Environmental Science & Technology

pubs.acs.org/est

Article

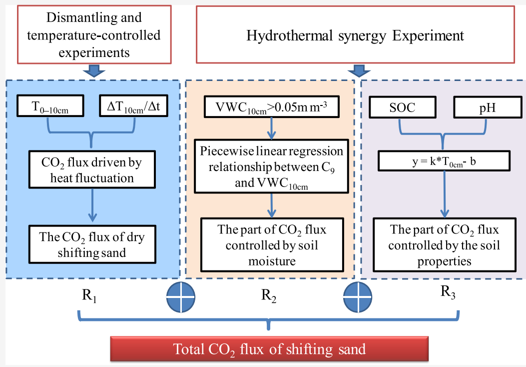
Desert Abiotic Carbon Sequestration Weakening by Precipitation

Fan Yang, Jianping Huang,* Chenglong Zhou, Xinghua Yang, Ali Mamtimin, Xinqian Zheng, Wen Huo, Fei Ji, Dongliang Han, Lu Meng, Jiacheng Gao, Meiqi Song, Yu Wang, and Congzhen Zhu

Cite This: *Environ. Sci. Technol.* 2023, 57, 7174−7184

Read Online

ABSTRACT: Desert carbon sequestration plays an active role in promoting carbon neutralization. However, the current understanding of the effect of hydrothermal interactions and soil properties on desert carbon sequestration after precipitation remains unclear. Based on the experiment in the hinterland of the Taklimakan Desert, we found that the heavy precipitation will accelerate the weakening of abiotic carbon sequestration in deserts under the background of global warming and intensified water cycle. The high soil moisture can significantly stimulate sand to release CO_2 at an incredible speed by rapidly increasing microbial activity and organic matter diffusion. At this time, the CO_2 flux in the shifting sand was synergistically affected by soil temperature and soil moisture. As far as soil properties are concerned, with less organic carbon substrate and stronger soil alkalinity, the carbon sequestration of shifting sand is gradually highlighted and strengthened at low temperature. On the contrary, the carbon sequestration of shifting sand is gradually weakened. Our study provides a new way to assess the contribution of desert to the global carbon cycle and improve the accuracy and scope of application.



KEYWORDS: *Taklimakan Desert, desert carbon sequestration, CO_2 flux; hydrothermal interaction, ensemble empirical mode decomposition (EEMD)*

1. INTRODUCTION

Enhancing carbon sequestration in terrestrial ecosystems is one of the most economical and feasible ways to achieve carbon neutrality.[1] In 2030, China's CO_2 emission peak is expected to reach 11 billion tons, and the terrestrial ecosystem is expected to undertake the neutralization task of 2.0−2.5 billion tons each year. Therefore, it has become an important research direction related to climate change and balanced social development to accurately assess the carbon budget capacity of each ecosystem and to seek scientific ways to increase sinks.[2] To date, most studies on the global carbon cycle and carbon sequestration capacity assessment for different ecosystems have mostly focused on high-productivity ecosystems such as forests, grasslands, wetlands, and farmland. At present, the determinable carbon sink rate of terrestrial ecosystems in China is approximately 1.03−1.6 billion tons per year.[3,4] This is still far from the carbon neutral target of the ecosystem.

Evidence is mounting that the vast desert ecosystem, which accounts for approximately 21% of the global land area, will absorb and sequester a large amount of CO_2 in the absence of photosynthesis to play a carbon sequestration role. It plays an active role in promoting carbon neutrality, narrowing the gap in missing carbon sinks, and mitigating climate warming.[5−7] Due to the extremely low productivity and the lack of organic substrate supply in the soil, the number, activity, and diffusion of soil microorganisms are limited in the extremely arid desert ecosystem,[8] which inhibit biological respiration in the desert and are dominated by abiotic physical and chemical processes with low CO_2 flux.[6,7,9] At the same time, the response of the desert ecosystem to environmental conditions is different from that of other ecosystems, and it is particularly vulnerable to climate and land use change.[10,11] Thus far, the main processes whereby deserts act as carbon sinks may include the following: (1) variation in the volume of gases caused by changes in pressure and temperature governed by the ideal gas law, (2) changes in the solubility of CO_2 in soil water films governed by Henry's Law, (3) pH-mediated CO_2 dissolution chemistry, and (4) surface adhesion of CO_2 onto soil minerals.[12−15] The sequestered CO_2 may gradually enter the groundwater through the leaching process and finally converge in the underground saline water layer with the movement of groundwater under the desert.[16] This process is similar to the inorganic carbon sink in the ocean.[17]

Received: December 16, 2022
Revised: April 8, 2023
Accepted: April 10, 2023
Published: April 20, 2023

https://doi.org/10.1021/acs.est.2c09470
Environ. Sci. Technol. 2023, 57, 7174−7184

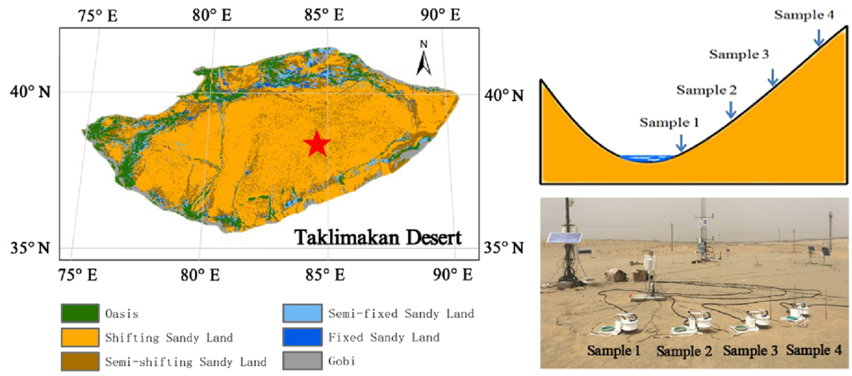


Figure 1. Left: the distribution of land cover types in the Taklimakan Desert (TD)[29] and the location of the National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang (red star). Right: the distribution of sampling points and the layout of instruments used in the field experiment. The soil samples collected at four parts of the dune slope were buried in the flat shifting sand to carry out the comparative observation of CO_2 flux of different samples.

The Taklimakan Desert (TD) of northwestern China, also called the "Sea of Death", is the second largest shifting desert in the world. It is a typical representative of deserts in the world. It has the characteristics of being located far from the sea and exhibiting the driest climate, the rarest vegetation, the most complex dune types, the highest mobility of dunes, the largest proportion of shifting sand areas, the thickest shifting sand layer, and the smallest sand particle size.[18] Our latest research revealed that both the expansion/contraction of soil air containing CO_2 caused by heat fluctuation in sand and the salt/alkali chemistry control the release/absorption processes of CO_2 in the TD. The small daily fluctuation of extremely low soil moisture is not enough to overcome the restrictive effect of long-term drought on the CO_2 flux of sand, which makes the contribution of soil moisture to the CO_2 flux in the sand very limited, and the fluctuation range is very small.[6,7] However, global warming has intensified the water cycle in recent years. This has led to a gradual increase in global total precipitation and extreme precipitation events, especially in arid and semiarid regions.[19] The TD is also affected by warming and humidification, which increase precipitation, and heavy precipitation events often occur.[20,21] The TD, which has been dry for a long time, is relieved temporarily after a heavy rainfall event. The total precipitation, precipitation frequency, and precipitation time are the key factors determining the impact of precipitation pulses on carbon exchange in desert ecosystems.[22] Compared with soil temperature, soil moisture has a stronger ability to regulate CO_2 flux in some cases and controls the sensitivity between CO_2 flux and soil temperature.[23−25] After precipitation falls in the desert, it will affect many key processes controlling the carbon budget of the desert, such as soil heat transfer, CO_2 dissolution in soil water, saline/alkali concentration in soil, microbial quantity and activity, and organic substrate diffusion. A high soil moisture can promote the dissolution of CO_2 in water and carbonate dissolution, thus enhancing the CO_2 influx in sand. At the same time, high soil moisture can also stimulate biological respiration to promote CO_2 release.[9] This leads to an uncertain impact on the carbon sequestration capacity of the desert.[9,26−28] The insufficient understanding of the impacts of hydrothermal interactions and soil properties on the CO_2 flux in deserts is the main problem causing uncertainty in evaluating the desert carbon sink capacity. This has led to the contribution and status of desert ecosystems not being accurately determined in the global carbon cycle.

