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ABSTRACT

Temperature sensitivity of soil respiration (Q_{10}) is a critical parameter in carbon cycle models with important implications for climate-carbon feedbacks in the 21st century. The common assumption of a constant Q_{10}, usually with a value of 2.0, was shown to be invalid by a previous model-data fusion study that reported biome-specific values of this parameter. We extend the previous analysis by demonstrating that these biome-level values of Q_{10} also are a function of dryness ($R^2 = 0.54$). When tundra and cultivated lands are excluded, the correlation is much stronger ($R^2 = 0.92$). Therefore dryness is the primary driver for variability in respiration-temperature sensitivity in forest and grassland ecosystems. This finding has important implications for the response of the terrestrial carbon cycle to climate change, as it implies that the increasing dryness would potentially accelerate the respiration temperature sensitivity feedback.

Keywords: Climate Change; Carbon Cycle; Soil Respiration; Dryness

1. Introduction

Globally, soil respiration releases CO_2 annually at a rate that is over an order of magnitude larger than anthropogenic releases [1]. Although soil heterotrophic respiration is currently balanced or slightly exceeded by terrestrial net primary productivity (NPP), relatively small changes in this large flux could have large impacts on the global net carbon balance. The most important climate driver of soil respiration is temperature, and increasing temperature is likely to induce a positive feedback between climate and the carbon cycle. Uncertainty about the strength of this feedback is a primary source of uncertainty for predicted behaviour of terrestrial carbon sinks in the latter half of this century [2,3]. Additionally, this sensitivity of respiration to temperature was shown to vary as functions of temperature, substrate, soil moisture and/or biome [4,5]. Despite this, many global carbon cycle models assume constant temperature sensitivity, or they assume a sensitivity that depends on only a limited subset of these factors.

Here we extend the analysis of Zhou *et al*. [4], who used an inversion approach to assimilate worldwide soil respiration measurements and measured soil organic carbon into a widely used carbon cycle model. The authors of that study concluded that Q_{10} is a function of biome, and that the assumption of a constant Q_{10} results in an underestimation of the respiration-temperature feedback intensity by 25%. Upon further analysis of this unique dataset, we find that the respiration-temperature sensitivity is also a strong function of dryness at the biome level. This finding has important implications for the behaviour of the carbon cycle in a changing climate: increasing dryness, which is likely in a warming climate [6], may increase the respiration-temperature sensitivity, accelerating decomposition and providing a stronger feedback to the climate system.

2. Methods

This analysis focuses on Q_{10}, the parameter controlling the temperature-dependence of soil respiration in the following way:

$$R(T) = R_{ref} Q_{10}^{(T-T_{ref})/10}, \qquad (1)$$

where $R(T)$ and R_{ref} are soil respiration at measured temperature (T) and reference temperature (T_{ref}), respectively, and Q_{10} is a factor by which respiration is multiplied when temperature is increased by 10°C. At $Q_{10} = 1$ respiration would be independent of temperature, while larger Q_{10} values indicates a stronger temperature dependence. In many ecosystem models, Q_{10} is treated as a

constant, the most common value being 2. However, considerable variation (1.3 to ~10) in Q_{10} values have been reported by numerous investigations [7-9]. Since van't Hoff introduced Q_{10} in 1898 it has been debated weather Q_{10} is a universal constant and what controls Q_{10} [1-9]. Since soil emissions of CO_2 are expected to have a positive feedback on global warming, modelling of climate change, its consequences and control strategies requires a clearer understanding of the Q_{10} of soils.

We examined climate control of Q_{10} at the level of biomes globally. Spatially resolved Q_{10} values were estimated at a resolution of 1° by 1° using a model-data fusion technique to assimilate worldwide soil respiration measurements and measured soil organic carbon [4]. The model used in that analysis was the Carnegie-Ames-Stanford Approach (CASA) model [10,11], which includes a CENTURY-based soil carbon module that simulates soil organic carbon processes using two carbon storage pools, in addition to litter and microbial pools. Following Zhou *et al.* [4], we averaged the estimated Q_{10} values for each biome except Desert and Shrub & Bare Ground, both of which are subject to prolonged periods of desiccation. Average temperature, precipitation and net radiation were estimated for each 1° by 1° grid cell and these climate variables were used to estimate biome dryness [12]:

$$I = \frac{\overline{R_n}}{L\overline{P}}, \qquad (2)$$

where $\overline{R_n}$ (MJ·m^{-2}·yr^{-1}) is an annual sum of net radiation, L (2.5 MJ·kg^{-1}) is a latent heat coefficient and $\overline{P}$ (mm·yr^{-1}) is the total annual precipitation. We then linked the biome-level Q_{10} values to biome-level climate and dryness data (**Table 1**).

3. Results and Discussion

We found that biome-level Q_{10} is significantly correlated to dryness ($R^2 = 0.54$, **Figure 1**) or to precipitation ($R^2 = 0.45$, Figure omitted) and is independent of net radiation and temperature. We expect that the correlation of Q_{10} with dryness is stronger than with precipitation because the soil moisture content is determined not only by precipitation (input), but also by energy available for evaporation (output). In our analysis, both tundra and cultivated soils appear to be outliers. When these systems are excluded, the correlation of biome-level Q_{10} with dryness is much higher ($R^2 = 0.92$).

