Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 2010, 22(7) 1057–1066
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Effect of temperature and moisture on soil organic carbon mineralization of predominantly permafrost peatland in the Great Hing'an Mountains, Northeastern China

Xianwei Wang[1,2,3], Xiuzhen Li[1,*], Yuanman Hu[1], Jiujun Lv[1,2], Ju Sun[1,2], Zongmei Li[1,2], Zhifeng Wu[1,2]

1. Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China. E-mail: wangxw003@163.com
2. Graduate School of Chinese Academy of Sciences, Beijing 100039, China
3. Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130012, China

Received 23 July 2009; revised 27 September 2009; accepted 08 April 2010

Abstract

Boreal peatlands represent a large global carbon pool. The relationships between carbon mineralization, soil temperature and moisture in the permafrost peatlands of the Great Hing'an Mountains, China, were examined. The CO_2 emissions were measured during laboratory incubations of samples from four sites under different temperatures (5, 10, 15, and 20°C) and moisture contents (0%, 30%, 60%, 100% water holding capacity (WHC) and completely water saturated). Total carbon mineralization ranged from 15.51 to 112.92 mg C under the treatments for all sites. Carbon mineralization rates decreased with soil depth, increased with temperature, and reached the highest at 60% WHC at the same temperature. The calculated temperature coefficient (Q_{10}) values ranged from 1.84 to 2.51 with the soil depths and moisture. However, the values were not significantly affected by soil moisture and depth for all sites due to the different peat properties ($P > 0.05$). We found that the carbon mineralization could be successfully predicted as a two-compartment function with temperature and moisture ($R^2 > 0.96$) and total carbon mineralization was significantly affected by temperature and moisture ($P < 0.05$). Thus, temperature and moisture would play important roles in carbon mineralization of permafrost peatlands in the Great Hing'an Mountains, indicating that the permafrost peatlands would be sensitive to the environment change, and the permafrost peatlands would be potentially mineralized under future climate change.

Key words: Great Hing'an Mountains; permafrost peatland; mineralization; climate change

DOI: 10.1016/S1001-0742(09)60217-5

Introduction

Northern peatland ecosystems cover about 3% of the earth's land surface and are of great importance in the global carbon cycle because they store approximately 30% of terrestrial soil carbon (Turunen et al., 2002). In the Great Hing'an Mountains, low temperatures, short growing season, partly water-saturation, and permafrost limit decomposition of organic matters resulted in an accumulation of organic matter in soils. Peat is partially decomposed plant material that accumulates where plant production exceeds organic matter losses through heterotrophic respiration, leaching or dissolved export, fire combustion or other disturbance-related losses and it represents the balance between CO_2 fixation by net primary production and carbon releases throughout the entire peat column (Turetsky, 2004). Peatlands in boreal and subarctic regions represent a large global carbon stock and a long-term sink for atmospheric CO_2 (Moore and Dalva, 1993).

Climate model predicted that global warming will be most intense at high latitudes (Räisänen et al., 2004). The response of peatland ecosystems to global change, including predicted increases in temperature and fire frequency, ongoing permafrost degradation, and land use changes, may be apparent in the short term (Turetsky et al., 2002; Roulet et al., 2007). Lying across the southern edge of permafrost of Eurasia, the permafrost boundary of the Great Hing'an Mountains has moved northward with the active layer deeper and total permafrost area shrinking remarkably in the last decades (Jin et al., 2007). Such changes may influence the plant and soil environments such as the rates of litter inputs, litter turnover rates, and organic matter quality in peatlands, with implications for regional peatland C emissions and storage (Turetsky, 2004). Updegraff et al. (2001) found that the rapid decomposition could result in a positive climatic feedback by accelerating the rate of increase in atmospheric CO_2 and CH_4 concentrations from the peatlands, despite increasing productivity with warmer mean temperatures, and longer growing seasons might be offset by increase decomposition rate.

* Corresponding author. E-mail: Landscape2001@sina.com

Although temperature and moisture would play active roles in determining carbon mineralization in all ecosystems, there are controversial findings about the relative importance of these two environmental controls in peatlands (Lafleur et al., 2005). While most studies found temperature to be an important control on peatland carbon mineralization (Silvola et al., 1996; Updegraff et al., 2001), the influence of soil moisture is less addressed. There is a general agreement that CO_2 emission increase with increasing temperature, and is higher under drained than flooded conditions to the peatland (Scanlon and Moore, 2000; Waddington et al., 2001).

There has been little research on the carbon mineralization of permafrost peatlands in the Great Hing'an Mountains. Understanding how peatland carbon cycling is controlled by soil temperature and moisture would be important in predicting response of peatlands to climate change. In this article, we collected peat samples from the predominately permafrost peatlands in the Great Hing'an Mountains, China. The objectives are to determine changes in carbon mineralization rates of peatlands across the sites, to quantify the effects of temperature and moisture on C mineralization and predict soil carbon mineralization as a function of soil temperature and moisture.

1 Materials and methods

1.1 Site description

The samples were collected from areas located in the Great Hing'an Mountains (46°26′–53°34′N, 119°30′–127°01′E) of Northeastern China. Permafrost in the Great Hing'an Mountains is an integral part of Eurasian continuous permafrost (Jin et al., 2007). We selected the peatlands in the predominantly continuous permafrost zone (continuity < 90%) which is distributed on the north slope of the Great Hing'an Mountains and cover about 6.16×10^4 km^2 (Zhou et al., 2003). The peatlands of Beijicun, Tuqiang and Zhuanglin were located on the northwest slope; while the peatlands of Huzhong and Feihushan were located on the northeast slope of the Great Hing'an Mountains (Fig. 1). The mean annual air temperature is –5.5°C and the annual precipitation is 400 mm for the sites on the northwest slope and 460 mm for the sites on the northeast slope from 1961 to 2000 (Jin et al., 2007). Most predominantly permafrost peatland is distributed in the wide valleys. The peatlands selected are similar in vegetation and water conditions and all of ombrotrophic bogs, dominated by *Ledum palustre*, *Vaccinium uliginosum*, *Sphagnum* spp., and *Larix gmelini* Rupr. The peat thickness of all sites ranges from 50 to 60 cm above the permafrost layer.

