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Review Article

Carbon sequestration in the desert

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Abstract

The desert ecosystems worldwide are vast and may play positive roles in promoting carbon neutrality, reducing carbon loss, and mitigating climate warming. However, due to the contradictions between different observation methods and the unclear internal driving mechanism, desert carbon sink has long been neglected and questioned after many years of research. Accurately determining the contribution of deserts to the global carbon cycle remains unclear, which limits the exploration of their potential for increased carbon sequestration. This review summarizes the current research and key scientific problems related to desert carbon sequestration and outlines the key future directions of desert carbon sequestration development. The key processes and three main driving mechanisms for controlling the carbon sink effect of shifting sand were first elucidated: heat driven, hydrothermal synergy, and soil properties. Based on this, we establish a scheme to estimate the CO_2 flux of shifting sand that considers both hydrothermal interactions and soil properties. According to this assessment, annual CO_2 net sequestration in the shifting sands of Taklimakan Desert is approximately 1.05×10^{-3} Pg, which will continue to decrease with climate change. Furthermore, the desertification prevention and control not only directly improve the regional ecological environment but also endow it with important significance in consolidating and enhancing the stability and capacity of carbon sinks in arid areas. This review effectively elucidates the mechanisms underlying desert carbon sequestration, improves carbon emission estimation in arid areas, and lays a foundation for accurately assessing the total carbon sequestration capacity of global deserts and their contribution to the carbon cycle.

Keywords

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1 Introduction

The global carbon balance is a core issue in climate change research and the focus of international policies [1–3]. The Paris Agreement aims to strengthen the global response to the threat of climate change, limit the rise in global average temperature to less than 2 °C relative to the pre-industrial period, and work toward a rise in temperature of less than 1.5 °C,

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thereby reducing the ecological risks caused by anthropogenic climate change [4]. In September 2020, at the general debate of the 75th session of the United Nations General Assembly, Chinese General Secretary Jinping Xi called on world leaders to promote the adoption of the Paris Agreement on climate change and pledged that by 2030, China's CO_2 emissions per unit of gross domestic product would be reduced by more than 65% compared with 2005. Guided by new development concepts, China aims to undertake a comprehensive green transformation by promoting high-quality development and striving to achieve carbon neutrality by 2060. Carbon neutrality is one of humanity's ultimate efforts to deal with the climate crisis, and if countries can follow their own plans to achieve zero carbon emissions within a few decades, future global warming may be limited to 1.5 or 2 °C, pulling humanity and the natural environment back from the brink of climate disaster. At the same time, to force energy and industrial emission reduction, promote technological progress and development transformation, and drive the comprehensive management of the ecological environment, and cultivate a new ecological economy. To date, more than 130 countries have proposed carbon neutrality targets, and most have committed to meeting these targets by 2050 or 2060. At present, China's annual CO_2 emissions are about 10 Pg, and peak CO_2 emissions are expected to reach 11 Pg in 2030 [5]. In response to this problem, the next 30 years will jointly promote carbon neutrality through a four-step process: reducing greenhouse gas emissions, protecting carbon sink capacity, increasing carbon sink capacity, and carbon capture. Among them, improving or restoring the structure and function of natural terrestrial ecosystem, optimizing the spatial layout of the regional terrestrial ecosystem, and effectively leveraging the role of the terrestrial ecosystem in carbon sequestration are important paths to achieve the goal of carbon neutrality. At present, this process is the most economical, safe, and effective means of carbon reduction available [5]. Therefore, accurately assessing and stimulating the carbon sequestration capacity of each ecosystem has become an important direction for research into the relationship between climate change and the balance of economic and social development.

To date, most assessments of the global carbon cycle and the carbon sequestration capacity of various ecosystems have focused on high-productivity ecosystems such as forests, grasslands, wetlands, farmlands, and oceans. According to various estimates, the annual amount of CO_2 absorbed in China's terrestrial ecosystem is approximately 0.7–1.2 Pg [5–9]. This amount falls far short of the carbon sequestration needed to achieve carbon neutrality for the ecosystem. In addition, in the global carbon cycle, about 1.5 ± 0.6 Pg of carbon per year is unaccounted and designated as missing carbon sink [10]. The vast desert ecosystem, which accounts for about 21% of global land area, absorbs and stores CO_2 in the absence of photosynthesis, plays a role in carbon sequestration, and makes positive contributions to carbon neutrality, reducing missing carbon sink, and mitigating climate warming. However, deserts are often overlooked in ecosystem carbon sink assessments due to a lack of data and low productivity [11–13]. Three key scientific problems in desert carbon sink research currently require resolution: (1) With the increasing number of measurement methods available, magnitude and phase contradictions have arisen between desert CO_2 fluxes obtained using different observation methods (e.g., open-path eddy covariance, closed-path eddy covariance, and LI-COR 8100A instrumentation), leading to large differences in desert carbon sequestration capacity evaluation results. Due to these differences, the carbon sink function of deserts remains an open question despite years of research. (2) The key processes controlling carbon exchange in desert ecosystems have been partially understood, but the exact contributions of these abiotic processes to desert carbon sinks and their internal composition and coordination mechanisms remain unclear. For this reason, establishing a parameterized scheme to accurately describe the process of desert carbon exchange is not possible, which limits the accurate assessment of desert carbon sequestration capacity, further impedes the accurate judgment of the contribution status of desert ecosystem to the carbon cycle and the long-term trend of desert carbon sequestration capacity under climate change, and limits in-depth exploration of carbon sequestration and sequestration potential in arid areas where deserts are widely spread. (3) Greater attention has been paid to the effects of wind and sand prevention, microclimate improvement, and economic benefits after desertification prevention and control, whereas the potential carbon sink benefits associated with desertification control are often ignored. As a result, uncertainties remain in the enhanced carbon sequestration capacity of deserts and the response of such enhancement to environmental conditions after the establishment of artificial protective forests.

In light of the three urgent scientific issues that require resolution, this paper reviews the research processes and significant findings related to the mechanisms of carbon sequestration in desert environments. The review is structured around three key aspects: the monitoring methods for desert CO_2 flux, the primary processes and mechanisms of carbon sequestration in deserts, and the role of desertification control in enhancing carbon sinks. Based on our latest research progress on the mechanism of carbon sequestration in the Taklimakan Desert, we summarize the current research status and future prospects regarding this mechanism. For the first time, we identified the key processes that control the carbon sequestration of shifting sand from three perspectives: heat driven, hydrothermal synergy, and soil properties. This study aims to enhance the comprehensive understanding of the mechanisms of carbon sequestration within desert ecosystems. This will establish a foundation for accurately assessing the total carbon sequestration and contribution of deserts to the global carbon cycle, thereby reducing the gap in “missing carbon sink”. Furthermore, it will provide essential support for enhancing the capacity of arid regions to cope with the risks and pressures associated with climate change.

2 Methods for monitoring CO_2 flux in deserts

Harsh environmental conditions result in low productivity in desert ecosystems, leading to weak CO_2 exchange. Accurate CO_2 flux measurements are critical for research on carbon sequestration in deserts. Without accurate observational data, revealing the mechanisms of CO_2 exchange in desert ecosystems and their internal processes is impossible, which in turn affects the differentiation of CO_2 sources and the development of estimation models. To address the challenges affecting CO_2 flux measurements, various monitoring techniques have been developed over the past few decades. The chamber technique, which directly measures CO_2 flux at the soil surface, is among the most commonly used approaches. Additionally, newer techniques such as the gas well method, which measures the vertical CO_2 concentration gradient in the soil profile and the eddy covariance method have been employed to monitor CO_2 flux. The eddy covariance system can measure high-frequency three-dimensional (3D) wind speed, temperature, CO_2, and water vapor concentrations in the environment. Through calculation of the covariance between horizontal wind speed components or material concentrations and vertical wind speed, turbulent flux values can be obtained [14,15]. This technique allows for long-term, continuous, and networked observations at fixed locations, minimizing environmental interference while accurately assessing the intensity of carbon source–sink relationships, as well as water and energy balances within ecosystems. Eddy covariance has gradually become established as one of the most reliable methods for investigating interactions between ecosystems and the atmosphere [16].

