INVERSE MODELING FOR SPATIAL PATTERN OF TEMPERATURE SENSITIVITY (Q_{10}) IN CHINA

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ABSTRACT:

Temperature sensitivity of soil respiration (Q_{10}) is an important parameter on evaluations of feedback intensity between soil carbon efflux and global warming. Although experiments of soil respiration indicate its value has high spatial heterogeneity due to influences of many spatially heterogeneous environmental factors, the coupled climate-carbon cycle models usually assume it a globally invariant constant for its spatial complexity. Therefore, revealing the spatial pattern of Q_{10} value and incorporating it into coupled climate-cycle models is an urgent scientific problem for reducing uncertainties of projected climate and atmospheric CO_2 content. In this study, an inversion analysis method, which combines a process-based terrestrial carbon cycle model (CASA model) with observations of soil organic carbon, was used to retrieve the spatial pattern of Q_{10} in China at 0.08 by 0.08 degree resolution. The results indicate that the optimal Q_{10} value for different spatial grid is spatially heterogeneous, which are matched with those derived from soil respiration observations. The mean Q_{10} values for different soil types range from 1.09 to 2.38. The results indicate that the spatial pattern of Q_{10} value is related with environmental factors, especially precipitation and top soil organic carbon content.

1. INTRODUCTION

Temperature sensitivity of soil respiration (Q_{10}) is the factor by which respiration is multiplied when temperature increases by 10℃ (Davidson et al., 2006b), and therefore it is an important parameter to evaluate the feedback intensity between soil carbon efflux and global warming (Cox et al., 2000; Luo et al., 2001; Friedlingstein et al., 2003; Reichstein et al., 2003). Biogeochemical models of combined effects of elevated atmospheric CO_2 concentrations and climate changes generally predict increases in terrestrial net primary production (NPP) and in carbon stocks (Cao & Woodward, 1998). However, the positive feedback between temperature and the release of CO_2 to the atmosphere by soil respiration could significantly reduce the magnitude of terrestrial carbon accumulation (Houghton et al., 1998).

Q_{10} is usually simplified and treated as a invariant constant in regional or global modeling (Friedlingstein et al., 2006), although the assumption of constant temperature sensitivities of respiration enzymes at all temperatures is incorrect (Davidson, 2006b) and the expected dependence on temperature is not found at the whole ecosystem level for decadal time scales (Denman et al., 2007). Therefore, it is an urgent need to quantify the temperature sensitivity at ecosystem scale; it is scientific foundation for predicting feedbacks of the terrestrial carbon cycle to climate warming (Holland et al., 2000; Luo, 2007).

Q_{10} value should be spatially heterogeneous as many environmental factors determine the Q_{10} values; theoretical and experimental evidence has indicated that Q_{10} values of soil organic carbon (SOC) decomposition equal a constant only under specific conditions (Davidson et al., 2006a). Because Q_{10} value is one of the most important parameter in coupled climate-carbon cycle modeled, the simplification by using a globally invariant Q_{10} value to substitute the spatially heterogeneous Q_{10} values will inevitably increase spatial uncertainties of the feedback intensity between terrestrial carbon cycle and the global warming (Tjoelker et al., 2001; Luo, 2007).

There have many spatially heterogeneous environmental factors influence the spatial distribution of Q_{10} values. The studies indicated that Q_{10} values are dependent on soil temperature (Lloyd and Taylor, 1994; Kirschbaum, 1995; Luo et al., 2001) and quantity and quality of soil organic matter (Taylor et al., 1989; Liski et al, 1999; Wan and Luo, 2003). An experimental phenomenon of decrease of Q_{10} with increasing temperature is commonly observed in nature (Tjoelker et al., 2001). Theoretical explanation for this phenomenon is that as temperature increases, there is a declining relative increase in the fraction of molecules with sufficient energy to react (Davidson et al., 2006a). The importance of substrate availability in enzyme-catalysed reactions is described by Michaelis-Menten kinetics, which indicates that the low substrate will induce the low Q_{10} values (Davidson et al., 2006b).

In addition to temperature and substrate, Q_{10} is also related to soil moisture (Davidson et al., 1998; Reichstein, 2002; Hui and Luo, 2004) and land cover types (Raich and Tufekcioglu, 2000). Variation in soil water content affects the diffusion of soluble substrates at low water content and the diffusion of oxygen at high water content, both of which can limit soil microbial respiration (Davidson et al., 2006b). As all influencing factors of temperature, moisture, and soil organic matter are spatially heterogeneous, it is natural to find that the Q_{10} estimated by soil respiration experiments varies widely and depends on the specific geographic location (Xu and Qi, 2001).

