Abiotic CO_2 uptake from the atmosphere by semiarid desert soil and its partitioning into soil phases

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摘要：沙漠可表现出强烈的CO_2通量下降的特性，这就是显著的碳沉降。 然而，由于无法确定通量测量的稳定性和准确的碳固定地点，这种假设受到强烈的挑战。本研究中，我们在中国北方的毛乌素沙漠中向自然（未杀菌的）土壤中添加$^{13}CO_2$，并量化固相土壤和气相中所添加的$^{13}CO_2$比例。 结果显示自然沙漠土壤吸收$^{13}CO_2$的平均速率为0.28 gm^{-2} d^{-1}. 在被吸收的$^{13}CO_2$中，气相中占0.0007%，然而，被吸收的20.0%的$^{13}CO_2$未被检测到。这些结果显示未受干扰的沙漠能够从大气中吸收CO_2，多数被固定的碳被存储在土壤固相中。

Abstract Deserts may show strong downward CO2 fluxes and thus could be a significant carbon sink. However, this hypothesis has been strongly challenged because of the failure to determine both the reliability of flux measurements and the exact location of fixed carbon. In this study, we added $^{13}CO_2$ to natural (unsterilized) soil in the Mu Us Desert in northern China and quantified the partitioning of added 13CO2 into soil solid and vapor phases. Results show that natural desert soil absorbed 13CO2 at a mean rate of 0.28 gm_2 d_1. Of the absorbed 13CO2, 7.1% was released over a 48 h period after 13CO2 feeding, 72.8% was stored in the soil solid phase, 0.0007% was found in the vapor phase, while 20.0% of the absorbed 13CO2 was undetected. These results indicate that undisturbed desert soils can absorb CO2 from the atmosphere, with the majority of fixed carbon conserved in the soil solid phase.

【小编注：本文中使用美国LGR公司的CO_2同位素分析仪测量$\delta^{13}C$和$^{12}CO_2$ 与 $^{13}CO_2$的浓度值，并与LI-COR公司的LI-8100-103土壤呼吸室连用，测量土壤$^{13}CO_2$的通量，这是在国内及国际上比较新颖的仪器应用方式，值得借鉴。】

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Key Points:

- We added $^{13}CO_2$ to natural (unsterilized) desert soil
- Soil absorbed $^{13}CO_2$ at a mean rate of 0.28g m^{-1} d^{-1}
- The majority of fixed carbon was conserved in the soil solid phase

Supporting Information:

- Tables S1–S3

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Abstract Deserts may show strong downward CO_2 fluxes and thus could be a significant carbon sink. However, this hypothesis has been strongly challenged because of the failure to determine both the reliability of flux measurements and the exact location of fixed carbon. In this study, we added $^{13}CO_2$ to natural (unsterilized) soil in the Mu Us Desert in northern China and quantified the partitioning of added $^{13}CO_2$ into soil solid and vapor phases. Results show that natural desert soil absorbed $^{13}CO_2$ at a mean rate of 0.28 g m^{-2} d^{-1}. Of the absorbed $^{13}CO_2$, 7.1% was released over a 48 h period after $^{13}CO_2$ feeding, 72.8% was stored in the soil solid phase, 0.0007% was found in the vapor phase, while 20.0% of the absorbed $^{13}CO_2$ was undetected. These results indicate that undisturbed desert soils can absorb CO_2 from the atmosphere, with the majority of fixed carbon conserved in the soil solid phase.

1. Introduction

Dry lands, including desert and semiarid ecosystems, cover about 41% of Earth's land surface [*Delgado-Baquerizo et al.*, 2013; *Reynolds et al.*, 2007]. Desert ecosystems have been considered a possible hidden loop in the global carbon cycle [*Stone*, 2008]. Early studies reported that net ecosystem CO_2 exchange (NEE) in some deserts in North America was similar to that occurring in temperate forests [*Hastings et al.*, 2005; *Jasoni et al.*, 2005; *Wohlfahrt et al.*, 2008], but these results have been strongly debated [*Schlesinger et al.*, 2009]. Carbon accretion in deserts has traditionally been attributed to primary productivity of desert plants or cryptobiotic crusts [*Emmerich*, 2003]. However, many reported NEE values are significantly higher than local net primary production (NPP) typical of deserts [*Chew and Chew*, 1965; *Whittaker and Niering*, 1975]. This discrepancy between NEE and NPP implies that there may be abiotic CO_2 fixation processes other than photosynthesis taking place in desert ecosystems.

