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• **Original Paper** •

Dataset Construction of CO_2 Flux over Shifting Sand in the Taklimakan Desert and Assessment of Carbon Sequestration Capacity

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ABSTRACT

Desert ecosystems, which cover extensive global regions, play an essential yet often-overlooked role in sequestering atmospheric CO_2 at substantial yet gradual rates, primarily due to insufficient monitoring, data scarcity, and limited research attention. Current assessments of terrestrial carbon sinks often exclude desert areas, creating critical "data gaps" that undermine the completeness and accuracy of global carbon budget evaluations. Focusing on the Taklimakan Desert, we developed a high-resolution CO_2 flux dataset (2000–22) for shifting sand areas, featuring hourly temporal resolution and 0.25° × 0.25° spatial coverage, through an empirical estimation scheme incorporating internal carbon sequestration processes, ERA5 multi-layer soil temperature/moisture data, and extensive field-measured soil properties (soil organic carbon, pH). Our analysis reveals that spatiotemporal CO_2 flux patterns are jointly controlled by shifting sand temperature, moisture, and soil characteristics, with the shifting sand area of the entire desert sequestering approximately 1.05×10^6 t CO_2 annually. While two-thirds of the area functions as carbon sinks, the northwestern margins (one-third of the total area) exhibit carbon-source behavior (peaking at 64.49 g m^{-2} yr^{-1}) due to higher precipitation and organic carbon content. The ongoing warm–wetting trend in northwestern China is reducing both the stability and rate of carbon sequestration in these shifting sands—processes that may accelerate through climate change feedbacks. These findings provide critical scientific evidence for assessing the role of the desert in climate mitigation and inform policy-making for carbon neutrality strategies.

Key words: Taklimakan Desert, CO_2 flux, carbon sequestration capacity, carbon sink, climate change

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Article Highlights:

- The Taklimakan Desert's shifting sand areas sequester ~1.05×10^6 t CO_2 annually.
- Two-thirds of the Taklimakan Desert is a carbon sink, while one-third is a source due to more rainfall.
- A 0.25° h^{-1} shifting sand CO_2 flux dataset for the Taklimakan Desert (2000–22) is developed.
- Warming–wetting weakens the carbon sink capacity in bare shifting sand deserts.

1. Introduction

As a pivotal component of the carbon cycle of the

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Earth, CO_2 flux dynamics directly reflect carbon exchange processes among the atmosphere, terrestrial ecosystems, and oceans (Zhou et al., 2020). Precise monitoring and quantification of CO_2 flux variations serve not only as the scientific foundation for projecting future climate trends but also as critical evidence for formulating effective mitigation strategies and achieving global carbon neutrality (Yang et al., 2023). With escalating climate crises, the accurate assessment of land–atmosphere–ocean carbon exchange has emerged as a central priority for both the international scientific community and policymakers. Achieving this goal requires integrating multi-scale observational technologies, interdisciplinary data–model fusion, and global collaborative frameworks, with outcomes directly shaping the implementation pathways for the temperature targets of the Paris Agreement. Against the background of contemporary climate change and carbon neutrality efforts, understanding the ecosystem carbon sequestration capacity has become indispensable.

In assessments of terrestrial carbon sink functions, ecosystems such as forests, croplands, wetlands, and grasslands have received extensive attention, while desert ecosystems—covering approximately 20% of global land area—have been consistently overlooked. Traditional perspectives regard deserts primarily as carbon sources due to their ecological fragility (Morgan et al., 2015; Wang et al., 2020a; Yue et al., 2021), low productivity, and sparse vegetation carbon density (Raich and Potter, 1995). However, emerging research has revealed previously unrecognized carbon sequestration mechanisms in desert ecosystems: thin water films on sand surfaces can capture atmospheric CO_2 (Fa et al., 2016); soil mineral surfaces adsorb CO_2 (Parsons et al., 2004); and carbonate dissolution coupled with silicate weathering significantly absorbs CO_2 (Monger et al., 2015; Schlesinger, 2017). Particularly in carbonate dissolution processes, the abundant saline–alkaline content in desert soils consumes soil CO_2 under moist conditions, creating substantial carbon sinks (Hilley et al., 2010; Matter et al., 2016). Studies have demonstrated enhanced carbon sequestration in shifting sands with increasing soil alkalinity, particularly under lower temperatures (Xie et al., 2009; Ma et al., 2013, 2014). The absorbed CO_2 ultimately enters groundwater systems through leaching processes, where it is stored in extensive desert aquifers (Li et al., 2015). These findings suggest that desert ecosystems exhibit distinct inorganic carbon sink characteristics and may represent a significantly underestimated global carbon sink given their vast spatial extent (Jasoni et al., 2005; Stone, 2008; Wohlfahrt et al., 2008; Yang et al., 2017; Yang et al., 2022). Nevertheless, persistent controversies remain in desert carbon sink research due to discrepancies between different CO_2 flux measurement methods and an incomplete understanding of internal driving mechanisms. Comparative studies between open-path and closed-path eddy covariance systems show significant measurement disparities despite shared theoretical foundations (Song et al., 2005; Haslwanter et al., 2009; Helbig et al., 2016), with open-path systems overestimating carbon sequestration in deserts like the Mojave, Gurbantünggüt, Mu Us, and Taklimakan (Wohlfahrt et al., 2008; Liu et al., 2012; Jia et al., 2014; Schlesinger, 2017), reporting sequestration rates exceeding net primary productivity without satisfactory explanation (Schlesinger, 2017). Furthermore, desert CO_2 budgets involve complex interactions between biological and abiotic processes, with some studies indicating that abiotic processes contribute >56% of daily CO_2 flux in alkaline soils (Wang et al., 2020b), while others suggest biological processes dominate net CO_2 exchange (Li et al., 2014). The increasing frequency of extreme precipitation events under climate change further complicates assessments by altering multiple abiotic factors controlling desert carbon budgets, including soil porosity, heat transfer, CO_2 solubility, and saline–alkaline concentrations. These challenges not only hinder the accurate evaluation of the contribution of the deserts to global carbon cycling but also limit exploration of their sequestration potential.

To address these scientific challenges, our research team conducted systematic investigations in the Taklimakan Desert, China. First, we identified the sources of discrepancies among CO_2 flux measurement methods through multi-point, long-term observational experiments. Second, we isolated the individual contributions of shifting sand components (pure sand, water, saline–alkaline substances, and microorganisms) to CO_2 flux and, by analyzing their interactions with hydrothermal factors, elucidated three distinct carbon sequestration mechanisms: thermal regulation, hydrothermal coupling, and soil property controls. Building on these findings, we developed an empirical CO_2 flux estimation model for shifting sands that integrates both hydrothermal interactions and soil properties (Yang et al., 2020a, 2020b, 2023). While the accuracy of the model has been validated at individual sites, achieving reliable regional-scale assessments requires incorporating high-resolution spatial data and long-term observational records to address current data limitations.