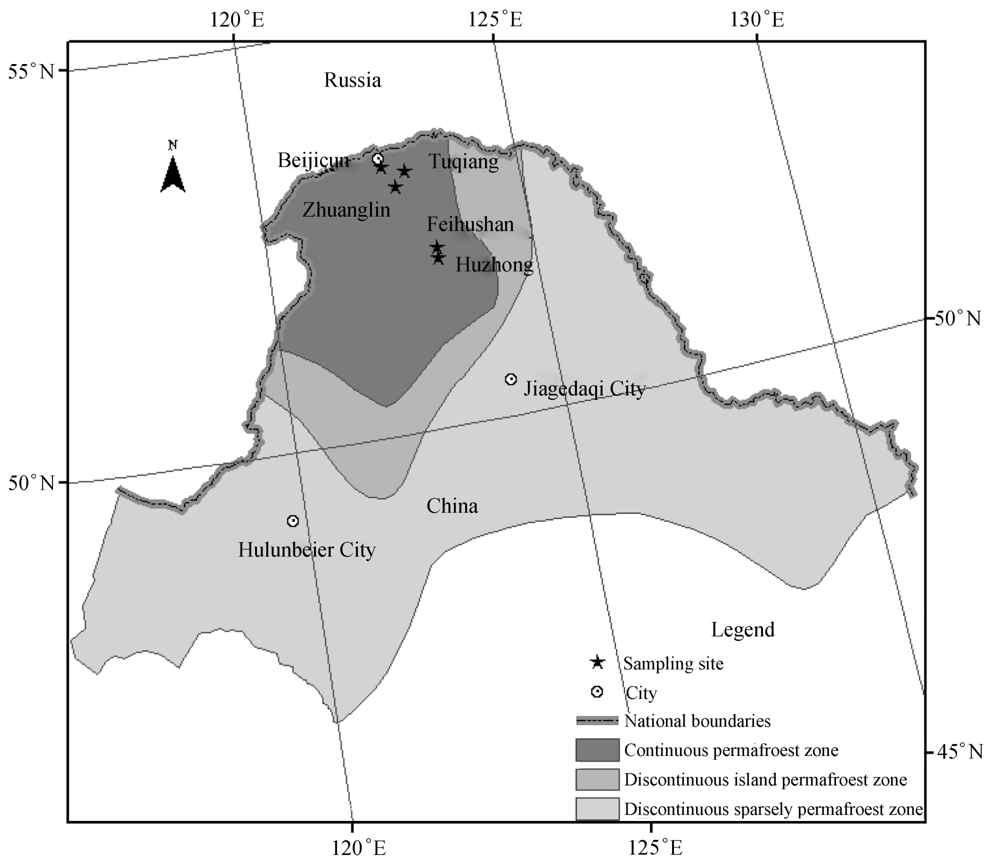

Fig. 1 Sites locations that we selected in the Great Hing'an Mountains. The frost zones were adapted from Jin et al. (2007).

1.2 Peat sampling and incubation experiment

Samples were collected from the selected peatlands in August 2007 with three random replicates. Peat was harvested with two depths intervals: (1) 10–20 cm, and (2) 20–30 cm. The layer 0–10 cm of the peat was removed, because this layer consisted almost entirely of living *Sphagnum* mosses which would influence the incubation results greatly. The samples were placed in zip-lock bags with headspaces removed and transported to the Northeast Normal University, China within 48–72 hr. Part of the samples were air dried, crushed, and sieved to 0.25 mm for chemical analysis. The left samples were cut into pieces of 0.5 cm, and were mixed to obtain a composite, homogeneous sample for each soil layer. The organic carbon (using Potassium Bichromate Titrimetric Method), total nitrogen (using Semimicro-Kjeldahl Method) and pH (using Potentiometer Method) were determined immediately following the laboratory methods described by Zhang (2000). Total water holding capacity (WHC) was determined following the method described by Rey et al. (2005). The results of the main peat soil characteristics are presented in Table 1.

Organic matter decomposition and CO_2 emission were measured in laboratory incubation experiments at controlled soil temperatures (5, 10, 15, and 20°C) and soil moisture (0%, 30%, 60%, 100% WHC and complete water saturation respectively). The 20 g samples were placed in 250 mL flasks in triplicates, and then, added distilled water corresponding to maximal water holding capacity until the target mass (0%, 30%, 60%, 100% WHC and complete water saturation) was reached. Then, the flasks with the peat samples and a beaker with 50 mL of 1 mol/L NaOH as CO_2 trap were placed into 1.5 L plastic barrels together. The barrels were immediately sealed with rubber stoppers, and incubated in constant temperature incubator (HPS-160, Donglian, China) at each temperature regime. Three blank samples were incubated in each batch of incubation.

Carbon dioxide evolved was trapped in the 1 mol/L NaOH solution. Following precipitation with added 3 mL of 1 mol/L $BaCl_2$, and the carbon dioxide concentration was determined by titration with 0.5 mol/L HCl. The trapping and determination was conducted at increasing time intervals on day 2, 5, 9, 14, 20, 30, and 40. Constant moisture content (± 0.1 g) was maintained by adding water corresponding to the loss of sample weight from weight balance with trapped gas sampled. These adjustments were performed at room temperature and took less than 20 min for all studied temperatures.

1.3 Temperature and moisture sensitivity calculation

Temperature coefficient, Q_{10}, is a widely used index of temperature dependence which describes the proportional change in rate given a 10°C change of temperature (Kirschbaum, 1995). The following Eqs. (1) and (2) can be used to describe the temperature dependence of carbon mineralization:

$$R = \alpha \exp(\beta T) \quad (1)$$

$$Q_{10} = \exp(10\beta) \quad (2)$$

where, R (mg/g C) is the measured carbon mineralization rate; T (°C) is the incubation temperature; and α and β are fitting parameters.

A two-component quadratic function was used to describe the response of carbon mineralization between temperature (T) and soil moisture (w) expressed as a percentage of the WHC following the function described by Rey et al. (2005):

$$\ln(C_m) = a + bT + cT^2 + dw + ew^2 \quad (3)$$

where, C_m (mg/g) is the total carbon mineralization; w (% WHC) is the soil moisture except for the completely saturated water condition; and a, b, c, d and e are fitting parameters of the polynomial equation. Carbon mineralization rates were transformed logarithmically since the rates had different variances for all treatments.

1.4 Statistical analysis

Differences in peat soil physiochemical variables between two layers were tested for all sites with Student's t-test. Cumulative mineralization amounts were calculated for all sites and soil depth using mean carbon mineralization rates (n = 3). To test differences between temperature sensitivity of different soil depths and moistures, we compared the 95% confidence intervals of the parameter β. Four-way analysis of variance (ANOVA) was performed using the GLM procedure of SAS (SAS Institute Inc., 2000) to assess temperature, moisture, depth (peat layers) and slope (collected peat samples at relative slopes in the predominantly permafrost zone) on mean total carbon mineralization. Temperature and moisture were considered