However, significant uncertainty regarding the use of eddy covariance systems in desert ecosystems remains, casting doubt on the carbon sequestration potential of deserts despite years of research. First, traditional open-path eddy covariance systems, which consist of an open-path infrared gas analyzer (IRGA) and an independent 3D sonic anemometer, such as the CSAT3 + LICOR7500 and Gill-R3-50 + LICOR7500 instrument combinations. Their measurement accuracy is limited due to spatial displacement between the two sensors, temporal asynchronicity, and self-heating effects resulting from the design of IRGA [17–19]. Through the integration of IRGA and sonic anemometer, infrared temperature has been replaced by sonic temperature, reducing sensor power consumption, applying a series of correction algorithms (e.g., IRGASON and EC150), partially addressing measurement accuracy issues caused by spatial separation, time lags, and self-heating [20]. Observations obtained using open-path eddy covariance in desert ecosystems have revealed carbon sequestration rates of 100 $g \cdot m^{-2} \cdot a^{-1}$ in Mojave Desert, 49 $g \cdot m^{-2} \cdot a^{-1}$ in Gurbantunggut Desert, 77 $g \cdot m^{-2} \cdot a^{-1}$ in Mu Us Desert, and 146 $g \cdot m^{-2} \cdot a^{-1}$ in Taklimakan Desert [21–24]. To date, no reasonable explanation has been proposed for these carbon sequestration rates, which are significantly higher than the net primary productivity values of their respective ecosystems [21]. In closed-path eddy covariance systems, sampled air is pumped into an analysis chamber containing a built-in IRGA. Although this method faces challenges such as high-frequency signal loss and a time lag between gas concentration measurement and the sonic anemometer signal, it generally provides high measurement accuracy due to reduced interference from external environmental factors, particularly with the use of short intake tubes and high flow rates [25]. However, field experiments comparing open-path and closed-path eddy covariance systems showed that CO_2 flux measurements obtained from the two methods, which have a shared theoretical foundation but differing observational techniques, showed opposite phases and numerical differences [20,26,27]. Analysis suggests that the main cause of these systematic deviations may be spectral effects, such as absorption line broadening [28]. When the actual CO_2 flux in an ecosystem is low, this bias becomes more pronounced, often manifesting as an unrealistic CO_2 uptake signal [27,29,30]. The harsh environmental conditions and naturally low CO_2 fluxes in desert ecosystems make this bias particularly evident at midday, when open-path eddy covariance observations frequently exhibit unrealistic CO_2 absorption peaks [31]. This error results in an overestimation of the carbon sink potential of deserts. Many scientists [27,32,33] attributed this bias to the use of low-frequency temperature measurements to assess high-frequency CO_2 concentrations in IRGA. Additionally, the absorption line broadening can be further exacerbated by fluctuations in atmospheric pressure and humidity, which alter the spectral characteristics of CO_2 absorption and complicate the accurate quantification of CO_2 fluxes. These spectral distortions are particularly challenging in arid environments, where extreme temperature gradients and low water vapor content can amplify measurement uncertainties. In May 2017, Campbell Scientific released a correction method for this bias, claiming that it could rectify temperature-induced spectral effects and improve the accuracy of CO_2 flux observations in north latitude ecosystems dominated by sensible heat [34]. However, field validation indicated that the correction method had very limited efficacy in desert ecosystems, with corrected observations still displaying abnormal daytime CO_2 uptake peaks. LI-COR8100A, as a representative of the chamber-based method, measures soil CO_2 flux by pumping the air from the chamber into an analyzer with a constant environment and detecting real-time changes in CO_2 concentration. Given the inherently low CO_2 flux in desert environments, the effectiveness of the LI-COR8100A in such areas was uncertain. Consequently, the instrument was calibrated prior to installation, and an evaluation experiment was conducted using a soil respiration collar sealed with plastic film. This plastic-wrapped soil respiration collar effectively blocked CO_2 exchange between the sand and the atmosphere, maintaining a stable CO_2 flux near zero, with an observation accuracy of ±0.02 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Thus, the LI-COR8100A offers reliable and accurate measurements of CO_2 flux in desert. Although the LI-COR8100A and eddy covariance methods differ in their principles and applications, their CO_2 flux results are comparable within this study area, which consists of a flat, unvegetated sandy desert. Therefore, accurately assessing the effectiveness of various observation methods for measuring desert CO_2 flux, clarifying the mechanisms underlying the discrepancies between various observation techniques, and selecting appropriate instruments for desert carbon sequestration research remain fundamental challenges.

To address these challenges, a comparative experiment was conducted in the non-vegetated shifting sand of Taklimakan Desert using a gradient meteorological tower (Fig. 1a) involving synchronous observations using open-path eddy covariance (IRGASON) (Fig. 1b), closed-path eddy covariance (EC155) (Fig. 1c), and a soil carbon flux chamber (LI-COR8100A) (Fig. 1d) [35]. The results showed that the CO_2 flux observed with the EC155 was highly consistent with the measurements from the LI-COR8100A, both of which accurately reflected actual CO_2 exchange in the desert. The abnormal negative CO_2 flux recorded by the IRGASON during the daytime led to overestimation of the carbon sequestration capacity of the Taklimakan Desert. Although high-frequency CO_2 flux observations obtained using IRGASON provided some correction of the unrealistic negative CO_2 flux compared to low-frequency data, that correction was limited in the desert ecosystem. Therefore, IRGASON CO_2 flux values for desert ecosystems require further correction. Based on this finding, the influence of environmental factors on discrepancies between CO_2 flux data from open-path and closed-path eddy covariance systems was analyzed, and a corresponding correction relationship was established. The incomplete correction of self-heating and spectral effects, which are caused by extreme solar radiation and low CO_2 flux in the arid desert environment, was hypothesized to be the primary reason for the differences between high-frequency CO_2 flux data observed with IRGASON and CO_2 flux data measured using EC155. Using this correction relationship, the high-frequency CO_2 flux data collected with IRGASON in 2017 were adjusted. Shifting sand was found to release CO_2 during the day, peaking at midday, whereas the sand absorbed CO_2 at night, demonstrating a carbon sequestration effect. Daily CO_2 exchange of the shifting sand showed a unimodal distribution throughout the year, with significant seasonal variation. From January to March and October to December, when the temperature difference in the soil between depths of 0 and 10 cm was less than 0.8 °C, and the net surface radiation was below 67 $W \cdot m^{-2}$, the shifting sand absorbed atmospheric CO_2. From April to September, when the temperature difference between 0 and 10 cm exceeded 0.8 °C, and the net surface radiation was greater than 67 $W \cdot m^{-2}$, the shifting sand released CO_2 into the atmosphere. In the dynamic balance of CO_2 release and absorption over the year, the absorption effect was stronger, indicating that shifting sand in the hinterland of Taklimakan Desert has clear carbon sequestration capacity, with an average CO_2 absorption rate of 6.31 $g \cdot m^{-2} \cdot a^{-1}$ [35]. Although the carbon sequestration potential is lower for the shifting sand of Taklimakan Desert than those in high-productivity ecosystems such as forests, grasslands, and farmlands (Table 1), the vast desert nonetheless plays positive roles in reducing carbon

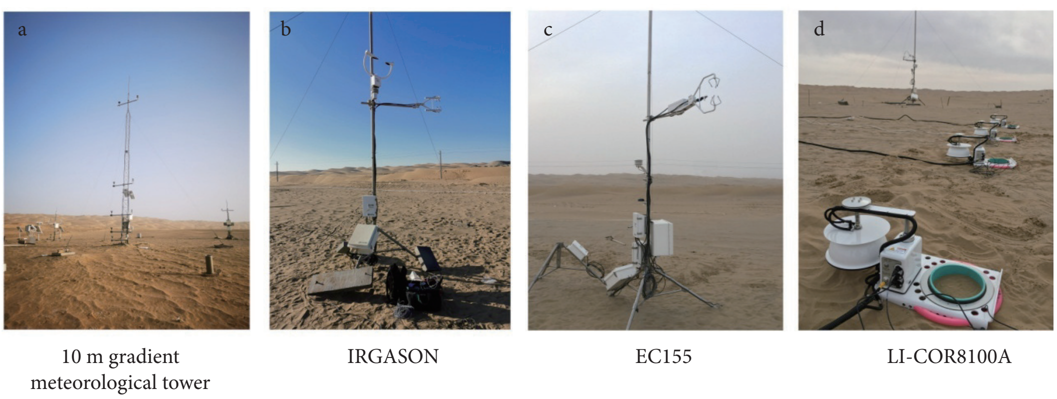

Fig. 1 Experimental setup for synchronous observation experiment of CO_2 flux in the central region of Taklimakan Desert. (a) 10 m gradient meteorological tower. (b) Open-path eddy covariance (IRGASON). (c) Closed-path eddy covariance (EC155). (d) Soil carbon flux chamber (LI-COR8100A).

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Table 1 Comparison of CO_2 sequestration rates in typical ecosystems and different deserts.

Ecosystem	Country/region	CO_2 sequestration rate ($g \cdot m^{-2} \cdot a^{-1}$)	Reference
Tropical forest	Africa	242	Hubau et al. (2020) [36]
Amazon rainforest	South America	88–139.33	Hubau et al. (2020) [36]
Coniferous forest	Tibetan Plateau	140.83	Tian et al. (2009) [37]
Temperate grassland	France	161.48	Soussana et al. (2004) [38]
Seagrass meadow	Southern England	275.48	Lima et al. (2023) [39]
Alpine meadow	Tibetan Plateau	99.83	Tian et al. (2009) [37]
Temperate cropland	North China	46.9 ± 21.1	Li et al. (2024) [40]
Lacustrine wetland	Egypt	29.00	Eid et al. (2024) [41]
Marshy wetland	China	91.80	Ma et al. (2016) [42]
Taklamakan Desert	China	6.31	This study
Arabian Desert	Middle East	0.73	Kamangar et al. (2023) [43]
Negev Desert	Israel	8.44	Kidron et al. (2015) [44]

emissions, mitigating climate change, and promoting sustainable development in arid regions dominated by desert ecosystems. Therefore, accurately assessing the carbon sequestration capacity of desert ecosystems is of great importance to elucidating the role of deserts in the global carbon cycle.