Based on the aforementioned empirical CO_2 flux estimation scheme, this study utilized hourly observational data of soil temperature (surface soil temperature, T_{0cm}; temperature at 10 cm depth, T_{10cm}) and soil moisture (volumetric water content at 10 cm depth, VWC_{10cm}) from 2004 to 2021 at Tazhong Station—a representative site in the hinterland of the Taklimakan Desert—along with soil organic carbon (SOC) and pH obtained from soil sampling. These data were used to estimate the hourly CO_2 flux variations in the shifting sands of the desert's central region during the corresponding period. Building on this, by integrating ERA5 (fifth generation ECMWF atmospheric reanalysis) data (2000–22, hourly multi-layer soil temperature and moisture) with extensive spatial sampling of SOC and pH across the desert, we analyzed spatiotemporal CO_2 flux patterns throughout the entire Taklimakan shifting sand region. The annual carbon sequestration capacity was subsequently calculated through temporal aggregation, enabling a comprehensive assessment of the desert's carbon sink potential. These findings aim to provide crucial insights into the role of deserts in global carbon cycling, offer new perspectives for exploring

their carbon sequestration capacity, and deliver scientific support for developing effective carbon reduction strategies to achieve net-zero targets.

2. Dataset construction

2.1. *Study area*

The Taklimakan Desert (36°50'–41°10'N, 77°40'–88°20'E), located in the center of the Tarim Basin in China, covers approximately 3.376 × 10^5 km^2, with shifting sands accounting for about 70% of its area (Fig. 1). As the largest desert in China and the second-largest shifting desert in the world (Mamtimin, 2015; Yang et al., 2016, 2017), it features a warm–temperate arid climate with mean annual precipitation below 50.0 mm and potential evaporation reaching 1500–3815 mm annually, showing a spatial decrease from north to south and west to east. The mean annual temperature is 10.0°C, with recorded extremes of 46.0°C and −32.6°C (Yang et al., 2020a). Prevailing winds average 1.5–3.0 m s^{-1}, and frequent dust storms occur due to abundant surface particulates. Dominated by aeolian soils, the desert margin also contains brown desert soils, saline soils, and meadow soils.

The Taklimakan Desert harbors unique soil carbon pools shaped by its distinctive geomorphology and extreme climatic conditions. Tazhong Station, located in the central region of the desert, provides representative CO_2 flux data for the shifting sands of the Taklimakan Desert. Our field experiments were conducted primarily at the Taklimakan Desert Atmosphere and Environment Observation and Experiment Station (Tazhong Station, 38°58'N, 83°39'E), established in 1996 at a 1099.3 m elevation, making it the only research station in the world that penetrates over 200 km into a desert interior. The location of the station in the homogeneous central desert makes it highly representative for monitoring CO_2 fluxes from shifting sands in the core region of the Taklimakan.

2.2. *Research design*

In our previous studies, we conducted systematic experiments including component contribution analysis, temperature-controlled experiments, and hydrothermal coupling tests on shifting sands in the Taklimakan Desert to elucidate the internal processes and driving mechanisms of desert carbon sequestration. These investigations enabled us to establish parameterized relationships characterizing the interactive effects of soil hydrothermal factors and soil properties on CO_2 fluxes from shifting sands. The parameterization scheme was rigorously validated through comprehensive CO_2 flux observations in representative areas of the Taklimakan Desert, ensuring its accuracy and reliability (Yang et al., 2020b, 2020c, 2023).

To estimate the CO_2 fluxes across the entire shifting sands of the Taklimakan Desert, we applied our validated parameterization scheme (Yang et al., 2023) to hourly measurements of T_{0cm}, T_{10cm}, and VWC_{10cm} from the shifting sand underlying surface of Tazhong Station (2004–21), combined with field-measured SOC and pH data. This enabled a detailed hourly CO_2 flux reconstruction for the central desert region. We then expanded this analysis to the entire desert using ERA5-derived hourly multi-layer soil temperature and moisture data (2000–22), integrated with spatially averaged SOC and pH values obtained through extensive multi-point sampling of shifting sands. We conducted comprehensive calculations of CO_2 fluxes and their spatiotemporal distributions across the entire shifting sand region of the Taklimakan Desert, with further analysis of the temporal and spatial variations in carbon sequestration capacity, thereby providing a scientific basis for subsequent research and management strategies (Fig. 2).

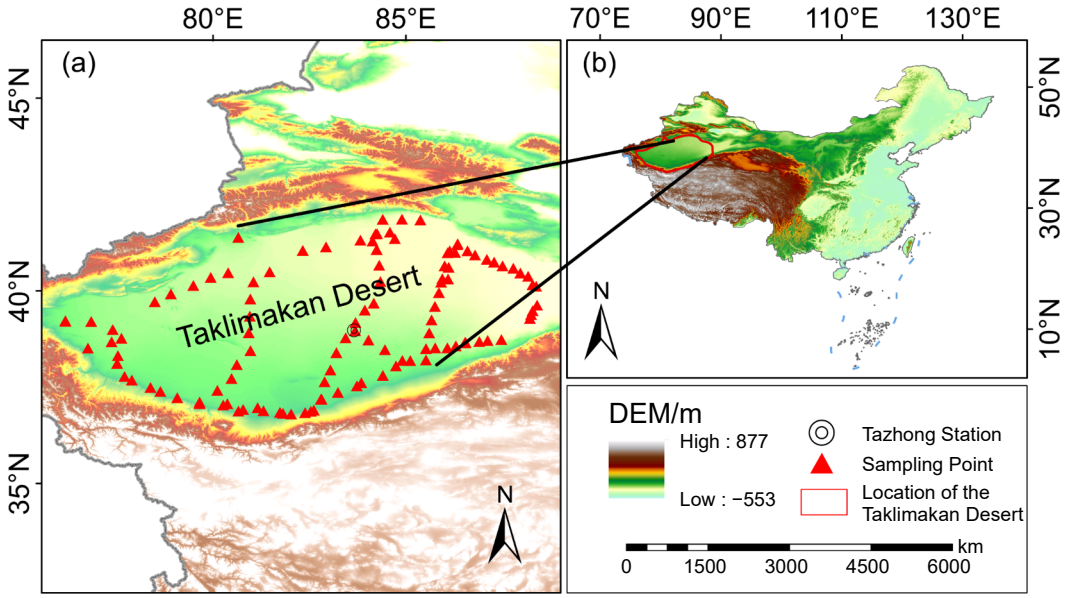


Fig. 1. (a) Overview of the study area and sampling sites (n = 120). (b) Location of the study area.