Table 1 Sampling sites and basic peat physicochemical properties of the peat

Site	Location	Altitude (m)	Peat layer (cm)	Organic carbon (%)	Total N (%)	pH	WHC (%)
Beijicun1	53°12′08″N	546	10–20	44.43 ± 1.76	1.31 ± 0.11	3.93 ± 0.08	507.24 ± 12.15
Beijicun2	122°16′43″E		20–30	40.56 ± 0.52	1.65 ± 0.05	3.52 ± 0.12	426.83 ± 10.38
Tuqiang1	52°55′59″N	467	10–20	45.16 ± 0.58	1.38 ± 0.09	3.86 ± 0.04	538.50 ± 14.67
Tuqiang2	122°46′26″E		20–30	43.37 ± 0.91	1.64 ± 0.09	3.72 ± 0.07	439.61 ± 11.83
Zhuanglin1	52°45′07″N	505	10–20	45.22 ± 0.90	1.43 ± 0.02	3.88 ± 0.15	583.66 ± 14.69
Zhuanglin2	122°37′57″E		20–30	41.30 ± 1.30	1.59 ± 0.09	3.58 ± 0.06	440.76 ± 13.87
Huzhong1	51°45′34″N	782	10–20	45.01 ± 0.97	1.41 ± 0.05	3.88 ± 0.13	594.38 ± 15.32
Huzhong2	123°02′34″E		20–30	41.03 ± 1.18	1.70 ± 0.09	3.70 ± 0.11	571.61 ± 13.65
Feihushan1	52°09′10″N	681	10–20	42.93 ± 1.24	1.34 ± 0.08	4.13 ± 0.06	544.67 ± 15.87
Feihushan2	122°57′18″E		20–30	37.86 ± 0.65	1.71 ± 0.04	3.90 ± 0.10	452.66 ± 12.82

WHC: water holding capacity.
Values are the mean ± standard error (SE).

as fixed effects; while depth and slope were considered as random effects. The significance of differences from least square means was tested at a 5% significance level. A two-compartment model was fitted to the carbon mineralization measured for all sites using nonlinear regression analysis (Procedure NLIN in SAS; SAS Institute Inc., USA, 2000). All values used in regression analyses are means of samples and all error bars showed the standard error of mean.

2 Results

2.1 Total mineralization and CO_2 emission

During 40 days of incubation, total mineralized C ranged from 15.51 (Feihushan: 20–30 cm, 0% WHC) to 38.11 mg C (Beijicun: 10–20 cm, 60% WHC) at 5°C and from 45.26 (Zhuanglin: 20–30 cm, 0% WHC) to 112.92 mg C (Beijicun: 10–20 cm, 60% WHC) at 20°C. At earlier phase, the rate of peat carbon mineralized decreased greatly, but it became stable after 30 days (Fig. 2). At 5°C, the average percentage of peat carbon mineralization was below 5%, while at 20°C, rates were about 12% for all sites and treatments.

Peat from different depths differed in physical and chemical properties (Table 1). With the increase of depth, the peat tended to have lower organic carbon, pH and WHC, and higher total N. Faster mineralization in upper layers than in deeper layers had been observed (Fig. 2). The carbon mineralization amounts at the deeper layers were 2.41% to 17.83% lower than those at the upper layers under the treatments across all sites.

2.2 Temperature dependence of carbon mineralization

As shown in Table 2, carbon mineralization of both depths responded to temperature following well a first-order exponential function from the peatlands in Tuqiang and Huzhong. The calculated Q_{10} values ranged from 1.84 to 2.51, varying with the soil depths and water contents for all sites. All moisture treatments showed a similar response to temperature, but there was no significant difference ($P > 0.05$) between treatments in the constant parameter (β) of the exponential function fitted for all sites. Although the trend with soil moisture regimes is clear, differences in the Q_{10} values to soil moisture were also not statistically significant between moistures ($P > 0.05$) for all sites. It indicated that the effects of the soil moisture on carbon mineralization would be complex for different sites, although the vegetations and the soil types were similar to the four sites. However, the temperature sensitivity measured as Q_{10} reached a peak at the 60% WHC (Table 2), indicating that contents of the 60% WHC could be the optimal soil moisture for the carbon mineralization under the studied treatments.

The calculated average Q_{10} values of peat carbon mineralization did not vary greatly with the depth and sites ($P > 0.05$). The calculated average Q_{10} values of

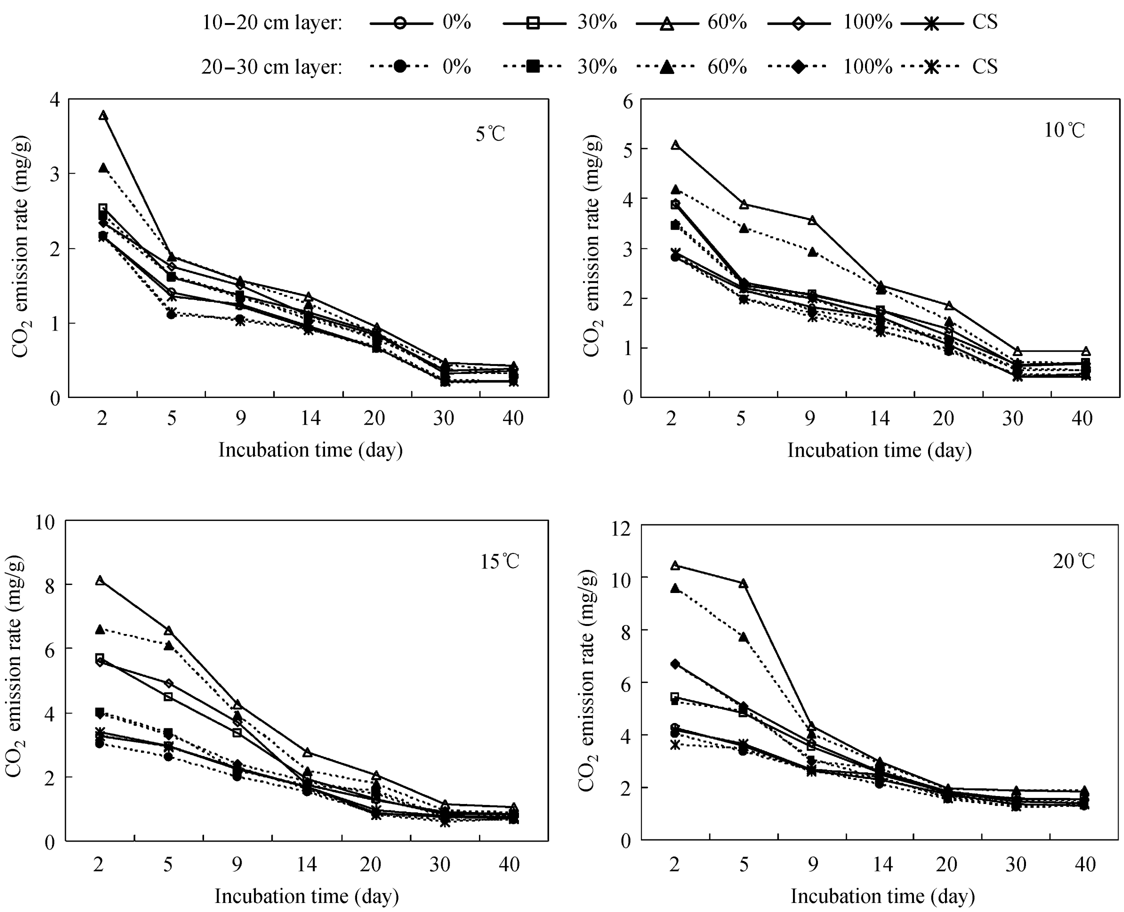

Fig. 2 Change in peat C mineralization rates of permafrost peatlands in Tuqiang site. CS: completely water saturated condition.