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Up to now, the apparent Q_{10} values of soil respiration is hardly estimated through theoretical methods and, therefore, are usually estimated by regressions of measured soil respiration rates against temperature and soil moisture factors (e.g., Raich et al., 1995; Fang et al. 2005). As these kinds of empirical models do not address the underlying physiological processes, the estimated Q_{10} values are probably so variable; the values that are significantly above 2.5 probably attribute to some unidentified process of substrate supply (Davidson et al., 2006b). In addition, reliability of the estimated Q_{10} values from measured soil respiration is also dependent on the precision of measure instruments; the static-chamber, for instance, may underestimate the true soil respiration (Raich et al., 2002).

In this study we use an inversion approach, which combines a process-based ecosystem model (CASA model) with the measured soil organic carbon (SOC), to retrieve the spatial distribution of Q_{10} in regional scale on 0.08 by 0.08 degree spatial resolution. After that, we compared them with those derived from experiment-based researches. Finally, we analyzed the statistical dependencies between our estimated Q_{10} values and the relevant environmental factors at regional scale.

2. METHODS AND DATA

2.1 Inversion algorithm

Storage and variation of soil organic carbon (SOC) depends on soil carbon input originated from ecosystem production, and on soil carbon output controlled by soil respiration and thereby related with Q_{10} value (Fang,C et al., 2005; Xu and Qi, 2001), climatic factors (Reichstein, et al., 2003; Hui and Luo, 2004), and plant chemistry and soil texture (Schimel et al., 1994). One distinct feature of Q_{10} is that it significantly impacts season variation of soil respiration and, eventually, impact the storage and the residence time of soil organic carbon (Thompson et al., 1996; Ise et al., 2006). During the long-term process of soil evolvement, organic carbon gradually accumulates in soil and evolves into a near steady state, with change of SOC in a year equaling zero (Nadelhoffer and Fry, 1988; Kessel et al., 1994). Therefore, the storage of SOC for a specific site is controlled by Q_{10}, climatic factors, soil properties, and C input that related with ecosystem production (as shown in Figure 1).

In this study, the measured SOC and the corresponding environmental factors of each spatial grid were used as constraints to estimate the optimal Q_{10}. Given these observed SOC and environmental factors, the optimal Q_{10} value for a specific site were estimated basing on rule that the deviation of the observed and modeled Q_{10}-related SOC being minimal. The modeled SOC storage for different Q_{10} values was conducted by Carnegie-Ames-Stanford Approach (CASA) (Potter et al., 1993; Field et al., 1995), which contains an ecosystem production submodel and a soil organic carbon submodel (Figure 2).

At each spatial grid x, we searched for the optimal value of Q_{10} in the domain Q $\in$ [Qmin,Qmax] such that

$$\left|S_{m,x}(Q_{10}^0(Q)) - S_{0,x}\right| \le \left|S_{m,x}(Q'_{10}) - S_{0,x}\right|, \forall Q'_{10} \in Q \qquad (1)$$

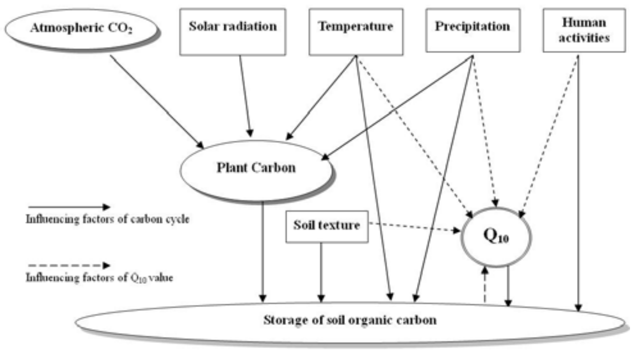

Figure 1. Schematic chart of interactions between carbon cycle and Q_{10} value

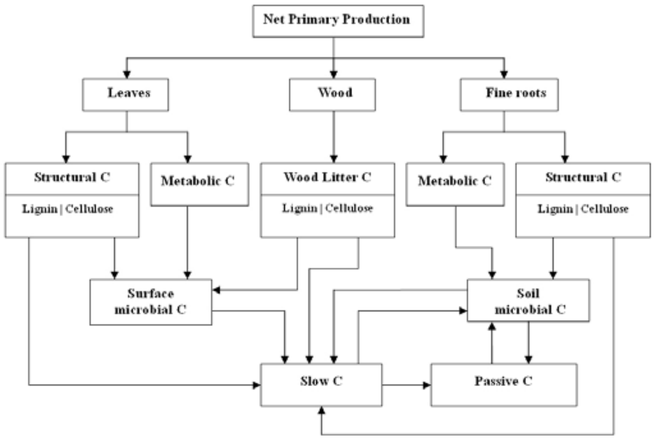

Figure 2. Carbon allocations and transfers among litter and soil organic carbon pools