In the hinterland of the TD, an observation experiment of the CO_2 flux of sand under hydrothermal interactions was conducted by collecting shifting sand samples with obvious water gradient changes in different parts of the dunes after heavy rainfall. This study was conducted to improve the understanding of the driving mechanism of the CO_2 budget in shifting sand through the analysis of the influence of hydrothermal interactions and soil properties on the CO_2 flux of shifting sand under the process of water loss. On this basis, we attempted to establish a scheme to estimate the CO_2 flux of shifting sand. In addition, the estimation scheme was verified by a CO_2 flux observation experiment at the northern edge and hinterland of the TD to enhance the comprehensive understanding of the carbon sequestration mechanism of desert ecosystems and to determine the advantages of desert ecosystems in promoting carbon neutralization. This will lay a foundation to accurately assess the total carbon sequestration of global deserts and their contribution to the carbon cycle.

2. MATERIALS AND METHODS

2.1. Site Description. The TD covers a total area of 3.376×10^5 km^2, of which approximately 70% is covered by continuous shifting sand.[29] It is one of the important sources of global dust aerosols.[30,31] This experiment was carried out in shifting sand around the National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang (38° 58′ N, 83° 39′ E, 1099 m above sea level), which is located in the hinterland of the TD (Figure 1). This station is considered the most representative station for the study of the TD. The region has a warm temperate arid desert climate, with an average annual precipitation of only 25.9 mm, concentrated from May to August.[32] In recent years, the precipitation and probability of heavy precipitation have increased in the study area with the gradual warming and humidifying climate in northwestern China. The annual potential evaporation is 3812.3 mm, nearly 150 times the annual average precipitation. The study area has four distinct seasons and a large temperature difference between day and night. The annual average temperature is 12.1 °C, with the maximum temperatures of 46.0 °C and the minimum temperatures of −32.6 °C. The easterly wind prevails throughout the year, with an average annual wind speed of 2.3 m s^{-1}. The extremely harsh environment results in almost no natural vegetation coverage in this area. The abundant shifting sand on the ground provides a sufficient material source for dust weather. The

https://doi.org/10.1021/acs.est.2c09470
Environ. Sci. Technol. 2023, 57, 7174−7184

Table 1. Description of the Physical and Chemical Properties of the Shifting Sand at Four Sampling Points[a]

sample no.	depth (cm)	initial VWC(m^3 m^{-3})	SOC (g kg^{-1})	pH	STS (g kg^{-1})	CO_3^{2-}(g kg^{-1})	HCO_3^-(g kg^{-1})	Cl^-(g kg^{-1})	SO_4^{2-}(g kg^{-1})
sample 1	0−10	0.169	0.811	9.61	8.50	0.008	0.104	0.554	2.221
	10−20		0.486	9.28	2.50	0.000	0.012	0.066	0.353
sample 2	0−10	0.05	0.584	9.35	12.00	0.018	0.105	3.900	1.201
	10−20		0.583	8.88	0.33	0.001	0.023	0.040	0.043
sample 3	0−10	0.058	0.499	8.35	1.25	0.000	0.014	0.084	0.396
	10−20		0.418	8.32	0.15	0.000	0.022	0.020	0.010
sample 4	0−10	0.017	0.104	8.53	0.28	0.000	0.021	0.027	0.084
	10−20		0.476	8.36	0.08	0.000	0.022	0.004	0.130

[a]VWC, SOC, and STS are soil moisture, soil organic carbon, and soil total salt, respectively.

annual average duration of floating dust and sand blowing exceeds 157 days, and the annual average duration of sand storms is 16 days.[18]

2.2. Experimental Design. A rare precipitation event of 34.0 mm occurred in the study area on May 14, 2021. With the continuous loss and flow of soil moisture, a gradient distribution of soil moisture gradually formed on the shifting sand slope two days later. Then, we set four sampling points along the slope from low to high (i.e., the direction of soil moisture gradually decreased), with an interval of 30 m between adjacent sampling points. Approximately 30 kg of 0−20 cm surface shifting sand was collected at each sampling point and placed into a plastic box, corresponding to samples 1−4. Four soil respiration collars with a cross-sectional area of 371.8 cm^2 and a height of 10 cm were embedded into each soil sample to a depth of 8 cm, and they were placed in the laboratory for two days to stabilize. Then, four soil samples with plastic boxes are buried in flat shifting sand, and the sand surface height inside and outside the plastic box was adjusted to remain consistent (Figure 1). From May 19 to 29, 2021, a soil CO_2 flux automatic measurement system equipped with four air chambers (Model LI-8100A fitted with a LI-8150 multiplexer, LI-COR, Nebraska, USA) was used to synchronously monitor the CO_2 flux of each sample every half an hour. In past research, we tested the application performance of LI-8100A in deserts, and the measurement accuracy of ±0.02 μmol m^{-2} s^{-1} met the experimental requirements.[32] In each soil sample, soil temperature sensors (Model 109, Campbell Scientific, USA) were installed at depths of 0 and 10 cm, and soil moisture sensors (SM926, Truwel Inc., China) were installed at a depth of 3 and 10 cm to monitor the change in the soil temperature and soil moisture during the entire observation period. In addition, soil samples from depths of 0−10 and 10−20 cm were collected at four sampling points to analyze the organic carbon content (SOC), pH, soil total salt (STS), and other properties of each sample (Table 1).

2.3. Statistical Analyses. *2.3.1. Ensemble Empirical Mode Decomposition (EEMD).* Empirical mode decomposition (EMD) is a signal decomposition method based on the time-scale characteristics of the data itself proposed by Huang et al. It is a time-frequency domain signal processing method without setting any basis function in advance.[33,34] EMD has obvious advantages in processing nonstationary and nonlinear data and has a high signal-to-noise ratio. With this method, complex signals can be decomposed into finite intrinsic mode functions (IMFs), and each IMF component contains the local characteristic information of the original signal at different time scales. However, the modal aliasing problem in this method makes feature extraction, model training, and pattern recognition difficult. To solve the problem of mode aliasing, Huang added white noise to the signal to propose the ensemble empirical mode decomposition (EEMD).

2.3.2. Establishment of the Parameter Scheme and Verification. EEMD was used to decompose the CO_2 flux of shifting sand under the combined control of soil water and heat to reveal the effects of soil moisture and soil temperature on the CO_2 flux of shifting sand. On this basis, combined with the properties of shifting sand, we established an empirical CO_2 flux estimation scheme for shifting sand. In addition, the estimation scheme was verified by using the observation data of dry riverbeds and shifting sand on the northern edge of the TD in January 2013 and the observation data of the CO_2 flux of shifting sand after artificial simulated precipitation in the desert hinterland in July 2019.

3. RESULTS

3.1. Effect of Precipitation on the CO_2 Flux of Shifting Sand. The CO_2 flux of dry shifting sand in the TD was calculated using the scheme established in previous experiments.[6] As expected, compared with Yang et al., who represented the CO_2 flux of dry shifting sand, the 34.0 mm precipitation event increased the daily fluctuation and daily total flux of CO_2 for samples 1−4. The increase degree gradually strengthened along the dune slope from high to low (i.e., the soil moisture changed from low to high) (Figure 2). Sample 1 released CO_2 at an incredibly high rate, which was most obvious in the first two days, and the carbon sink completely disappeared at night. The stimulating effect of the

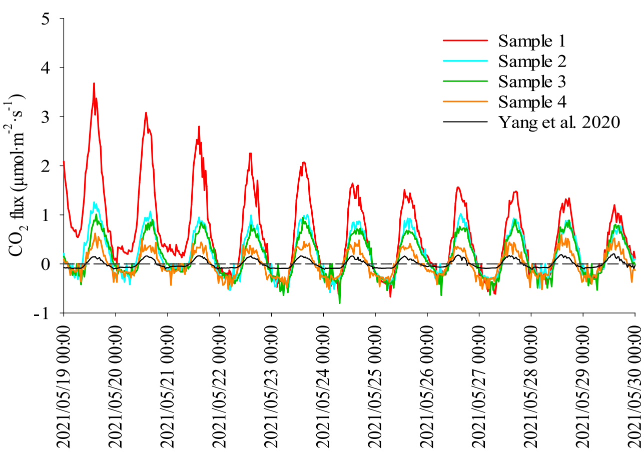


Figure 2. Comparison of the CO_2 flux of different samples after rainfall. The soil moisture gradually decreased along the dune slope from low to high, and the corresponding samples were samples 1−4. In addition, Yang et al. is a scheme established in previous experiments to estimate the CO_2 flux of dry shifting sand in the TD.