Table 2 Parameter values obtained from fitting an exponential function for the response of carbon mineralization to soil temperature under five soil moisture regimes (% WHC) in Tuqiang and Huzhong

Peat	Moisture	α	β	Q_{10}	P	R^2
Tuqiang1	0% WHC	16.16 ± 1.61 b	0.073 ± 0.007 b	2.08 ± 0.08 b	0.010	0.980
	30% WHC	21.01 ± 1.77 b	0.070 ± 0.006 b	2.01 ± 0.07 b	0.008	0.985
	60% WHC	27.04 ± 5.17 d	0.076 ± 0.008 b	2.14 ± 0.09 b	0.034	0.933
	100% WHC	21.48 ± 1.59 b	0.070 ± 0.005 a	2.01 ± 0.06 b	0.006	0.988
	CS	15.89 ± 1.76 b	0.074 ± 0.014 c	2.10 ± 0.16 c	0.011	0.978
Tuqiang2	0% WHC	14.95 ± 1.69 b	0.072 ± 0.008 b	2.05 ± 0.09 b	0.013	0.975
	30% WHC	19.59 ± 0.92 a	0.067 ± 0.003 a	1.95 ± 0.04 a	0.003	0.995
	60% WHC	23.05 ± 2.65 c	0.076 ± 0.008 b	2.14 ± 0.09 b	0.012	0.976
	100% WHC	19.01 ± 1.19 a	0.071 ± 0.005 a	2.03 ± 0.05 a	0.004	0.992
	CS	15.00 ± 1.31 a	0.074 ± 0.006 b	2.10 ± 0.07 b	0.007	0.985
Huzhong1	0% WHC	14.19 ± 1.77 b	0.077 ± 0.009 a	2.16 ± 0.10 c	0.014	0.973
	30% WHC	19.60 ± 2.27 c	0.073 ± 0.008 b	2.08 ± 0.10 b	0.013	0.974
	60% WHC	24.37 ± 5.64 d	0.082 ± 0.009 b	2.27 ± 0.10 b	0.046	0.910
	100% WHC	19.32 ± 4.00 d	0.075 ± 0.015 c	2.12 ± 0.17 c	0.038	0.925
	CS	13.67 ± 1.63 b	0.076 ± 0.017 c	2.14 ± 0.19 c	0.011	0.978
Huzhong2	0% WHC	13.08 ± 1.50 a	0.076 ± 0.008 b	2.14 ± 0.09 b	0.012	0.976
	30% WHC	16.49 ± 1.60 b	0.076 ± 0.007 b	2.14 ± 0.08 b	0.009	0.983
	60% WHC	20.13 ± 4.57 d	0.082 ± 0.012 c	2.27 ± 0.13 c	0.040	0.922
	100% WHC	16.38 ± 1.71 b	0.080 ± 0.008 b	2.23 ± 0.09 b	0.009	0.982
	CS	12.92 ± 2.11 c	0.081 ± 0.017 c	2.25 ± 0.19 c	0.021	0.959

Values are mean ± SE. Values with different letters are significantly different between temperatures at 5% level of probability.

carbon mineralization decreased with increasing depth in Beijicun, Tuqiang and Feihushan, while increased with increasing depth in Zhuanglin and Huzhong (Table 3). As a whole, the average Q_{10} values in the upper layer were slightly higher than the values in the deeper layer for all sites indicating that the peat in the deeper layer would be also sensitive to the warming temperature. The average Q_{10} values of the sites in the northeast slope (Huzhong and Feihushan) were slightly higher than those of the sites in the northwest slope (Beijicun, Tuqiang and Zhuanglin). Thereby, the peatlands on the northeast slope would be more sensitively response to the warm temperature than those on the northwest slope.

2.3 Interactions of site conditions on carbon mineralization

The total amount of carbon mineralized during the experimental period increased significantly with temperature and optimal moisture. Samples incubated at high temperature were more responsive to soil moisture than samples incubated at low temperature. Mineralization rates for peat samples incubated at four temperature regimes increased with increasing moisture up to 60% WHC, and then decreased at 100% WHC and complete saturation. In completely water saturated condition, peat mineralization was retarded, probably due to the absence of oxygen available.

As shown in Table 4, total carbon mineralization was significantly affected by temperature and moisture ($P < 0.001$), and the interaction of temperature and moisture was significant ($P < 0.001$). There was also a significant interaction between temperature and depth, temperature and slope, moisture and depth, and moisture and slope ($P < 0.05$). But interaction among all variables was not significant ($P > 0.05$). We used a multiple polynomial regression to predict carbon mineralization rates as a function of temperature and moisture based on the measurements (Fig. 3). The model predicted mineralization very well ($P < 0.001$) and the parameters obtained for the polynomial regression were highly significant (Table 5). In general, soil moisture was less sensitive to soil carbon mineralization rates than soil temperature (Bridgham et al., 1998; Bubier et al., 1998). But in our study, both temperature and moisture influenced carbon mineralization significantly ($P < 0.05$). Therefore, soil temperature and soil moisture were needed for accurate prediction of carbon mineralization in permafrost peatlands of the Great Hing'an Mountains.

Table 3 Average Q_{10} for all sites

Site	Layer (cm)	Average Q_{10}
Beijicun1	10–20	2.05 ± 0.03
Beijicun2	20–30	1.96 ± 0.05
Tuqiang1	10–20	2.07 ± 0.02
Tuqiang2	20–30	2.06 ± 0.03
Zhuanglin1	10–20	2.09 ± 0.04
Zhuanglin2	20–30	2.15 ± 0.07
Huzhong1	10–20	2.15 ± 0.03
Huzhong2	20–30	2.20 ± 0.03
Feihushan1	10–20	2.44 ± 0.03
Feihushan2	20–30	2.37 ± 0.04

Values are mean ± SE.

