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Convergence in temperature sensitivity of soil respiration: Evidence from the Tibetan alpine grasslands

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ABSTRACT

Recent studies proposed a convergence in the temperature sensitivity (Q_{10}) of soil respiration (R_s) after eliminating confounding effects using novel approaches such as Singular Spectrum Analysis (SSA) or the mixed-effects model (MEM) method. However, SSA has only been applied to eddy covariance data for estimating the Q_{10} with air temperature, which may result in underestimations in responses of below-ground carbon cycling processes to climate warming in coupled climate-carbon models; MEM remains untested for its suitability in single-site studies. To examine the unconfounded Q_{10} of R_s, these two novel methods were combined with directly measured R_s for 6 years in two Tibetan alpine ecosystems. The results showed that, 1) confounded Q_{10} of R_s estimated from seasonal R_s-temperature relationship positively correlated with the seasonality of R_s, and 2) estimates of unconfounded Q_{10} of R_s using SSA (mean = 2.4, 95% confidence interval (CI): 2.1–2.7) and MEM (mean = 3.2, 95% CI: 2.3–4.2) were consistent with the theoretical subcellular-level Q_{10} ($\approx$2.4). These results support the convergence in the Q_{10} of R_s and imply a conserved R_s-temperature relationship. These findings indicate that the seasonality of R_s has to be eliminated from estimating the Q_{10} of R_s, otherwise the estimates should be questionable. They also indicate that seasonal Q_{10} and its responses to warming should not be directly used in carbon-climate models as they contain confounding effects.

1. Introduction

Soil respiration (R_s) is a critical component of terrestrial ecosystems carbon cycle (Davidson and Janssens, 2006; Giardina et al., 2014; Luo, 2007). It is predicted to be stimulated by the pronounced global warming based on the universally observed positive R_s-temperature relationship, creating a positive feedback between climatic warming and soil respiration (Bond-Lamberty and Thomson, 2010a; Lloyd and Taylor, 1994; Yvon-Durocher et al., 2012). However, large uncertainty remains in the predicted strength of such positive feedback. The Q_{10} of R_s, a factor by which the rate of R_s is multiplied when temperature rises by 10 °C (Davidson and Janssens, 2006; Lloyd and Taylor, 1994), is one of the crucial parameters to reduce such uncertainty (Exbrayat et al., 2014; Jones et al., 2003; Knorr et al., 2005; Tan et al., 2010; Todd-Brown et al., 2014). While some studies have shown a consistent Q_{10} of R_s in various types of ecosystems (Mahecha et al., 2010; Yvon-Durocher

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et al., 2012), other investigations have demonstrated a considerable variability of estimated Q_{10} of R_s (Peng et al., 2009; Wang et al., 2014a). Reconciling such a discrepancy becomes a critical task for a reliable prediction of climate-carbon feedback in the future.

The variability in observed Q_{10} of R_s can be partly attributed to the methods used to estimate Q_{10}. Estimating Q_{10} from natural temperature gradients may contain the influences of non-temperature driven confounding factors that covary with temperature. For example, comparing R_s across seasons is commonly used for estimating Q_{10} of R_s (Davidson et al., 2006; Lloyd and Taylor, 1994; Suseela et al., 2012; Suseela and Dukes, 2013). However, seasonal changes in R_s are driven by both temperature and non-temperature driven processes, such as vegetation activity (Curiel Yuste et al., 2004; Wang et al., 2010), litter inputs (Gu et al., 2008), and soil water content (Reichstein et al., 2005; Xu and Baldocchi, 2004). For example, high R_s rates in summer are attributable to both high temperature and high overall vegetation activities that provide substrates for R_s (Curiel Yuste et al., 2004; Högberg et al., 2001; Wang et al., 2010), evidenced by a positive correlation between Q_{10} of R_s and the amplitudes of seasonal variations in vegetation activities (Curiel Yuste et al., 2004; Wang et al., 2010). Soil water content could also influence both R_s and the estimated Q_{10} of R_s (Geng et al., 2012; Liu et al., 2016, 2009); summer drought can reduce R_s (Selsted et al., 2012) and counteract the influence of high temperature on R_s, masking the response of R_s to temperature. In summary, Q_{10} estimated from seasonal temperature gradients includes a suite of non-temperature driven confounding effects and thus does not truly reflect the responses of R_s to changing temperature. Given the high sensitivity of projected future climate to the Q_{10} of R_s (Randerson et al., 2009; Tan et al., 2010; Todd-Brown et al., 2013), it is imperative to eliminate the non-temperature driven confounding effects when estimating the Q_{10} of R_s for an accurate prediction of how soil carbon flux will respond to climatic warming (Curiel Yuste et al., 2004; Mahecha et al., 2010; Wang et al., 2010).

