Can soil respiration estimate neglect the contribution of abiotic exchange?

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Abstract: This study examines the hypothesis that soil respiration can always be interpreted purely in terms of biotic processes, neglecting the contribution of abiotic exchange to CO₂ fluxes in alkaline soils of arid areas that characterize 5% of the Earth's total land surface. Analyses on flux data collected from previous studies suggested reconciling soil respiration as organic (root/microbial respiration) and inorganic (abiotic CO₂ exchange) respiration, whose contributions in the total CO₂ flux were determined by soil alkaline content. On the basis of utilizing meteorological and soil data collected from the Xinjiang and Central Asia Scientific Data Sharing Platform, an incorporated model indicated that inorganic respiration represents almost half of the total CO₂ flux. Neglecting the abiotic module may result in overestimates of soil respiration in arid alkaline lands, which partly explains the long-sought “missing carbon sink”.

Keywords: soil respiration; abiotic exchange; hypothetical system; incorporated model; missing carbon sink

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Motivated by increasing atmospheric carbon dioxide and the climate changes it produced, the world's scientific community made a huge effort to investigate the sources and sinks in the global carbon cycle (Detwiler and Hall, 1988; Keeling et al., 1996). It was demonstrated that the global CO₂ budget cannot be balanced unless a “missing carbon sink” is involved (Le Quéré et al., 2003). Numerous studies claimed to find the missing sink, but none of them were widely accepted (Tans et al., 1990; Schindler, 1999; Wofsy, 2001).

Alkaline soils are widely distributed over arid and semi-arid regions, occupying about 7×10^8 hm² or 10%–15% of arid and semi-arid soils (Xie et al., 2009). The arid and semi-arid soils represent 30% of the earth's land surface (Lal et al., 2003) and their area may further increase in this century under the current climatic conditions because of the global trend towards increasing desertification (Huenneke et al.,

2002). Over long time periods, large amounts of soil inorganic carbon (SIC) have been sequestered in the form of carbonates, which range from 750 to 950 Pg C (Schlesinger, 1985; Lal et al., 2000). It is the third largest global carbon pool, only less than the oceanic (38,000 Pg C) and soil organic (1,550 Pg C) carbon pools (Schlesinger, 1997). Considering the large SIC storage in alkaline soils of arid lands, these soils may be significant in the global carbon budget accounting.

Recent studies revealed that the role of SIC in the carbon cycle remains poorly understood, and the extent to which alkaline soils modulate the regional and global SIC dynamics is inadequately studied (Stevenson and Verburg, 2006). CO₂ absorption by alkaline soils (disclosed by negative CO₂ fluxes) was demonstrated in the Gurbantunggut Desert of China, suggesting alkaline soils could be a net CO₂ sink (Xie et al., 2009). The sink size would be huge enough to explain the long-sought missing sink if it was represen-

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tative over other arid regions and in other ecosystems (Stone, 2008). The finding in the Gurbantunggut Desert is not anomalous. A study of the Railroad Valley (RRV) playa in Nevada, USA also revealed highly alkaline soil (pH>10) with an even higher rate of CO₂ absorption (Yates et al., 2012). This role of abiotic CO₂ fluxes in alkaline soils of arid lands in the global carbon cycle hence demands a better understanding.

The objective of this research was to examine whether the contribution of abiotic exchange to CO₂ flux can be neglected when estimating soil respiration in arid alkaline soils. The concept of soil respiration was reconciled as organic and inorganic respiration. Using data collected from previous studies (Xie et al., 2009; Chen et al., 2013; Wang et al., 2013), the widely recognized Q₁₀ model was incorporated with an abiotic module as suggested by a previous study (Wang et al., 2013) to quantify soil respiration and approximate the contribution of abiotic exchange. The role of arid alkaline soils in the global carbon cycle was estimated under the hypothesis that the parameters of the incorporated Q₁₀ model are universally applicable.