3 Discussion

3.1 Peat carbon mineralization rate

Rates of CO_2 production measured through laboratory incubation of peat samples represent heterotrophic respiration from a given mass. In our study, the total carbon mineralization ranged from 15.51 to 112.92 mg C, and 2.59% to 12.85% of the C was mineralized after 40 days of incubation. In China, many studies reported the carbon mineralization of wetland and forest soils in the mountains (Wang et al., 2003; Yang et al., 2005, 2008; Zhang et al., 2005, 2007a; Ai et al., 2007; Gao et al., 2009). Yang et al. (2005) studied carbon mineralization of fen peat with

Table 4 Results of four-way analysis of variance of the total carbon mineralization with depth and slope as random effects and temperature and moisture as fixed effects

Source	Type III				
	df	Sum of squares	F	P	Partial eta squared
Temperature	3	73,904.33	251.04	< 0.0001	0.99
Moisture	4	18,717.44	60.888	< 0.0001	0.97
Depth	1	1349.24	10.87	0.0165	0.64
Slope	1	321.84	6.84	0.0429	0.52
Temperature × Moisture	12	2664.00	35.15	< 0.0001	0.98
Temperature × Depth	3	224.30	14.57	0.0001	0.83
Temperature × Slope	3	77.67	5.07	0.0180	0.63
Moisture × Depth	4	212.11	20.54	0.0126	0.85
Moisture × Slope	4	105.46	4.98	0.0394	0.55
Temperature × Moisture × Depth	12	43.67	1.44	0.2275	0.46
Temperature × Moisture × Slope	12	62.43	2.06	0.0740	0.55
Temperature × Moisture × Depth × Slope	20	50.54	0.25	0.9996	0.04
Error	120	1216.01			

Table 5 Equations fitted to the data for the CO_2 emission with soil temperature and moisture for all sites

Site	Layer (cm)	Equation	R^2
Beijicun1	10–20	$\ln(C_m) = 2.6177 + 0.0939T - 0.0009T^2 + 0.0186w - 0.0002w^2$	0.979
Beijicun2	20–30	$\ln(C_m) = 2.7421 + 0.0647T - 0.0003T^2 + 0.0169w - 0.0001w^2$	0.970
Tuqiang1	10–20	$\ln(C_m) = 2.5261 + 0.1195T - 0.0019T^2 + 0.0153w - 0.0001w^2$	0.966
Tuqiang2	20–30	$\ln(C_m) = 2.6257 + 0.0834T - 0.0005T^2 + 0.0140w - 0.0001w^2$	0.967
Zhuanglin1	10–20	$\ln(C_m) = 2.1445 + 0.1661T - 0.0037T^2 + 0.0175w - 0.0001w^2$	0.972
Zhuanglin2	20–30	$\ln(C_m) = 2.2293 + 0.1340T - 0.0023T^2 + 0.0160w - 0.0001w^2$	0.976
Huzhong1	10–20	$\ln(C_m) = 2.1913 + 0.1669T - 0.0037T^2 + 0.0160w - 0.0001w^2$	0.983
Huzhong2	20–30	$\ln(C_m) = 2.1580 + 0.1506T - 0.0029T^2 + 0.0141w - 0.0001w^2$	0.982
Feihushan1	10–20	$\ln(C_m) = 1.9761 + 0.1775T - 0.0036T^2 + 0.0162w - 0.0001w^2$	0.977
Feihushan2	20–30	$\ln(C_m) = 2.0136 + 0.1526T - 0.0027T^2 + 0.0152w - 0.0001w^2$	0.959

C_m: total carbon mineralization; T: incubation temperature; w: soil moisture.

incubation at the same temperature regimes in Sanjiang Plain and found the percentages of carbon mineralization ranged from 3.1% to 15.6% after 33 days. Ai et al. (2007) reported a carbon mineralization of alpine meadow soil with incubation for 61 days in the Qilian Mountains and the percentages of carbon mineralization varied from 9% to 30%. Zhang et al. (2007b) studied carbon mineralization of paddy soils from South China with incubation and found the mean percentage of carbon mineralization was about 25% within 32 days incubation. Gao et al. (2009) found a significant positive relationship between CO_2 productions of peat soils and increasing temperature in the Tibetan alpine marsh by using laboratory incubation. The carbon mineralization is dependent on soil temperature, moisture and reduction-oxidation conditions in different soil types. Therefore, it is difficult to compare these results of different studies. In short-term incubation studies, most of the measured CO_2 is released from the active C pool, which is generally small in mineral soils. Despite these small proportions of soil carbon mineralization, active C pool could contribute much to total soil respiration. Dioumaeva et al. (2003) found a significant decomposition in feather moss peat using incubation experiments in Manitoba, Canada, and thought the sustained warming could lead to a significant loss of carbon from the peatlands. Dorrepaal et al. (2009) showed that approximately 1°C warming would accelerate total ecosystem respiration rates on average by 60% in spring and by 52% in summer using field manipulation experiments in a subarctic peatland, Sweden.

The peat of 10–20 cm layer produced more CO_2 than those of 20–30 cm layer in our study. Faster mineralization in the upper layers was not only because the upper layers had more organic carbon, but also because the upper layer carbon was more labile and could be easily decomposed. Faster mineralization in the upper layers than in deeper layers had also been observed from other studies (Turetsky, 2004; Rey et al., 2005; Yang et al., 2008). The older soils at deeper layers contained higher proportions of recalcitrant carbon than the younger soil organic matter at the surface, and the decay potential and accordingly its temperature decreased significantly with depth in the soil (Christensen et al., 1999). Some studies argued that carbon decomposition and CO_2 production varied inversely with depth (Updegraff et al., 1995; Waddington et al., 2001). In our study, the carbon mineralization would decrease with the depth and the carbon mineralization amounts at the deeper layers were 2.41%–17.83% lower than those at the upper layers under the treatments across all sites.

3.2 Temperature sensitivity of carbon mineralization

In our study, the calculated Q_{10} values ranged from 1.84 to 2.51 across all sites and treatments. They were similar or smaller than the Q_{10} values reported in other studies (Table 6). We found that some of the variation in Q_{10} values reported in the literatures was similar for the boreal ecosystems, meaning that the soil carbon mineralization should be accelerated under warmer temperature in the boreal ecosystem. Although the temperature dependence of soil carbon mineralization on different quality fractions of organic material is still under debate, Q_{10}

