.
Malcolm, G. M., J. C. Lopez-Gutierrez, R. T. Koide, and D. M. Eissenstat (2008), Acclimation to temperature and temperature sensitivity of metabolism by ectomycorrhizal fungi, *Global Change Biol.*, *14*, 1169–1180.
Min, K., C. A. Lehmeier, F. Ballantyne, A. Tatarko, and S. A. Billings (2014), Differential effects of pH on temperature sensitivity of organic carbon and nitrogen decay, *Soil Biol. Biochem.*, *76*, 193–200.
Moyano, F. E., S. Manzoni, and C. Chenu (2013), Responses of soil heterotrophic respiration to moisture availability: An exploration of processes and models, *Soil Biol. Biochem.*, *59*, 72–85.
Peng, S. S., S. L. Piao, T. Wang, J. Y. Sun, and Z. H. Shen (2009), Temperature sensitivity of soil respiration in different ecosystems in China, *Soil Biol. Biochem.*, *41*, 1008–1014.
Piao, S. L., J. Y. Fang, L. M. Zhou, Q. H. Guo, M. Henderson, W. Ji, Y. Li, and S. Tao (2003), Interannual variations of monthly and seasonal normalized difference vegetation index (NDVI) in China from 1982 to 1999, *J. Geophys. Res.*, *108*(D14), 4401, doi:10.1029/2002JD002848.
Plante, A. F., R. T. Conant, J. Carlson, R. Greenwood, J. M. Shulman, M. L. Haddix, and E. A. Paul (2010), Decomposition temperature sensitivity of isolated soil organic matter fractions, *Soil Biol. Biochem.*, *42*, 1991–1996.
Rousk, J., S. D. Frey, and E. Baath (2012), Temperature adaptation of bacterial communities in experimentally warmed forest soils, *Global Change Biol.*, *18*(10), 3252–3258.
Shen, C., J. Xiong, H. Zhang, Y. Feng, X. Lin, X. Li, W. Liang, and H. Chu (2013), Soil pH drives the spatial distribution of bacterial communities along elevation on Changbai Mountain, *Soil Biol. Biochem.*, *57*, 204–211.
Shibata, H., T. Hiura, Y. Tanaka, K. Takagi, and T. Koike (2005), Carbon cycling and budget in a forested basin of southwestern Hokkaido, northern Japan, *Ecol. Res.*, *20*, 325–331.
Sierra, C. A. (2012), Temperature sensitivity of organic matter decomposition in the Arrhenius equation: Some theoretical considerations, *Biogeochemistry*, *108*, 1–15.
Sinsabaugh, R. L., et al. (2008), Stoichiometry of soil enzyme activity at global scale, *Ecol. Lett.*, *11*, 1252–1264.
Tucker, C. L., J. Bell, E. Pendall, and K. Ogle (2013), Does declining carbon-use efficiency explain thermal acclimation of soil respiration with warming?, *Global Change Biol.*, *19*, 252–263.
Wagai, R., A. W. Kishimoto-Mo, S. Yonemura, Y. Shirato, S. Hiradate, and Y. Yagasaki (2013), Linking temperature sensitivity of soil organic matter decomposition to its molecular structure, accessibility, and microbial physiology, *Global Change Biol.*, *19*, 1114–1125.
Wang, G., Y. Zhou, X. Xu, H. Ruan, and J. Wang (2013), Temperature sensitivity of soil organic carbon mineralization along an elevation gradient in the Wuyi Mountains, China, *Plos One*, *8*, e53914, doi:10.1371/journal.pone.0053914.
Wang Q., Wang D., Wen X. F., Yu G. R., He N. P., and Wang R. F.. 2015. Differences in SOM decomposition and temperature sensitivity among soil aggregate size classes in temperate grasslands. *Plos One*, *10*, e0117033, doi:10.1371/journal.pone.0117033.
Weedon, J. T., R. Aerts, G. A. Kowalchuk, R. van Logtestijn, D. Andringa, and P. M. van Bodegom (2013), Temperature sensitivity of peatland C and N cycling: Does substrate supply play a role?, *Soil Biol. Biochem.*, *61*, 109–120.
Wei, H., B. Guenet, S. Vicca, N. Nunan, H. AbdElgawad, V. Pouteau, W. J. Shen, and I. A. Janssens (2014), Thermal acclimation of organic matter decomposition in an artificial forest soil is related to shifts in microbial community structure, *Soil Biol. Biochem.*, *71*, 1–12.
Wetterstedt, J. A. M., T. Persson, and G. I. Agren (2010), Temperature sensitivity and substrate quality in soil organic matter decomposition: Results of an incubation study with three substrates, *Global Change Biol.*, *16*, 1806–1819.
Whitby, T. G., and D. M. Michael (2013), Native temperature regime influences soil response to simulated warming, *Soil Biol. Biochem.*, *60*, 202–209.
Xu, G., H. Jiang, Y. B. Zhang, H. Korpelainen, and C. Y. Li (2013), Effect of warming on extracted soil carbon pools of Abies faxoniana forest at two elevations, *Forest Ecol. Manag.*, *310*, 357–365.
Xu, X., Y. Q. Luo, and J. Z. Zhou (2012), Carbon quality and the temperature sensitivity of soil organic carbon decomposition in a tallgrass prairie, *Soil Biol. Biochem.*, *50*, 142–148.
Xu, Z., G. Yu, X. Zhang, J. Ge, N. He, Q. Wang, and D. Wang (2015), The variations in soil microbial communities, enzyme activities and their relationships with soil organic matter decomposition along the northern slope of Changbai Mountain, *Appl. Soil Ecol.*, *86*, 19–29.
Zhang, W. D., X. F. Wang, and S. L. Wang (2013), Addition of external organic carbon and native soil organic carbon decomposition: A Meta-analysis, *Plos One*, *8*, e54779, doi:10.51371/journal.pone.0054779.
Zhang, X. S., and D. A. Yang (1995), Eastern and northern transects of China research, *Quat. Sci.*, *01*, 43–52.
Zheng, Z. M., G. R. Yu, Y. L. Fu, Y. S. Wang, X. M. Sun, and Y. H. Wang (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, Z. Y., C. Guo, and H. Meng (2013), Temperature sensitivity and basal rate of soil respiration and their determinants in temperate forests of North China, *Plos One*, *8*, e81793, doi:10.81371/journal.pone.0081793.
Zhu, B. A., and W. X. Cheng (2011), Constant and diurnally-varying temperature regimes lead to different temperature sensitivities of soil organic carbon decomposition, *Soil Biol. Biochem.*, *43*, 866–869.
Zimmermann, M., and M. I. Bird (2012), Temperature sensitivity of tropical forest soil respiration increase along an altitudinal gradient with ongoing decomposition, *Geoderma*, *187*, 8–15.