https://doi.org/10.5194/egusphere-2026-4692
Preprint. Discussion started: 26 August 2026

A physico-chemical framework for explaining the generation mechanism of Nocturnal Soil CO_2 Uptake in Deserts

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Abstract. Nocturnal soil CO_2 influx (Fs) has been widely documented in global deserts, while the underlying mechanisms remain unclear. Based on 563 observations from 30 published studies across five major desert regions in the world, we employed multiple linear mixed-effects models (LMMs), random forest (RF) regression, polynomial regression, and structural equation modeling (SEM) to quantify the effects of air-soil temperature difference (ΔT = Ta - Ts), soil water content (θv), soil pH, and ln(clay/sand) on soil nocturnal CO_2 influx (Fs), and to establish a physico-chemical framework for explaining the generation mechanism of Fs. The results displayed a global mean Fs of −0.195 μmol m^{-2} s^{-1}, with the strongest CO_2 uptake occurring in the Central Asian Desert Area and the weakest in the North American Desert Area. Fs showed a significantly positive correlation with ΔT and negative correlations with θv, pH, and ln(sand/clay). SEM revealed that ln(sand/clay) and θv influenced Fs both directly and indirectly. The relationships of ΔT, θv, pH, and ln(clay/sand) with Fs suggested exerted pronounced effects on nocturnal CO_2 influx in desert soils. The correlation analysis demonstrated that these environmental factors may serve as important drivers in the generation of nocturnal soil CO_2 influx. Integrating our results ad previous studies, we proposed a comprehensive physico-chemical mechanism framework. In this framework, thermal convection driven by the temperature difference served as the physical driving force, continuously transporting atmospheric CO_2 into soil. One fraction is temporarily stored as gas in soil pores, and the other fraction enters chemical reactions under alkaline conditions. The above physico-chemical processes generated the nocturnal CO_2 influx process in desert soils.

1 Introduction

Deserts cover approximately 20% of Earth's land surface, and form a major component of the terrestrial biosphere (Lancaster, 2009). Their soil carbon dynamics therefore need to be represented in global carbon-budget assessments. Net soil-atmosphere CO_2 flux has traditionally been interpreted as positive, a release to the atmosphere driven by heterotrophic and autotrophic respiration (Vargas et al., 2011). Field observations from arid regions now document a contrasting pattern: when soil respiration is minimal or eliminated, soils often absorb atmospheric CO_2 at night and produce negative fluxes (Yates et al., 2013; Fa et al., 2015; Liu et al., 2015a; Fa et al., 2018b; Sagi et al., 2021; Lopez-Canfin et al., 2022a; Kim et al., 2024),

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suggest a potential dryland carbon sink process associated with nocturnal soil dynamics and have motivated growing research attention (Soper et al., 2017; Islam et al., 2026).

Despite increasingly broad observational evidence, the mechanisms underlying nocturnal CO_2 uptake remain unclear (Fa et al., 2018a; Bekin and Agam, 2023). Most studies have examined individual environmental drivers, with temperature and soil water content receiving the most attention. Several studies link uptake to air and soil temperature (Hamerlynck et al., 2013; Ma et al., 2015; Sagi et al., 2021; Kim et al., 2024). For instance, temperature governs CO_2 diffusion within the soil (Shanhun et al., 2012), and the soil atmosphere temperature difference correlates with nocturnal CO_2 flux (Gao et al., 2021). Soil moisture can facilitate uptake by dissolving CO_2 into pore water (Ball and Virginia, 2015; Bekin and Agam, 2023). Besides these, higher soil pH has been associated with stronger uptake (Xie et al., 2009), and soil texture is expected to influence uptake by modulating porosity and gas transport processes (Mordhorst et al., 2014). These driver-specific studies identify plausible controls, but they leave interactions among drivers insufficiently resolved. As a result, they cannot fully explain how uptake responds to changing environmental conditions.