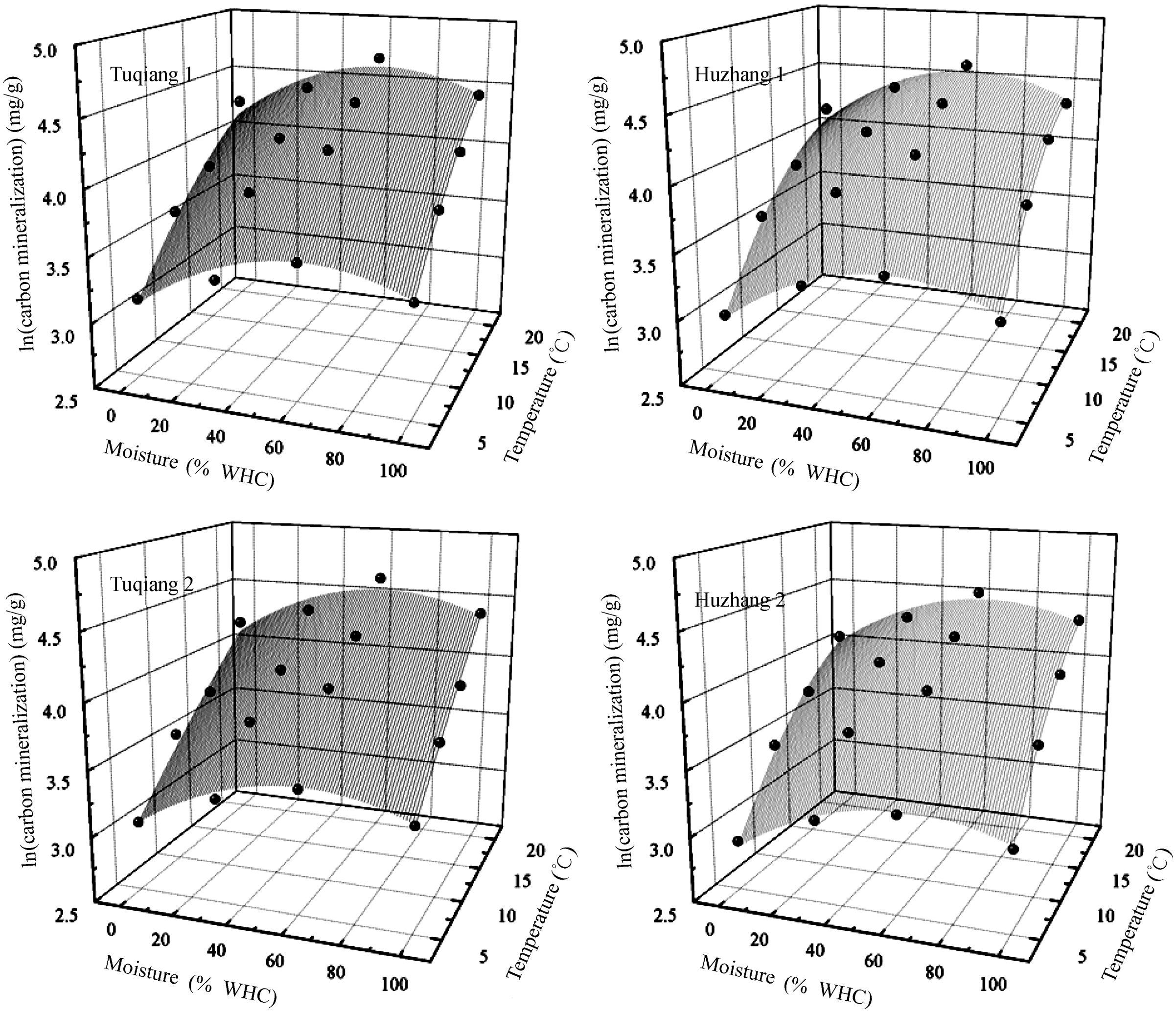

Fig. 3 Measured (circles) and modeled (polynomial equation) carbon mineralization as a function of soil temperature and soil moisture in Tuqiang (1, 2) and Huzhong (1, 2).

Table 6 Summary of Q_{10} values for various soil types in different incubation and field studies

Soil type	Measurement	Q_{10}	Site	Reference
Peat	Incubation	1.84–2.51	Great Hing'an Mountains, China	This study
Peat	Field	2.0–2.9	Finland	Silvola et al., 1996
Peat	Incubation	2.4–4.8	Scotland	Chapman and Thurlow, 1998
Sediment wetland	Incubation	2.2–12.7	Ultuna, Sweden	Lomander et al., 1998
Peat	Incubation	3.1–4.4	Manitoba, Canada	Dioumaeva et al., 2003
Forest soils	Field	2.19–3.91	Changbai Mountain, China	Wang et al., 2003
Peat	Field	2.24–4.14	Ontario, Canada	Lafleur et al., 2005
Forest soils	Incubation	2.2–3.3	Lazio, Italy	Rey et al., 2005
Tundra soils	Incubation	1.9–2.4	Igarka, Russia	Rodionow et al., 2005
Sediment wetland	Incubation	2.0–3.6	Sanjiang Plain, China	Yang et al., 2005

values are calculated to compare different studies generally and to deduce possible climate-change feedback effects (Kirschbaum, 2006). Some studies showed that the increase in temperature might lead to a positive feedback effect to permafrost peatlands, because warming would cause an increase in atmospheric CO_2 by stimulating the decomposition of organic matter in the soil (Gorham, 1991; Hogg et al., 1992; Updegraff et al., 2001). Other studies showed a negative feedback effect more likely to some of permafrost peatland regions, because the increased atmospheric concentration of CO_2 would have a fertilizing effect on soils, boosting plant production (Camill, 1999; Turetsky et al., 2002). Peatlands are believed to function as a net sink for atmospheric CO_2, but the individual peatland might switch annually form net carbon sinks to sources (Waddington et al., 2001). Understanding of the future response of boreal peatlands to climate change needs more data support on peatland carbon emission from different permafrost regions.

Different proportions of organic matter components would result in different rates of decomposition and different patterns of temperature sensitivity (Dioumaeva et al., 2003). Although the peat in the upper layer would release more CO_2 than the peat in the deeper layer, we have not found significant difference in Q_{10} among different peat physicochemical properties and depth layers in our study. Fang et al. (2005) reported that soil organic matter decomposition and soil respiration rates were significantly affected by changes in soil organic matter components associated with soil depth, and Yang et al. (2008) showed there would be a quadratic parabola relationship between the Q_{10} values and the horizons of wetland soil in Sanjiang Plain, China. However, Reichstein et al. (2005) found the Q_{10} values of forest soil were independent of soil horizon in Germany and the values were stable at around 2.7. Rey et al. (2005) found there was no significant difference in the temperature sensitivity of carbon mineralization between horizons of forest soil. There is still no consensus on the relationship between temperature sensitivity of soil carbon mineralization and soil horizon. Some average Q_{10} values were increase with the depth in our study, while the others values showed the reverse trend (Table 3). Despite increase or decrease trends, the Q_{10} values of the deeper layers were close to the values of the upper layers. It means that the deeper layers soil would be sensitive to the warming temperature and the contribution of the deeper layers should not be ignored. Goulden (1998) suggested that warming might significantly increase the contribution of the deep carbon pool to soil respiration.

The temperature sensitivity Q_{10} values of the northeast slope peat (Huzhong and Zhuanglin) showed a tendency to be higher than the data of the northwest slope peat (Beijicun, Tuqiang and Zhuanglin), although no significant difference was observed under all treatments. It means that peatlands on the northeast slope in the predominantly permafrost zone of the Great Hing'an Mountains would response more sensitively to global warming than those on the northwest slope. It is possibly because the nitrogen contents of the peatlands on the northeast slope are higher than the peatlands on the northwest slope. Boreal peatland has generally been thought to be nitrogen-limited, and the nitrogen affects the microbial activity in a complex pattern (Updegraff et al., 2001). Turetsky (2004) thought the short-term incubation should be useful for assessing spatial and temporal heterogeneity in soil CO_2 emission and found the peatlands in the permafrost gradation regions produced more CO_2 than the other permafrost peatland types in western of Canada. More research should be conducted to accurately predict the response of carbon mineralization to the global warming for the different zones in the Great Hing'an Mountains.