https://doi.org/10.1021/acs.est.2c09470
Environ. Sci. Technol. 2023, 57, 7174−7184

precipitation gradually decreased over time. During the observation period, sample 1 released 4.62 g of CO_2 into the atmosphere. For samples 2 and 3, the effect of the precipitation on the CO_2 flux was not as obvious as that of sample 1. The diurnal carbon emissions and nocturnal carbon sequestration of samples 2 and 3 were enhanced at the same time. During the observation period, samples 2 and 3 successively released 1.49 and 1.12 g of CO_2 into the atmosphere. The diurnal fluctuation of sample 4 also increased, but the CO_2 released during the day and absorbed at night was in balance, i.e., it basically remained carbon neutral. The response of the CO_2 flux of shifting sand to this precipitation event made us very curious. To further analyze the stimulating effect of precipitation, we removed the CO_2 flux of dry shifting sand from each sample in the subsequent analysis (Figure S1).

3.2. Control of CO_2 Flux of Shifting Sand by Hydrothermal Synergy. As shown in Figures 3 and 4, the

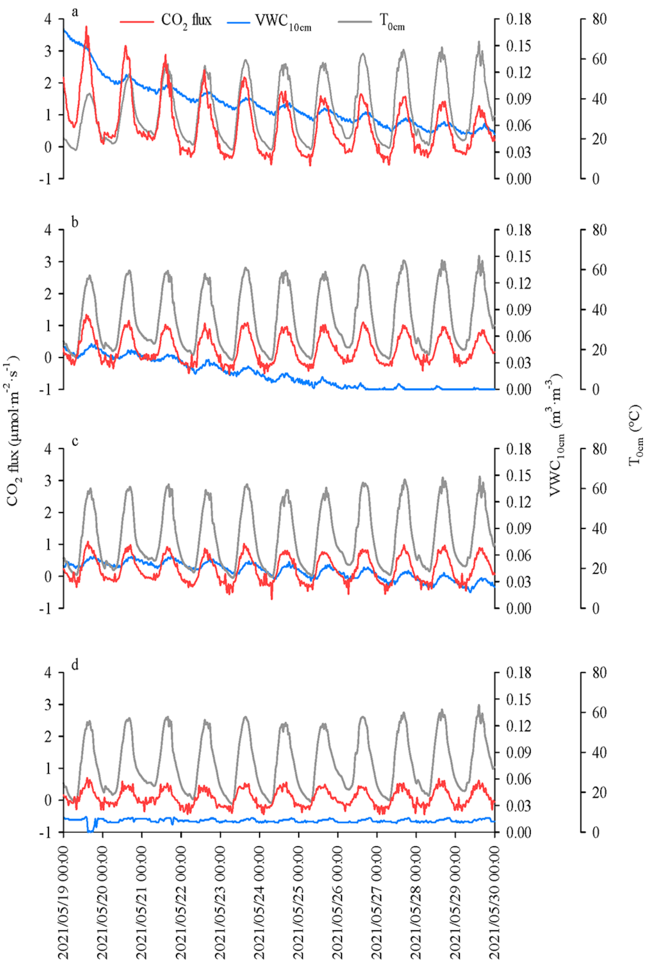


Figure 3. Relationship between the CO_2 flux of samples 1−4 and the soil moisture at 10 cm (VWC_{10cm}) and the surface soil temperature (T_{0cm}) after the removal of the CO_2 flux of dry shifting sand; a, b, c, and d represent samples 1−4, respectively.

CO_2 flux of each sample showed a synchronous daily variation with the surface soil temperature (T_{0cm}) after the CO_2 flux of dry shifting sand was removed. Soil temperature is one of the key factors driving the CO_2 flux of shifting sand.[35,36] However, precipitation stimulation will weaken the synchronization between the CO_2 flux and soil temperature. This was most significant in sample 1. The soil moisture at 10 cm (VWC_{10cm}) of sample 1 reached 0.169 m^3 m^{-3} at the beginning of the experiment. In the process of decreasing the soil moisture, the diurnal fluctuation in the CO_2 flux of shifting sand showed an obvious weakening trend while maintaining a good diurnal variation. This shows that the CO_2 flux of sample 1 was obviously affected by the synergistic effect of T_{0cm} and VWC_{10cm}. In contrast, the VWC_{10cm} of samples 2−4 was far lower than that of sample 1. Their CO_2 fluxes had a good linear relationship only with T_{0cm} ($R^2 > 0.808$, $P < 0.001$), i.e., not with VWC_{10cm}. Therefore, after analyzing the CO_2 flux and VWC_{10cm} of all samples (Figure 5), we found that the stimulatory effect of soil moisture on the CO_2 flux of the shifting sand had an obvious threshold on both hourly and daily scales. When the VWC_{10cm} was higher than 0.05 m^3 m^{-3}, the stimulatory effect of soil moisture was more obvious, and the CO_2 flux of shifting sand increased rapidly with increasing soil moisture. When the VWC_{10cm} was lower than 0.05 m^3 m^{-3}, the stimulatory effect of soil moisture was not obvious—it slightly enhanced the diurnal release and nighttime absorption of CO_2 by shifting sand and was strictly controlled by T_{0cm}.

3.3. Dismantling the Synergism of Soil Water and Heat. To further understand the synergistic effect of soil water and heat, the CO_2 flux of sample 1 after removal of the CO_2 flux of dry shifting sand was disassembled by the EEMD method. As shown in Figure 6, C_4 and C_9 of the nine IMFs obtained had significant daily fluctuations and gradually decreasing trends, respectively. According to the change trend, they had good correspondence with T_{0cm} and VWC_{10cm}, respectively, of sample 1. Based on the above analysis, C_9 was further analyzed as part of the CO_2 flux under the strict control of VWC_{10cm}. During the observation period, C_9 and VWC_{10cm} showed a decreasing trend and significant piecewise linear relationship. When VWC_{10cm} is between 0.05 and 0.12 m^3 m^{-3}, C_9 increases rapidly with the increase of VWC_{10cm} ($R^2 > 0.933$, $P < 0.001$). When VWC_{10cm} is greater than 0.12 m^3 m^{-3}, the increasing speed of C_9 with the increase of VWC_{10cm} becomes relatively slow ($R^2 > 0.940$, $P < 0.001$). The sum of C_1−C_8 can be regarded as part of the CO_2 flux under the strict control of T_{0cm}. The pattern of diurnal change between C_{1-8} and T_{0cm} was highly consistent and showed a significant linear relationship ($R^2 > 0.734$, $P < 0.001$) (Figure 7). Based on a comparison of Figure 4a,b, after the disassembly of EEMD, the regression relationships between CO_2 flux and T_{0cm} and VWC_{10cm} were enhanced. This means that, after removal of the CO_2 flux of dry shifting sand, the CO_2 flux of sample 1 revealed the corresponding control parts of soil temperature and soil moisture.