With respect to abiotic carbon fixation, it has frequently been observed that alkaline soils can absorb CO_2 from the atmosphere [*Ball et al.*, 2009; *Fa et al.*, 2015; *Liu et al.*, 2015; *Ma et al.*, 2013; *Parsons et al.*, 2004; *Xie et al.*, 2009; *Yates et al.*, 2013]; this may be an overlooked process, which could potentially explain the observed discrepancy. However, this abiotic CO_2 influx has not been completely accepted as a well-validated pattern of carbon fixation [*Eshel et al.*, 2007; *Schlesinger et al.*, 2009; *Serrano-Ortiz et al.*, 2010; *Walvoord et al.*, 2005]. Many of these authors have been asked to reconfirm their flux measurements and present a logical answer to the question of where the carbon goes [*Schlesinger et al.*, 2009]. When taking into account the vast areas associated with deserts and semiarid ecosystems, studies of abiotic carbon absorption have been relatively few, suggesting that net CO_2 absorption may only happen occasionally. Furthermore, the downward CO_2 fluxes have been captured both on natural (undisturbed) soils [*Ma et al.*, 2014; *Parsons et al.*, 2004; *Yates et al.*, 2013] and sterilized soils [*Fa et al.*, 2015; *Liu et al.*, 2015; *Ma et al.*, 2013]. These results, indicative of abiotic CO_2 fluxes, need to be reconfirmed, especially for the results from sterilized soils, because sterilization with steam may affect the accuracy of net abiotic carbon absorption [*Schlesinger et al.*, 2009; *Stone*, 2008]. More importantly, the fate of the absorbed CO_2 in soil is largely unknown and needs to be explicitly examined in order to understand the long-term consequence of abiotic carbon absorption [*Ma et al.*, 2014; *Serrano-Ortiz et al.*, 2010; *Stone*, 2008]. Whether the absorbed CO_2 in soil is released into the atmosphere again or it is preserved in the soil, long term remains unknown. This information is essential for validating the existence of this abiotic CO_2 absorption process and confirming the stability of absorbed CO_2. Currently, there is little information on the partitioning of CO_2 in desert soil phases.

Table 1. Soil Properties (0–15 cm Depth)

Soil Property	Value
Bulk density (g cm^{-3})	1.54 ± 0.02
Total porosity (%)	42 ± 3
Soil organic carbon (mg kg^{-1})	1125.4 ± 126
Soil inorganic carbon (mg kg^{-1})	3775.6 ± 142
pH	8.60 ± 0.06
Electrical conductivity (dS m^{-1})	4.84 ± 0.42
CO_3^{2-} (cmol kg^{-1})	0.04 ± 0.01
HCO_3^- (cmol kg^{-1})	0.45 ± 0.03
Cl^- (cmol kg^{-1})	0.22 ± 0.03
Mg^{2+} (cmol kg^{-1})	0.48 ± 0.04
Ca^{2+} (cmol kg^{-1})	5.21 ± 0.18
K^+ (cmol kg^{-1})	0.58 ± 0.05
Na^+ (cmol kg^{-1})	41.23 ± 3.12

In this study, we added $^{13}CO_2$ to natural soil and quantified the partitioning of added $^{13}CO_2$ into soil solid and vapor phases in the Mu Us Desert, northwest China. Our objectives were to test whether natural alkaline desert soils can sequester CO_2 from the atmosphere and reveal the exact location of absorbed carbon.