Building on these observed relationships between environmental factors and CO_2 influx, several mechanistic hypotheses have been proposed. A hypothesis suggesting that thermal convection driven by temperature differences generated nocturnal CO_2 influx in soil was proposed (Gao et al., 2021). Meanwhile, a conceptual framework emphasized nocturnal soil cooling and CO_2 dissolution in water films (Sagi et al., 2021). These hypotheses have provided important linkages between environmental conditions and the occurrence of nocturnal CO_2 uptake, yet they were mostly developed and tested within the context of single-factor effects.

No single factor accounts for the full range of observed uptake (Yue et al., 2018). Interactions among soil texture, soil moisture, temperature, and pH are therefore likely to shape the process. Soil texture regulates hydraulic conductivity (Wankmüller et al., 2024). Soil moisture changes thermal conductivity, potentially modulating temperature-driven uptake (Wu et al., 2025). Soil pH changes as soil water evaporates (Romero-Mujalli et al., 2019), affecting both CO_2 dissolution and carbonate precipitation. These coupled effects are crucial to the proposed physicochemical mechanisms, yet they remain weakly addressed. Importantly, most evidence also comes from long-term monitoring at single sites. Because soil texture and pH vary little within a site, their effects on flux cannot be separated reliably from other site-specific conditions. A cross-site synthesis across the world's major deserts is therefore needed to quantify each factor's contribution and their interactions by using spatial variation in texture, pH, temperature, and moisture.

Here, we compile published observations to assess the independent and interactive effects of temperature, soil moisture, pH, and soil texture on nocturnal CO_2 uptake. The specific objectives were: (1) to quantify the independent contributions of each environmental factor on nocturnal CO_2 uptake, (2) to resolve the direction and strength of direct and indirect pathways linking these factors to soil CO_2 uptake, and (3) to develop an integrated physicochemical framework for nocturnal soil CO_2 uptake in deserts.

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2 Materials and Methods

2.1 Data Sources

We searched Web of Science, China National Knowledge Infrastructure, and Scopus databases to compile published observations of nocturnal CO_2 uptake in desert soils. Topic searches used the following query: ("abiotic soil CO_2 flux" OR "negative CO_2 flux" OR "soil CO_2 uptake" OR "soil CO_2 influx") AND ("desert" OR "dune"). Studies were retained when they met three criteria: (1) the study area was located in desert regions; (2) the article provided extractable quantitative data, including but not limited to CO_2 flux rates; and (3) the mean, sample sizes, standard deviations (SD), and standard errors (SE) of response variables were reported or could be calculable. A total of 30 studies meeting these criteria were ultimately selected.

2.2 Data Extraction

From each eligible study, we extracted study location (latitude and longitude), mean annual precipitation (MAP), mean annual temperature (MAT), hourly mean nocturnal soil CO_2 influx, corresponding air temperature (Ta, °C), soil temperature (Ts, °C), electrical conductivity (EC, $dS \cdot m^{-1}$), soil pH, soil volumetric water content (θv, m^3 m^{-3}), and soil texture (ln(clay/sand)). For studies reporting gravimetric water content (%, g g-1), we converted using the equation θv = θg × ρb, where θv is volumetric water content, θg is gravimetric water content, and ρb is soil bulk density (g cm^{-3}). Currently, measured soil texture data and publicly available grid products are relatively complete at global and regional scales (Fao and Iiasa, 2023). However, due to the high cost and operational complexity of high-resolution non-destructive imaging techniques, systematic direct measurements of soil porosity remain relatively scarce (Li et al., 2026). In arid sandy soils, fine particles (clay and silt) are the primary determinants of water and nutrient retention, even at low concentrations. We therefore used the log-ratio of clay to sand content, ln(clay/sand), as an index of soil texture fineness to represent the capacity of soils to retain moisture and support microbial activity. All CO_2 influx values were uniformly converted to μmol m^{-2} s^{-1}. When values were reported only in figures, we extracted numerical data using WebPlotDigitizer-4.8. A total of 563 valid data points were collected from the 30 selected studies. In this study, the 12 major global deserts were divided into five regions: the Central Asian Desert Area, the Circum-Mediterranean Desert Area, the North American Desert Area, the South Africa Desert Area, and the Antarctic Desert Area (**Fig. 1**).