where $S_{0,x}$ = measured SOC of grid x
Q= domain of Q_{10} value
Q_{10}^0 = the optimal Q_{10} value
Q'_{10} = arbitrary Q_{10} value
$S_{m,x}(Q_{10}^0(Q))$ = modeled SOC with Q_{10}^0
$S_{m,x}(Q'_{10})$ = modeled SOC with Q'_{10}

After the optimal Q_{10} values for all grids are estimated, the modeled mean SOC in China has the minimal deviation with the mean observations:

$$J(Q) = \frac{\sum_x \left|S_{m,x}(Q_{10}^0(x)) - S_{0,x}\right| \times a(x)}{\sum_x a(x)} \qquad (2)$$

where a(x) = grid area of x

J = the mean deviation between the modeled and observed SOC, which depends on the optimal Q_{10} value of each grid and therefore related with the searching domain Q.

The reasonable low limit (Qmin) of domain Q is relatively easy to assign. In this study Qmin equals 1, which means that soil respiration do not change with temperature; it usually appears at soil type of Entisol where SOC is absent. The reasonable upper limit (Qmax), however, is somewhat difficult to confirm, as the estimated upper limit derived from soil respiration measures change greatly and some values are so high (>10). Davidson et al. (2006b) think that the estimated Q_{10} values that significantly above 2.5 are unreasonable and it probably attributed to some unidentified process of substrate supply. In this study, we did not appoint Qmax value in advance, but constrain it by using a prior knowledge, i.e., the optimal Qmax should make the retrieved mean Q_{10} value in China match with the mean value derived from soil respiration measures.

2.2 Verification

To make sure if the spatial patterns of Q_{10} values estimated from the inversion algorithm are reasonable and compatible with those derived from soil respiration experiments, we did some verification by comparing our inverted Q_{10} values at different spatial locations with those derived from soil respiration measures. The data sources come from the peer-reviewed papers that contains ecosystems of forest, grassland, meadow, and cropland.

2.3 Data

The data set of measured SOC in this study are from the second national soil survey of China, which is composed of records of 2473 typical soil profiles and compiled by Wang et al. (2001, 2003). The NDVI data set used in this study is for the period 1982 to 1999 and is the standard 8-km bimonthly continental product of Global Inventory Monitoring and Modeling Studies (GIMMS) group (Tucker et al., 2004), which are available at website http://glcf.umiacs.umd.edu/. The meteorological data required as input for the CASA included monthly mean temperature, precipitation, and solar radiation. These data sets provided by China Meteorological Data Sharing Service System at website http://cdc.cma.gov.cn/. The data sets of soil and vegetation types come from the 1:4000000 maps that compiled by institute of Geographic Sciences and Natural Resources Research, CAS. All of those global data sets were resampled to same geographic projection and spatial resolution (0.08 by 0.08 degree).

3. RESULTS AND DISCUSSIONS

3.1 Spatial Pattern of Q_{10}

Given the environmental factors that potential affect the temperature sensitivity (Figure 1), the optimal Q_{10} value of a certain spatial grid was well constrained by SOC observation. From the viewpoint of regional scale, the optimal Q_{10} value is related with range of the domain Q. When Qmax equals 2.5, the inverted Q_{10} values were best matched with the observation-based Q_{10} values. This is consistent with the study conducted by Davidson et al. (2006b), who think Q_{10} value that significantly above 2.5 is unusual and it probably deduced by ignorance of some site-specific process of substrate supply.

Under the domain $Q \in [1, 2.5]$, the spatial patterns of the optimal Q_{10} values in regional scale are estimated. It shows that the optimal Q_{10} value for different grids has a great spatial heterogeneity. The mean Q_{10} values for different soil types range from 1.09 to 2.38, with the highest values in Volcanic soils, Mountain meadow soils and Latosolic red soils and the lowest value in Cold brown calcic soils, Gray desert soils and Frigid desert soils (Table 1).