3.4. Regulatory Effect of Shifting Sand Properties on the CO_2 Flux. After removal of the control effect of soil moisture, the CO_2 flux of shifting sand was still significantly affected by soil temperature. Therefore, the soil temperature was a very important factor controlling the CO_2 flux of shifting sand from beginning to end. Soil moisture also plays an important role in regulation and may exceed the role of soil temperature in some periods, but the regulation of soil moisture is sporadic and has a threshold. As shown in Figure 8a, there was a certain difference in the strong linear regression relationship between the CO_2 flux of each sample and T_{0cm} after removal of the CO_2 flux of dry shifting sand and the control effects of soil moisture. We determined that the difference was mainly due to the responses of different shifting sand sample properties (such as organic carbon substrate,

https://doi.org/10.1021/acs.est.2c09470
Environ. Sci. Technol. 2023, 57, 7174−7184

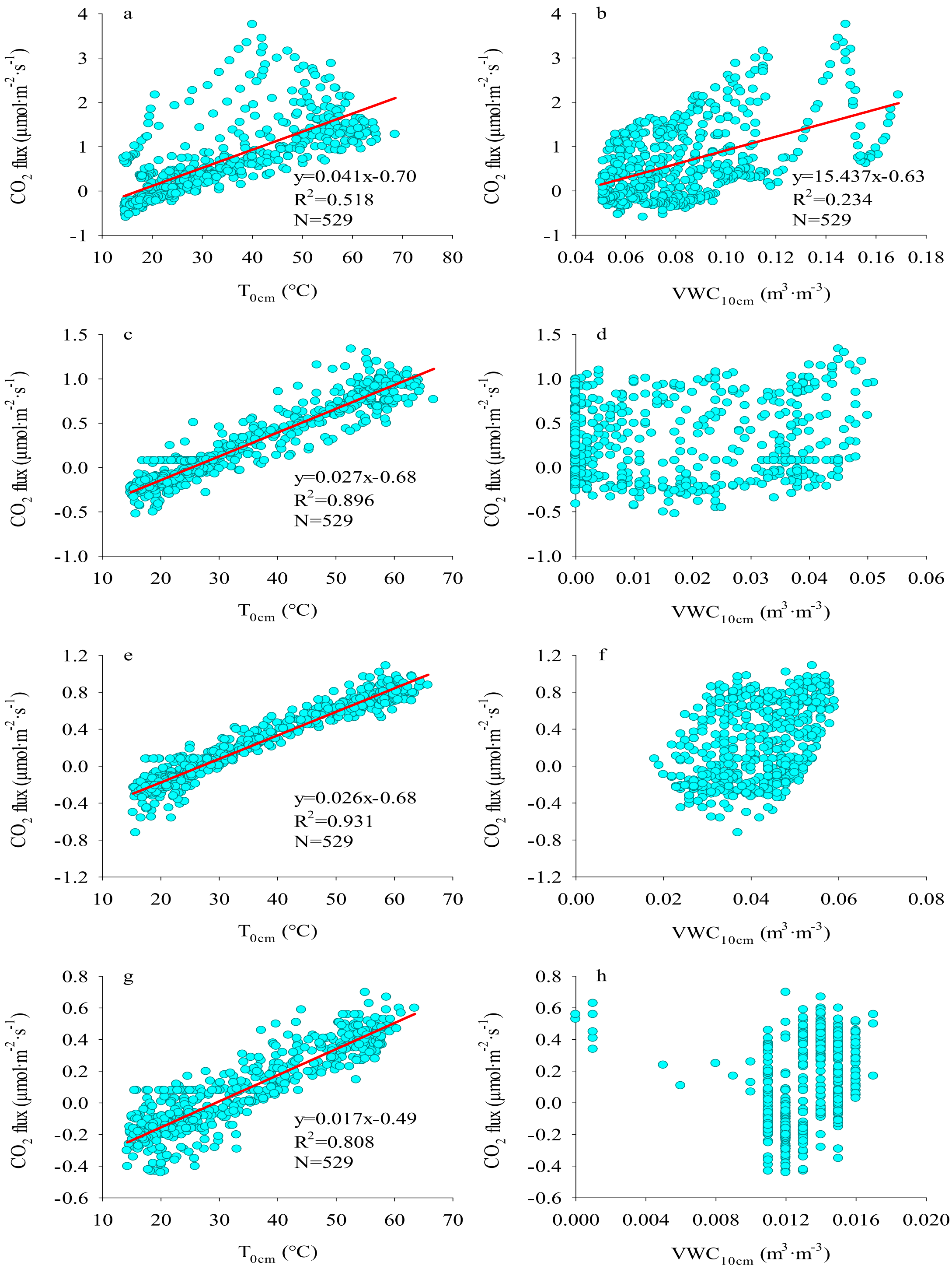


Figure 4. Regression relationship between the CO_2 flux of samples 1−4 and the surface soil temperature (T_{0cm}) and the soil moisture at 10 cm (VWC_{10cm}) after the removal of the CO_2 flux of dry shifting sand; a, c, e, and g represent the regression relationships between samples 1−4 and T_{0cm}, respectively, and b, d, f, and h represent the regression relationship between samples 1−4 and VWC_{10cm}, respectively.

microbial number, enzyme activity, pH, etc.) to soil temperature fluctuations.

SOC and pH are the best indicators to measure soil health. In combination with the sample property analysis data (Table 1), we determined that the SOC and pH can be used as two key factors to reflect the difference in shifting sand properties and to analyze the mentioned difference in the temperature response. To make the analysis results more universal across the TD, based on the observation data of the four current samples, the CO_2 flux observation data of the shifting sand in the study area in October 2013, May 2015, and July 2019 were included for comprehensive analysis. As shown in Figure 8b,c, the slope (k) and intercept (b) of the linear regression between the CO_2 flux data excluding the carbon exchange of dry shifting sand and T_{0cm} had significant linear relationships with the SOC and pH, respectively, of the shifting sand ($R^2 > 0.899$, $P < 0.001$). This also means that more organic carbon and more neutral in shifting sand will increase the CO_2 flux. On the

https://doi.org/10.1021/acs.est.2c09470
Environ. Sci. Technol. 2023, 57, 7174−7184

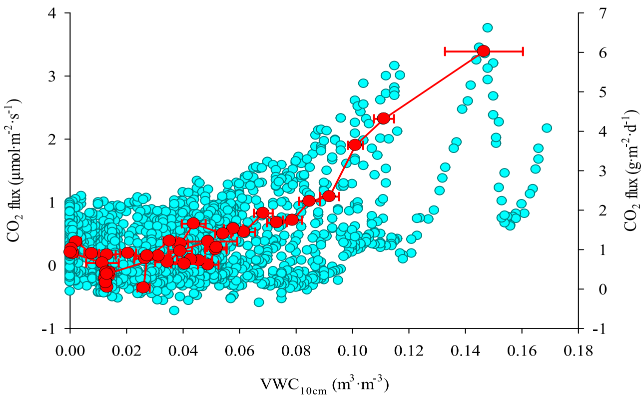


Figure 5. Regression relationship between the CO_2 flux of all samples and the soil moisture at 10 cm (VWC_{10cm}) on hourly (blue) and daily scales (red) after the removal of the CO_2 flux of dry shifting sand.

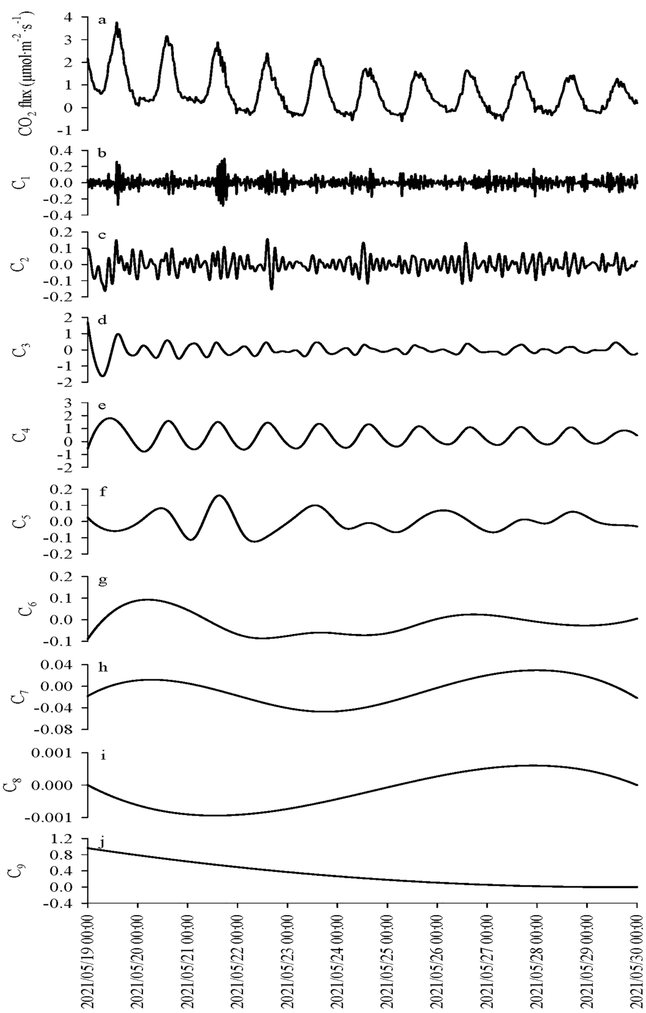


Figure 6. Nine IMFs were obtained from sample 1 by EEMD after removal of the CO_2 flux of dry shifting sand. (a) The CO_2 flux of sample 1 after the removal of the CO_2 flux of dry shifting sand. (b−j) Nine IMFs from C_1 to C_9.

contrary, the reduction of organic carbon and the increase of alkalinity in shifting sand will reduce CO_2 emissions and highlight the role of carbon sequestration. At the same time, the carbon sink capacity is enhanced at low temperature.