2. Materials and Methods

2.1. Site Description

The study site is located at the Yanchi Research Station, Ningxia Province, China (37°48′N, 107°22′E), on the southwest edge of the Mu Us Desert. The research site has a temperate continental monsoon climate with 275 mm (1954–2013) mean annual precipitation and 7°C mean annual temperature. Elevation is 1550 m above sea level. Average relative humidity is 51%, and the frost-free period lasts 128 days [*Liu et al.*, 2015]. The soil type is aripsamment; soil properties are given in Table 1. The vegetation at the site is dominated by *Artemisia ordosica*, *Astragalus mongolicum*, *Salix psammophila*, and *Tamarix chinensis* (canopy coverage ≤ 30%).

2.2. $^{13}CO_2$ Addition and Detection Experiment

2.2.1. $^{13}CO_2$ Addition

In the study site, a sample plot (100 m × 100 m) was randomly selected to conduct $^{13}CO_2$ experiments. Six square collars (25 cm long, 25 cm wide, and 20 cm high; no top and bottom) constructed with steel sheets (0.5 cm thick) were inserted into the soil, with 2 cm exposed above the soil surface. The collars were excavated with intact soil; the bottoms were sealed immediately with steel sheets to avoid gas leakage, and the sealed collars with intact soil were backfilled in the original positions to equilibrate them with the surroundings. For the six placed collars, three collars were prepared to be covered with steel boxes and to be added $^{13}CO_2$. The remaining three collars were not covered with boxes and left untreated; they were used as the control for measuring soil $^{13}CO_2$ flux and analyzing $\delta^{13}C$ of soil solid and vapor phases.

Three steel boxes (25 cm long, 25 cm wide, and 70 cm high) with no bottoms were prepared, with each box having a 5 mm diameter hole on its lateral side. One side of a steel square backsplash (24.8 cm long and 24.8 cm wide) was set on the internal side of the box (50 cm away from the top) using a hinge. One side of the backsplash was connected with one end of a soft wire (1 m long), and the other end of the line crossed the hole of the box and was held outside to control the backsplash. The three boxes were immersed in NaOH liquor (5 mol L^{-1}) up to 2 cm to eliminate CO_2, when the backsplashes were pulled up (Figure 1a). Two hours later, the backsplashes were slowly put back down (Figure 1b). The space above the boxes was closed to avoid atmospheric CO_2 invasion during transfer of the boxes to the square collars. After the boxes were placed on three random square collars and pushed 15 cm deep into the soil, the backsplashes were slowly pulled up to allow for the CO_2 exchange between the soil and the head space of the box (Figure 1c). A 150 mL syringe was used to extract 140 mL of gas, which was injected into a carbon dioxide isotope analyzer Model CCIA-EP (912-0003; Los Gatos Research, Mountain View, CA, USA) to measure initial $^{12}CO_2$ concentration. A quantity (10 mL) of $^{13}CO_2$ (concentration: >99.99%) was injected into each box (Figure 1d), and the initial $^{13}CO_2$ concentration in the box was 295.34 μmol mol^{-1}. The hole was immediately sealed with glass cement, when $^{13}CO_2$ injection was completed. After 24 h, 140 mL mixed gas from each box was injected into the Model CCIA-EP to analyze final $^{12}CO_2$ and $^{13}CO_2$ concentrations.

2.2.2. Soil $^{13}CO_2$ Flux Measurements

Each box was removed from the square collar after gas extraction. A PVC collar (20.3 cm diameter and 20 cm high) was inserted 2 cm into the soil in each of the six square collars. The Model CCIA-EP was connected with a LI-8100-103 chamber (LI-COR Environmental), and the chamber was fitted with a PVC collar to measure the $^{13}CO_2$ flux for soil with added $^{13}CO_2$ and for the control soil. The $^{13}CO_2$ flux was measured for 5 min every 2 h over 48 h.