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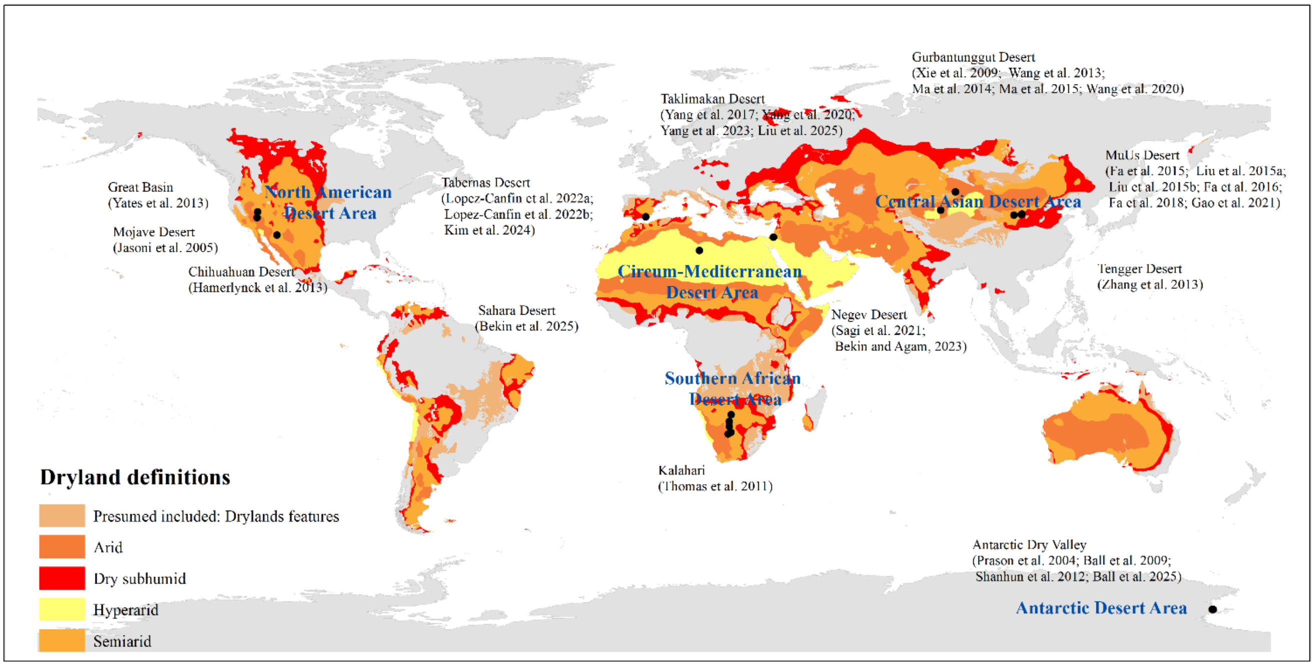

Figure 1: Distribution of studied sites across major deserts and arid regions worldwide. The map includes the North American Desert Area (including the Great Basin Desert (Yates et al., 2013), the Mojave Desert (Jasoni et al., 2005), and the Chihuahuan Desert (Hamerlynck et al., 2013)), the Circum-Mediterranean Desert Area (including the Sahara Desert (Bekin et al., 2025), the Tabernas Desert (Lopez-Canfin et al., 2022a; Lopez-Canfin et al., 2022b; Kim et al., 2024), and the Negev Desert (Sagi et al., 2021; Bekin and Agam, 2023)), the Southern African Desert Area (including the Kalahari Desert (Andrew David et al., 2011)), the Central Asian Desert Area (including the Mu Us Desert (Fa et al., 2015; Liu et al., 2015a; Liu et al., 2015b; Fa et al., 2016; Fa et al., 2018b; Gao et al., 2021), the Tengger Desert (Zhang et al., 2013), the Taklamakan Desert (Yang et al., 2017; Yang et al., 2020a; Yang et al., 2020b; Liu et al., 2025), and the Gurbantunggut Desert (Xie et al., 2009; Wang et al., 2013; Ma et al., 2014; Ma et al., 2015; Wang et al., 2020)), and the Antarctic Desert Area (including the Antarctic Dry Valleys (Parsons et al., 2004; Ball et al., 2009; Shanhun et al., 2012; Ball and Virginia, 2015)). The base map was designed and developed by UNEP-WCMC (2007). For more information on this map, visit https://data-gis.unep-wcmc.org/ (last access: 17 May 2026).