3.3 Effect of soil temperature and moisture on carbon mineralization

The mineralization of soil organic matter depends on temperature and moisture, which influence mineralization processes through their effects on microbial activity in the soil (Leirós et al., 1999). The amounts of peat carbon mineralization during our incubation experiments increased with temperature and optimal range of moisture. Similar changing trends had been obtained from other wetlands studies (Moore and Dalva, 1993; Yang et al., 2008). Our results showed that total carbon mineralization was significantly affected by temperature and moisture and the interaction between temperature and moisture was also significant in our study ($P < 0.001$). Many studies found that soil temperature, moisture, and the interaction between temperature and moisture could significantly affect the CO_2 production in wetland soils (Moore and Dalva, 1993; Turetsky, 2004; Yang et al., 2008; Gao et al., 2009). However, Bridgham et al. (1998) and Bubier et al. (1998) suggested that temperature was more important than moisture for carbon mineralization despite the latter was significantly correlated to peat CO_2 emission. Yang et al. (2008) found the temperature and the interaction between temperature and moisture were significantly affected carbon mineralization of wetland soils in Sanjiang plain of China, but the effect of moisture was not significant. Generally, moisture availability and water table position are important controls on C mineralization in peatlands (Turetsky, 2004). Lloyd and Taylor (1994) had found respiration and mineralization increase exponentially with increase of temperature when soil moisture or other factors are not limiting. The relationship between carbon mineralization and soil moisture are still not clear, because of interactions with other biological factors, such as changes in the oxygen available and microbial communities. We found that soil moisture was as important in influencing carbon mineralization as temperature according to the analysis of ANOVA and polynomial modeling in the permafrost peatlands of the Great Hing'an Mountains. In our study, the optimal soil moisture is 60% WHC under the treatments. Howard and Howard (1993) found the same water content on carbon mineralization through incubation. Zhang et al. (2005) derived the optimal soil moisture as 66% WHC in the fen peat of Sanjiang Plain, China.

It is important for the reliable prediction of carbon dynamics under climate change to understand the sensitivity of carbon mineralization to soil temperature and soil moisture. A number of different mathematical expressions have been used to describe the curve response of soil carbon mineralization to temperature and moisture (Lafleur et al., 2005; Reichstein et al., 2005). Whether to use a linear or a curve-linear description of the temperature response remains a problem in modeling peat decomposition. In our study, a two-compartment model based on temperature and moisture successfully fits the dynamics of peat carbon mineralization (Fig. 3). It means that the temperature and moisture have strong influence on carbon mineralization of the permafrost peatlands, and both the variables should be needed for accurate prediction of carbon mineralization. Non-liner regressions have been used for many other soil types to estimate mineralization rates of carbon as functions of soil temperature and moisture (Lomander et al., 1998; Leirós et al., 1999; Rey et al., 2005; Wennman and Kätterer, 2006). However, the wider applicability of this model might be limited because the shape of this function varies with soil types, and the values of parameters are specific with particular sites.

Boreal ecosystems are predicted to receive the most drastic warming in this century (Räisänen et al., 2004). Climate warming would accelerate permafrost thaw. In our study area, widespread degradation of permafrost in boreal peatlands of Northeast China has occurred with climate warming since last century (Jin et al., 2007). Permafrost degradation causes major changes in hydrology, insolation, topography, and species composition in peatlands and such changes could have dramatic effects on carbon cycle in boreal regions (Gorham, 1991; Camill, 1999; Turetsky, 2004). Our results showed that the soil carbon mineralization was significantly affected by the temperature and moisture in the permafrost peatlands. Therefore, the warming temperature and precipitation pattern in the future climate change would have strong influence on the peatlands carbon cycles in the Great Hing'an Mountains. It means that the permafrost peatlands would be potential mineralized due to the environment change under future climate change. Our future research would focus on the estimation of carbon storage of permafrost peatlands in the Great Hing' an Mountains, and investigation of CO_2 emission in the fields. Those works would have important consequences for carbon cycling in peatlands and for understanding of future responses of permafrost peatlands to climate change.

4 Conclusions

The results of incubation experiment showed that carbon mineralization rates of permafrost peatlands decreased with soil depth, increased with temperature, and reached the highest at optimal moisture (60% WHC) at the same temperature in the Great Hing'an Mountains. Total carbon mineralization of permafrost peatlands was significantly affected by soil temperature and moisture. It means that the mineralization of peat organic carbon would be very sensitive to the changes of environmental hydro-thermal factors. Thus, the permafrost peatlands would be potentially mineralized in the future climate change. In addition, the contribution of the carbon mineralization of deeper layers should not be ignored under global warming, and peatlands across the northeast slope in the predominately permafrost zone of the Great Hing'an Mountains might have strong response to global warming.

A multiple regression model successfully predicted carbon mineralization as a function of temperature and moisture. Of course, the model and laboratory incubation method should not be enough to predict the response of carbon mineralization of permafrost peatlands to climate change accurately in the Great Hing'an Mountains. To better characterize the response of carbon mineralization on climate change, future studies should focus on more detailed characterization of soil quality and microbial communities, measuring carbon mineralization in the field and studying the effects of freezing-thawing cycles on carbon mineralization of permafrost peatlands.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 40671013, 40871245). We thank Mr. Zhenling Gao who helped with assistance in work field. We also thank Prof. Wang Shenzhong and Ms. Zhou for the incubation experiment at Northeast Normal University.

References

Ai L, Wu J L, Zhu G, Liu J Q, Tian Z Q, 2007. The mineralization of alpine meadow soil organic carbon and factors in influencing it in the Qilian Mountain. *Prataculturae Science*, 16(5): 22–33.

Bridgham S D, Updegraff K, Pastor J, 1998. Carbon, nitrogen, and phosphorus mineralization in northern wetland. *Ecology*, 79(5): 1545–1561.

Bubier J, Grill P M, Moore T R, Savage K, Varner R, 1998. Seasonal patterns and controls on net ecosystem CO_2 exchange in a boreal peatland complex. *Global Biogeochemical Cycles*, 12: 703–714.

Camill P, 1999. Patterns of boreal permafrost peatland vegetation across environmental gradients sensitive to climate warming. *Botany*, 77(5): 721–733.

Chapman S J, Thurlow, M, 1998. Peat respiration at low temperatures. *Soil Biology and Biochemistry*, 30(8): 1013–1021.

Christensen T R, Jonasson S, Callaghan T V, Havström M, 1999. On the potential CO_2 release from tundra soils in a changing climate. *Applied Soil Ecology*, 11(2): 127–134.

Dioumaeva I, Trumbore S, Schuur E A G, Goulden M L, Litvak M, Hirsch A I, 2003. Decomposition of peat from upland boreal forest: Temperature dependence and sources of respired carbon. *Journal of Geophysical Research*, 108: 1–12.