1 Materials and methods

1.1 Data sources

The term “soil respiration” in the present study refers to “the apparent soil respiration” (F_c , soil CO₂ flux). F_c data were collected from previous studies conducted in three arid alkaline lands, the Tarim River Basin, Manas River Basin and Sangong River Basin of Xinjiang Uygur autonomous region of China (Xie et al., 2009; Chen et al., 2013; Wang et al., 2013). From 2005 to 2006, sterilization treatments on bare alkaline soils were launched in the Sangong and Tarim River Basins. Alkaline soils were sampled at bare sites from three ecosystems (alkaline-saline desert, abandoned farmland and oasis farmland) with 15 replications. Each soil sample was root-sieved, air-dried and divided into two subsamples, one of which was sterilized. Two LI-8100s were employed to simultaneously measure the F_c of unsterilized and sterilized samples, as stated by Xie et al. (2009). In July of 2012, F_c measurements with six replications were conducted at alkaline lands without vegetation in the Manas River Basin, covering three kinds of landforms (dry delta,

alluvial plain and the edge of alluvial fan). The results further demonstrated CO₂ absorption by alkaline soils, as described by Wang et al. (2013). The analyses presented in this study were based on surface air temperature (T_{as}), soil alkalinity (pH), soil temperature (T_s) and water content (θ_s) at a 0–5 cm depth. The data were collected from the Xinjiang and Central Asia Scientific Data Sharing Platform (<http://midasia.geodata.cn/Portal/index.jsp>).

1.2 Modeling analysis

Simultaneous measurements of F_c of sterilized and unsterilized soil collars with sealed bottoms prove that soil sterilization is a feasible method for partitioning the biotic and abiotic flux components. However, this method requires laborious analyses, thus remains infeasible for large-scale application. It is almost impossible to gather data for intact alkaline soils in arid areas. Therefore, approximating F_c partitions must be conducted using other methods. In a previous study, the F_c model was developed from the Q₁₀ model and formulated as (Wang et al., 2013):

$$\begin{cases} F_c = F_a + F_x \\ F_a = R_{10} Q_{10}^{(T-10)/10} \\ F_x = r_7 q_7^{pH-7} + \lambda T + \mu \theta_s + e \end{cases} \quad (1)$$

Where r_7 is the referred value of $f(pH)=r_7 q_7^{pH-7}$ at pH=7; q_7 is the factor by which $f(pH)$ is multiplied when pH value increases by 1; and λ , μ , and e are regression coefficients.

This presented an approximate method to quantify the contribution of soil abiotic CO₂ exchange to F_c in alkaline soils of arid areas. The determined parameter values are $\lambda=0.0059$, $\mu=0.0003$, $r_7=3.0191$, $q_7=0.7562$, $e=-2.5081$, $R_{10}=0.3625$, and $Q_{10}=1.5$.

In this study, these parameters are hypothetically applicable worldwide, and so the model has global implications. The concept of soil respiration was reconciled as soil organic respiration (the root/microbial respiratory component) and soil inorganic respiration (soil abiotic CO₂ exchange). It was also found to have a relationship with the temperature sensitivity of both components of the abiotic preponderance (defined as the proportion of negative CO₂ flux). The traditional Q₁₀ model was performed on flux data collected from previous studies to illustrate the necessity to incorporate an abiotic module when estimating alkaline soil respiration. With determined parameters, the above

abiotic module (F_x) was employed to approximate the soil inorganic respiration and evaluate the role of alkaline soils in the global carbon cycle.

2 Results

2.1 CO₂ flux system in alkaline lands

A hypothetical system of alkaline soil CO₂ fluxes was established. The system reconciles the concept of soil respiration as soil organic respiration (from biological processes) and soil inorganic respiration (from unknown non-biological processes), with a CO₂ circulation hidden in the deep soil layers and even in the groundwater (Fig. 1). Note that the well-known abiotic processes, the formation and dissolution of soil carbonates and the subterranean ventilation of soil CO₂ (Schimel et al., 1994) are not included in soil inorganic respiration. Such a partition is designed to encourage scientific explorations of soil inorganic respiration mechanisms after the exclusion of known abiotic processes.