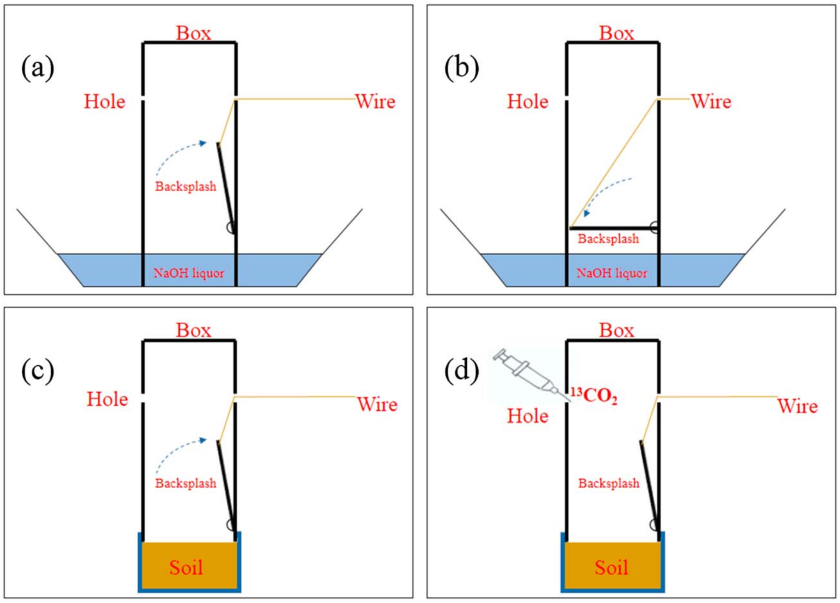

Figure 1. Schematic diagram of $^{13}CO_2$ addition ((a) the original CO_2 in the box was eliminating by NaOH liquor; (b) backsplash was put back down to avoid atmospheric CO_2 invasion during the boxes being transferred; (c) the backsplash was pulled up to keep the inside space of the box through up and down, after the box was placed on collar; and (d) $^{13}CO_2$ was injected into the box placed on collar).

2.2.3. δ^{13}C Analyses of Soil Solid and Vapor Phases

After measurement of the soil $^{13}CO_2$ flux, a 250 mL gas sample was collected from each of the six square collars using a soil gas sampler (DIK-5520-13; Daiki Rika Kogyo, Saitama, Japan); samples were placed in aluminum foil bags. From each aluminum foil bag, 140 mL of gas was extracted using a syringe, with these injected into the Model CCIA-EP to measure δ^{13}C for the vapor phase. A 50 g soil sample from each of the six square collars was collected to determine δ^{13}C for the solid phase after soil gas sample collection. All the soil samples (both deriving from $^{13}CO_2$ treated soils and control soils) were treated with 5.25% sodium hypochlorite for 15 days to remove organic matter [*Landi et al.*, 2003] and then dried at 72°C for 8 h. All the soil samples were ground and sieved to <0.075 mm for analysis of ^{13}C abundance. The method for determining δ^{13}C in the soil solid phase is described in *Nordt et al.* [1998]. The process of adding $^{13}CO_2$, measuring soil $^{13}CO_2$ flux measurements, and soil sampling was repeated 7 times in October 2012, for a total of 21 data sets.

2.3. Data Processing and Analysis

The absorbed $^{13}CO_2$ within the square collar was calculated as follows:

$$M = \frac{(C_{\text{final}} - C_{\text{initial}}) \times V_{\text{box}} \times S}{R_t \times 1000} \tag{1}$$

where M is total absorbed $^{13}CO_2$ (mg), C_{final} is final $^{13}CO_2$ concentration (μmol mol^{-1}), C_{initial} is initial $^{13}CO_2$ concentration (μmol mol^{-1}), V_{box} is the volume of the box exposing above the soil surface (L), S is relative molecular mass of $^{13}CO_2$ (g mol^{-1}), and R_t is the molar volume of gas (L mol^{-1}).s