4. DISCUSSION

4.1. Precipitation Stimulates the Release of CO_2 from Nonvegetated Shifting Sand. In desert ecosystems with low long-term water availability, precipitation events usually occur as rare pulse events, which have an important impact on desert carbon reserves. In the nonvegetated shifting sand of the TD, we found that the soil moisture significantly stimulated the shifting sand to release CO_2 at an incredibly high rate by rapidly awakening dormant microorganisms, improving the microbial activity and substrate diffusion when the soil moisture at 10 cm was higher than 0.05 m^3 m^{-3} under the stimulation of desert rainfall events. With the continuous loss of soil moisture, the stimulation of precipitation gradually declined. This phenomenon, i.e., that precipitation stimulated the desert to release CO_2, is similar to the research results of Ma et al.[27] and Sagi et al.[9] Under the background that global warming has intensified the water cycle, the increase in total precipitation and extreme precipitation events will accelerate the attenuation of the current carbon sink rate of 1.6 million tons per year of shifting sand in the TD.[7] However, it is different from the phenomenon that the carbon sink intensity increased with an increase in precipitation in the Chihuahua Desert,[37] the Mu Us Desert,[38] and the Badain Jaran Desert.[39] Different deserts will cause different responses of CO_2 flux to precipitation due to different soil properties. In addition, the enhancement of the desert carbon sink by precipitation may be closely related to the mentioned desert not being completely nonvegetated. Under the stimulation of precipitation, the photosynthesis of desert sparse vegetation is enhanced, which strengthens the role of the desert carbon sink. In the nonvegetated shifting sand of the TD, the occasional heavy precipitation not only did not fundamentally alleviate the continuous drought but also did not improve the vegetation coverage. Therefore, the carbon sink intensity of nonvegetated shifting sand will not increase due to the occasional precipitation but will continue to decrease.

4.2. Soil Properties Affect the Response of CO_2 Flux to Soil Temperature. Compared with the increase in soil moisture by precipitation, the soil temperature affects all processes of the CO_2 flux of shifting sand from beginning to end.[40] In particular, the effect of soil temperature remained prominent after the precipitation stimulated the shifting sand to release CO_2. This means that the soil temperature not only controls the expansion/contraction of soil air containing CO_2 but also controls the decomposition of the soil substrate, the carbon sequestration of salt/alkali chemistry, and other processes with the participation of soil moisture. This is different from the sensitivity of CO_2 flux to soil temperature controlled by soil moisture in the Mu Us Desert. In particular, the CO_2 flux and soil temperature will be completely decoupled under the condition of low soil moisture.[25] In addition, SOC and pH were used to express the difference in the CO_2 flux response to soil temperature caused by shifting sand properties after excluding the soil water control. The linear increasing relationship between SOC and k reflected the sensitivity of substrate supply and decomposition to soil temperature, and the linear decreasing relationship between pH and b more closely reflected the role of the inorganic carbon sink of soil salt/alkali. Therefore, the CO_2 generated by substrate decomposition gradually decreased with a less organic carbon substrate. At the same time, as the soil tends to be more alkaline, the solubility of CO_2 increases

https://doi.org/10.1021/acs.est.2c09470
Environ. Sci. Technol. 2023, 57, 7174−7184

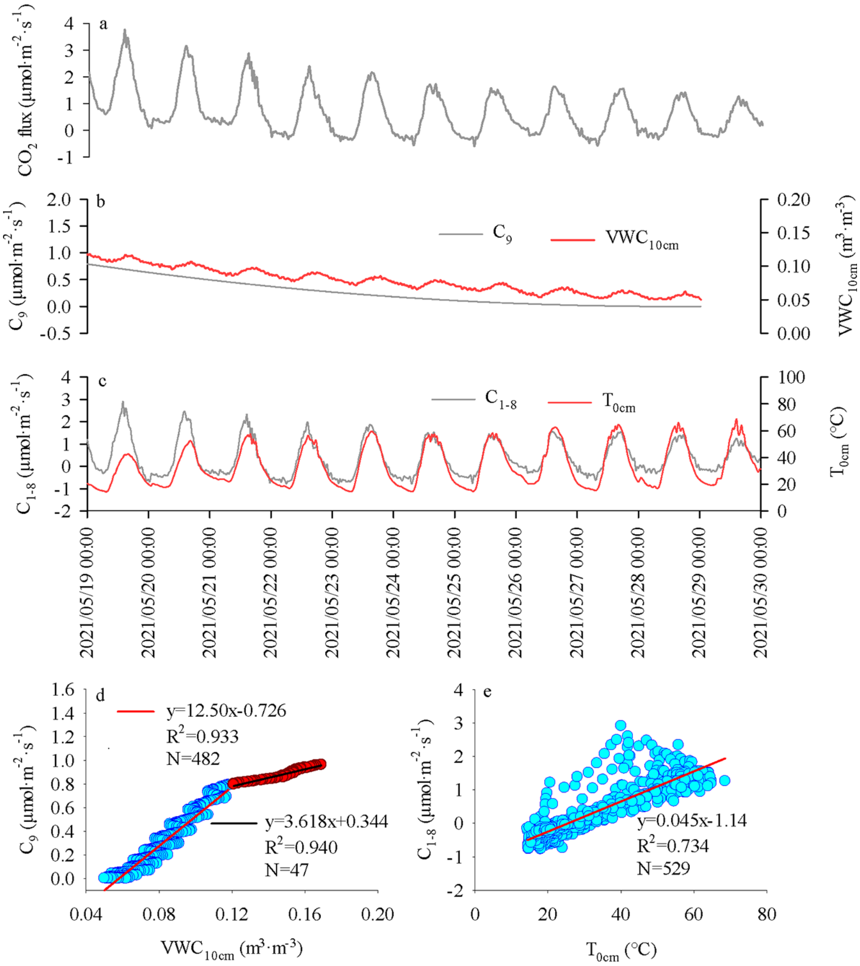


Figure 7. After EEMD disassembly, the corresponding relationship between C_9 and the sum of C_1−C_8 (C_{1-8}) and VWC_{10cm} and T_{0cm}. (a) The CO_2 flux of sample 1 after removal of the CO_2 flux of dry shifting sand. (b) The time series of C_9 and VWC_{10cm}. (c) The time series of C_{1-8} and VWC_{10cm}. (d, e) Their respective regression relationships.

exponentially with increasing pH,[41] which promotes CO_2 influx in shifting sand. Then, under smaller corresponding k and b, the carbon sequestration of shifting sand will gradually play a role and will be strengthened at low soil temperature. This result was similar to that obtained in the research of Ma et al.,[42] Zhao et al.,[43] and Sagi et al.[9]

4.3. Empirical Scheme for Estimating CO_2 Flux of Shifting Sand. With the further understanding of the effect of hydrothermal synergy and soil properties on carbon exchange of shifting sand, this also provides a possible way to evaluate the carbon sink capacity of shifting sand in the TD. The process framework of the estimation scheme was determined in detail (Figure 9). First, the disassembly experiment and temperature control experiment in a previous study were used to determine the effect of the soil temperature difference and temperature change rate on the expansion/contraction of air containing CO_2 in shifting sand, and then the CO_2 flux of dry shifting sand (R_1) was estimated.[6,7] Second, we assessed whether the soil moisture at 10 cm of shifting sand exceeded the threshold value of 0.05 m^3 m^{-3}. If the soil moisture threshold was exceeded, the piecewise linear regression relationship between C_9 and soil moisture based on EEMD was used to estimate the part of CO_2 flux controlled by soil moisture (R_2). In this process, the effect of soil moisture on stimulating the rapid release of CO_2 from shifting sand became relatively slow when the soil moisture at 10 cm was higher than 0.12 m^3 m^{-3}. This may be caused by high soil moisture reducing the gas permeability of shifting sand and forming an anoxic environment. If it was lower than the threshold value of soil moisture, the stimulation of soil moisture was directly ignored. Finally, the temperature response relationship of CO_2 flux controlled by SOC and pH was used to estimate the part of CO_2 flux controlled by the soil properties of shifting sand (R_3). The superposition of the above three CO_2 fluxes is the total CO_2 flux of shifting sand. The internal logic of the estimation scheme conforms to the theoretical framework of carbon sequestration in arid areas[9] and has better practical operability.