Experimental analyses highlighted that soil pH level is a key factor in the CO₂ flux system. A comparison between the responses to T_s of F_c in the steril-

ized and unsterilized soils of alkaline-saline deserts (excluding sparse vegetation) indicated that the reduction of the sensitivity of F_c to T_s might be attributed to soil inorganic respiration in highly alkaline soils (Fig. 2). An exponential relationship between F_c and T_{as} exists within each alkaline site (or each ecosystem) with a given degree of soil alkalization, but the robustness of the exponential relationships can differ among different sites (Fig. 3). According to the incorporated Q_{10} model, this finding might be explained by the difference in the degree of soil alkalization (soil pH) between these alkaline sites. Coupled with the relationship between the soil pH and the proportion of negative F_c , soil pH is a key explanatory factor in the variability of F_c .

2.2 Necessity to incorporate the abiotic module

Performance of the traditional soil respiration model $F_c = R_{10} Q_{10}^{T_s - 10/10}$ revealed that F_c cannot be accurately described by the Q_{10} model with seasonal variability along two ecological gradients (soil alkalization and vegetation seasonality). This is more evident in the alkaline-saline desert than in the oasis farmland (Fig. 4). As alkaline-saline desert has a higher degree of

Fig. 1 A hypothetical system of carbon dioxide efflux and influx in alkaline soils, where the concept of soil respiration is reconciled as a sum of organic respiration (related to biological processes), inorganic respiration (from unknown non-biological processes) and interaction between them. The flux intensity is represented by the arrow length.

Fig. 2 Response of soil respiration (F_c) to soil temperature at the 0–5cm soil depth (T_s) at three alkaline sites, where the F_c was measured before (a–c) and after (d–f) soil sterilization (sparse vegetation was ruled out).

Fig. 3 Dependence of soil respiration (F_c) on T_s (red dots) and T_{as} (black dots) at sites with different pH values (a, pH–8.5; b, pH–8.7; c, pH–9.2) and the relationship between pH values and the proportion of negative F_c (d). The proportion of negative F_c (blue bars) and related sample size (green bars) are represented by the bar height.

Fig. 4 Performance of the Q_{10} model along double ecological gradients (soil alkalization and vegetation seasonality), where soil alkalization was compared between oasis farmland (a, spring; b, summer; c, autumn) and alkaline-saline desert (d, spring; e, summer; f, autumn).

alkalization and salinization and less vegetation coverage, it therefore poses the question: do soil alkalinity and vegetation determine the dominance of soil organic and inorganic respiration that results in different sensitivities of F_c to T_s in the alkaline-saline desert and oasis farmland?

With the assumption that soil alkalinity and vegetation do have these effects, the hypothetical system of CO_2 fluxes in alkaline soils was analyzed. Deficiencies in the Q_{10} model can be explained by the hypothetical system of CO_2 fluxes in alkaline soils, as follows: soil organic respiration (with a well-known sensitivity to T_s) becomes weaker than soil inorganic respiration in the farmland during autumn, particularly at the end of the growing season, and cannot dominate F_c , so the deficiency in the Q_{10} model is more evident in autumn than in spring and summer. In alkaline-saline desert, however, perennial plants grow faster in summer, so the deficiency in the Q_{10} model is more evident in spring and autumn. The weaker abiotic processes never dominate F_c and cannot explain such a

difference.

2.3 Analyses

Using the incorporated Q_{10} model and meteorological and soil data (1979–2011) collected from the Xinjiang and Central Asia Scientific Data Sharing Platform implies that soil inorganic respiration represents almost half of the total soil respiration, suggesting arid alkaline soils might be the location of the long-sought “missing carbon sink”. The overall soil organic respiration amounts to 0.68 Pg C/a, which is consistent with estimates of root/microbial respiratory components of soil respiration in the Biome-BGC model (0.7 Pg C/a). The overall soil inorganic respiration amounts to 0.63 Pg C/a. The intensity of soil inorganic respiration is almost equal to that of soil organic respiration and the total sum of soil CO_2 fluxes was only 0.05 Pg C/a, implying that alkaline soils are only a slight source of the atmospheric CO_2 . Thus, arid soil respiration was likely overestimated by traditional Q_{10} models (Fig. 5).