2.3 Data Extraction

This study investigated the independent contributions of individual environmental factors to nocturnal CO_2 influx and their interactions. For each study, we extracted monthly aggregated hourly mean values of nighttime (18:00–06:00) CO_2 flux (Fs) and the corresponding environmental variables, including air temperature (Ta), soil temperature (Ts), soil volumetric water content (θv), soil pH, and soil texture. Fs was designated as the response variable, and ΔT, θv, pH, and ln(clay/sand) were used as predictor variables.

Given that observations were nested within study sites (i.e., multiple data points from the same site are not statistically independent), we used linear mixed-effects models (LMMs) for all regression analyses, with "site" included as a random intercept. All continuous predictors were mean-centered prior to modelling to reduce multicollinearity.

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To compare mean Fs among the five desert regions (Central Asian, Circum-Mediterranean, North American, Southern African, and Antarctic Desert Areas), we used a one-way analysis of variance (ANOVA), followed by Tukey's honest significant difference (HSD). A significance level of $\alpha = 0.05$ was applied throughout.

Pearson correlation analysis was performed to assess bivariate relationships between Fs and all continuous predictors (Ta, Ts, ΔT, θv, pH, and ln(sand/clay)). To capture potential nonlinear relationships, we constructed polynomial regression models incorporating quadratic terms for each predictor, and we also implemented random forest (RF) regression—a non-parametric machine-learning method that does not assume linearity. The RF model was built using the randomForest package in R, with 1000 trees (ntree = 1000). Variable importance was quantified by the percentage increase in mean squared error (%IncMSE). To visualize the marginal effect of each predictor on Fs while holding other variables at their mean values, we generated partial dependence plots from the RF model.

To explicitly quantify the independent and shared (interactive) contributions of environmental factors to Fs variation, we conducted hierarchical partitioning (HP). The method decomposes the total explained variance (R^2) into the unique contribution of each single factor, the contributions of pairwise interactions, and higher-order interactions.

To further capture potential nonlinear relationships, polynomial regression models incorporating quadratic terms were constructed. Additionally, structural equation modelling (SEM) was employed to explore the relative importance of various environmental factors influencing Fs and to disentangle their direct and indirect pathways (Lefcheck, 2016). Model fit was evaluated using Fisher 's C statistic and the Akaike Information Criterion (AIC).

All statistical analyses were performed in the R 4.5.1 (R Core Team, 2025) with RStudio (Posit Team, 2025), primarily using ggplot2 packages (Wickham, 2016).

3 Results

3.1 Spatial variation of Fs across global desert regions

The 563 observations included in this study were derived from different desert regions globally. Nocturnal Fs ranged from -0.512 to -0.025 μmol m^{-2} s^{-1}, with a mean value of -0.195 μmol m^{-2} s^{-1}. Substantial spatial variation in Fs was observed across the five desert biogeographic regions. The mean Fs values were −0.224 ± 0.063 μmol m^{-2} s^{-1} for the Central Asian Desert Area, −0.178 ± 0.057 μmol m^{-2} s^{-1} for the Circum-Mediterranean Desert Area, −0.138 ± 0.033 μmol m^{-2} s^{-1} for the North American Desert Area, −0.179 ± 0.030 μmol m^{-2} s^{-1} for the Southern African Desert Area, and −0.204 ± 0.053 μmol m^{-2} s^{-1} for the Antarctic Desert Area (Fig. 2). The North American Desert Area exhibited the highest mean Fs (i.e., weakest CO_2 uptake), significantly higher than those of the Central Asian and Antarctic Desert Areas. No significant difference was found between the Central Asian and Antarctic Desert Areas, both of which had the lowest Fs levels.

