Short Communication

Constant and diurnally-varying temperature regimes lead to different temperature sensitivities of soil organic carbon decomposition

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In a 122-day incubation experiment with two soil types under four temperature treatments, we examined whether the temperature sensitivity of soil organic carbon (SOC) decomposition differed between constant and diurnally-varying soil temperature regimes. We calculated the Q10 values after accounting for changes in substrate availability and quality among treatments over time. The Q10 values under constant temperature regime were consistently and significantly higher than those under diurnally-varying temperature regime, particularly in the later stages of decomposition (by up to 30%). This result indicated that different temperature regime was one of the important factors causing the current controversy about the temperature sensitivity of SOC decomposition in published reports.

The temperature dependence of soil organic carbon (SOC) decomposition effectively controls whether and how much CO₂ will be released to the atmosphere under global warming, and to what extent this release of CO₂ from SOC may lead to further climatic warming (Davidson and Janssens, 2006; Heimann and Reichstein, 2008). Despite the appreciable amount of experimental and modeling work in the past few decades, there is still no scientific consensus on the temperature sensitivity of SOC decomposition (Kirschbaum, 2006; von Lützow and Kögel-Knabner, 2009), largely due to the fact that different experimental settings have often been used in separate studies (Davidson et al., 2006; Subke and Bahn, 2010). Among these experimental settings, temperature control regimes, e.g. diurnally and seasonally varying temperatures vs. preset constant temperatures, may play a significant role in causing this controversy.

In most lab incubation experiments (e.g. Reichstein et al., 2000; Conant et al., 2008), jars filled with soil samples were incubated in several incubators where temperature was maintained at a constant level throughout the entire experimental duration. The temperature sensitivity of SOC decomposition (Q10) was calculated based on CO₂ efflux measurements at different temperatures. In contrast, in most field warming experiments (e.g. Luo et al., 2001; Hartley et al., 2007), soil CO₂ efflux was measured under both ambient and warming treatments in which soil temperature varied diurnally and seasonally. The calculated Q10 values based on CO₂ efflux measurements under both ambient and warming treatments were usually lower than those from lab incubation experiments (Kirschbaum, 2006). To what degree the difference in temperature regimes between these two groups of experiments has resulted in inconsistent Q10 values remains unexplored.

In this study, we incubated two soils (a farm soil and a grassland soil) under two temperature regimes (constant vs. diurnally-varying), each of which has two average temperatures. Soil CO₂ efflux was measured five times during the 122-day incubation period and Q10 was calculated for the two soil temperature regimes. Our main objective was to determine whether Q10 differs significantly between the two soil temperature regimes.

The experiment was conducted in three growth chambers. We filled 16 bottom-capped PVC pots (diameter 15 cm, height 40 cm) with either 8.3 kg air-dried “farm” soil or 7.5 kg air-dried “grassland” soil. The farm soil and the grassland soil were both sandy loam, collected from the top 0–30 cm of an organic farm (converted from the nearby grassland in 1974) and an annual grassland on University of California at Santa Cruz campus, respectively. After four decades of farming, the farm soil has less carbon (0.94% vs. 1.10% and nitrogen (0.11% vs. 0.13%) compared to the grassland soil.

To minimize the initial disturbance effect on CO₂ efflux due to air-drying, sieving, packing, and rewetting the soils, all pots were pre-incubated at room temperature (22 °C) for 30 days before the 122-day experiment started. There were four soil temperature...
treatments in this study. Eight pots were incubated in growth chamber #1 with constant 25 °C air and soil temperature (“constant-high” treatment); another eight pots were incubated in growth chamber #2 with constant 20 °C air and soil temperature (“constant-low” treatment). The other 16 pots were incubated in growth chamber #3 with air temperature changing from 15 to 25 °C diurnally and a time-weighted average of 20 °C. Using automatically controlled electric heating cables buried in the pots, we heated eight pots (“varying-high” treatment, 21–28 °C range and 24.5 °C average) by 4.5 °C compared to the other eight pots (“varying-low” treatment, 16.5–23.5 °C range and 20 °C average) based on soil temperature measurements by thermocouples at 15 cm depth (Zhu and Cheng, 2011). Gravimetric soil moisture content in each pot was maintained at 25% throughout the experiment by periodic weighing and watering with deionized water. Anaerobic conditions were prevented by forcing the ambient air through each pot for 30 min every 6 h using an aeration pump.

During 10–12, 20–22, 40–42, 80–82 and 120–122 days after the start of the incubation experiment, we measured SOC decomposition rate using a closed-circulation CO2 trapping system (Cheng et al., 2003). Briefly, we sealed the pot with non-toxic silicone rubber and removed CO2 inside the pot by circulating the isolated air through a soda lime column for 1 h. Then CO2 produced in the sealed pot was trapped in a 400 mL 0.5 M NaOH solution for 30 min every 6 h during a 48-h period. Four blanks were included to correct for possible contamination from carbonate in the NaOH stock solution and from sample handling. An aliquot of each NaOH solution was analyzed for inorganic C using a Shimadzu TOC-5050A Total Organic Carbon Analyzer.