Soil Taxonomy	Q_{10}	Soil Taxonomy	Q_{10}
Latosols	1.78	Limestone soils	2.08
Latosolic red soils	2.21	Volcanic soils	2.38
Red soils	1.87	Purplish soils	1.88
Yellow soils	2.10	skeletal soil	1.29
Yellow brown soils	1.65	Lithosols	1.26
Yellow cinnamon soils	1.77	Meadow soils	1.85
Brown soils	1.54	fluvo-aquic soil	1.70
Dark-brown soils	1.61	Sajiang black soils	2.21
Bleached Beijiang Soils	1.37	Shrub meadow soils	1.85
Brown coniferous forest soils	2.04	Mountain meadow soils	2.23
Torrid red soils	1.47	Bog soils	1.85
Cinnamon soils	1.63	Solonchaks	1.72
Gray-cinnamon soils	2.11	Coastal solonchaks	1.77
Black soils	1.86	Acid sulphate soils	1.45
Gray forest soils	1.57	Frigid plateau solonchaks	2.01
Chernozems	2.05	Solonetzs	1.68
Castanozems	2.12	Paddy soils	2.17
Castano cinnamon soils	1.68	irrigated silting soils	1.78
Dark loessial soils	2.23	irrigated desert soils	1.91
Brown caliche soils	1.65	Felty soils	1.90
Sierozems	2.14	Dark felty soils	1.89
Gray desert soils	1.09	Frigid calcic soils	1.92
Gray-brown desert soils	1.13	Cold calcic soil	1.63
Brown desert soils	1.11	Cold brown calcic soils	1.03
Loessial soils	1.75	Frigid desert soils	1.10
red clay	1.72	Cold desert soils	1.67
Neo-alluvial soils	2.01	Frigid frozen soils	1.36
Takyr	1.31	Others	1.27
Aeolian soils	1.19		

Table 1. Means of Q_{10} values for each Great Group in Chinese Soil Taxonomy

3.2 Verification

The comparison between the inverted and observed Q_{10} values that derived from the regression between measured soil respiration and temperature shows that the retrieved Q_{10} values, in general, match with the observation-based Q_{10} values, with the correlation coefficient of 0.70.

3.3 Statistical dependency of Q_{10} on Environmental Factors

Correlation analysis indicates that the Q_{10} values estimated by inverse method are statistically related with their environmental factors, especially content of soil organic carbon and precipitation.

The correlation analysis indicates that the Q_{10} values positively correlated with soil organic carbon and soil nitrogen contents, with the correlation coefficients of 0.69 and 0.65 respectively. The positive correlation between Q_{10} and soil organic carbon is consistent with the prior studies that soil organic matter quantity influences soil respiration and its sensitivity (Taylor et al., 1989; Liski et al., 1999). The positive correlation has also been observed in the experiment study conducted by Zhang et al. (2005) who found Q_{10} values are significantly positive correlated with soil organic carbon and dissolved organic carbon.

The positive correlation between Q_{10} and soil organic carbon content is probably because the magnitude and structure of soil organic carbon is one of the key factors that impact soil apparent respiration (Davidson et al., 2006a). Because soil N concentration is covaried with soil C from the viewpoints of the classical soil-forming factors (Jenny, 1941; 1980), the positive correlation between Q_{10} and soil C causes Q_{10} also positively correlated with soil N.

In addition, our inverted Q_{10} value is positively correlated with precipitation ($r = 0.45$). This is consistent with the studies that show that soil moisture is positively correlated with the temperature sensitiviy of soil respiration (Davidson et al., 1998; Qi and Xu, 2002; Yuste et al., 2003). The causes of precipitation on Q_{10} value is probably because that variation in soil water content affects the diffusion of soluble substrates (Davidson et al., 2006b). As the content of SOC in China is positive correlated with precipitation (Zhou et al., 2003), so the positive correlation between Q_{10} values and precipitation is consistent with the positive correlation between Q_{10} values and SOC content.

4. CONCLUSIONS

Temperature sensitivity of soil respiration (Q_{10} value) and its spatial pattern is a crucial parameter for projecting the climate change and atmospheric CO_2 concentration in the future. Q_{10} values have a high spatial heterogeneity as its values are controlled by many spatially heterogeneous environmental factors. The inversion analysis showed that the observations of soil organic carbon content and soil respiration could be used to retrieve the spatial pattern of Q_{10} value. The inverted spatially heterogeneous Q_{10} values could be matched with those derived from observations of soil respirations in different spatial site. Our estimated Q_{10} values and environmental factors have similar statistical dependencies with those derived from soil respiration measures. That is, Q_{10} value is linearly correlated ($r = 0.45$) with precipitation and logarithmically correlated ($r = 0.69$) with soil organic carbon content of top layer (0-30cm).

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