Soil $^{13}CO_2$ flux was calculated as follows:

$$\text{Flux} = \frac{d^{13}CO_2}{dt} \times \frac{PV}{ART} \times \frac{1\ \text{L}^{13}CO_2}{10^6\ \mu\text{L}^{13}CO_2} \times \frac{13\ \text{g C}}{\text{mol}^{13}CO_2} \times \frac{3600\ \text{s}}{\text{h}} \tag{2}$$

where $d^{13}CO_2/dt$ is the slope of change in $^{13}CO_2$ concentration over time (μL CO_2 L air^{-1} s^{-1}), P is atmospheric pressure (atm), V is chamber volume, T is air temperature (K), A is the collar surface area (0.03245 m^2), and R is the universal gas constant (0.08206 L atm mol^{-1} K^{-1}). The flux is in units of mg C m^{-2} h^{-1}. The chamber volume is the sum of the collar volume and the chamber cap volume [*Savage et al.*, 2008].

The $^{13}CO_2$ emitted from soil following addition of $^{13}CO_2$ was calculated as follows:

$$M_{\text{emitted}} = \frac{\sum F_{\text{added}} - \sum F_{\text{control}}}{24\ \text{h}} \times 48\ \text{h} \qquad (3)$$

where M_{emitted} is total $^{13}CO_2$ emitted from the soil following addition of $^{13}CO_2$ (mg), F_{added} is the $^{13}CO_2$ flux for soil with added $^{13}CO_2$ (C m^{-2} h^{-1}), and F_{control} is the $^{13}CO_2$ flux for the control soil (C m^{-2} h^{-1}).

The $^{13}CO_2$ absorbed into the soil solid phase within the square collar was calculated as follows:

$$M_{\text{solid}} = C_{\text{SIC}} \times B \times V \times \left[\frac{\left(1000 + \delta^{13}C_{\text{added}}\right) \times R_{\text{st}}}{1000 + \left(1000 + \delta^{13}C_{\text{added}}\right) \times R_{\text{st}}} - \frac{\left(1000 + \delta^{13}C_{\text{control}}\right) \times R_{\text{st}}}{1000 + \left(1000 + \delta^{13}C_{\text{control}}\right) \times R_{\text{st}}}\right] \times 1000 \qquad (4)$$

where M_{solid} is total $^{13}CO_2$ stored in the soil solid phase, C_{SIC} is the SIC content (g kg^{-1}), B is bulk density (g cm^{-3}), V is the volume of soil in the square collar (cm^3), $\delta^{13}C_{\text{added}}$ is the $\delta^{13}C$ value for the soil solid phase with added $^{13}CO_2$, and $\delta^{13}C_{\text{control}}$ is the $\delta^{13}C$ value for the soil solid phase in the control. $R_s = {}^{13}C/{}^{12}C$ and R_{st} correspond to the stable isotope ratio in the reference standard [*Friedman and O'Neil,* 1977].

The $^{13}CO_2$ absorbed into the soil vapor phase in the square collar was calculated as per equation (5) below:

$$M_{\text{vapor}} = C_{CO_2} \times P_{\text{soil}} \times V \times \left[\frac{\left(1000 + \delta^{13}C_{\text{added}}\right) \times R_{\text{st}}}{1000 + \left(1000 + \delta^{13}C_{\text{added}}\right) \times R_{\text{st}}} - \frac{\left(1000 + \delta^{13}C_{\text{control}}\right) \times R_{\text{st}}}{1000 + \left(1000 + \delta^{13}C_{\text{control}}\right) \times R_{\text{st}}}\right] \times 1000 \qquad (5)$$

where M_{vapor} is total $^{13}CO_2$ stored in the soil vapor phase, P_{soil} is soil porosity, V is the volume of soil within the square collar (cm^3), $\delta^{13}C_{\text{added}}$ is the $\delta^{13}C$ value for soil with added $^{13}CO_2$, and $\delta^{13}C_{\text{control}}$ is the $\delta^{13}C$ value for the control soil.

One-way analysis of variance was used to test for differences in $\delta^{13}C$ for soil solid and vapor phases between soil with added $^{13}CO_2$ and the control soil. Descriptive statistics were used to calculate averages and standard deviations of data for each set of replicates. All of the above statistical analyses were conducted in MATLAB 7.11.0 (R2010b; The Mathworks Inc., Natick, MA, USA).