To account for the possible confounding effect of differences in substrate availability and quality among different temperature treatments in parallel incubation, we calculated Q10 using the following equation (Conant et al., 2008; Xu et al., 2010):

$$Q_{10} = \left( \frac{t_{\text{low}}}{t_{\text{high}}} \right)^{\frac{10}{\Delta T}}$$

where $t_{\text{high}}$ and $t_{\text{low}}$ are the time required to respire the same fraction of SOC at the higher ($T_{\text{high}}$) and lower ($T_{\text{low}}$) temperatures, and $\Delta T$ is the actual incubation temperature differential ($\Delta T = T_{\text{high}} - T_{\text{low}}$). We used a Monte Carlo method to estimate the 95% confidence interval of the Q10 values (Fig. 1C–D). Briefly, first we calculated 16 Q10 values based on all 16 combinations of 4 replicates at high temperature ($t_{\text{high}}$) and 4 replicates at low temperature ($t_{\text{low}}$). Then we randomly selected 4 numbers from the 16 Q10 values and got a mean Q10 value ($n = 4$); repeated this process 1000 times and got 1000 mean values; calculated the mean and SD of these 1000 values; and finally calculated the 95% confidence interval (mean ± 1.96 (SD/n^0.5); $n = 4$).

Instantaneous respiration rate declined by 45–51% in farm soil and by 39–43% in grassland soil over the 122 days of incubation (Fig. 1A–1B), while cumulative respiration rate during the 122-day period accounted for 3.9–5.5% of original farm SOC and 4.0–5.1% of.

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**Fig. 1.** A–B: changes in instantaneous soil respiration rate (mg C g soil C⁻¹ day⁻¹) with days after incubation during the 122-day incubation period in four different soil temperature treatments and two soil types. Error bars represent standard deviation (SD, $n = 4$). C–D: changes in temperature sensitivity of SOC decomposition ($Q_{10}$ value) with cumulative SOC respired during the 122-day incubation period under two soil temperature regimes and two soil types. Error bars represent 95% confidence interval estimated by the Monte Carlo method ($n = 4$).
original grassland SOC (data not shown). Both instantaneous and cumulative respiration rates did not differ markedly between “constant-low” treatment and “varying-low” treatment, while they were higher in “constant-high” treatment than in “varying-high” treatment.

The Q₁₀ values were higher in farm soil than in grassland soil and appeared to increase at the last stage of incubation in both soils (Fig. 1C–1D). More importantly, Q₁₀ values under constant temperature regime were consistently and significantly (P < 0.05) higher by 9–30% than those under diurnally-varying temperature regime. This result is observed in both soils and is more significant at the last stage of incubation (Fig. 1C–1D).

The mechanisms leading to the higher Q₁₀ under constant temperature regime than under diurnally-varying temperature regime are not clear at this point. We have ascertained that the reported negative curve-linear relationship between Q₁₀ value derived from short-term lab incubations and the mean temperature used for each Q₁₀ value determination (Q₁₀ = exp[10 × 241.5/ (T – 31.79)]², Kirschbaum, 2000) does not result in any meaningful difference in Q₁₀ values between the two temperature regimes. A potential cause may be associated with possible differences in microbial community composition between the two temperature regimes. Soil microbes are a diverse mixture of different species with different optimum temperatures (Tₜₚ) for growth and respiration (Balser and Wixon, 2009). Under constant temperature regimes, species whose Tₜₚ is close to the constant soil temperature may have a competitive advantage than other species whose Tₜₚ is away from the constant soil temperature. Over time, the constant temperature regime may selectively favor microbes already genetically better adapted to the temperature level. By contrast, under diurnally-varying temperature regimes, a more diverse community of microbes may coexist because more species are likely to experience their Tₜₚ during this diurnal temperature range. Therefore, compared to the more diverse community including a wide range of microbes under diurnally-varying temperature regime, the community dominated by few genetically more adapted microbes under constant temperature regime may produce more CO₂ and thus lead to higher Q₁₀. This hypothesis has been indirectly supported by an empirical study which showed that different soil temperatures progressively selected microbial communities growing better at the specific temperature (‘species sorting’ hypothesis; Bárcenas-Moreno et al., 2009). Therefore, microbial community composition may progressively diverge among different temperature regimes, which can lead to different Q₁₀ of SOC decomposition. Unfortunately, we don’t have data on microbial community composition in this study. There are some evidence in the literature that microbial community composition will be increasingly different between constant-high and constant-low temperature treatments in lab soil-incubation experiments (e.g. Zogg et al., 1997; Pettersson and Bååth 2003; Balser and Wixon, 2009), but direct evidence of different microbial community composition between constant and diurnally-varying temperature treatments (but with same/similar temperature) is not yet available. More studies are needed to further test the generality of our findings and to explore the mechanistic explanations.

There is a long-lasting debate on the temperature sensitivity of SOC decomposition between different studies, particularly between lab incubation experiments and field warming experiments (Davidson and Janssens, 2006; Kirschbaun, 2006; von Lützow and Kögel-Knabner, 2009). Other than the factors already advanced to explain the difference, such as substrate availability (Gu et al., 2004; Gershenson et al., 2009), root/rhizosphere respiration (Hartley et al., 2007; Schindlbacher et al., 2009), rhizosphere priming effect (Bader and Cheng, 2007; Zhu and Cheng, 2011), our results suggest that different soil temperature regimes (constant vs. diurnally-varying) can contribute to different Q₁₀ between studies. When soils are maintained at constant temperatures (e.g. in lab incubation studies), genetically better adapted soil microbes may progressively outcompete other less well-adapted microbes at each temperature level. In contrast, when soils are subjected to diurnally-varying temperatures (e.g. in field warming studies), a more diverse community of soil microbes are likely to coexist in this more variable temperature regime. The intrinsic temperature dependence of SOC decomposition may be realized to a different extent by different microbial communities between constant and diurnally-varying temperature regime. Therefore, our study, for the first time, identified an important factor — difference in soil temperature regime — that can contribute to the lack of scientific consensus on the temperature dependence of SOC decomposition.

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