3 Major processes of desert carbon sequestration

Quantitative analyses of the contributions of biological and abiotic processes to carbon exchange in deserts have indicated that such exchange is mainly controlled by abiotic processes [45–49]. Surface turbulence, soil air volume expansion, precipitation of dissolved CO_2 from soil water, desorption of CO_2 adsorbed to the soil matrix, carbonate precipitation, and decomposition of soil organic matter are the main CO_2 release processes in desert ecosystems [46,49,50]. In contrast, under the influence of soil moisture, chemical reactions may occur in desert saline–alkali soils, leading to carbonate dissolution and driving the desert ecosystem to absorb atmospheric CO_2 [45,51]. Secondly, decreased soil temperature [50,52,53] and increased soil moisture [54,55] can accelerate the absorption of atmospheric CO_2 by desert ecosystems. Ma et al. [47] and Ma et al. [48] found that CO_2 exchange in the desert was mainly controlled by inorganic CO_2 flux, which was in turn regulated by soil temperature, and high-pH saline–alkali soil in deserts could absorb atmospheric CO_2 under low-temperature conditions. Carbon exchange in desert ecosystems is mainly controlled by four abiotic processes: gas volume changes driven by pressure and temperature changes controlled by the ideal gas law, changes in CO_2 solubility in the water film surrounding soil particles controlled by Henry's law, pH-mediated carbonate dissolution, and CO_2 adherence to the surfaces of soil minerals [21,45,49,50,56]. Recent research has shown that CO_2 absorbed by the desert gradually enters desert groundwater through the leaching process and eventually gathers in an underground saline aquifer under the vast desert as the groundwater moves. This process is similar to the inorganic carbon sink in the ocean [57]. However, the exact contributions of these abiotic processes to desert carbon sequestration, as well as their internal process interactions and coordination mechanisms, remain unclear. With climate change, extreme precipitation events in deserts have occurred frequently in recent years, which in turn affects several key factors that control desert carbon exchange, including desert soil porosity, soil heat transfer, soil water dissolution of CO_2, soil salinity concentration, and microbial species and activity. At present, in-depth research on these processes is lacking, hindering the establishment of a parameterization scheme that accurately describes the desert carbon exchange process, and thus the accurate assessment of desert carbon sequestration capacity.

3.1 Heat-driven mechanism of desert carbon sequestration

To address these unanswered questions, the processes contributing to CO_2 flux were quantitatively evaluated, and the magnitude of each component (i.e., sand, moisture, salinity, and microorganisms) was accurately measured within the shifting sand in the hinterland of Taklimakan Desert through a disassembly experiment. Artificial temperature-controlled experiments were conducted to identify the mechanism driving heat transmission for CO_2 exchange under prolonged arid conditions in the shifting sand. Prolonged extreme drought in desert regions leads to very limited contributions of soil moisture (Fig. 2b) and soil microorganisms (Fig. 2d) to CO_2 flux from shifting sand. In contrast, the expansion and contrac-

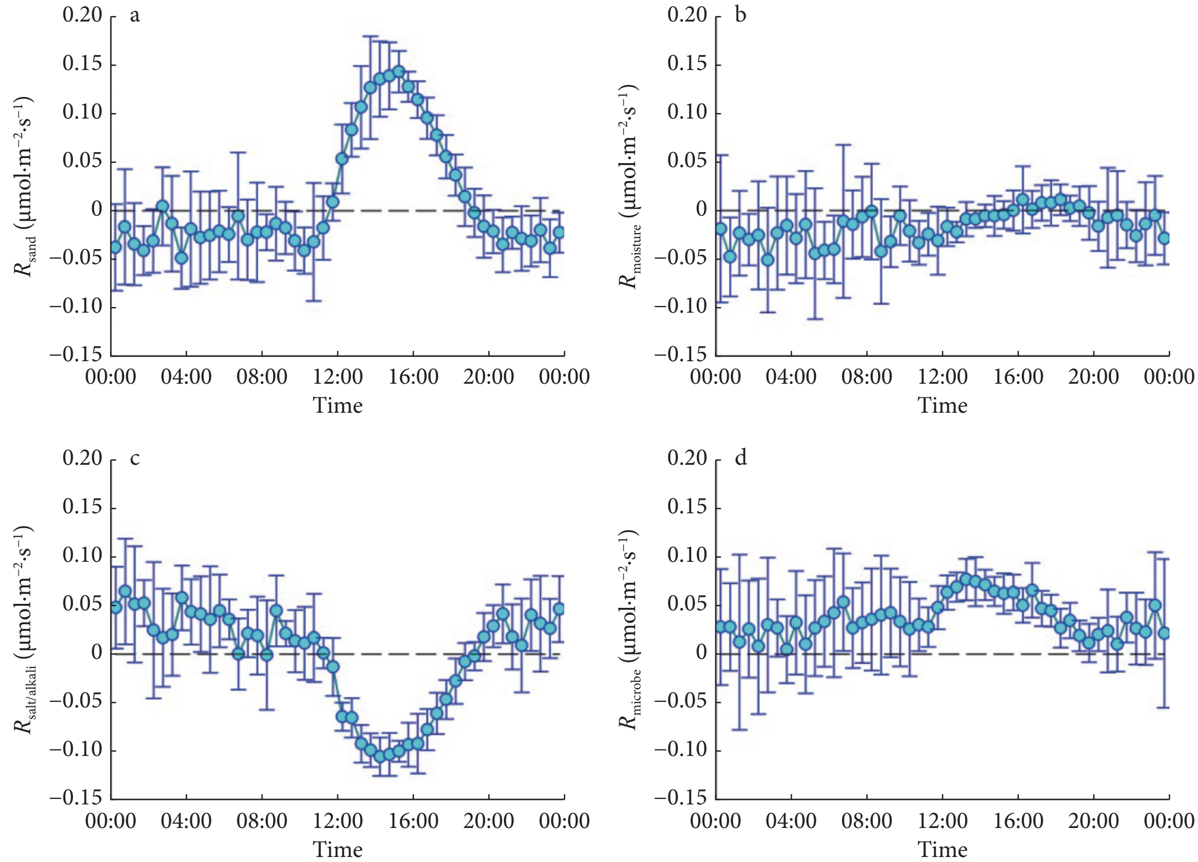

Fig. 2 Contributions of various shifting sand components to daily dynamic total CO_2 flux in the Tazhong shifting sands of Taklimakan Desert. Daily CO_2 flux contributions of pure sand (R_{sand}) (a), moisture ($R_{moisture}$) (b), saline/alkali ($R_{salt/alkali}$) (c), microorganisms ($R_{microbe}$) (d). Error bars indicate the standard deviation of the multi-day average of the CO_2 flux contribution of each component. Reproduced with permission from Ref. [58] ©2020, Science China Press.

tion of soil air containing CO_2 caused by temperature fluctuations of shifting sand contribute strongly to total CO_2 exchange in shifting sand. Thus, a dramatic increase (decrease) in soil temperature promotes the expansion (contraction) of soil air, causing shifting sand to exhibit strong release (absorption) of CO_2 (Fig. 2a). The loose, porous structure of sand provides an inherent advantage for the expansion and contraction of soil air during sharp temperature changes. This process, combined with chemical carbon sequestration driven by soil salts and alkali conditions, dominates CO_2 release and absorption in dry shifting sands. They are tightly regulated by the soil temperature difference representing the direction of heat flow from the soil and the soil temperature change rate representing the absorption or release of heat from the soil (Fig. 2c). Thus, the heat-driven mechanism of carbon sequestration in shifting sand of deserts was revealed, and a parameterization scheme for estimating CO_2 flux in dry shifting sands was established (Fig. 3) [58,59].

3.2 Hydrothermal mechanism of desert carbon sequestration

Global warming has intensified the water cycle in recent years, leading to a dramatic increase in total global precipitation and extreme precipitation events, particularly in arid and semi-arid regions [60]. Total precipitation, precipitation frequency, and precipitation time are key determinants of the impact of precipitation pulses on carbon exchange in desert ecosystems. The carbon sink intensity of desert ecosystems increases after rainfall under the condition of long-term low soil moisture availability [61,62]. However, soil CO_2 release is enhanced after desert rainfall pulses [49,63–65], and the strength of the carbon sink decreases with increasing rainfall. Warming and humidification are also evident in arid regions of Northwest China, including Taklimakan Desert, which has experienced increases in precipitation and extreme precipitation events [66–75]. The entry of precipitation into shifting sand affects a number of key processes controlling desert carbon exchange, such as soil heat transfer, soil water dissolution of CO_2, soil saline and alkaline concentrations, microbial abundance and activity, and soil nutrient transport. The long-standing arid state of shifting sands is lost after desert precipitation events. With increasing precipitation in the desert, the effect of soil moisture on the CO_2 flux of shifting sands must be added to the assessment scheme described above, which considers only heat-driven temperature fluctuations in shifting sands during

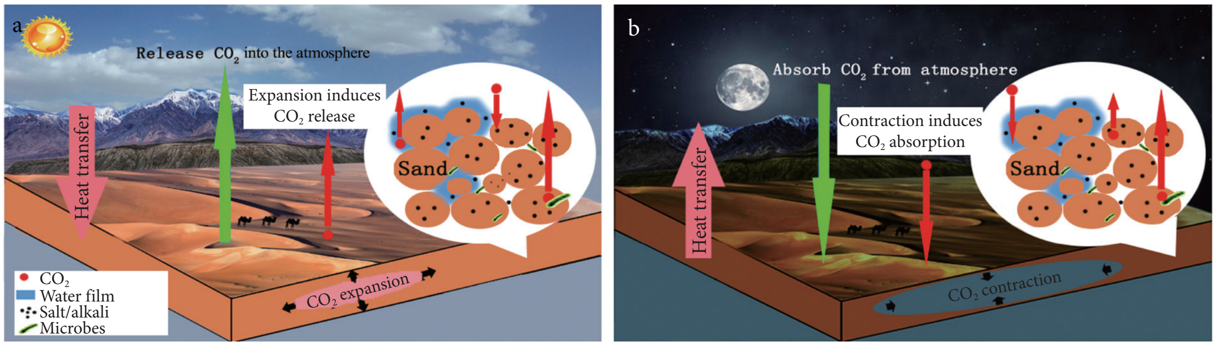

Fig. 3 The CO_2 exchange processes in dry shifting sands of Taklimakan Desert during daytime (a) and nighttime (b), respectively. Reproduced with permission from Ref. [58] ©2020, Science China Press.

drought as a driver of carbon sequestration.