3. Results

3.1. $^{13}CO_2$ Absorption Rate

After $^{13}CO_2$ was injected into the box, the initial $^{12}CO_2$ and $^{13}CO_2$ concentrations in the box were 156.19 μmol mol^{-1} and 295.34 μmol mol^{-1}, respectively, and total CO_2 concentration ($^{12}CO_2 + {}^{13}CO_2$) was 454.53 μmol mol^{-1}. After 24 h, the final $^{12}CO_2$ and $^{13}CO_2$ concentrations in the box were 499.67 μmol mol^{-1} and 44.75 μmol mol^{-1}, respectively, and $^{13}CO_2$ had reduced by 250.59 μmol mol^{-1}. Natural soil with an area of 625 cm^2 absorbed 17.3 mg $^{13}CO_2$ d^{-1}, corresponding to a $^{13}CO_2$ absorption rate of 0.28 g m^{-2} d^{-1}.

3.2. Emission of Absorbed $^{13}CO_2$

The emission rate of added $^{13}CO_2$ decreased from 1.0183 mg m^{-2} h^{-1} after 1 h to 0.2 mg m^{-2} h^{-1} after 36 h and further to 0.1 mg m^{-2} h^{-1} after 48 h (Figure 2). Over 48 h, $^{13}CO_2$ emitted from the square collar totaled 1.2308 mg, accounting for 7.1% of absorbed $^{13}CO_2$ (17.3 mg).

3.3. Partitioning of Absorbed $^{13}CO_2$ Into Soil Vapor and Solid Phases

$\delta^{13}C$ for the soil solid phase with added $^{13}CO_2$ was −1.9‰ (Figure 3a), significantly greater than for the control soil ($n = 21$, $p < 0.05$). The percentage of ^{13}C in soil inorganic carbon (SIC) was 1.1091% for soil with added $^{13}CO_2$ and 1.1036% for control soil. SIC content was 3775.6 mg kg^{-1}; ^{13}C in the square collar totaled 0.7349 g for soil with added $^{13}CO_2$ and 0.7313 g for control soil. Added ^{13}C stored in the soil solid phase in the square collar was therefore 3.6411 mg (12.6038 mg $^{13}CO_2$), accounting for 72.8% (Figure 4) of absorbed $^{13}CO_2$ (17.3 mg).

The $\delta^{13}C$ for the soil vapor phase with added $^{13}CO_2$ was −7.8‰ (Figure 3b), significantly greater than for the control soil ($n = 21$, $p < 0.05$). The percentage of ^{13}C of total CO_2 ($^{12}CO_2 + {}^{13}CO_2$) was 1.1027% for soil with added $^{13}CO_2$ and 1.0998% for the control soil. The total CO_2 ($^{12}CO_2 + {}^{13}CO_2$) concentration was 473 μmol mol^{-1}, and ^{13}C in the square collar was 48.4072 μg for soil with added $^{13}CO_2$ and 48.2817 μg for the control soil. Added $^{13}CO_2$ stored in the soil vapor phase was therefore 0.1254 μg, accounting for

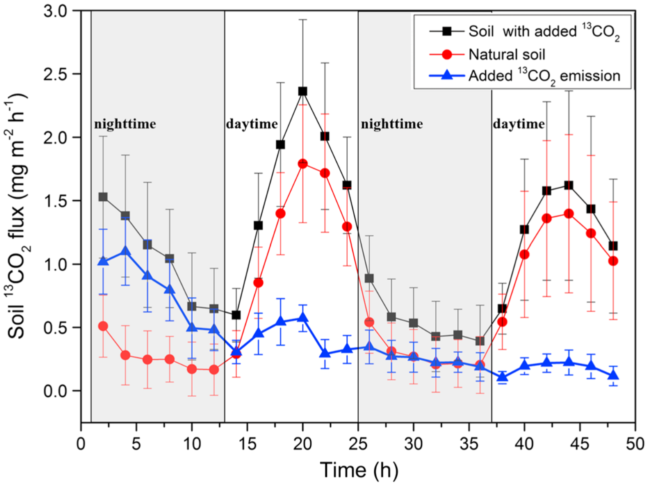

Figure 2. Temporal variations in soil $^{13}CO_2$ fluxes of soil with added $^{13}CO_2$ and natural soil within 48 h after addition of $^{13}CO_2$ (mean ± standard deviation (SD), $n = 21$). Added $^{13}CO_2$ emission is the difference between soil with added $^{13}CO_2$ and natural soil. The shadow and white areas in the figure represented the nighttime and the daytime, respectively.