2.3. *Data collection and validation*

2.3.1. *ERA5 soil temperature and moisture data*

We employed ERA5 soil temperature and moisture data (Albergel et al., 2018; Gleixner et al., 2020), obtained from the ECMWF official data platform. The data processing involved two key steps: First, we performed temporal alignment of the downloaded ERA5 soil temperature and moisture data and conducted a comparative analysis with in situ measurements from Tazhong Station. Second, since ERA5 soil temperature data does not directly provide T_{10cm}, we established a temperature correction relationship based on the observed soil temperature gradient at Tazhong Station to calculate both T_{0cm} and T_{10cm}. The calculation formulas are as follows:

$$T_{0cm} = 1.1527\text{skt} - 1.9469\,, \quad (1)$$

$$T_{10\,cm} = -1.5516 + 0.4026\text{stl1} + 0.7636\text{stl2}\,. \quad (2)$$

In Eq. (1), "skt" represents the ERA5 skin temperature. The derived T_{10cm} values were temporally adjusted with a 3-h backward shift to account for soil thermal lag effects. Before correction, the ERA5 skin temperature underestimated the measured surface temperature by an average of 1.74°C. After correction, this bias was reduced to 0.03°C, and the overall RMSE was lowered by 58%. The consistency between the corrected ERA5 skin temperature and the measured data was significantly improved, enabling a more accurate representation of the actual temperature conditions over the underlying surface of the Taklimakan Desert.

2.3.2. *Shifting sand SOC and pH data*

Between 2020 and 2022, our research team conducted three systematic field campaigns across the Taklimakan Desert, collecting a total of 120 surface shifting sand samples (65 in the first batch, 35 in the second, and 20 in the third),

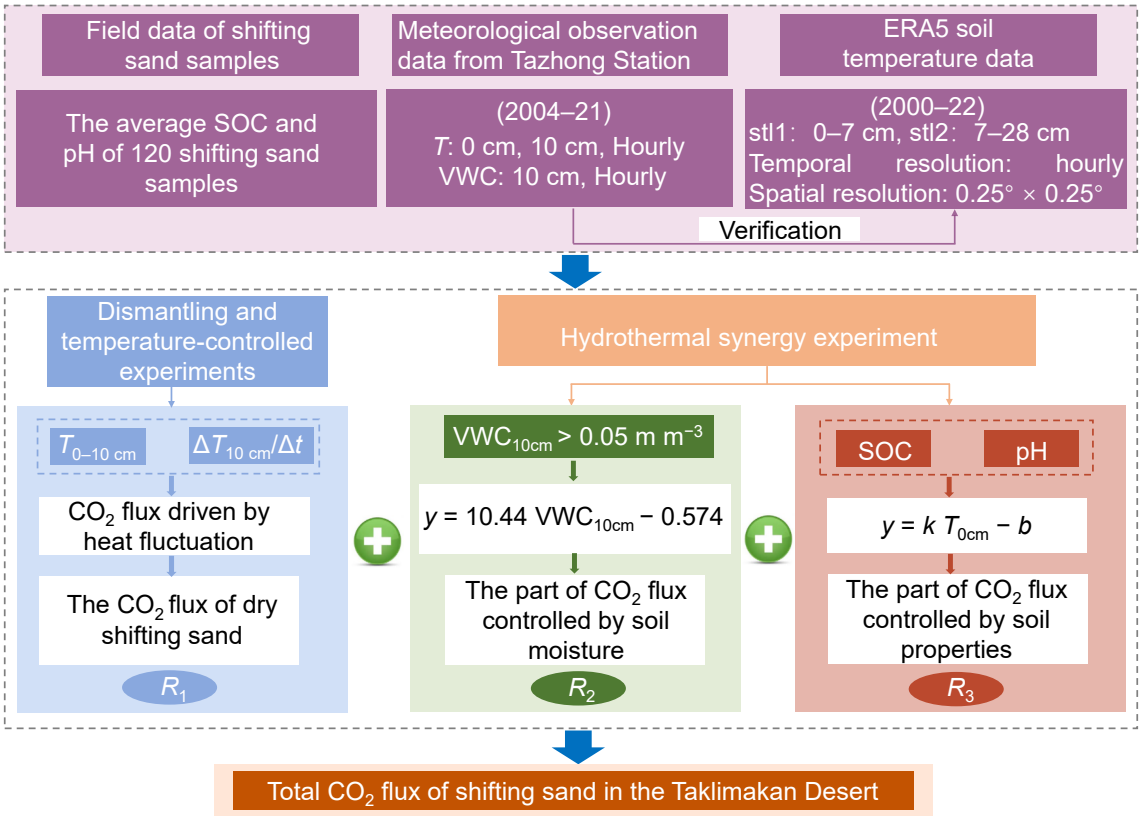


Fig. 2. Flowchart of CO_2 flux calculation decomposition for desert shifting sands. $T_{0–10cm}$ denotes the temperature difference between soil depths of 0 cm and 10 cm (units: °C). $\Delta T_{10cm}/\Delta t$ represents the change in soil temperature at 10 cm depth between two consecutive time steps divided by the time interval (units: °C min^{-1}). "stl1" represents the first-layer soil temperature (typically 0–7 cm depth; units: °C) and "stl2" denotes the second-layer soil temperature (typically 7–28 cm depth; units: °C) from the ERA5 dataset. R_1 corresponds to the thermally driven component, where soil temperature variations alter interstitial gas volume in shifting sands, consequently affecting CO_2 diffusion and release. R_2 represents the moisture-controlled CO_2 flux component—when soil moisture exceeds a critical threshold, it rapidly activates dormant microorganisms and facilitates soluble substrate diffusion, significantly stimulating high-rate CO_2 emissions from desert soils. R_3 constitutes the soil-property-controlled CO_2 flux component, where SOC and pH serve as optimal indicators of soil health status. SOC provides substrates for microbial decomposition and respiration, while pH regulates microbial activity and enzyme function, collectively governing CO_2 production and release processes.

as spatially distributed in Fig. 1. All samples underwent laboratory analysis to determine the precise SOC content and pH values. Due to logistical constraints in the desert interior, the sampling sites exhibited some spatial heterogeneity. We therefore adopted the statistical mean of all samples as representative values for the desert region, with measured averages of pH 7.47 (neutral to slightly alkaline) and an SOC content of 0.21 g kg^{-1}. This approach ensures scientific rigor while accurately reflecting the fundamental physicochemical characteristics of the shifting sand matrix of the desert.