Based on a hydrothermal interaction experiment, after heavy rainfall in the desert, the soil moisture content at a depth of 10 cm in the shifting sand was found to be greater than 0.05 $m^3 \cdot m^{-3}$, therefore, microorganisms in the shifting sand rapidly broke dormancy after the extreme drought was alleviated, increasing microbial activity and facilitated the diffusion of soluble substrates, which caused the shifting sand to release CO_2 at a significantly higher rate (up to 3.68 $\mu mol \cdot m^{-2} \cdot s^{-1}$) [76] over a short period of time. This stimulating effect of moisture over a clear threshold diminishes over time as the moisture dissipates. This phenomenon is similar to the research results of Ma et al. [63] and Sagi et al. [65] on the response of CO_2 flux to precipitation in the desert, but contrasts with observations that carbon sink intensity increases with increasing rainfall in Chihuahuan Desert [77], California Desert [78], Mu Us Desert [55], and Badain Jaran Desert [62]. The promotion of carbon sequestration capacity in these deserts by rainfall may be related to the fact that such areas do not lack vegetation. Under the stimulation of precipitation, the photosynthesis of sparse vegetation is enhanced, thereby intensifying desert carbon sequestration. In addition, the clear threshold of the soil moisture stimulation effect provided new insights into the role of moisture in driving desert CO_2 fluxes.

Soil temperature affects all processes related to desert CO_2 flux and plays a decisive role. In particular, after desert precipitation alleviates extreme drought and stimulates CO_2 flux in shifting sand, the role of soil heat remains prominent. This means that with the participation of soil moisture, soil heat both regulates the expansion and contraction of soil air containing CO_2 and controls diverse processes including the decomposition of substrates and saline–alkali chemical carbon sequestration. This finding contrasts with results reported for Mu Us Desert, where soil moisture was found to regulate the sensitivity of the relationship between CO_2 flux and soil temperature, such that under of low soil moisture conditions, CO_2 flux and soil temperature were completely disconnected [61]. Based on the above results, the hydrothermal synergistic driving mechanism of carbon sequestration process in shifting sand was revealed.

3.3 Soil property-related mechanisms of desert carbon sequestration

After removing the contributions of the heat-driven and hydrothermal synergistic mechanisms of shifting sand CO_2 flux, differences in the responses of shifting sand CO_2 flux to temperature among desert areas remained. The properties of the shifting sand itself were found to be the main factors causing this phenomenon. Soil organic carbon and pH are the best indicators of soil health and key to explaining these observed differences. As the organic carbon substrate concentration in shifting sand increases and the soil becomes closer to neutral pH, the release of CO_2 from shifting sand will increase. Conversely, under alkaline conditions, the solubility of CO_2 increases exponentially with pH as organic carbon substrates become less abundant, and soils become more alkaline [55]. The carbon sequestration function of shifting sand gradually takes effect and is enhanced at low temperatures. This result is supported by the findings of Ma et al. [63] and Sagi et al. [65].

3.4 Establishment of a shifting sand CO_2 flux estimation scheme

Based on the three driving mechanisms outlined above, a shifting sand CO_2 flux estimation scheme was established that simultaneously considered hydrothermal interactions and soil property factors (Fig. 4) [79]. This scheme clarifies the mechanism of carbon sequestration in shifting sands of desert and provides a potential method for assessing the total amount of carbon sequestration in deserts and its contribution to the global carbon cycle. According to this scheme, the CO_2 flux in Taklimakan Desert shifting sand area was calculated annually from 2000 to 2022. Fig. 5 shows the spatial distribution and trend of annual average CO_2 flux (R_s) over the past 23 years. Two thirds of the shifting sand areas in Taklimakan Desert have carbon sequestration functions, with a maximum annual CO_2 sequestration rate of 19.25 ± 5.04 $g \cdot m^{-2} \cdot a^{-1}$. The shifting sand located on the western and northern edges of the desert is the main area of CO_2 release for the entire desert due to the higher precipitation and organic carbon content found at the edge of the agricultural area. Annual net sequestration of approximately $1.05 \times 10^{-3} \pm 0.96 \times 10^{-3}$ Pg of CO_2 in the entire Taklimakan Desert shifting sand area (Fig. 5) [76].

The heat-driven mechanism is the underlying physical process of CO_2 flux in shifting sand, and its intensity depends on the loose and porous structure of the sand layer, the temperature difference between day and night, and the heat transfer rate. Under extreme drought conditions, due to extremely low soil microbial activity, heat-driven gas volume changes dominate CO_2 flux as the core mechanism of carbon balance. Meanwhile, the heat-driven effect will be regulated by soil properties. For example, the solubility of CO_2 increases exponentially with decreasing temperature in alkaline shifting sand, and the cooling driven shrinkage process synergistically enhances CO_2 absorption with chemical carbon fixation of saline–alkali. On the contrary, the expansion process caused by warming, combined with accelerated decomposition of organic carbon and decreased solubility of CO_2, weakens the car-

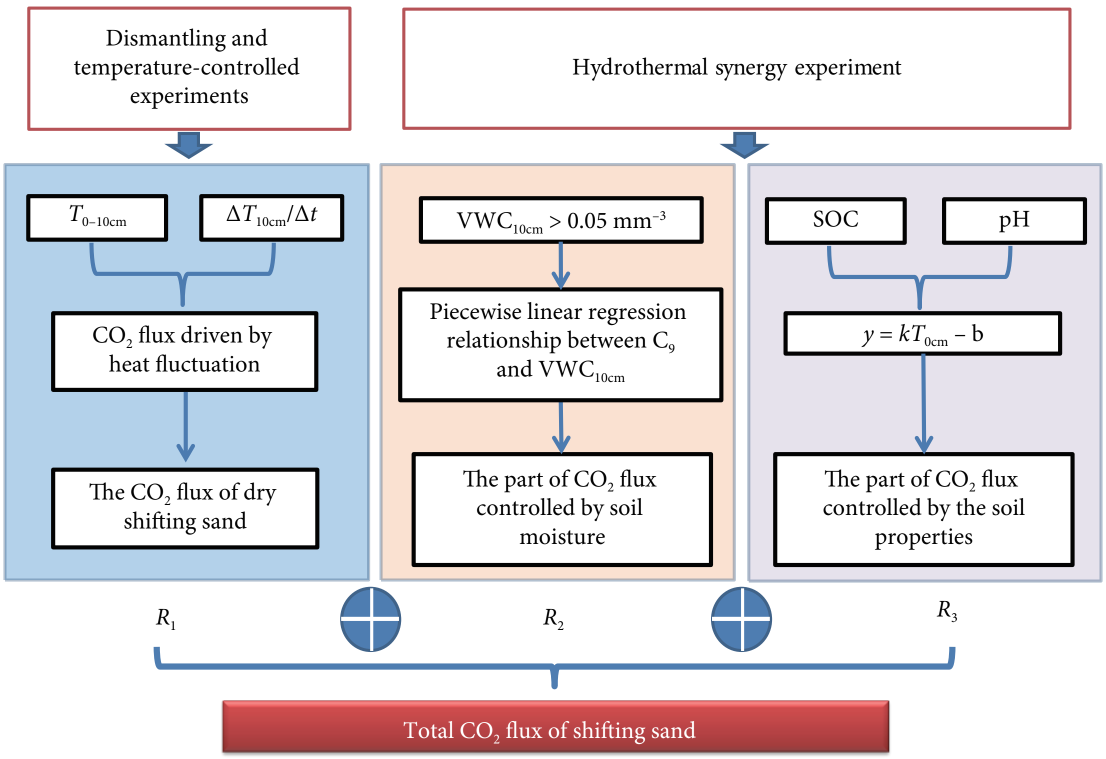

Fig. 4 Framework of Taklimakan Desert shifting sand CO_2 flux estimation scheme. VWC_{10cm}, soil moisture at 10 cm; SOC, soil total salt; T_{0cm}, surface soil temperature; k, slope; b, intercept; R_1, the CO_2 flux of dry shifting sand; R_2, the part of CO_2 flux controlled by soil moisture; R_3, the part of CO_2 flux controlled by the soil properties of shifting sand. Reproduced with permission from Ref. [79] ©2023, American Chemical Society.