The above scheme was verified by using the observation data of CO_2 exchange in the dry riverbed and shifting sand on the northern edge of the TD. In the experiment, as the soil moisture at 10 cm did not exceed the threshold value of 0.05 m^3 m^{-3}, the stimulation of soil moisture was considered not obvious. In addition, the observation data of the CO_2 flux of shifting sand after simulated precipitation in the hinterland of the TD were used to verify the above scheme again. On July 16, 2019, distilled water with a corresponding precipitation of 5 mm was added to the shifting sand. As shown in Figures S2 and S3, there was a good linear relationship between the estimated value and observed data ($R^2 > 0.678$, $P < 0.001$). This shows that the empirical scheme well estimated the CO_2 flux of shifting sand in the TD.

https://doi.org/10.1021/acs.est.2c09470
Environ. Sci. Technol. 2023, 57, 7174−7184

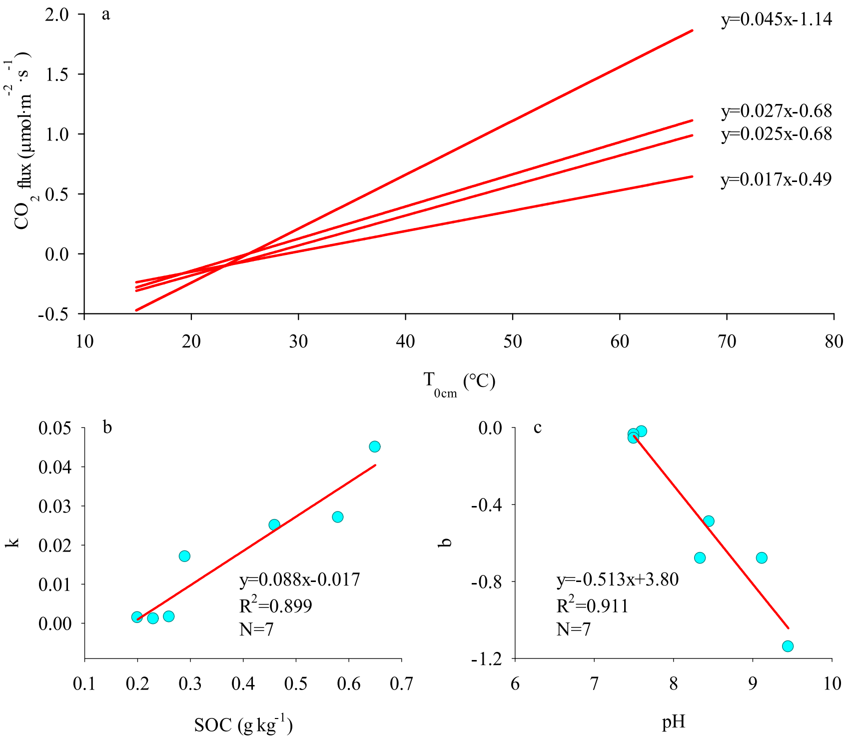


Figure 8. (a) Linear regression of different samples between the CO_2 flux and T_{0cm} after excluding the CO_2 flux of dry shifting sand and the stimulation of soil moisture. (b−c) The relationship between the slope (k) and intercept (b) of the linear regression relationship and soil organic carbon (SOC) and pH of shifting sand.

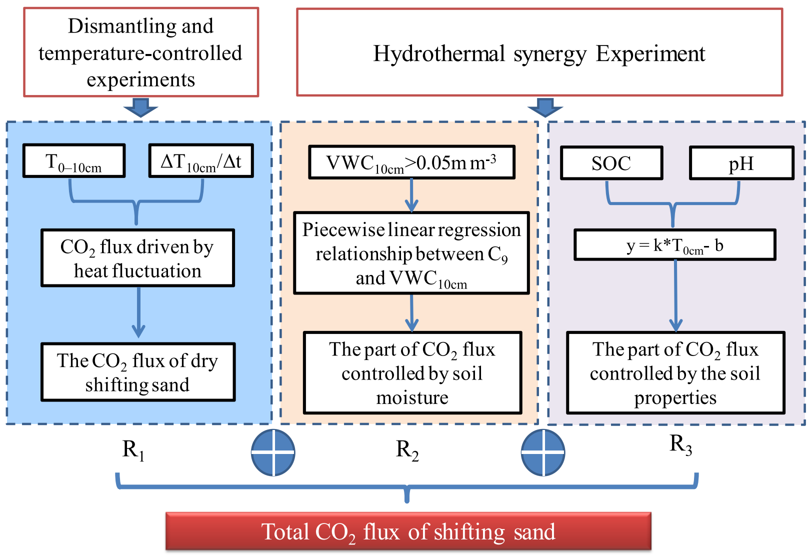


Figure 9. Process framework of empirical scheme for estimating the CO_2 flux of shifting sand in the Taklimakan Desert. T_{0-10cm}, $\Delta T_{10cm}/\Delta t$, VWC_{10cm}, and SOC are difference in soil temperature between depths of 0 and 10 cm, rate of change in soil temperature at a depth of 10 cm, soil moisture at 10 cm, and soil organic carbon, respectively.

5. CONCLUSIONS

Global warming has intensified the water cycle, resulting in an increase in total precipitation and extreme precipitation events in deserts. This will affect several key processes controlling carbon sequestration in deserts. Based on the experiment in the hinterland of the Taklimakan Desert, we found that the soil moisture significantly stimulated the shifting sand to release CO_2 at an incredibly high rate by rapidly awakening dormant microorganisms, improving the microbial activity and substrate diffusion when the soil moisture at 10 cm was higher than 0.05 $m^3\ m^{-3}$ under the stimulation of desert rainfall events. The heavy precipitation will accelerate the weakening of abiotic carbon sequestration in deserts under the background of global warming and intensified water cycle. At this time, the CO_2 flux in the shifting sand was synergistically affected by soil temperature and soil moisture. Since then, the stimulation of precipitation gradually declined with the continuous loss of soil moisture. During the period when the soil moisture was lower than the threshold, the CO_2 budget of shifting sand was only strictly controlled by the soil temperature. As far as soil

https://doi.org/10.1021/acs.est.2c09470
Environ. Sci. Technol. 2023, 57, 7174−7184

properties are concerned, with less organic carbon substrate and stronger soil alkalinity, the carbon sequestration of shifting sand is gradually highlighted and strengthened at low temperature. On this basis, we have established and verified an empirical scheme for estimating CO_2 flux of shifting sand in TD. The scheme is very helpful for the desert carbon cycle, and it can also provide a good theoretical basis for estimating the carbon sequestration capacity of desert ecosystems. In the future, we will continue to optimize the scheme to improve the estimation accuracy through more observation experiments.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c09470.