3. Results and discussion

3.1. *Estimation of CO_2 fluxes from shifting sands in the central Taklimakan desert*

This study quantified the hourly CO_2 flux variations in the shifting sands of the central Taklimakan Desert during the study period. As shown in Fig. 3, incorporating the effects of soil moisture (R_2) and soil properties (R_3) on CO_2 fluxes in shifting sands, in addition to the thermally driven component (R_1) resulting from thermal expansion and contraction of CO_2-containing soil air, significantly enhances the interannual variability of CO_2 fluxes, intensifying CO_2 emissions during summer while strengthening carbon sequestration in winter. On an annual scale, the daily total CO_2 fluxes exhibit seasonal variations, consistently transitioning from a winter carbon sink to a summer carbon source before reverting to a sink state—a phenomenon arising from the superposition of multiple processes within the shifting sand system. Soil temperature has been identified as the primary driver (Fang and Moncrieff, 2001; Sánchez et al., 2003; Rodeghiero and Cescati, 2005; Ma et al., 2013, 2014; Fa et al., 2015, 2016), where rapid temperature increases/decreases promote soil air expansion/contraction, leading to pronounced CO_2 release/uptake by the shifting sands. The unique loose and porous structure of shifting sands provides inherent advantages for soil air expansion/contraction during extreme temperature variations (Raich and Potter, 1995; Yang et al., 2023). In the unvegetated, shifting sand areas of the central Taklimakan Desert, when sporadic precipitation events increase soil moisture at 10 cm depth beyond 0.05 m^3 m^{-3}, dormant microorganisms are rapidly activated, microbial activity increases, and soluble substrate diffusion is enhanced, resulting in significant short-term CO_2 emissions from the shifting sands. This moisture stimulation effect, which exhibits a distinct threshold, gradually diminishes over time as moisture is lost, and is particularly pronounced in unvegetated shifting sand areas (Yang et al., 2023). SOC and pH also play critical regulatory roles in CO_2 fluxes, with SOC serving as the substrate for microbial decomposition and respiration, while pH influences microbial and enzymatic activity in the soil (Delgado-Baquerizo et al., 2013). As SOC decreases and soils become more alkaline, CO_2 solubility increases exponentially with pH under alkaline conditions (Seinfeld and Pandis, 2006). This leads to reduced CO_2 fluxes, which are further suppressed by declining temperatures in the shifting sand. Within this dynamic balance of release and uptake, CO_2 fluxes exhibit seasonal patterns of wintertime absorption and summertime release. In this study, constrained by the extreme natural conditions and

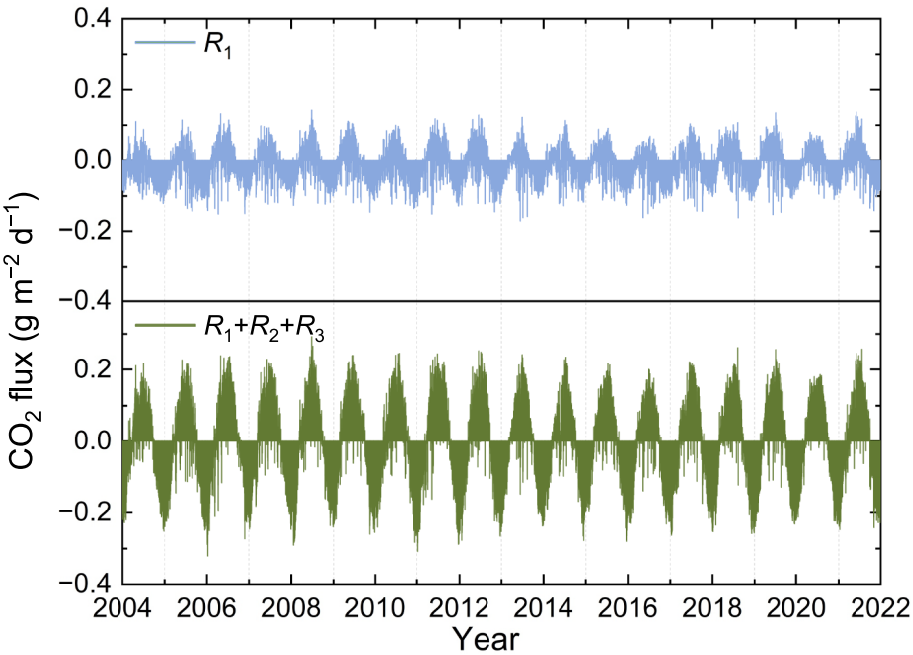


Fig. 3. Fluctuations in daily total CO_2 flux from shifting sands of the Taklimakan Desert hinterland during 2004–21. R_1, R_2, and R_3 represent the thermally driven, moisture-controlled, and soil-property-controlled components of the CO_2 flux, respectively.

accessibility limitations in the Taklimakan Desert, the shifting sand sampling sites used to determine key soil parameters (SOC and pH) are primarily concentrated near the desert margins and along major transportation routes (Fig. 1). This spatial inhomogeneity may affect the accuracy of CO_2 flux estimates, and addressing this limitation remains a key direction for future research.

On an annual scale, the counterbalancing effects among thermal expansion/contraction of CO_2-laden soil air, carbon sequestration by saline–alkaline processes, organic carbon decomposition, and moisture interactions, collectively result in a clearly defined and stable carbon sink effect in the shifting sands of the central Taklimakan Desert, with an average CO_2 sequestration rate of 4.85 g m^{-2} yr^{-1}. This value is substantially lower than the carbon sequestration rates reported for the other arid and semi-arid desert regions listed in Table 1 (e.g., 102–127 g m^{-2} yr^{-1} for the Mojave Desert, USA). This discrepancy highlights the uniqueness of the Taklimakan Desert as an extremely arid desert. The comparison shows that regions with higher sequestration rates in Table 1 generally receive annual precipitation exceeding 150 mm, and some of the studied areas possess sparse vegetation cover, where carbon sink processes may be jointly influenced by both biological and abiotic processes. In contrast, the hinterland of the Taklimakan Desert, which is the focus of this study, experiences extremely low annual precipitation (approximately 25.9 mm) and has almost no surface vegetation. Its CO_2 flux is primarily governed by abiotic processes. Therefore, the relatively low sequestration rate revealed in this study precisely reflects the true magnitude of desert carbon sinks dominated by abiotic processes under extremely arid and vegetation-free conditions. This clarifies that significant differences exist in desert carbon sink functions under varying climatic and surface conditions. Furthermore, as shown in Table 2, we found a gradual weakening trend in the carbon sink rate of the central shifting sands of the Taklimakan Desert from 2004 to 2021. Subsequent analysis of the relationship between annual carbon sequestration capacity and key environmental factors during 2004–21 revealed that the carbon sequestration capacity of the desert consistently decreases with increasing T_{0cm} and soil temperature difference between 0 and 10 cm ($T_{0–10cm}$), initially increasing and then decreasing in response to precipitation (Fig. 4). The maximum carbon sequestration capacity (up to 10.04 g m^{-2} yr^{-1}) occurs at annual precipitation levels of between 20 and 30 mm. This pattern likely relates to temperature-driven expansion of CO_2-containing soil air, which pumps more CO_2 from the shifting sand into the atmosphere, thereby reducing sequestration. Additionally, when annual precipitation exceeds 25 mm, rainfall triggers short-term CO_2 release through microbial activation and organic carbon decomposition, progressively diminishing the carbon sink capacity. Consequently, under global warming scenarios with intensified hydrological cycles, the carbon sequestration potential of unvegetated shifting sands in the central Taklimakan Desert is projected to continue declining.