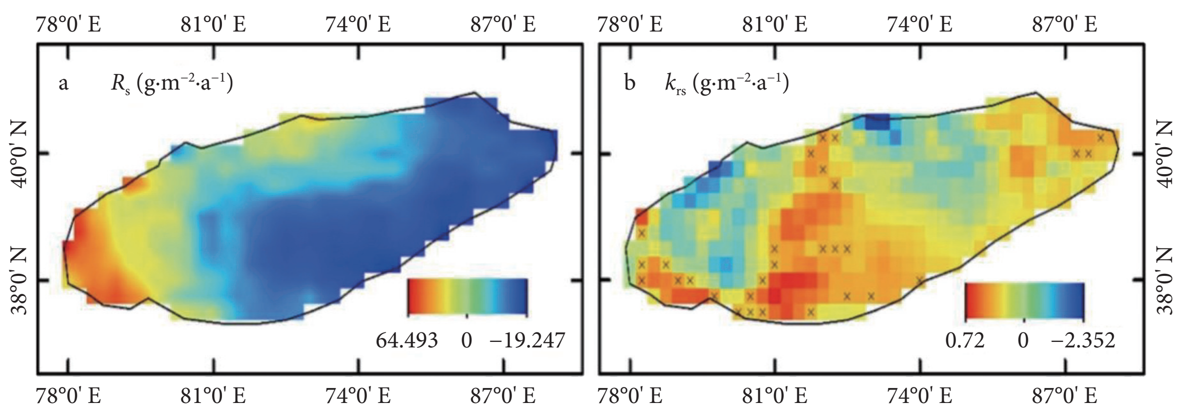

Fig. 5 Spatial distribution of R_s (a) and its variation trend (k_{rs}) (b) through shifting sand area of the Taklimakan Desert from 2000 to 2022. Reproduced with permission from Ref. [76] ©2023, The Author. × represents that the pixel does not pass the significance test ($p > 0.05$), while all other regions passed the significance test ($p < 0.05$).

bon sequestration effect. In addition, the hydrothermal mechanism is activated when precipitation causes the soil moisture content at a depth of 10 cm to exceed the threshold of 0.05 $m^3 \cdot m^{-3}$. At this point, the hydrothermal synergy mechanism may temporarily mask the direct effect of heat-driven and alter soil properties. As water evaporates, the heat-driven mechanism takes over again. This dynamic transformation manifests as a "pulse like release to gradual absorption" pattern of CO_2 flux on an interannual or seasonal scale. Finally, high organic carbon content typically promotes microbial respiration and releases CO_2. However, in alkaline shifting sand with low organic carbon content, the high pH values enhance the solubility of CO_2, accelerate carbonate precipitation, and exhibit stronger carbon sequestration potential at low temperatures. Overall, desert carbon sequestration is the result of dynamic coupling of physical, chemical, and biological processes at the spatiotemporal scale. Understanding the interactions between their mechanisms and their environmental dependencies requires a comprehensive combination of *in-situ* observations, controlled experiments, and cross scale models.

4 Desertification control promotes carbon sequestration

Desertification is not a purely natural phenomenon, as it is closely related to environmental, economic, and social development [80–83]. Desertification is estimated to cause huge direct economic losses, as well as historical carbon losses of 20–30 Pg worldwide. Assuming that two thirds of historical carbon losses can be reused, the total potential for organic carbon sequestration within 50 years is 12–20 Pg [80]. Land use and management practices aimed at sequestering organic carbon include afforestation with appropriate species, soil management on farmland, pasture management, and the restoration of degraded soils and ecosystems through afforestation and conversion to other restorative land uses [80,84]. According to a previous study, the estimated potential global soil organic carbon sequestration is approximately 1 Pg per year [80]. Therefore, desertification control can improve the regional ecological environment, while also transforming desertified land into important areas of terrestrial carbon sequestration. Such control is key to consolidating and enhancing the carbon sequestration capacity of ecosystems in arid regions, thereby providing an economical and reliable measure to slow or delay global warming. In particular, this process will not compete with land use for agriculture and food production [85]. Past research has focused on the roles of desertification control in preventing wind and sand movement, improving microclimates, and enhancing economic benefits, whereas its potential carbon sequestration benefits have long been overlooked [86].

In recent years, China has implemented numerous national key ecological projects, including the control of sandstorm sources in Beijing and Tianjin, the conversion of farmland to forests and grasslands, Three North Protection Forest Program, and the comprehensive control of rocky desertification, thereby achieving a historic transformation from sand causing human retreat to green spaces causing sand retreat. On this basis, Chinese General Secretary Jinping Xi emphasized the need to "make every effort to win the tough battle at the bend of Yellow River, the annihilation battle in Horqin and Hunshandake sandy areas, and the blockade battle at Hexi Corridor and edge of Taklimakan Desert". Afforestation and reforestation are important methods for preventing and controlling desertification, representing economical and effective measures to increase carbon storage in desert ecosystems and slow atmospheric CO_2 concentration increases [87,88]. The selection of tree species and afforestation modes are key factors in increasing carbon storage in desert artificial forest ecosystems. Forest species suitable for artificial carbon sequestration have high growth rates and wood density, along with low decomposition rates. Fast-growing species sequester more carbon than slow-growing species, biomass production is higher in mixed forests than that in pure forests, and the rate of carbon sequestration varies among tree species. As of 2016, the total area of artificial *Haloxylon Ammodendron* forests in Hexi Corridor reached 89,000 ha. Within that region, Minqin County had the earliest development time and the largest afforestation scale of artificial *Haloxylon Ammodendron* forests, with a preserved area of 43,500 ha. These forests play a key role in improving microclimate, soil quality, biodiversity, and carbon sequestration. An artificial *Haloxylon Ammodendron* forest ecosystem has been estimated to sequester 434 $g \cdot C \cdot m^{-2} \cdot a^{-1}$ [86]. However, in arid areas, precipitation is scarce, evaporation is strong, and sandstorms are large. Therefore, the impacts of natural environmental factors on afforestation and emission reduction remain highly uncertain in arid environments compared to other regions. Clarifying the carbon sequestration processes occurring in artificial forests planted for desertification control and their relationships with environmental factors provides a basis for objective evaluation of carbon sequestration potential and the formulation of management measures.

In response to these issues, CO_2 flux was monitored in an artificial shelter forest in the hinterland of Taklimakan Desert from 2018 to 2019 using a closed-path eddy covariance system [89]. The enhancement effect of the establishment of the artificial shelter forest on the carbon sequestration capacity of the desert and the mechanism underlying its responses to precipitation events of various intensities were analyzed to clarify the carbon cycle in desert ecosystems and support the development and implementation of management measures for desert artificial forests. The establishment of artificial shelter forests in deserts adds plant photosynthesis to existing inorganic carbon sequestration processes, increasing the carbon sequestration capacity of desert ecosystems approximately 150-fold, with an annual absorption of CO_2 amount reaching approximately 1000 g·m^{-2} (Fig. 6). This change improves the regional ecological environment, while also transforming desertified land into an important site for terrestrial carbon sequestration. In addition, precipitation events of different intensities have different regulatory effects on carbon exchange. Extremely low precipitation (<2 mm) has almost no impact on carbon exchange in artificial shelter forests. When precipitation reaches approximately 4 mm, the saturated water vapor pressure difference is reduced in the short term, promoting enhanced photosynthesis and improving the carbon absorption capacity of these forests. Precipitation (>8 mm) simultaneously stimulates soil CO_2 release and plant photosynthesis. In the dynamic balance of soil CO_2 release and photosynthesis stimulated by precipitation, there is a soil moisture threshold (0.12 m^3·m^{-3}) at a depth of 5 cm, which can well indicate the intensity of the stimulating effect of precipitation on both. The mutual game between these two processes resulted in a trend of first decreasing and then increasing carbon exchange in a protective forest (Fig. 7) [89].

5 Conclusion and future prospects

In this review, we discussed recent advances in desert carbon sequestration research and the critical scientific challenges associated with such research. By integrating recent findings from desert carbon sequestration studies conducted in Takli-

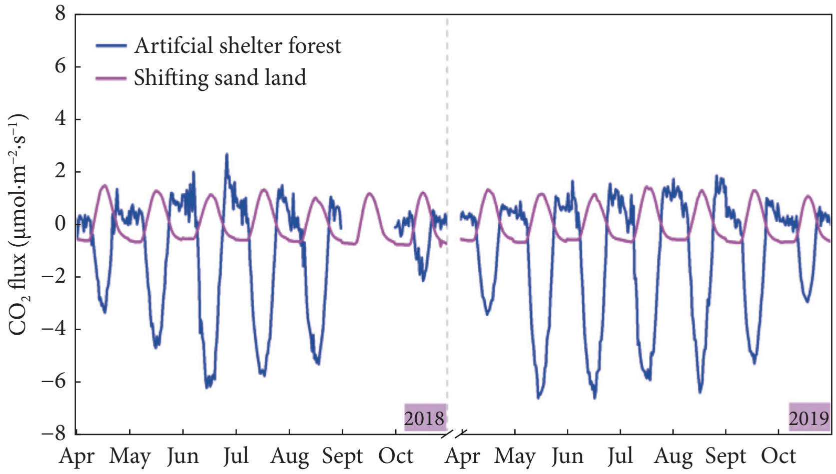

Fig. 6 Comparison of monthly average daily changes in CO_2 flux between artificial shelter forests and shifting sand in the hinterland of the Taklimakan Desert during the growing seasons of 2018 and 2019. Reproduced with permission from Ref. [89] ©2024, Institute of Atmospheric Physics/Chinese Academy of Sciences, and Science Press.