> The CO_2 flux of samples 1−4 after the CO_2 flux of dry shifting sand was removed (Figures S1) and the CO_2 flux estimation scheme of shifting sand established in this study verified by the measured data in the TD (Figures S2 and S3) (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Jianping Huang − *Collaborative Innovation Center for Western Ecological Safety, College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, China;* orcid.org/0000-0003-2845-797X; Phone: +86 (931) 891-4282; Email: hjp@lzu.edu.cn

Authors

Fan Yang − *Institute of Desert Meteorology, China Meteorological Administration/National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang/Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration/Xinjiang Key Laboratory of Desert Meteorology and Sandstorm/Key Laboratory of Tree-ring Physical and Chemical Research, China Meteorological Administration, Urumqi 830002, China; Collaborative Innovation Center for Western Ecological Safety, College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, China*

Chenglong Zhou − *Institute of Desert Meteorology, China Meteorological Administration/National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang/Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration/Xinjiang Key Laboratory of Desert Meteorology and Sandstorm/Key Laboratory of Tree-ring Physical and Chemical Research, China Meteorological Administration, Urumqi 830002, China; Collaborative Innovation Center for Western Ecological Safety, College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, China*

Xinghua Yang − *Institute of Desert Meteorology, China Meteorological Administration/National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang/Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration/Xinjiang Key Laboratory of Desert Meteorology and Sandstorm/Key Laboratory of Tree-ring Physical and Chemical Research, China Meteorological Administration, Urumqi 830002, China*

Ali Mamtimin − *Institute of Desert Meteorology, China Meteorological Administration/National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang/Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration/Xinjiang Key Laboratory of Desert Meteorology and Sandstorm/Key Laboratory of Tree-ring Physical and Chemical Research, China Meteorological Administration, Urumqi 830002, China*

Xinqian Zheng − *Xinjiang Agro-Meteorological Observatory, Urumqi 830002, China*

Wen Huo − *Institute of Desert Meteorology, China Meteorological Administration/National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang/Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration/Xinjiang Key Laboratory of Desert Meteorology and Sandstorm/Key Laboratory of Tree-ring Physical and Chemical Research, China Meteorological Administration, Urumqi 830002, China*

Fei Ji − *Collaborative Innovation Center for Western Ecological Safety, College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, China*

Dongliang Han − *Collaborative Innovation Center for Western Ecological Safety, College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, China*

Lu Meng − *Institute of Desert Meteorology, China Meteorological Administration/National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang/Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration/Xinjiang Key Laboratory of Desert Meteorology and Sandstorm/Key Laboratory of Tree-ring Physical and Chemical Research, China Meteorological Administration, Urumqi 830002, China*

Jiacheng Gao − *Institute of Desert Meteorology, China Meteorological Administration/National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang/Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration/Xinjiang Key Laboratory of Desert Meteorology and Sandstorm/Key Laboratory of Tree-ring Physical and Chemical Research, China Meteorological Administration, Urumqi 830002, China*

Meiqi Song − *Institute of Desert Meteorology, China Meteorological Administration/National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang/Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration/Xinjiang Key Laboratory of Desert Meteorology and Sandstorm/Key Laboratory of Tree-ring Physical and Chemical Research, China Meteorological Administration, Urumqi 830002, China*

Yu Wang − *Institute of Desert Meteorology, China Meteorological Administration/National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang/Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration/Xinjiang Key Laboratory of Desert Meteorology and Sandstorm/Key Laboratory of Tree-ring Physical and Chemical Research, China Meteorological Administration, Urumqi 830002, China*

https://doi.org/10.1021/acs.est.2c09470
Environ. Sci. Technol. 2023, 57, 7174−7184

Congzhen Zhu − *Institute of Desert Meteorology, China Meteorological Administration/National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang/Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration/Xinjiang Key Laboratory of Desert Meteorology and Sandstorm/Key Laboratory of Tree-ring Physical and Chemical Research, China Meteorological Administration, Urumqi 830002, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.2c09470

Author Contributions

J.H., F.Y., and C.Z. designed the study and contributed to the ideas, data analysis, interpretation, and manuscript writing. All of the authors contributed to the discussion and interpretation of the manuscript. All of the authors reviewed the manuscript.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was jointly supported by the Innovation and development project of China Meteorological Administration (CXFZ2022J043), the National Natural Science Foundation of China (41888101), the Natural Science Foundation of Xinjiang Uygur Autonomous Region (2022D01E104), the Scientific and Technological Innovation Team (Tianshan Innovation Team) project (2022TSYCTD0007), the China Postdoctoral Science Foundation (2022MD723851), and the Fundamental Scientific Research Business Expenses of the Central Public Welfare Scientific Research Institute (IDM2018005).

■ REFERENCES

(1) Yang, Y.; Shi, Y.; Sun, W.; Chang, J.; Zhu, J.; Chen, L.; Wang, X.; Guo, Y.; Zhang, H.; Yu, L.; Zhao, S.; Xu, K.; Zhu, J.; Shen, H.; Wang, Y.; Peng, Y.; Zhao, X.; Wang, X.; Hu, H.; Chen, S.; Huang, M.; Wen, X.; Wang, S.; Zhu, B.; Niu, S.; Tang, Z.; Liu, L.; Fang, J. Terrestrial carbon sinks in China and around the world and their contribution to carbon neutrality. *Sci. China Life Sci.* **2022a**, *65*, 861−895.

(2) Zhou, G.; Zhou, M.; Zhou, L.; Ji, Y. Advances in the carbon sink potential of terrestrial ecosystems in China. *Chin. Sci. Bull.* **2022**, *67*, 3625−3632.

(3) Wang, Y.; Wang, X.; Wang, K.; Chevallier, F.; Zhu, D.; Lian, J.; He, Y.; Tian, H.; Li, J.; Zhu, J.; Jeong, S.; Canadell, J. G. The size of the land carbon sink in China. *Nature* **2022**, *603*, E7−E9.

(4) Chen, B.; Chen, F.; Ciais, P.; Zhang, H.; Lü, H.; Wang, T.; Chevallier, F.; Liu, Z.; Yuan, W.; Peters, W. Challenges to achieve carbon neutrality of China by 2060: status and perspectives. *Sci. Bull.* **2022**, *67*, 2030−2035.

(5) Stone, R. Have desert researchers discovered a hidden loop in the carbon cycle? *Science* **2008**, *320*, 1409−1410.

(6) Yang, F.; Huang, J.; He, Q.; Zheng, X.; Zhou, C.; Pan, H.; Huo, W.; Yu, H.; Liu, X.; Meng, L.; Han, D.; Ali, M.; Yang, X. Impact of differences in soil temperature on the desert carbon sink. *Geoderma* **2020a**, *379*, No. 114636.

(7) Yang, F.; Huang, J.; Zhou, C.; Yang, X.; Ali, M.; Li, C.; Pan, H.; Huo, W.; Yu, H.; Liu, X.; Zheng, X.; Han, D.; He, Q.; Meng, L.; Chang, J. Taklimakan desert carbon-sink decreases under climate change. *Sci. Bull.* **2020b**, *65*, 431−433.

(8) Yuste, J. C.; Janssens, I. A.; Carrara, A.; Meiresonne, L.; Ceulemans, R. Interactive effects of temperature and precipitation on soil respiration in a temperate maritime pine forest. *Tree Physiol.* **2003**, *18*, 1263−1270.

(9) Sagi, N.; Zaguri, M.; Hawlena, D. Soil CO_2 influx in drylands: A conceptual framework and empirical examination. *Soil Biol. Biochem.* **2021**, *156*, No. 108209.

(10) Feng, Q.; Cheng, G.; Mikami, M. The carbon cycle of sandy lands in China and its global significance. *Clim. Change* **2001**, *48*, 535−549.

(11) Wang, G.; Ma, H.; Qian, J.; Chang, J. Impact of land use changes on soil carbon, nitrogen and phosphorus and water pollution in an arid region of northwest China. *Soil Use. Manage.* **2004**, *20*, 32−39.

(12) Parsons, A. N.; Barrett, J. E.; Wall, D. H.; Virginia, R. A. Soil carbon dioxide flux in Antarctic dry valley ecosystems. *Ecosystems* **2004**, *7*, 286−295.

(13) Xie, J.; Li, Y.; Zhai, C.; Li, C.; Lan, Z. CO_2 absorption by alkaline soils and its implication to the global carbon cycle. *Environ. Geol.* **2009**, *56*, 953−961.

(14) Fa, K. Y.; Zhang, Y. Q.; Wu, B.; Qin, S. G.; Liu, Z.; She, W. W. Patterns and possible mechanisms of soil CO_2 uptake in sandy soil. *Sci. Total Environ.* **2016**, *544*, 587−594.