3.2. *Spatial distribution of carbon sequestration capacity in the shifting sand underlying surface of the Taklimakan Desert*

Through analyzing the spatial distribution of the annual average CO_2 flux (R_s) over the shifting sand underlying surface of the Taklimakan Desert from 2000 to 2022, significant spatial differences in carbon sequestration capacity were observed (Fig. 5). Across the entire shifting desert, orange areas representing CO_2-fixing regions account for two-thirds of the total area, with a maximum annual carbon sequestration rate of 19.25 g m^{-2} yr^{-1}. In contrast, green and blue areas representing CO_2-emitting regions cover one-third of the shifting sand area, primarily distributed along the western edge (Kashgar region) and northern edge (Aksu region) of the desert, where the maximum annual CO_2 emission rate reaches 64.49 g m^{-2} yr^{-1}. This phenomenon may be attributable to the relatively higher precipitation in the Kashgar and Aksu regions, as increased rainfall can enhance microbial activity and organic carbon decomposition, thereby promoting CO_2 release (Jasoni et al., 2005). Additionally, both areas are located on the fringes of agricultural zones, where the shifting sand soils exhibit relatively higher organic carbon content and microbial activity. To validate the above hypothesis, we conducted a detailed analysis of the individual components (R_1, R_2, and R_3) of the shifting sand CO_2 flux (Fig. 6). The spatial distributions of R_1, R_2, and R_3 reveal that R_1 (thermal expansion and contraction) and R_3 (soil properties) pri-

Table 1. Comparison of carbon sequestration rates in typical arid and semi-arid desert regions (Schlesinger, 2017).

Study area	Annual precipitation (mm)	Carbon sequestration rate (g m^{-2} yr^{-1})	Reference(s)
Baja California, Mexico	174	39–52	Hastings et al. (2005)
Mojave Desert, USA	150	102–127	Jasoni et al. (2005); Wohlfahrt et al. (2008)
Gurbantunggut Desert, China	160	62–622	Xie et al. (2009)
Fukang, China	173	49	Liu et al. (2012);
	164	25	Ma et al. (2014)
Ningxia, China	287	77	Jia et al. (2014);
	275	28	Liu et al. (2015)
Hinterland of the Taklimakan Desert, China	25.9	1.32	This study

Notes: The value for this study (1.32 g m^{-2} yr^{-1}) is expressed in carbon units, converted from the CO_2 sequestration rate (4.85 g m^{-2} yr^{-1}).

Table 2. Annual CO_2 flux variations in the shifting sand of the Taklimakan Desert hinterland (2004–21). Regression equations: for R_1, $y = 0.143x - 291.93$; for $R_1+R_2+R_3$, $y = 0.220x - 449.06$.

Year	Annual CO_2 flux R_1 (g m^{-2} yr^{-1})	Annual CO_2 flux $R_1+R_2+R_3$ (g m^{-2} yr^{-1})
2004	−11.756	−10.047
2005	−10.713	−9.857
2006	−4.286	−1.038
2007	−6.495	−2.942
2008	−5.759	−4.453
2009	−4.548	−1.674
2010	−7.855	−5.560
2011	−5.166	−3.587
2012	−6.380	−6.008
2013	−8.892	−5.654
2014	−5.714	−6.502
2015	−5.265	−3.253
2016	−10.431	−9.080
2017	−6.308	−4.885
2018	−5.135	−4.475
2019	−3.666	−2.262
2020	−5.315	−3.934
2021	−3.143	−2.120

marily govern the CO_2 fixation across the shifting sand underlying surface of the entire desert. In contrast, R_2 (soil moisture control) dominates CO_2 release, with the Kashgar (western edge) and Aksu (northern edge) regions emerging as the primary CO_2-emitting areas due to their relatively higher precipitation levels.

Analysis of the variation trends in different components of the shifting sand underlying surface from 2000 to 2022 revealed that cool-colored areas, representing regions with declining carbon sequestration capacity, account for approximately two-thirds of the entire shifting desert area (Fig. 5b). This suggests that the carbon sequestration capacity of most shifting sand regions in the Taklimakan Desert has been gradually weakening due to climate change, primarily driven by the rapid CO_2 release caused by intense precipitation events (Fig. 6d). Consequently, under global warming and an intensified hydrological cycle, this trend is expected to progressively diminish the abiotic carbon sink potential of unvegetated deserts.

3.3. *Temporal variation of carbon sequestration capacity in the Taklimakan Desert's shifting sand underlying surface*