Several recent studies attempted to estimate the unconfounded Q_{10} of R_s (or ecosystem respiration, ER) using novel approaches. For example, Mahecha et al. (2010) applied Singular Spectrum Analysis (SSA) with eddy covariance data to estimate the Q_{10} of ER, assuming that non-temperature driven confounding effects remain constant in short term. They reported a convergent Q_{10} of ~1.4 across various types of ecosystems. Yvon-Durocher et al. (2012) employed a mixed-effects modeling approach to estimate unconfounded Q_{10} of R_s and found a consistent Q_{10} of about 2.4 for R_s and ER. Although these novel approaches eliminated the non-temperature driven confounding effects to a large extent, several limitations remain in these approaches. For instance, the mixed-model approach assumes that the non-temperature driven confounding effects are random across sites and are zero on average. Such an assumption may be suitable for a meta-analysis but may not apply to single-site studies, which remains to be tested. Estimating Q_{10} of R_s using eddy covariance data as in Mahecha et al. (2010) includes both the aboveground and belowground respirations. Also, Q_{10} estimated using air temperature instead of soil temperature may underestimate the true Q_{10} of R_s because soils typically experience less temperature fluctuation compared to the corresponding air temperature (Graf et al., 2011; Xu and Qi, 2001). Using direct measurements of R_s, soil temperature and the SSA has the potential to alleviate these shortcomings in Mahecha et al. (2010). Together, combining high-resolution measurements of soil R_s and temperature with multiple novel statistical approaches is a proper way to examine the robustness of the estimated Q_{10} of R_s and improve the current understanding of the temperature sensitivity of soil respiration.

In this study, multiple approaches were applied to estimate the Q_{10} of R_s based on continuous measurements of R_s and temperature in alpine grasslands in Tibetan Plateau. The alpine grassland ecosystem in this region provides an ideal model system to investigate this problem. On the one hand, the large soil carbon storage in this region (Shi et al., 2012; Yang et al., 2008) could exhibit strong feedback to the warming climate (Zhuang et al., 2010). On the other hand, the pronounced seasonality of vegetation could confound the estimated Q_{10} of R_s (Wang et al., 2014b), making it an ideal place to compare various methods of estimating the temperature dependence of R_s.

In this study, hourly R_s was automatically measured in a mesic grassland ecosystem (6-years) and a meadow ecosystem (3-years) in the Tibetan Plateau. Three methods were employed to estimate the Q_{10} of R_s. Specifically, the conventional regression method was used for estimating the Q_{10} of R_s from seasonal temperature changes; two novel methods, the SSA (Golyandina and Korobeynikov, 2014; Mahecha et al., 2010) and the mixed-effects model (MEM) method (Yvon-Durocher et al., 2012), were employed to eliminate temperature independent confounding factors and estimate the intrinsic Q_{10} of R_s. The non-temperature driven processes, such as the vegetation activity, contribute to the pronounced seasonality of R_s in the Tibetan alpine grasslands (Wang et al., 2014b), which can positively affect on the estimated Q_{10} of R_s (Curiel Yuste et al., 2004; Mahecha et al., 2010; Wang et al., 2010). Thus, the regression method that does not account for these confounding effects was hypothesized to give rise to a higher Q_{10} of R_s in the Tibetan alpine ecosystems. Furthermore, two novel methods that could eliminate the confounding effects were hypothesized to result in the Q_{10} of R_s consistent with the intrinsic Q_{10} of aerobic metabolic reactions at the subcellular level ($Q_{10} \approx 2.4$) (Gillooly et al., 2001; Raven and Geider, 1988; Vetter, 1995; Yvon-Durocher et al., 2012).

2. Materials and methods

2.1. Site description

This study was performed at the Haibei Alpine Grassland Ecosystem Research Station (Haibei Station, 101°12′E, 37°30′N, 3200 m a.s.l.), located in the northeastern part of the Tibetan Plateau, China. This area has a continental monsoon climate, with a short growing season (Wang et al., 2014b). From 2008 to 2013, the mean annual air temperature was −1.08 °C (ranging from −1.82 to −0.81 °C). The mean annual precipitation was 416.8 mm (ranging from 350.6 to 501.3 mm) (Table 1), and ~90% of the precipitation was concentrated in the growing season from May to September (Wang et al., 2014b).

This study was conducted in two sites, a mesic grassland site and a meadow site. The soils at the mesic grassland site and the meadow site are Mat-Cryic Cambisols and Fib-Orthic Histosols, respectively (Chinese

Table 1
Average values of climate, soil, vegetation and soil respiration (R_s) characteristics of the two study sites. Values in brackets are the range of mean annual precipitation and the range of the daily mean temperature. Values following ± are the standard error of the means (n = 3–4 for R_s of the mesic grassland and n = 3–5 for R_s in the meadow).

	Mesic grassland	Meadow
Mean annual precipitation (mm)	416.8 (350.6–501.3)*	416.8 (350.6–501.3)*
Mean air temperature (°C)	−1.08 (−22.70–14.99)*	−1.08 (−22.70–14.99)*
Mean soil temperature (°C)	2.45 (−10.68–15.41)	2.77 (−9.23–14.97)
Mean soil moisture (v/v)	29.6 ± 1.07	32.4 ± 1.78
Soil pH	7.85 ± 0.07	7.57 ± 0.18
Soil organic carbon (%)	7.82 ± 0.09	22.8 ± 0.56
Soil total nitrogen (%)	0.58 ± 0.03	1.72 ± 0.08
Above ground biomass (g m^{-2})	372.2 ± 22.5	310.8 ± 15.2
Annual cumulative R_s (g C m^{-2})	681.5 ± 24.7	574.5 ± 44.9
Growing-season cumulative R_s (g C m^{-2})	597.7 ± 24.0	487.5 ± 42.4

*Denotes two sites shared the data of a same weather station as the distance between sites is small (~1.5 km).