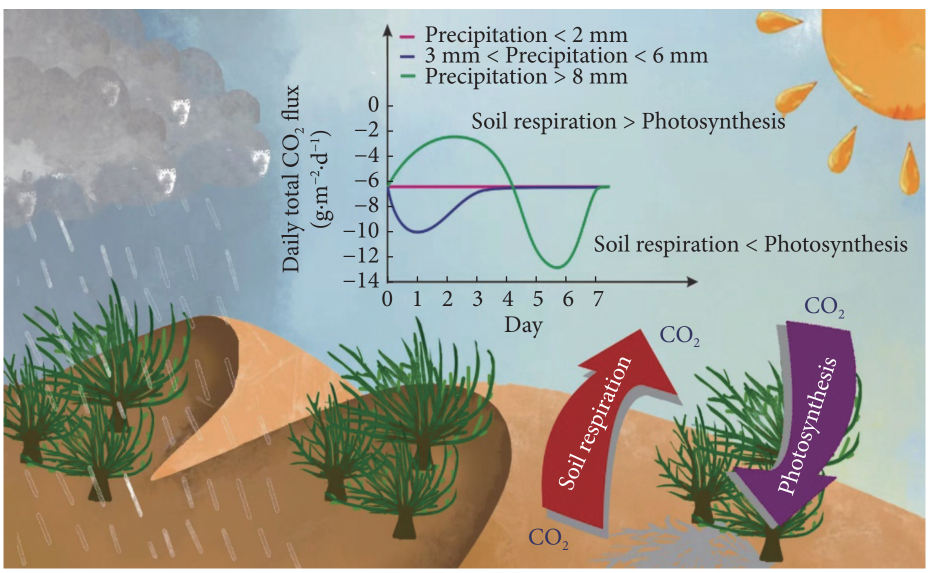

Fig. 7 Response of CO_2 flux in artificial shelter forests of the Taklimakan Desert to various magnitudes of precipitation. Reproduced with permission from Ref. [89] ©2024, Institute of Atmospheric Physics/Chinese Academy of Sciences, and Science Press.

makan Desert, we determined that the impact of the expansion and contraction of CO_2-containing soil air due to thermal fluctuations on the total amount of CO_2 exchange within the shifting sand was unexpectedly significant. This long-term hidden process, combined with the chemical carbon sequestration of saline–alkali soil, dominates the release and absorption of CO_2 in dry shifting sand. The mechanism underlying carbon sequestration in shifting sand, which was influenced by hydrothermal factors, was also elucidated. Based on the above results, an empirical model for estimating CO_2 flux in shifting sand was developed that accounted for hydrothermal combination and soil characteristics. According to the assessment, the annual CO_2 sequestration potential of the shifting sand area of Taklimakan Desert was estimated at approximately 1.05×10^{-3} Pg. This study clarifies the mechanisms underlying desert carbon sequestration and presents a plausible framework for evaluating cumulative carbon sequestration within desert ecosystems and its role in the global carbon cycle. However, several issues require further research.

First, to address the anomalous negative CO_2 fluxes observed when using the IRGASON during daylight hours in extremely arid desert settings, using only a simple regression model to correct it is far from sufficient. Therefore, the necessary first step is to examine the observation mechanism of open-path eddy covariance technique, followed by the development of tailored correction methods. This will effectively improve the application performance of open-path eddy covariance systems in extreme environments such as deserts. Moreover, there is a need to develop CO_2 analyzers that are more resistant to interference, compact, and affordable. By directly integrating these analyzers into 3D sonic anemometer and chambers, we can enable multi-point *in-situ* precise measurements. This approach will accurately reflect the real carbon exchange in ecosystems and provide a solid basis for precise estimation of total carbon sequestration in desert ecosystems and their role in the carbon cycle.

Second, CO_2 absorbed by desert ecosystems has been suggested to gradually enter the groundwater via leaching processes and ultimately accumulate in underground saline aquifers beneath the expansive desert, following the flow of groundwater. This process is similar to the inorganic carbon sink in the ocean [48]. However, in deserts with extremely low precipitation that does not induce such leaching, the precise storage location of CO_2 within shifting sands remains unclear. Furthermore, it is still unknown whether the captured CO_2 will participate in long-distance transport with sand particles during frequent sandstorms. Therefore, isotope analysis is necessary to obtain further evidence of carbon sequestration in these desert systems.

Third, the method used to estimate CO_2 fluxes in shifting sand has clarified carbon sequestration processes in desert ecosystems. Nevertheless, the depiction of certain processes within this method is partially based on statistical analyses of experimental observations. At the same time, there is still uncertainty in the estimation of CO_2 flux in other deserts around the world for this scheme due to the limitations of observation experiment data duration and location. Thus, it is essential to delineate the CO_2 exchange process in desert systems by elaborating on the physical, chemical, and biological mechanisms within the framework of the established method. Calibration with an expanded set of field observations across various sites is crucial to continuing refinement of the method, thereby enhancing its estimation accuracy and broadening its applicability. The key breakthrough directions for future research include developing a dynamic model based on process mechanisms to replace empirical statistical models, establishing a comprehensive model that incorporates biological and abiotic coupling, constructing a coevolution system for data models, implementing a research paradigm that combines long-term observational studies with process experiments, and developing multi-source data fusion technologies based on machine learning.

Finally, desert ecosystem not only includes the shifting sand area but also various surface types such as fixed and semi-fixed sandy land with vegetation cover, saline–alkali land, gobi, and lakes. These ecosystems exhibit diverse forms of carbon sequestration and strong carbon sink potential. The mechanism of carbon sequestration in desert shifting sands has now been elucidated, however, systematic assessment of carbon sequestration capacity across diverse environments, including fixed and semi-fixed sandy land, saline–alkali land, gobi, and lake systems, has not yet been conducted. The establishment of a high-caliber carbon-neutral monitoring network for desert regions, enhancement of the assessment and prediction systems for the carbon sink capacity of diverse surface types, and determination of the baseline carbon sequestration capacity of desert ecosystems in Northwest China are essential future steps. In addition, combining efforts related to plant selection and breeding, water utilization, as well as characteristic industry and management modes in desertification control projects, an advanced demonstration area for desertification control can be constructed. Carry out research and development of pathways and key technologies to enhance carbon sequestration in the demonstration zone, in order to achieve the full release of potential carbon sequestration functions. This can effectively increase the space available for carbon emissions in arid areas, support the transformation of new types of industrialization, and enhance the capacity of northwest arid region to respond to the risks of climate change, promoting sustainable development.

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Author contribution statement

Fan Yang, Jianping Huang, and Chenglong Zhou designed the study and contributed to the ideas, data analysis, interpretation and manuscript writing; Ali Mamtimin, Xinqian Zheng, Xinghua Yang, and Mingjie Ma contributed to data collection and investigation; Wen Huo, Dongliang Han, Yu Wang, and Qing Gong were responsible for methodology development, provision of experimental resources, and experiment execution; Ping Yang, Silalan Abudukade, Yihan Liu, and Fapeng Zhang performed manuscript review, editing, proofreading, and final approval of the published version. All of the authors contributed to the discussion and interpretation of the manuscript. All the authors have approved the final manuscript.

Data availability

Not applicable.

Declaration of competing interest

All the contributing authors report no conflicts of interest in this work

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Use of AI statement

None.

References

[1] Schlesinger, W. H., Andrews, J. A. (2000). Soil respiration and the global carbon cycle. *Biogeochemistry* 48, 7–20.

[2] Houghton, R. A. (2007). Balancing the global carbon budget. *Annu. Rev. Earth Planet. Sci.* 35, 313–347.

[3] Piao, S. L., Fang, J. Y., Ciais, P., Peylin, P., Huang, Y., Sitch, S., Wang, T. (2009). The carbon balance of terrestrial ecosystems in China. *Nature* 458, 1009–1013.

[4] Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* 534, 631–639.

[5] Piao, S. L., He, Y., Wang, X. H., Chen, F. H. (2022). Estimation of China's terrestrial ecosystem carbon sink: Methods, progress and prospects. *Sci. China Earth Sci.* 65, 641–651.

[6] Yu, G. R., Zhu, J. X., Xu, L., He, N. P. (2022). Technological approaches to enhance ecosystem carbon sink in China: Nature-based solutions. *Bull. Chin. Acad. Sci.* 37, 490–501.

[7] Yu, G. R., Hao, T. X., Zhu, J. X. (2022). Discussion on action strategies of China's carbon peak and carbon neutrality. *Bull. Chin. Acad. Sci.* 37, 423–434.

[8] Yang, Y. H., Shi, Y., Sun, W. J., Chang, J. F., Zhu, J. X., Chen, L. Y., Wang, X., Guo, Y. P., Zhang, H. T., Yu, L. F., et al. (2022). Terrestrial carbon sinks in China and around the world and their contribution to carbon neutrality. *Sci. China Life Sci.* 65, 861–895.

[9] Wang, Y. L., Wang, X. H., Wang, K., Chevallier, F., Zhu, D., Lian, J. H., He, Y., Tian, H. Q., Li, J. S., Zhu, J. X., et al. (2022). The size of the land carbon sink in China. *Nature* 603, E7–E9.

[10] Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., et al. (2022). Global carbon budget 2022. *Earth Syst. Sci. Data* 14, 4811–4900.

[11] Yang, B., Gong, J. R., Zhang, Z. H., Li, X. B., Wang, B., Zhu, C. C., Shi, J. Y., Zhang, W. Y., Yue, K. X. (2020). Spatial variation of carbon turnover time and carbon uptake in a Chinese desert steppe ecosystem. *Ecol. Indic.* 112, 106120.