Estimation of carbon sequestration capacity in the

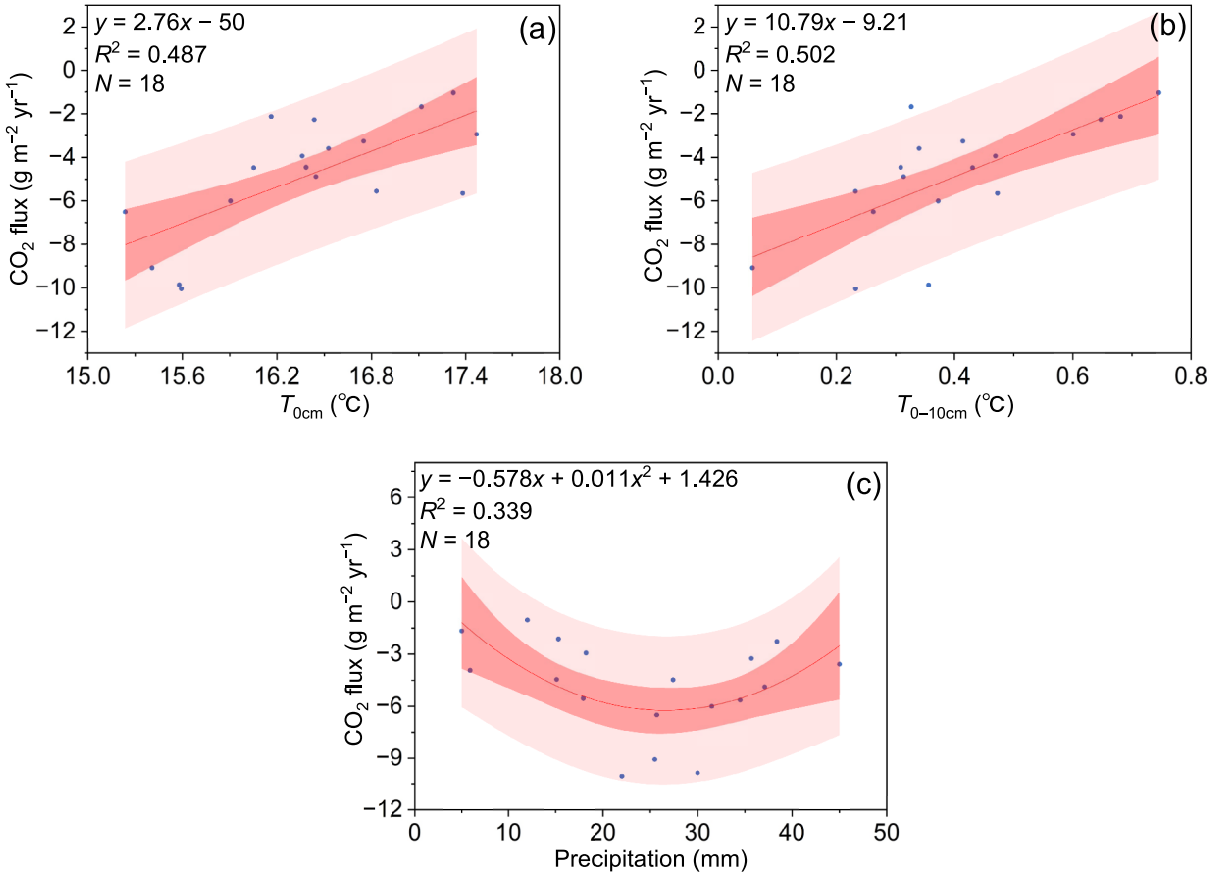


Fig. 4. Regression relationships between annual CO_2 flux in shifting sand of the Taklimakan Desert hinterland (2004–21) and: (a) mean annual T_{0cm}, (b) mean annual $T_{0–10cm}$, and (c) annual precipitation. Blue dots represent observed data points, the red solid line indicates the regression fit, the pink band represents the 95% prediction interval, and the red band corresponds to the 95% confidence interval.

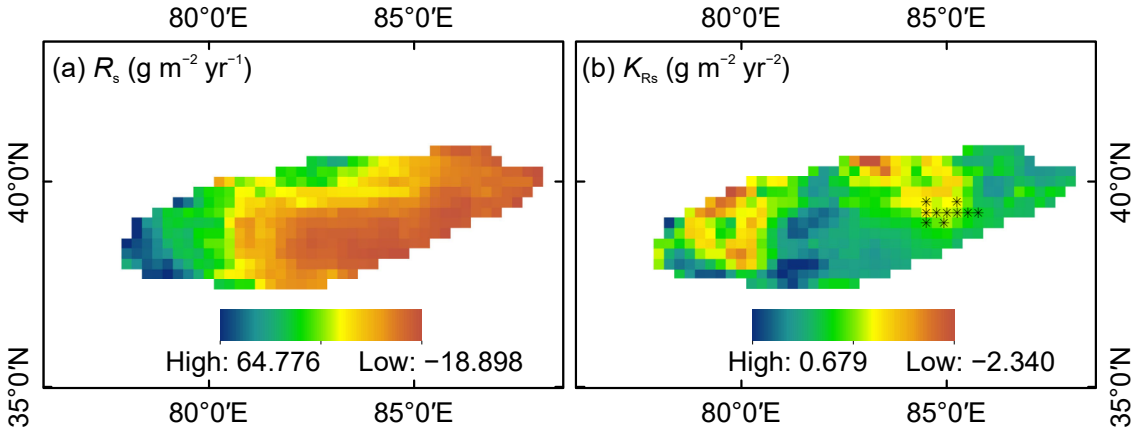


Fig. 5. Spatial distribution of the annual mean CO_2 flux (R_s) over the shifting sand underlying surface in the Taklimakan Desert (2000–22). Panels (a) and (b) represent the spatial patterns of multi-year averages and temporal trends of R_s, respectively. Asterisks (*) represent the significance level of $p < 0.05$.

shifting sands of the Taklimakan Desert (2000–22) revealed significant interannual fluctuations (Fig. 7). While the shifting sand surface generally functions as a carbon sink, its capacity proves unstable due to pronounced CO_2 emissions in specific years. Building upon prior research findings, we conducted synchronous analysis with corresponding annual mean VWC_{10cm} data, revealing that elevated soil moisture significantly diminishes the shifting sand carbon sequestration capacity and can even reverse it to CO_2 emission status (Fig. 8). This phenomenon is most pronounced in years with relatively higher soil moisture content (2003, 2010, and 2016), during which the entire shifting sand surface exhibits strong carbon source characteristics.

A significant exponential relationship was identified between soil moisture and annual carbon sequestration in shifting sands, where a mean yearly soil moisture (VWC_{10cm}) exceeding 0.004 m^3 m^{-3} triggers rapid CO_2 release through enhanced microbial activity and organic carbon decomposition, directly diminishing the carbon sequestration capacity and converting the entire shifting sand surface to a carbon source. While the hyper-arid central Tazhong region maintains persistent carbon sequestration due to chronically low precipitation, the shifting sand surface of the Taklimakan Desert exhibits a measurable but unstable carbon sequestration capacity, with instability occurring during anomalously wet years, reflecting the characteristic low resistance of fragile desert ecosystems to environmental perturbations. In these moisture-limited ecosystems where precipitation typically occurs as rare pulse events, soil moisture gains disproportionately strong control over shifting sand CO_2 fluxes upon surpassing the critical threshold (Conant et al., 2004). Excluding years with elevated soil moisture due to excessive precipitation, the shifting sand surface sequesters approximately 1.05×10^6 t CO_2 annually.

Global warming intensifies the hydrological cycle, increasing both total precipitation and extreme precipitation events worldwide, which stimulates thermal expansion of air within shifting sands and rapidly activates dormant microbial communities through individual precipitation events, enhancing microbial activity and substrate diffusion to accelerate organic carbon decomposition in desert systems, thereby promoting short-term CO_2 release from shifting sands to the atmosphere (Marcott et al., 2013). This process, akin to other fragile ecosystems with low disturbance resistance, progressively reduces both the stability and rate of carbon sequestration in the shifting sands of the Taklimakan Desert, with these effects subject to acceleration through climate change–induced positive feedback mechanisms. Our study finds that sporadic heavy rainfall events in deserts can promote carbon release, while unvegetated deserts can significantly enhance carbon sequestration upon the inclusion of vegetation photosynthesis. Against the backdrop of the "warm–wetting" trend in Northwest China, the increase in heavy precipitation may potentially exert a long-term dual effect on the carbon sink of the Taklimakan Desert. Based on current research, sporadic heavy precipitation in the desert has not effectively alleviated drought or promoted vegetation expansion. Therefore, under the current "warm–wetting" conditions, desert precipitation remains in a state that promotes carbon release. However, if desert precipitation further increases in the future, along with adjustments in precipitation structure that effectively alleviate drought and facilitate vegetation recovery, the incorporation of photosynthesis could significantly enhance desert carbon sequestration. Whether there exists a precipitation threshold for this dual effect has not yet been clearly reported, but existing studies suggest that in arid and semi-arid ecosystems, precipitation exceeding 25 mm may trigger germination in many desert plants. However, this may not translate into ecosystem carbon accumulation unless subsequent rainfall events allow seedling survival and growth or substantial water is stored in the soil (Beatley, 1974; Huxman et al., 2004). Under such conditions, increased precipitation would favor the growth and spatial expansion of pioneer desert vegetation, thereby shifting the role of increased precipitation from weakening abiotic carbon sinks to enhancing biological carbon sinks through vegetation growth. Furthermore, from a carbon sequestration perspective, desertification control not only