0.0007% (Figure 4) of absorbed $^{13}CO_2$ (17.3 mg). It should be noted that 20.0% of the absorbed $^{13}CO_2$ was not detected in our study.

4. Discussion

4.1. Abiotic CO_2 Absorption by Natural Desert Soil

Natural soil from our study site sequestered CO_2 at a rate of 0.28 g m^{-2} d^{-1}. Similar negative net CO_2 exchange rates were found in northern China [*Xie et al.*, 2009] and North America [*Yates et al.*, 2013] between sterilized alkaline soils and the atmosphere. Net CO_2 absorption was detected both on natural and sterilized soil, indicating that CO_2 absorption is an actual function of alkaline soils. The $^{13}CO_2$ absorption rate in this study was lower than those reported previously [*Xie et al.*, 2009; *Yates et al.*, 2013], likely as a result of differences in soil property (i.e., pH and electrical conductivity) among study sites. Additionally, the box used in this study was closed and not large enough to supply sufficient $^{13}CO_2$, which may have also decreased the carbon absorption rate. A higher box was not used in this study, because $^{13}CO_2$ may accumulate at the bottom of the box and elevate the $^{13}CO_2$ concentration on surface soils. Future research may be able to include a design with a height allowing a sufficient supply of $^{13}CO_2$ without increasing $^{13}CO_2$ concentration at the bottom.

4.2. Location of the Absorbed Carbon

After $^{13}CO_2$ was added, the majority of $^{13}CO_2$ was observed in the soil solid phase (Figure 4). Even if some of the added $^{13}CO_2$ may initially adhere to soil particle surfaces, this was cleared prior to measurement of $\delta^{13}C$. Soil was immersed in sodium hypochlorite liquor to eliminate organic carbon, and this alkaline liquor can sequester $^{13}CO_2$ on the soil particle surface. In addition, the higher $\delta^{13}C$ observed in soil with added $^{13}CO_2$ could not have been due to carbonate recrystallization, because recrystallization of carbonates is a very slow process (occurring over centuries or millennia) [*Ryskov et al.*, 2008]. On a short time scale, the quantity of recrystallized carbonate would be very small and could only be detected with ^{14}C labeling [*Gocke et al.*, 2010, 2011; *Gocke and Kuzyakov*, 2011]. Ruling out surface adhesion of CO_2 onto soil minerals and carbonate

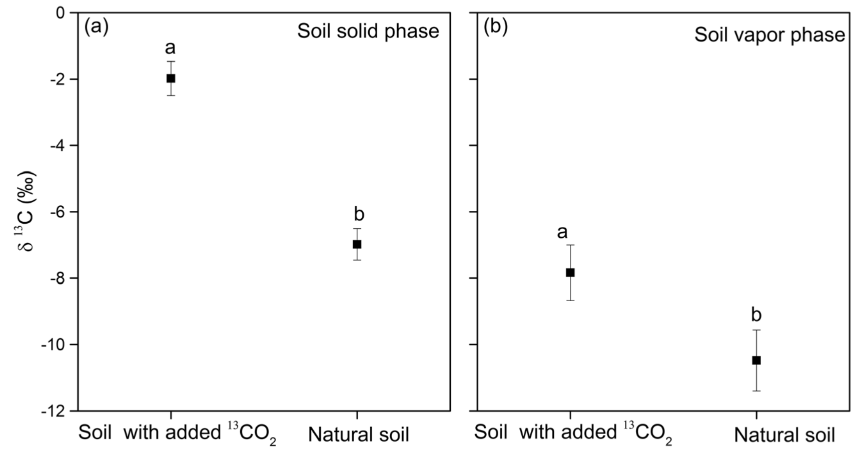

Figure 3. (a and b) ^{13}C abundance (‰) in soil with added $^{13}CO_2$ and natural soil (mean ± SD, $n = 21$, $p < 0.05$).