Fig. 5 Evolution of soil respiration (F_c), soil organic respiration (F_a) and soil inorganic respiration (F_i) in Central Asia during 1979–2011 based on the incorporated modeling analysis

3 Discussion

Soil respiration was estimated by soil CO_2 flux measurements (Schimel et al., 2001) and traditionally interpreted as roots/microbial respiration (Nguyen, 2003). Previously, a series of publications investigated the significance of soil pH on soil respiration, most of which focused on non-alkaline areas. Laskowski (2003) investigated acidic forest soil (pH: 3.8–6.0) and found that soil pH was positively correlated with soil CO_2 fluxes. This was also demonstrated in a subsequent investigation of acidic agricultural soil (pH: 3.4–6.8), which revealed that a significant, positive correlation existed between pH and soil basal respiration (Kermitt, 2006). All these studies suggested the inclusion of soil alkalinity as a main determinant in the empirical modeling of soil respiration. Differing from previous studies, this research focused on alkaline soils and found that soil pH was negatively correlated with soil CO_2 fluxes.

The Q_{10} model has been utilized worldwide when quantifying the intensity of soil respiration, using temperature as the only global explanatory factor (Wang et al., 2010). However, results in both the present and previous studies suggest pH has a significant impact on soil respiration, especially on arid alkaline soils. The soil pH can thus be a significant factor to determine the intensity of soil respiration at both alkaline and non-alkaline sites. Reth et al. (2005) identified the influence of soil chemistry (including soil pH) as an additional predictor and demonstrated the spatial

variation of soil respiration in the studied field was significantly correlated with soil pH. It is strongly suggested that soil pH be included in previous and future Q_{10} models for more reliable soil respiration experimental results, regardless of the alkalinity of the site.

This research implies that soil abiotic CO_2 exchange is a crucial component of soil CO_2 fluxes in alkaline soils in arid areas, and can explain the “anomalous” CO_2 fluxes in the apparent soil respiration. Further research is still necessary to investigate whether these processes are significant in terrestrial CO_2 sinks (Schlesinger et al., 2009). The introduction of the abiotic module in the incorporated model can be considered a descriptor for the part of F_c that remains unexplained by the biotic module.

In alkaline dryland ecosystems (different from other carbonate ecosystems), the well-known abiotic processes include the abiotic subterranean ventilation of CO_2 (Serrano-Ortiz et al., 2010; Sanchez-Cañete et al., 2011), dissolution of soil carbonates (Gombert, 2002; Kowalski et al., 2008), and groundwater recharge of dissolvable carbon (Scanlon et al., 2006). These processes were included in the hypothetical system (short arrows in the left side of Fig. 1). However, as stated in previous publications where flux data were collected (Chen et al., 2013; Wang et al., 2013; Xie et al., 2013), this research only considered clear days when these known abiotic processes are not hypothetically strong enough to affect the soil respiration's sensitivity to temperature. The interaction between soil organic and inorganic respiration only hypothetically existed, but further evidence is required. The inclusion of all these processes is complex, and the interaction between soil organic and inorganic respiration is also complicated. Therefore, further research on the system of alkaline soil CO_2 fluxes and the incorporated soil respiration model is merited.

4 Conclusion

Soil respiration in alkaline soils of arid areas cannot be interpreted purely in terms of biotic processes since the contribution of abiotic exchange to CO_2 flux is un-neglectable. The concept of alkaline soil respiration should be reconciled as soil organic respiration (the root/microbial respiratory component) and soil inorganic respiration (abiotic CO_2 exchange). With

parameters in the incorporated Q_{10} model hypothetically representing global convergent values, soil inorganic respiration represents almost half of the total soil respiration in alkaline lands. This suggests alkaline soils in arid lands are the location of the long-sought “missing carbon sink”.

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