(15) Schlesinger, W. An evaluation of abiotic carbon sinks in deserts. *Global Change Biol.* **2017**, *23*, 25−27.

(16) Oki, T.; Kanae, S. Global hydrological cycles and world water resources. *Science* **2006**, *313*, 1068−1072.

(17) Li, Y.; Wang, Y. G.; Houghton, R. A.; Tang, L. S. Hidden carbon sink beneath desert. *Geophys. Res. Lett.* **2015**, *42*, 5880−5887.

(18) Yang, F.; He, Q.; Huang, J.; Ali, M.; Yang, X.; Huo, W.; Zhou, C.; Liu, X.; Wei, W.; Cui, C.; Wang, M.; Li, H.; Yang, L.; Zhang, H.; Liu, Y.; Zheng, X.; Pan, H.; Jin, L.; Zou, H.; Zhou, L.; Liu, Y.; Zhang, J.; Meng, L.; Wang, Y.; Qin, X.; Yao, Y.; Liu, H.; Xue, F.; Zheng, W. Desert environment and climate observation network over the Taklimakan Desert. *B. Am. Meteorol. Soc.* **2021a**, *102*, E1172−E1191.

(19) Donat, M. G.; Lowry, L. A.; Alexander, L. V.; O'Gorman, P. A.; Maher, N. More extreme precipitation in the world's dry and wet regions. *Nat. Clim. Change* **2016**, *6*, 508−513.

(20) Zhang, Q.; Yang, J.; Wang, W.; Ma, P. L.; Lu, G. Y.; Liu, X. Y.; Yu, H. P.; Fang, F. Climatic warming and humidification in the arid region of northwest China: Multi-scale characteristics and impacts on ecological vegetation. *J. Meteorol. Res-PRC* **2021**, *35*, 113−127.

(21) Yao, J.; Chen, Y.; Chen, J.; Zhao, Y.; Mao, W. Intensification of extreme precipitation in arid Central Asia. *J. Hydrol.* **2021**, *598*, No. 125760.

(22) Lou, Y. Q.; Zhou, X. H. *Soil respiration and the environment*; Elsevier, Inc.: London, U.K., 2006.

(23) Carbone, M. S.; Winston, G. C.; Trumbore, S. E. Soil respiration in perennial grass and shrub ecosystems: linking environmental controls with plant and microbial sources on seasonal and diel timescales. *J. Geophys. Res.* **2008**, *113*, G2.

(24) Phillips, C. L.; Nickerson, N.; Risk, D.; Bond, B. J. Interpreting diel hysteresis between soil respiration and temperature. *Global Change Biol.* **2011**, *17*, 515−527.

(25) Wang, B.; Zha, T. S.; Jia, X.; Wu, B.; Zhang, Y. Q.; Qin, S. G. Soil moisture modifies the response of soil respiration to temperature in a desert shrub ecosystem. *Biogeosciences* **2014**, *11*, 259−268.

(26) Wang, Y. H.; Chen, J. Q.; Zhou, G. S.; Shao, C. L.; Chen, J.; Wang, Y.; Song, J. M. Predominance of precipitation event controls ecosystem CO_2 exchange in an Inner Mongolian desert grassland, China. *J. Cleaner Prod.* **2018**, *197*, 781−793.

(27) Ma, J.; Zheng, X. J.; Li, Y. The response of CO_2 flux to rain pulses at a saline desert. *Hydrol. Process.* **2012**, *26*, 4029−4037.

(28) Yu, P.; Xu, H.; Wang, W.; Zhang, P.; Zhao, X.; Gong, J. Response of soil respiration to artificial rainfall in different parts of sand dunes. *J. Desert Res.* **2012**, *32*, 437−441.

(29) Wang, Y. M.; Wang, J. H.; Yan, C. Z. Data set of desert (sand) distribution in China with scale of 1:100000. *Cold Arid Regions Sci.* **2005**, 10.3972/westdc.006.2013.db.

(30) Chen, S.; Huang, J.; Li, J.; Jia, R.; Jiang, N.; Kang, L.; Ma, X.; Xie, T. Comparison of dust emissions, transport, and deposition between the Taklimakan Desert and Gobi Desert from 2007 to 2011. *Sci. China Earth Sci.* **2017a**, *60*, 1338−1355.

(31) Chen, S.; Huang, J.; Kang, L.; Wang, H.; Ma, X.; He, Y.; Yuan, T.; Yang, B.; Huang, Z.; Zhang, G. Emission, transport and radiative effects of mineral dust from Taklimakan and Gobi Deserts: comparison of measurements and model results. *Atmos. Chem. Phys.* **2017b**, *17*, 2401−2421.
(32) Yang, F.; Huang, J.; Zheng, X.; Huo, W.; Zhou, C.; Wang, Y.; Han, D.; Gao, J.; Ali, M.; Yang, X.; Sun, Y. Evaluation of carbon sink in the Taklimakan Desert based on correction of abnormal negative CO_2 flux of IRGASON. *Sci. Total Environ.* **2022b**, *838*, No. 155988.
(33) Huang, N. E.; Shen, Z.; Long, S. R.; Wu, M. C.; Shih, H. H.; Zheng, Q.; Yen, N. C.; Tung, C. C.; Liu, H. H. The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *Proc. R. Soc. London, Ser. A* **1998**, *454*, 903−995.
(34) Huang, N. E.; Shen, Z.; Long, S. R. A new view of nonlinear water waves: The Hilbert spectrum. *Annu. Rev. Fluid Mech.* **1999**, *31*, 417−457.
(35) Zhou, T.; Shi, P.; Hui, D.; Luo, Y. Global pattern of temperature sensitivity of soil heterotrophic respiration (Q_{10}) and its implications for carbon-climate feedback. *J. Geophys. Res-Biogeol.* **2009**, *114*, G02016.
(36) Carvalhais, N.; Forkel, M.; Khomik, M.; Bellarby, J.; Jung, M.; Migliavacca, M.; Mu, M.; Saatchi, S.; Santoro, M.; Thurner, M.; Weber, U.; Ahrens, B.; Beer, C.; Cescatti, A.; Randerson, J. T.; Reichstein, M. Global covariation of carbon turnover times with climate in terrestrial ecosystems. *Nature* **2014**, *514*, 213−217.
(37) Mielnick, P.; Dugas, W. A.; Mitchell, K.; Havstad, K. Long-term measurements of CO_2 flux and evapotranspiration in a Chihuahuan desert grassland. *J. Arid Environ.* **2005**, *60*, 423−436.
(38) Fa, K. Y.; Liu, J. B.; Zhang, Y. Q.; Wu, B.; Qin, S. G.; Feng, W.; Lai, Z. R. CO_2 absorption of sandy soil induced by rainfall pulses in a desert ecosystem. *Hydrol. Process.* **2014**, *29*, 2043−2051.
(39) Yang, P.; Zhao, L.; Liang, X.; Niu, Z.; Zhao, H.; Wang, Y.; Wang, N. Response of net ecosystem CO_2 exchange to precipitation events in the Badain Jaran Desert. *Environ. Sci. Pollut. Res.* **2022c**, *29*, 36486−36501.
(40) Yang, F.; Ali, M.; Zheng, X.; He, Q.; Yang, X.; Huo, W.; Liang, F.; Wang, S. Diurnal dynamics of soil respiration and the influencing factors for three land-cover types in the hinterland of the Taklimakan Desert. *China. J. Arid Land* **2017**, *9*, 568−579.
(41) Seinfeld, J. H.; Pandis, S. N. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change (Second Edition)*; John Wiley & Sons, Inc.: New Jersey, 2016.
(42) Ma, J.; Wang, Z. Y.; Stevenson, B. A.; Zheng, X. J.; Li, Y. An inorganic CO_2 diffusion and dissolution process explains negative CO_2 fluxes in saline/alkaline soils. *Sci. Rep.* **2013**, *3*, 2025.
(43) Zhao, X.; Conrads, H.; Zhao, C.; Ingwersen, J.; Stahr, K.; Wei, X. The effect of different temperature and pH levels on uptake of CO_2 in Solonchaks. *Geoderma* **2019**, *348*, 60−67.

https://doi.org/10.1021/acs.est.2c09470
Environ. Sci. Technol. 2023, 57, 7174−7184