[12] Lal, R. (2019). Carbon cycling in global drylands. *Curr. Climate Change Rep.* 5, 221–232.

[13] Zhang, J. J., Hao, X. M., Hao, H. C., Fan, X., Li, Y. H. (2021). Climate change decreased net ecosystem productivity in the arid region of central Asia. *Remote Sens.* 13, 4449.

[14] Baldocchi, D. (2008). "Breathing" of the terrestrial biosphere: Lessons learned from a global network of carbon dioxide flux measurement systems. *Aust. J. Bot.* 56, 1–26.

[15] Baldocchi, D. (2014). Measuring fluxes of trace gases and energy between ecosystems and the atmosphere—The state and future of the eddy covariance method. *Glob. Chang. Biol.* 20, 3600–3609.

[16] Baldocchi, D. D . (2020). How eddy covariance flux measurements have contributed to our understanding of global change biology. *Glob. Chang. Biol.* 26, 242–260.

[17] Bogoev, I. (2014). Improved eddy flux measurements by open-path gas analyzer and sonic anemometer co-location. In Proceedings of the 2014 American Geophysical Union Fall Meeting, San Francisco, CA, USA.

[18] Moore, C. J. (1986). Frequency response corrections for eddy correlation systems. *Bound. Layer Meteorol.* 37, 17–35.

[19] Burba, G. G., McDermitt, D. K., Grelle, A., Anderson, D. J., Xu, L. K. (2008). Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers. *Glob. Chang. Biol.* 14, 1854–1876.

[20] Haslwanter, A., Hammerle, A., Wohlfahrt, G. (2009). Open-path vs. closed-path eddy covariance measurements of the net ecosystem carbon dioxide and water vapour exchange: A long-term perspective. *Agric. For. Meteor.* 149, 291–302.

[21] Schlesinger, W. H. (2017). An evaluation of abiotic carbon sinks in deserts. *Glob. Chang. Biol.* 23, 25–27.

[22] Wohlfahrt, G., Fenstermaker, L. F., Arnone III, J. A. (2008). Large annual net ecosystem CO_2 uptake of a Mojave Desert ecosystem. *Glob. Chang. Biol.* 14, 1475–1487.

[23] Liu, R., Li, Y., Wang, Q. X. (2012). Variations in water and CO_2 fluxes over a saline desert in western China. *Hydrol. Process.* 26, 513–522.

[24] Jia, X., Zha, T. S., Wu, B., Zhang, Y. Q., Gong, J. N., Qin, S. G., Chen, G. P., Qian, D., Kellomäki, S., Peltola, H. (2014). Biophysical controls on net ecosystem CO_2 exchange over a semiarid shrubland in northwest China. *Biogeosciences* 11, 4679–4693.

[25] Yu, G. R., Sun, X. M. (2017). Principles of Flux Measurement in Terrestrial Ecosystems. 2nd ed. Beijing: Higher Education Press, p 243.

[26] Song, X., Yu, G. R., Liu, Y. F., Sun, X. M., Ren, C. Y., Wen, X. F. (2005). Comparison of flux measurement by open-path and close-path eddy covariance systems. *Sci. China Ser. D Earth Sci.* 48, 74–84.

[27] Helbig, M., Wischnewski, K., Gosselin, G. H., Biraud, S. C., Bogoev, I., Chan, W. S., Euskirchen, E. S., Glenn, A. J., Marsh, P. M., Quinton, W. L., et al. (2016). Addressing a systematic bias in carbon dioxide flux measurements with the EC150 and the IRGASON open-path gas analyzers. *Agric. For. Meteor.* 228–229, 349–359.

[28] Detto, M., Verfaillie, J., Anderson, F., Xu, L. K., Baldocchi, D. (2011). Comparing laser-based open- and closed-path gas analyzers to measure methane fluxes using the eddy covariance method. *Agric. For. Meteor.* 151, 1312–1324.

[29] Ham, J. M., Heilman, J. L. (2003). Experimental test of density and energy-balance corrections on carbon dioxide flux as measured using open-path eddy covariance. *Agron. J.* 95, 1393–1403.

[30] Ono, K., Miyata, A., Yamada, T. (2008). Apparent downward CO_2 flux observed with open-path eddy covariance over a non-vegetated surface. *Theor. Appl. Climatol.* 92, 195–208.

[31] Wang, W., Xu, J. P., Gao, Y. Q., Bogoev, I., Cui, J., Deng, L. C., Hu, C., Liu, C., Liu, S. D., Shen, J., et al. (2016). Performance evaluation of an integrated open-path eddy covariance system in a cold desert environment. *J. Atmos. Oceanic Technol.* 33, 2385–2399.

[32] Wang, L. M., Lee, X., Wang, W., Wang, X. F., Wei, Z. W., Fu, C. S., Gao, Y. Q., Lu, L., Song, W. M., Su, P. X., et al. (2017). A meta-analysis of open-path eddy covariance observations of apparent CO_2 flux in cold conditions in FLUXNET. *J. Atmos. Oceanic Technol.* 34, 2475–2487.

[33] Russell, E. S., Dziekan, V., Chi, J. S., Waldo, S., Pressley, S. N., O'Keeffe, P., Lamb, B. K. (2019). Adjustment of CO_2 flux measurements due to the bias in the EC150 infrared gas analyzer. *Agric. For. Meteor.* 276–277, 107593.

[34] Campbell Scientific. (2017). Improved Flux Measurements from Campbell Scientific Open-Path Gas Analyzers: Utilizing Sonic Temperature to Account for Spectroscopic Effects on CO_2 Density. Logan: Campbell Scientific.

[35] Yang, F., Huang, J. P., Zheng, X. Q., Huo, W., Zhou, C. L., Wang, Y., Han, D. L., Gao, J. C., Mamtimin, A., Yang, X. H., et al. (2022). Evaluation of carbon sink in the Taklimakan Desert based on correction of abnormal negative CO_2 flux of IRGASON. *Sci. Total Environ.* 838, 155988.

[36] Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., et al. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* 579, 80–87.

[37] Tian, Y. Q., Xu, X. L., Song, M. H., Zhou, C. P., Gao, Q., Ouyang, H. (2009). Carbon sequestration in two alpine soils on the Tibetan Plateau. *J. Integr. Plant Biol.* 51, 900–905.

[38] Soussana, J. F., Loiseau, P., Vuichard, N., Ceschia, E., Balesdent, J., Chevallier, T., Arrouays, D. (2004). Carbon cycling and sequestration opportunities in temperate grasslands. *Soil Use Manage.* 20, 219–230.

[39] Lima, M. D. A. C., Ward, R. D., Joyce, C. B. (2023). Carbon sequestration and geochronology in southern England's seagrass meadows. *Carbon Footprints* 2, 20.

[40] Li, Y. Y., Ma, P. P., Wu, Z. F., Chen, J., Zhao, Y. F. (2024). Estimating spatiotemporal variations of cropland soil organic carbon and its sequestration potential in central China from 1984 to 2019. *CATENA* 245, 108333.

[41] Eid, E. M., Keshta, A. E., Shaltout, K. H., Baldwin, A. H., Sharaf El-din, A. A. (2017). Carbon sequestration potential of the five Mediterranean lakes of egypt. *Fundam. Appl. Limnol.* 190, 87–96.

[42] Ma, K., Liu, J. G., Balkovič, J., Skalský, R., Azevedo, L. B., Kraxner, F. (2016). Changes in soil organic carbon stocks of wetlands on China's Zoige Plateau from 1980 to 2010. *Ecol. Model.* 327, 18–28.

[43] Kamangar, M., Kisi, O., Minaei, M. (2023). Spatio–temporal analysis of carbon sequestration in different ecosystems of Iran and its relationship with agricultural droughts. *Sustainability* 15, 6577.

[44] Kidron, G. J., Li, X. R., Jia, R. L., Gao, Y. H., Zhang, P. (2015). Assessment of carbon gains from biocrusts inhabiting a dunefield in the Negev Desert. *Geoderma* 253–254, 102–110.

[45] Xie, J. X., Li, Y., Zhai, C. X., Li, C. H., Lan, Z. D. (2009). CO_2 absorption by alkaline soils and its implication to the global carbon cycle. *Environ. Geol.* 56, 953–961.

[46] Wang, Z. Y., Xie, J. B., Wang, Y. G., Li, Y. (2013). Soil inorganic CO_2 flux in relation to soil pH and electric conductivity in saline/alkaline soils. Chin. J. Ecol. 32, 2552–2558.

[47] Ma, J., Liu, R., Tang, L. S., Lan, Z. D., Li, Y. (2014). A downward CO_2 flux seems to have nowhere to go. *Biogeosciences* 11, 6251–6262.

[48] Ma, J., Wang, Z. Y., Stevenson, B. A., Zheng, X. J., Li, Y. (2013). An inorganic CO_2 diffusion and dissolution process explains negative CO_2 fluxes in saline/alkaline soils. *Sci. Rep.* 3, 2025.

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

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

[51] Stone, R. (2008). Have desert researchers discovered a hidden loop in the carbon cycle. *Science* 320, 1409–1410.

[52] Ball, B. A., Virginia, R. A., Barrett, J. E., Parsons, A. N., Wall, D. H. (2009). Interactions between physical and biotic factors influence CO_2 flux in Antarctic dry valley soils. *Soil Biol. Biochem.* 41, 1510–1517.