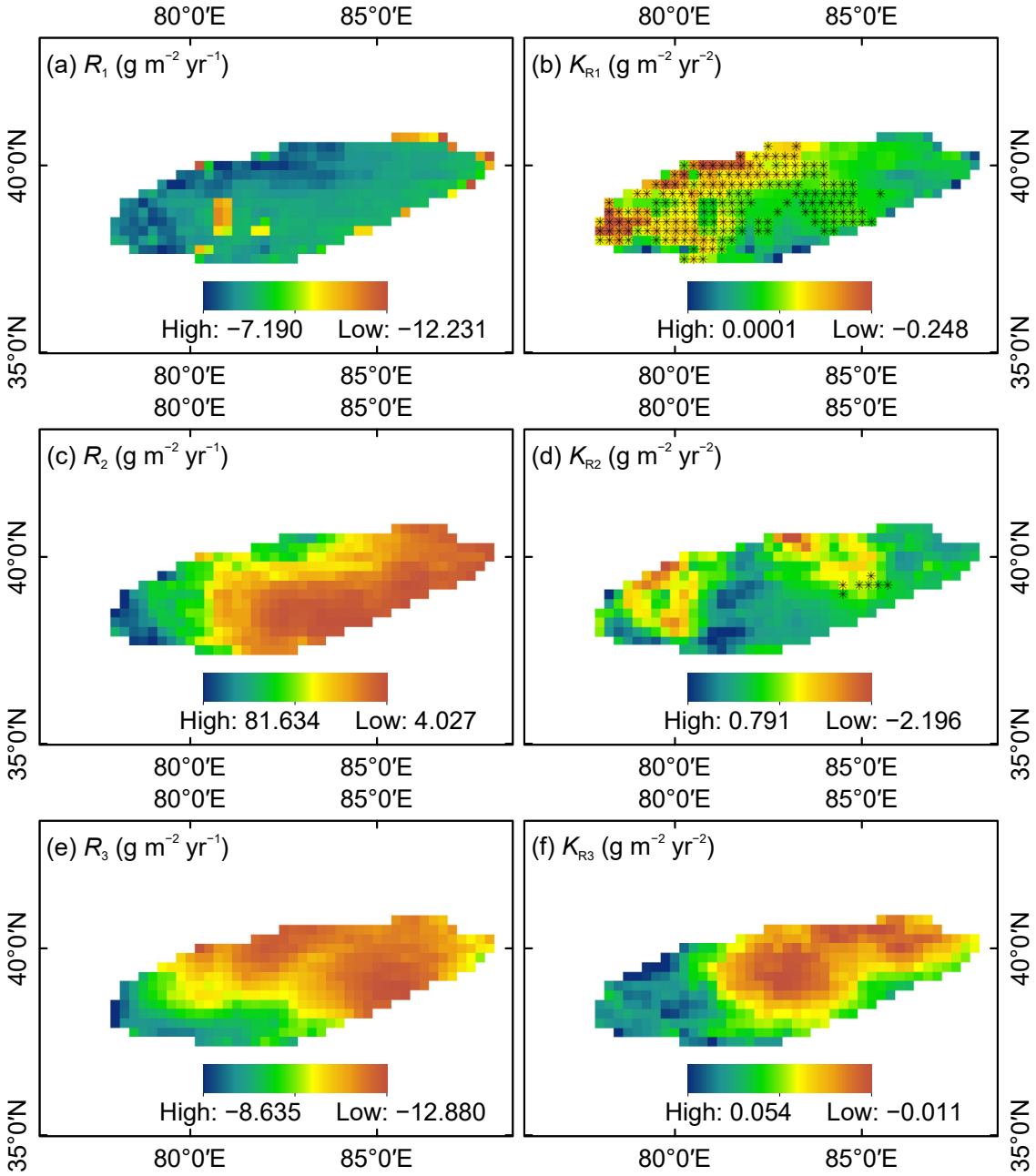


Fig. 6. Spatial distributions and temporal trends of annual mean CO_2 flux components (R_1, R_2, and R_3) over the shifting sand underlying surface in the Taklimakan Desert (2000–22). Panels (a) and (b) show multi-year averages and trends for R_1, (c) and (d) for R_2, and (e) and (f) for R_3, respectively. Asterisks (*) represent the significance level of $p < 0.05$.

directly improves regional ecological environments but also holds significant potential for reinforcing carbon sink stability and enhancing sequestration capacity in arid ecosystems.

4. Summary and outlook

This study employed our established empirical CO_2 flux estimation scheme—incorporating hydrothermal interactions and soil properties—integrated with long-term observational data and high-precision meteorological datasets to comprehensively analyze the carbon sequestration capacity and spatiotemporal variation characteristics of the shifting sand underlying surface of the Taklimakan Desert, thereby providing critical scientific evidence for understanding the role of deserts in the global carbon cycle.

This study reveals the carbon sequestration capacity and its spatiotemporal characteristics in the shifting sand underlying surface of the Taklimakan Desert. On an annual scale, the daily total CO_2 flux exhibits cyclical variability, systematically transitioning from winter carbon sinks to summer carbon sources before reverting to sink conditions. The interior shifting sands of the desert demonstrate significant