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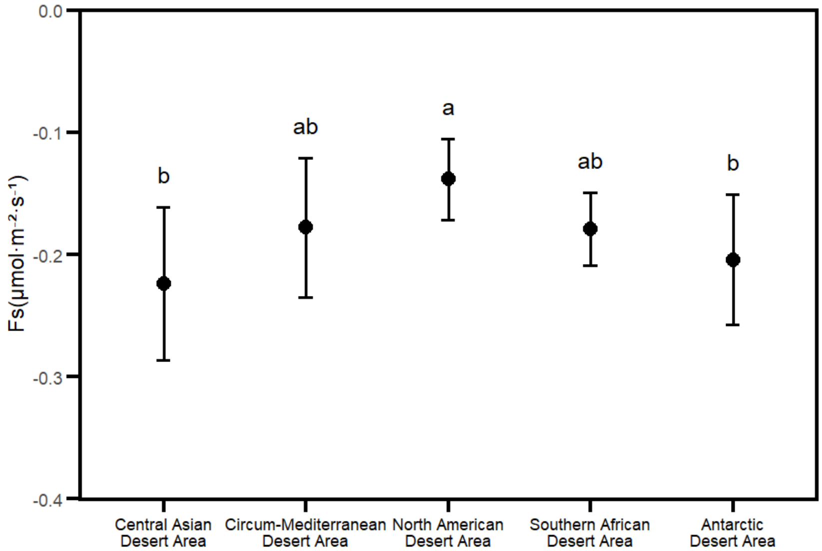

Figure 2: Fs among five major desert regions. Points represent means with 95% confidence intervals. Different letters indicate the obvious discrepancy across different areas.

3.2 Independent and interactive effects of environmental factors on Fs

Based on the 563 observations compiled from the 30 selected studies, we quantified the effects of temperature, soil moisture, pH, and soil texture on nocturnal soil CO_2 influx using Pearson correlation, linear mixed-effects models (LMM), random forest (RF) regression, polynomial regression, and hierarchical partitioning (HP).

Pearson correlation analysis revealed that Fs exhibited a significant positive correlation with air-soil temperature difference (ΔT, $r = 0.36$, $p < 0.001$), and negative correlations with soil water content (θv, $r = -0.32$, $p < 0.001$), soil pH ($r = -0.37$, $p < 0.001$), and ln(sand/clay) ($r = -0.18$, $p < 0.001$). Notably, no significant correlation was detected between Fs and Ts individually (Fig. 3). In addition, moderate to weak correlations were observed among the environmental factors: ΔT was negatively correlated with θv ($r = -0.31$), θv was negatively correlated with ln(sand/clay) ($r = -0.13$), while all other pairwise correlations were weak.

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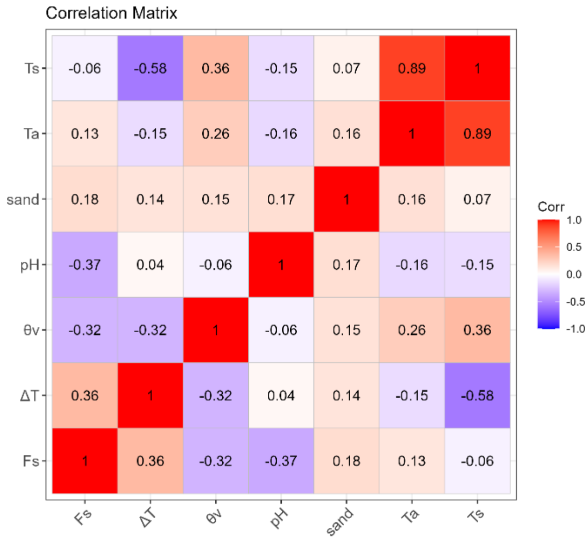