[53] Hamerlynck, E. P., Scott, R. L., Sánchez-Cañete, E. P., Barron-Gafford, G. A. (2013). Nocturnal soil CO_2 uptake and its relationship to subsurface soil and ecosystem carbon fluxes in a Chihuahuan Desert shrubland. *J. Geophys. Res. Biogeosci.* 118, 1593–1603.

[54] Cuezva, S., Fernandez-Cortes, A., Benavente, D., Serrano-Ortiz, P., Kowalski, A. S., Sanchez-Moral, S. (2011). Short-term CO_2(g) exchange between a shallow karstic cavity and the external atmosphere during summer: Role of the surface soil layer. *Atmos. Environ.* 45, 1418–1427.

[55] Fa, K. Y., Liu, J. B., Zhang, Y. Q., Wu, B., Qin, S. G., Feng, W., Lai, Z. R. (2015). CO_2 absorption of sandy soil induced by rainfall pulses in a desert ecosystem. *Hydrol. Process.* 29, 2043–2051.

[56] Wang, X. J., Wang, J. Y., Wang, J. P. (2021). Seasonality of soil respiration under gypsum and straw amendments in an arid saline–alkali soil. *J. Environ. Manage.* 277, 111494.

[57] Li, Y., Wang, Y. G., Houghton, R. A., Tang, L. S. (2015). Hidden carbon sink beneath desert. *Geophys. Res. Lett.* 42, 5880–5887.

[58] Yang, F., Huang, J. P., Zhou, C. L., Yang, X. H., Ali, M., Li, C. F., Pan, H. L., Huo, W., Yu, H. P., Liu, X. Y., et al. (2020). Taklimakan Desert carbon-sink decreases under climate change. *Sci. Bull.* 65, 431–433.

[59] Yang, F., Huang, J. P., He, Q., Zheng, X. Q., Zhou, C. L., Pan, H. L., Huo, W., Yu, H. P., Liu, X. Y., Meng, L., et al. (2020). Impact of differences in soil temperature on the desert carbon sink. *Geoderma* 379, 114636.

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

[61] Wang, Y. H., Chen, J. Q., Zhou, G. S., Shao, C. L., Chen, J., Wang, Y., Song, J. M. (2018). Predominance of precipitation event controls ecosystem CO_2 exchange in an Inner Mongolian Desert grassland, China. *J. Clean. Prod.* 197, 781–793.

[62] Yang, P., Zhao, L. Q., Liang, X. R., Niu, Z. M., Zhao, H., Wang, Y. Y., Wang, N. A. (2022). Response of net ecosystem CO_2 exchange to

precipitation events in the Badain Jaran Desert. *Environ. Sci. Pollut. Res.* 29, 36486–36501.
[63] Ma, J., Zheng, X. J., Li, Y. (2012). The response of CO_2 flux to rain pulses at a saline desert. *Hydrol. Process.* 26, 4029–4037.
[64] Seinfeld, J. H., Pandis, S. N. (2006). Chemistry of the atmospheric aqueous phase. In Atmospheric Chemistry and Physics: From Air Pollution to Climate Change. New York: John Wiley & Sons, p 242–302.
[65] Sagi, N., Zaguri, M., Hawlena, D. (2021). Soil CO_2 influx in drylands: A conceptual framework and empirical examination. *Soil Biol. Biochem.* 156, 108209.
[66] Shi, Y. F., Shen, Y. P., Li, D. L., et al. (2003). Characteristics and trends of climate shift from warm-dry to warm-humid in northwest China. Quat. Res. 23, 152–164.
[67] Shi, Y. F., Shen, Y. P., Hu, R. J . (2002). Preliminary study on signal, impact and foreground of climatic shift from warm-dry to warm-humid in Northwest China. J. Glaciol. Geocryol. 24, 219–226.
[68] Chen, D. D., Dai, Y. J. (2009). Characteristics of Northwest China rainfall intensity in recent 50 years. Chin. J. Atmos. Sci. 33, 923–935.
[69] Li, B. F., Chen, Y. N., Li, W. H., Chen, Z. S., Zhang, B. H., Guo, B. (2013). Spatial and temporal variations of temperature and precipitation in the arid region of Northwest China from 1960–2010. Fresen. Environ. Bull. 22, 362–371.
[70] Wei, K., Wang, L. (2013). Reexamination of the aridity conditions in arid northwestern China for the last decade. *J. Climate* 26, 9594–9602.
[71] Ren, G. Y., Yuan, Y. J., Liu, Y. J., Ren, Y. Y., Wang, T., Ren, X. Y. (2016). Changes in precipitation over northwest China. Arid Zone Res. 33, 1–19.
[72] Zhang, Q., Yang, J. H., Wang, W., Ma, P. L., Lu, G. Y., Liu, X. Y., Yu, H. P., Fang, F. (2021). Climatic warming and humidification in the arid region of Northwest China: Multi-scale characteristics and impacts on ecological vegetation. *J. Meteor. Res.* 35, 113–127.
[73] Yao, J. Q., Chen, Y. N., Chen, J., Zhao, Y., Tuoliewubieke, D., Li, J. G., Yang, L. M., Mao, W. Y. (2020). Intensification of extreme precipitation in arid central Asia. *J. Hydrol.* 35, 125760.
[74] Zhou, C. L., Yang, X. H., Huo, W., Zhong, X. J., Yang, F., He, Q. (2017). Characteristics of precipitation in the hinterland of the Taklimakan Desert. J. Desert Res. 37, 343–348.
[75] Zhong, X. J., Gao, Y. X., Ma, K., Zhang, A. Q., Zhou, C. L. (2016). Analysis of rainfall variation in hinterland of Taklamakan Desert. *Bull. Soil Water Conserv.* 36, 303–307.
[76] Yang, F. (2023). Carbon sequestration mechanism and assessment of carbon sink capacity in the Taklimakan Desert. Ph.D. Dissertation. Lanzhou University, Lanzhou, China.
[77] Mielnick, P., Dugas, W. A., Mitchell, K., Havstad, K. (2005). Long-term measurements of CO_2 flux and evapotranspiration in a Chihuahuan Desert grassland. *J. Arid Environ.* 60, 423–436.
[78] Hastings, S. J., Oechel, W. C., Muhlia-Melo, A. (2005). Diurnal, seasonal and annual variation in the net ecosystem CO_2 exchange of a desert shrub community (Sarcocaulescent) in Baja California, Mexico. *Glob. Chang. Biol.* 11, 927–939.
[79] Yang, F., Huang, J. P., Zhou, C. L., Yang, X. H., Mamtimin, A., Zheng, X. Q., Huo, W., Ji, F., Han, D. L., Meng, L., et al. (2023). Desert abiotic carbon sequestration weakening by precipitation. *Environ. Sci. Technol.* 57, 7174–7184.
[80] Lal, R. (2004). Carbon sequestration in dryland ecosystems. *Environ. Manage.* 33, 528–544.
[81] Martínez-Valderrama, J., Ibáñez, J., Del Barrio, G., Sanjuán, M. E., Alcalá, F. J., Martínez-Vicente, S., Ruiz, A., Puigdefábregas, J. (2016). Present and future of desertification in Spain: Implementation of a surveillance system to prevent land degradation. *Sci. Total Environ.* 563–564, 169–178.
[82] Huang, J. P., Yu, H. P., Guan, X. D., Wang, G. Y., Guo, R. X. (2016). Accelerated dryland expansion under climate change. *Nat. Climate Change* 6, 166–171.
[83] Huang, J. P., Yu, H. P., Dai, A. G., Wei, Y., Kang, L. T. (2017). Drylands face potential threat under 2 °C global warming target. *Nat. Climate Change* 7, 417–422.
[84] Duan, Z. H., Xiao, H. L., Dong, Z. B., He, X. D., Wang, G. (2001). Estimate of total CO_2 output from desertified sandy land in China. *Atmos. Environ.* 35, 5915–5921.
[85] Hirt, H., Boukcim, H., Ducousso, M., Saad, M. M. (2023). Engineering carbon sequestration on arid lands. *Trends Plant Sci.* 28, 1218–1221.
[86] Ma, Q. L., Wang, X. Y., Chen, F., Wei, L. Y., Zhang, D. K., Jin, H. J. (2021). Carbon sequestration of sand-fixing plantation of *Haloxylon ammodendron* in Shiyang River Basin: Storage, rate and potential. *Glob. Ecol. Conserv.* 28, e01607.
[87] Zhang, Z. S., Li, X. R., Liu, L. C., Jia, R. L., Zhang, J. G., Wang, T. (2009). Distribution, biomass, and dynamics of roots in a revegetated stand of *Caragana Korshinskii* in the Tengger Desert, northwestern China. *J. Plant Res.* 122, 109–119.
[88] Wang, S. Q., Huang, Y. (2020). Determinants of soil organic carbon sequestration and its contribution to ecosystem carbon sinks of planted forests. *Glob. Chang. Biol.* 26, 3163–3173.
[89] Sun, Y. W., Yang, F., Huang, J. P., Zheng, X. Q., Mamtimin, A., Zhou, C. L., Abudukade, S., Gao, J. C., Li, C. F., Ma, M. J., et al. (2024). Precipitation controls on carbon sinks in an artificial green space in the Taklimakan Desert. *Adv. Atmos. Sci.* 41, 2300–2312.

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