Dorrepaal E, Toet S, Logtestijn S P, Swart E, 2009. Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. *Nature*, 460: 616–621.

Fang C, Smith P, Moncrieff J B, Smith J U, 2005. Similar response of labile and resistant soil organic matter pools to changes in temperature. *Nature*, 433: 57–59.

Gao J Q, Ouyang H, Xu X L, Zhou C P, 2009. Effects of temperature and water saturation on CO_2 production and nitrogen mineralization in Alpine wetland soils. *Pedosphere*, 19(1): 71–77.

Gorham E, 1991. Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications*, 1(2): 182–195.

Goulden M L, 1998. Sensitivity of boreal forest carbon balance to soil thaw. *Science*, 279: 214–216.

Hogg E H, Lieffers V J, Wein R W, 1992. Potential carbon losses from peat profiles: Effects of temperature, drought cycles, and fire. *Ecological Applications*, 2(3): 298–306.

Howard D M, Howard P J A, 1993. Relationships between CO_2 evolution, moisture content and temperature for a range of soil types. *Soil Biology and Biochemistry*, 25(11): 1537–1546.

Jin H J, Yu Q H, Guo D X, He R X, 2007. Degradation of permafrost in the Xing'an Mountains, Northeast China. *Permafrost and Periglacial Processes*, 18: 245–258.

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 Biology and Biochemistry*, 27(6): 753–760.

Kirschbaum M U F, 2006. The temperature dependence of organic-matter decomposition – still a topic of debate. *Soil Biology and Biochemistry*, 38(9): 2510–2518.

Lafleur P M, Moore T R, Roulet N T, Frolking S, 2005.

Ecosystem respiration in a cool temperate bog depends on peat temperature but not water table. *Ecosystems*, 8(6): 619–629.

Leirós M C, Trasar-Cepeda C, Seoane S, Gil-Sotres F, 1999. Dependence of mineralization of soil organic matter on temperature and moisture. *Soil Biology and Biochemistry*, 31(3): 327–335.

Lloyd J, Taylor A, 1994. On the temperature dependence of soil respiration. *Functional Ecology*, 8: 315–323.

Lomander A, Kätterer T, Andrén O, 1998. Modelling the effects of temperature and moisture on CO_2 evolution from top-and subsoil using a multi-compartment approach. *Soil Biology and Biochemistry*, 30(14): 2023–2030.

Moore T R, Dalva M, 1993. The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. *Journal of Soil Science*, 44: 651–664.

Räisänen J, Hansson U, Ullerstig A, Döscher R, Graham L P, Jones C et al., 2004. European climate in the late twenty-first century: Regional simulations with two driving global models and two forcing scenarios. *Climate Dynamics*, 22(1): 13–31.

Reichstein M, Subke J A, Angeli A C, Tenhunen J D, 2005. Does the temperature sensitivity of decomposition of soil organic matter depend upon water content, soil horizon, or incubation time? *Global Change Biology*, 11(10): 1754–1767.

Rey A, Petsikos C, Jarvis P G, Grace J, 2005. Effect of temperature and moisture on rates of carbon mineralization in a Mediterranean oak forest soil under controlled and field conditions. *European Journal of Soil Science*, 56(5): 589–599.

Rodionow A, Flessa H, Kazansky O, Guggenberger G, 2005. Organic matter composition and potential trace gas production of permafrost soils in the forest tundra in northern Siberia. *Geoderma*, 135: 49–62.

Roulet N T, Lafleur P M, Richard P J H, Moore T R, Humphreys E R, Bubier J, 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology*, 13(2): 397–411.

Scanlon D, Moore T D, 2000. Carbon dioxide production from peatland soil profiles: the influence of temperature, oxic/anoxic conditions and substrate. *Soil Science*, 165(2): 153–160.

Silvola J, Alm J, Ahlholm U, Nykanen H, Martikainen P J, 1996. CO_2 fluxes from peat in boreal mires under varying temperature and moisture condition. *Journal of Ecology*, 84(2): 219–228.

Turetsky M R, Wieder R K, Vitt D H, 2002. Boreal peatland C fluxes under varying permafrost regimes. *Soil Biology and Biochemistry*, 34(7): 907–912.

Turetsky M R, 2004. Decomposition and organic matter quality in continental peatlands: the ghost of permafrost past. *Ecosystems*, 7(7): 740–750.

Turunen J, Tomppo E, Tolonen K, Reinikainen A, 2002. Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and subarctic regions. *Holocene*, 12(1): 69–80.

Updegraff K, Pastor J, Bridgham S D, Johnston C A, 1995. Environmental and substrate controls over carbon and nitrogen mineralization in northern wetlands. *Ecological Applications*, 5(1): 151–163.

Updegraff K, Bridgham S D, Pastor J, Weishampel P, Harth C, 2001. Response of CO_2 and CH_4 emissions from peatlands to warming and water table manipulation. *Ecological Applications*, 11(2): 311–326.

Waddington J M, Rotenberg P A, Warren F J, 2001. Peat CO_2 production in a natural and cutover peatland: Implications for restoration. *Biogeochemistry*, 54(2): 115–130.

Wang M, Ji L Z, Li Q R, Liu Y Q, 2003. Effects of soil temperature and moisture on soil respiration in different forest types in Changbai Mountain. *Applied Ecology*, 14(8): 1234–1238.

Wennman P, Kätterer T, 2006. Effects of moisture and temperature on carbon and nitrogen mineralization in mine tailings mixed with sewage sludge. *Environmental Quality*, 35(4): 1135–1141.

Yang G R, Zhang W J, Tong C L, Wu J S, 2005. Effects of temperature on the mineralization of organic carbon in sediment of wetland. *Ecology Science*, 25(2): 243–248.

Yang J S, Liu J S, Sun L N, 2008. Effects of temperature and soil moisture on wetland soil organic carbon mineralization. *Ecology Science*, 27(1): 38–42.

Zhang Z Y, 2000. Development and utilization of peat resources. Chinese Jilin Science and Technology Press, Changchun. 191–202.

Zhang W J, Tong C L, Yang G R, Wu J S, 2005. Effects of water on mineralization of organic carbon in sediment from wetlands. *Ecology Science*, 25(2): 249–253.

Zhang L H, Song C C, Wang D X, Wang Y Y, 2007a. Relationship of ecosystem respiration with temperature, nitrogen and plant in freshwater marshes. *Chinese Journal of Environmental Science*, 28(1): 1–8.

Zhang X H, Li L Q, Pan G X, 2007b. Topsoil organic carbon mineralization and CO_2 evolution of three paddy soils from south China and the temperature dependence. *Journal of Environmental Sciences*, 19(3): 319–326.

Zhou M, Yu X X, Feng L, Wang L H, Na P S, 2003. Effects of permafrost and wetland in forests in Great Hing'an Mountains on ecology and environment. *Journal of Beijing Forestry University*, 25(6): 91–93.