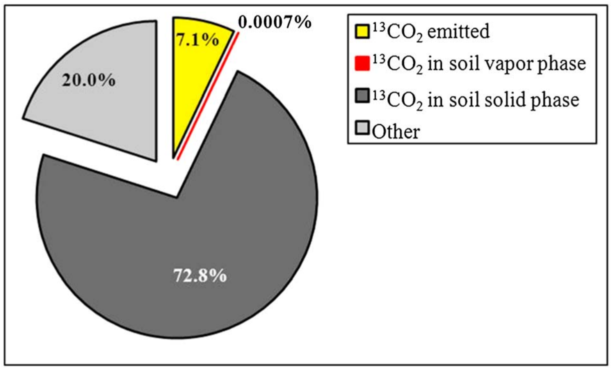

Figure 4. Distribution of adsorbed $^{13}CO_2$ in the soil phases. (Other represents added $^{13}CO_2$ that was not accounted for in our study.)

recrystallization, we speculate that the absorbed carbon may become part of newly formed matter and be conserved in certain minerals (quartz, calcite, plagioclase, and potash feldspar) of the solid phase. This could be the subject of future studies. The $^{13}CO_2$ stored in the solid phase should be relatively stable. Since added $^{13}CO_2$ was still preserved in the soil solid phase after immersion in sodium hypochlorite liquor and drying, this implies that it could not be easily removed with variations in soil water or temperature. The results of soil $^{13}CO_2$ fluxes following $^{13}CO_2$ addition also suggest that the $^{13}CO_2$ conserved in the solid phase may be stable (Figure 4). Although the intensity of $^{13}CO_2$ emissions was initially large, it decreased to 0.1 mg m^{-2} h^{-1} after 48 h and subsequently declined further (Figure 2). Within the initial 48 h after $^{13}CO_2$ addition, emitted CO_2 only accounted for 7.1% of absorbed $^{13}CO_2$. After 48 h, the $^{13}CO_2$ emission rate was too low to induce substantial erosion of added $^{13}CO_2$ over a long period. The partitioning of absorbed CO_2 into soil solid and vapor phases in our study therefore indicated that the exact location of absorbed carbon should be in the soil solid phase and that abiotic carbon sequestration is a nontrivial process within the carbon cycle of desert ecosystems.

The result that the majority of absorbed $^{13}CO_2$ was fixed in the soil solid phase may help to improve understanding of the mechanism of abiotic CO_2 absorption. Most previous studies found that soil absorbed a substantial amount of atmospheric CO_2 at night, while acting as a weak CO_2 source during the day [*Liu et al.*, 2015; *Ma et al.*, 2013; *Parsons et al.*, 2004; *Xie et al.*, 2009; *Yates et al.*, 2013]. The phenomenon can be interpreted as dissolution and exsolution of CO_2, modified by temperature [*Liu et al.*, 2015; *Ma et al.*, 2013; *Shanhun et al.*, 2012]. Synthesizing our results and the literatures, the mechanism of abiotic CO_2 absorption can be inferred and described as follows: Atmospheric CO_2 enters the soil and dissolves in soil water, and most of the dissolved CO_2 returns to the atmosphere when the temperature increases. The remaining dissolved CO_2 reacts with some matters in the soil and is stored in the soil solid phase. Even though it remains unknown how CO_2 is sequestered in the solid phase, our finding that the majority of dissolved CO_2 was fixed in the solid phase at least verifies that such a process indeed occurs. We further estimate that the 20.0% of absorbed $^{13}CO_2$ that remained undetected (Figure 4) was conserved in soil water, which may be confirmed in future studies.

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