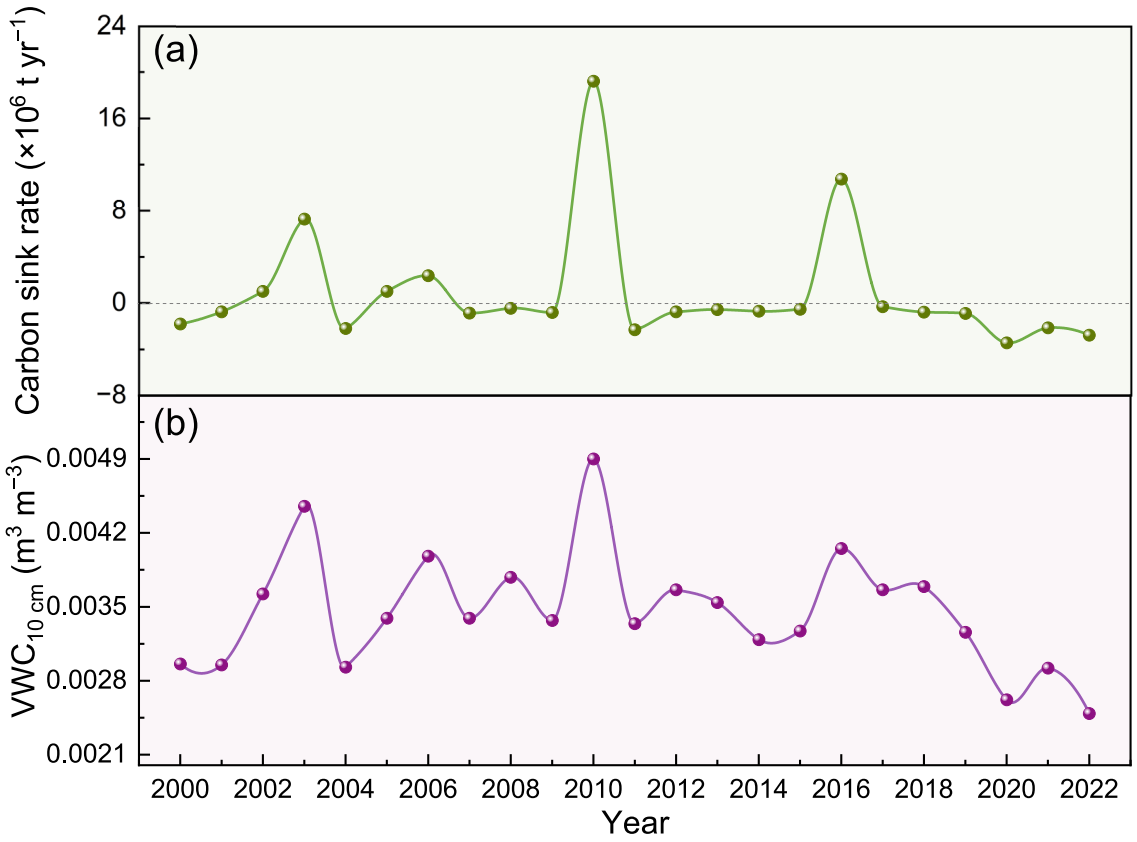


Fig. 7. Annual (a) carbon sink rate and (b) mean VWC_{10cm} in the shifting sand underlying surface of the Taklimakan Desert (2000–22).

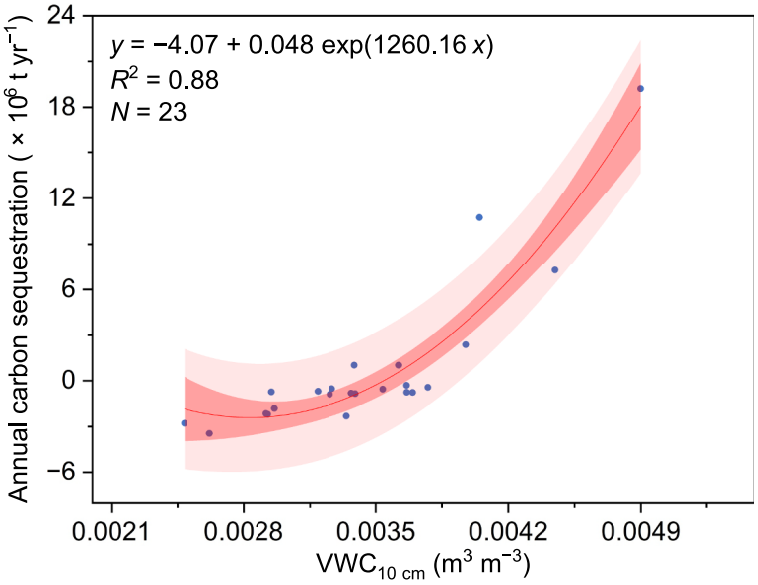


Fig. 8. Relationship between the annual carbon sink rate and mean VWC_{10cm} in the shifting sand underlying surface of the Taklimakan Desert (2000–22). Blue dots represent observed data points; the red solid line indicates the regression fit; the pink band represents the 95% prediction interval; and the red band corresponds to the 95% confidence interval.

carbon sequestration, with an average annual rate of 4.85 g m^{-2} yr^{-1}, amounting to approximately 1.05 × 10^6 t CO_2 fixed annually across the entire shifting sand surface. Spatially, two-thirds of the desert area functions as carbon sinks (maximum sequestration: 19.25 g m^{-2} yr^{-1}), while one-third—primarily distributed along the western (Kashgar)

and northern (Aksu) margins—acts as carbon sources (maximum emission: 64.49 g m^{-2} yr^{-1}). Global warming–induced hydrological intensification has increased precipitation (particularly short-duration heavy rainfall) in the vegetation-free central desert, yet without fundamentally alleviating chronic aridity or promoting vegetation expansion. This process has progressively reduced both the stability and rate of carbon sequestration in the shifting sands of the Taklimakan. However, long-term increases in precipitation combined with enhanced desertification control could potentially improve the sequestration capacity and stability through vegetation-driven photosynthesis. These findings provide scientific support for desert ecosystem management, suggesting that policymakers should incorporate carbon sequestration considerations into desert restoration strategies to strengthen aridland carbon sinks for climate change mitigation.

The CO_2 flux dataset developed for the Taklimakan Desert in this study partially reflects the carbon sequestration capacity of the desert; however, future validation and optimization of its temporal and spatial resolution require incorporating additional long-term monitoring station data. Concurrently, a comprehensive understanding of carbon sequestration mechanisms across global desert regions is necessary to accurately assess the total desert carbon storage and its precise role in the global carbon cycle. Additionally, although the activation threshold for R_2 ($VWC_{10cm} > 0.05$ m^3 m^{-3}) was experimentally derived based on long-term observational data from Tazhong Station, its applicability across the entire desert, especially in the northwestern margin regions with distinct precipitation characteristics, still requires further refinement. Within climate change mitigation strategies, arid regions with extensive desert coverage should be prioritized, with research breakthroughs in desert carbon sequestration mechanisms as a potential foundation for evaluating and enhancing carbon sink capacities across diverse ecosystems. Furthermore, establishing high-standard observation networks is imperative to improve assessment and prediction systems for carbon sink potential in arid ecosystems, quantify baseline sequestration capacities, explore carbon storage potential, and strengthen climate change resilience in drylands. These advancements will effectively expand carbon emission allowances for arid regions, create developmental space for new industrialization models, promote sustainable development, and provide fundamental data support for achieving the Dual Carbon Goals of China.

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Data availability statement. All datasets supporting this study are permanently archived in certified repositories under non-restrictive licenses (CC0 or CC BY). Specifically: ERA5 hourly data are available at https://doi.org/10.24381/cds.adbb2d47 (Hersbach et al., 2023); soil temperature–difference impact data are available at https://doi.org/10.5061/dryad.0zpc866tw (Yang et al., 2020d); Taklimakan Desert CO_2 flux data are accessible at https://www.ncdc.ac.cn/portal/metadata/review/22c62e6e-ae57-4f40-956b-16553fb5a5fd?lang=en with corresponding DOI: https://doi.org/10.12072/ncdc.idm.db6928.2025 (currently available in Chinese interface; English version in preparation) (Yang et al., 2025).

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