It is not surprising that the Q_{10} value for agricultural soil is an outlier (**Figure 1**) because cultivation (including tillage, fertilization, irrigation and drainage) accelerates soil respiration in ways that are not adequately captured by CASA [7]. The high Q_{10} value for tundra may be a consequence of the non-linearity of respiration with respect to temperature, particularly as T approaches 0°C. In systems with permafrost, which are poorly represented by CASA, the high Q_{10} value is also likely related to depth of the active layer. As the soil column warms, the depth of unfrozen soil increases and exposes more soil organic matter to decomposition [13]. In actuality this increases the base respiration rate, but the strong correlation of this effect with temperature causes it to be interpreted by the model-data fusion technique as a higher Q_{10} value. Thus both cultivated soil and tundra Q_{10} values are as high as grasslands even though the dryness of these systems is similar to deciduous forests.

Our results demonstrate that the temperature sensitivity of soil respiration-aggregated at the biome level, is controlled by dryness, and that soils in different biomes respond differently to dryness. As can be seen in **Figure 1**, the temperature sensitivity of forest soil respiration to dryness is much less than that of grasslands, which may also related to substrate quality (woody and non-woody components). This implies that conversion of forest to pasture and agriculture would increase temperature sensitivity of soil respiration, accelerating CO_2 emissions

Table 1. Climate characteristics of biomes (ten-year average, 1986-1995) and Q_{10} values estimated by an inversion approach developed by Zhou et al. [4]. The vegetation is coded according to the IGBP classification. The sources and calculation method of biome-climate data in the table can be found in Zhou *et al.* [17].

| Code	Biome	P	T	R_n	Dryness	Q_{10}	Area
		(mm·a^{-1})	(°C)	(MJ·M^{-2}·a^{-1})			(10^4 km^{-2})
1	Broadleaf evergreen forest	2171	25.1	4662	0.86	1.50	13.3
2	Broadleaf deciduous forest and woodland	913	15.2	3650	1.60	1.75	3.3
3	Mixed coniferous and broadleaf deciduous forest and woodland	883	8.6	2694	1.22	1.61	6.5
4	Coniferous forest and woodland	517	−2.5	1944	1.50	1.71	12.9
5	High latitude deciduous forest and woodland	438	−5.6	1889	1.73	1.63	5.8
6	C3 wooded grassland	1097	14.0	3446	1.26	1.67	4.5
7	C4 wooded grassland	1304	23.0	4413	1.35	1.59	17.1
8	C3 grassland	433	7.0	2953	2.73	1.97	11.3
9	C4 grassland	566	23.4	4066	2.87	2.02	8.9
10	Tundra	316	−10.8	1287	1.63	2.03	7.0
11	Cultivation	799	13.6	3262	1.63	1.99	13.3
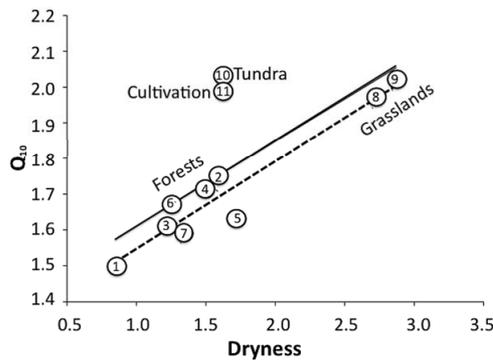
Figure 1. Biome-level Q_{10} versus dryness. The solid regression line with $R^2 = 0.54$ includes all data points, while the dashed regression line with $R^2 = 0.92$ excludes two outliers (tundra and cultivation). Dryness is defined as $R_n/(LP)$, where R_n (MJ$\cdot$m$^{-2}\cdot$a^{-1}) and P (mm$\cdot$a^{-1}) are global annual mean net radiation and precipitation for a biome respectively, and L = 2.5 MJ$\cdot$kg^{-1} is the enthalpy of vaporization. The number on each data point indicates vegetation type that can be found in Table 1.

and global warming [14,15]. Furthermore, we reiterate the findings of Zhou *et al*. [4] that models of soil responses to climate change, at least at the biome level, should not assume $Q_{10} = 2$, but need to accommodate the sensitivity of soil respiration in different soil types to dryness. Thus, the feedback to terrestrial ecosystems from respiration temperature sensitivity may accelerate more than previously predicted if climate change causes an increase in dryness.

Uncertainties may result from the methods of Zhou *et al*. [4], in which the International Geosphere-Biosphere Programme (IGBP) soil organic carbon (SOC) dataset was used to optimize the Q_{10} parameter in the CASA model. A significant part of the total SOC is relatively recalcitrant and resistant to decomposition, while soil respiration is mostly produced from the newly shed plant litter, and surface SOC. This may lead to an underestimate of the optimized Q_{10} because the decomposition of the recalcitrant SOC is slower than assumed by the model [16]. However, at the global scale, this underestimation of the optimized Q_{10} is mitigated because Zhou *et al*. [4] constrained the optimization process such that the global mean optimized Q_{10} is equal to the global mean value of Q_{10} (1.72) of soil respiration measurements in major ecosystems of the world as reported by Raich *et al*. [1]. While local biases in Q_{10} may result if the modeled SOC quality is not correct, comparisons against site-level soil respiration data in Zhou *et al*. [4] show consistent improvement when optimized values are used compared to a globally constant value. Theoretically, the biome Q_{10} reflects apparent temperature sensitivity that is controlled by environmental constraints [16]. Our results demonstrate that dryness is the most important control on Q_{10} among environmental constraints at biome level.

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