Figure 3: Pearson correlation heatmap illustrating the relationships between Fs and environmental factors across global desert ecosystems. The heatmap displays only the lower triangle of the symmetric correlation matrix. The analyzed variables include: Fs, ΔT, θv, soil pH, ln(sand/clay), Ta, and Ts. The color gradient corresponds to the Pearson correlation coefficient (r), with blue tones indicating positive correlations and red tones indicating negative correlations, spanning from -1 (perfect negative correlation) to 1 (perfect positive correlation). Numerical values within each cell represent the specific correlation coefficients between the paired variables.

The linear mixed effects model (with site as random effect) showed that ΔT, θv, pH, and ln(sand/clay) collectively explained a significant portion of Fs variation (marginal R^2 = 0.307, conditional R^2 = 0.789). All four factors had statistically significant fixed effects ($p < 0.01$). The random intercept for site accounted for substantial variance.

To capture potential nonlinear relationships, we performed random forest (RF) regression. The RF model explained 71.52% of the variance in Fs, indicating that nonlinear relationships are important. Variable importance, measured by the increase in mean squared error (%IncMSE), revealed that pH was the most important predictor (103.4%), followed by ΔT (82.3%), ln(clay/sand) (80.0%), and θv (72.8%) (Fig. 4).

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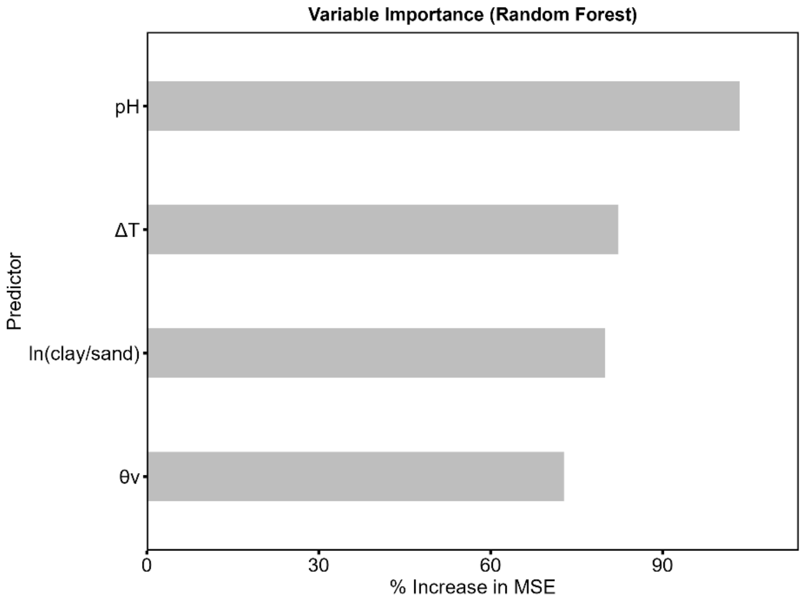

Figure 4: Variable importance of environmental factors for soil CO_2 flux quantified by random forest model. The x-axis represents the percentage increase in mean squared error (% Increase in MSE), with higher values indicating stronger explanatory capacity of variables.

Partial dependence plots (Fig. 5) further elucidated the marginal effect of each predictor on Fs after accounting for other variables. The response to ΔT was negative, indicating stronger uptake with larger temperature gradients, but it exhibited a clear nonlinear pattern. In contrast, the response to pH was nearly linear and steep across the centered pH range, with Fs becoming more negative as pH increased and showing no sign of saturation within the observed range. The response to θv was also negative but exhibited a threshold like pattern, with Fs decreasing sharply at low moisture levels and then plateauing, indicating diminishing returns of moisture on uptake beyond a certain threshold. For soil texture, the response was weakly negative and nearly linear across the centered ln(sand/clay) range, consistent with a moderate facilitation effect of coarse texture on gas entry. These patterns confirm that the effects of ΔT and θv on Fs are predominantly nonlinear or threshold driven, which linear models cannot adequately capture.

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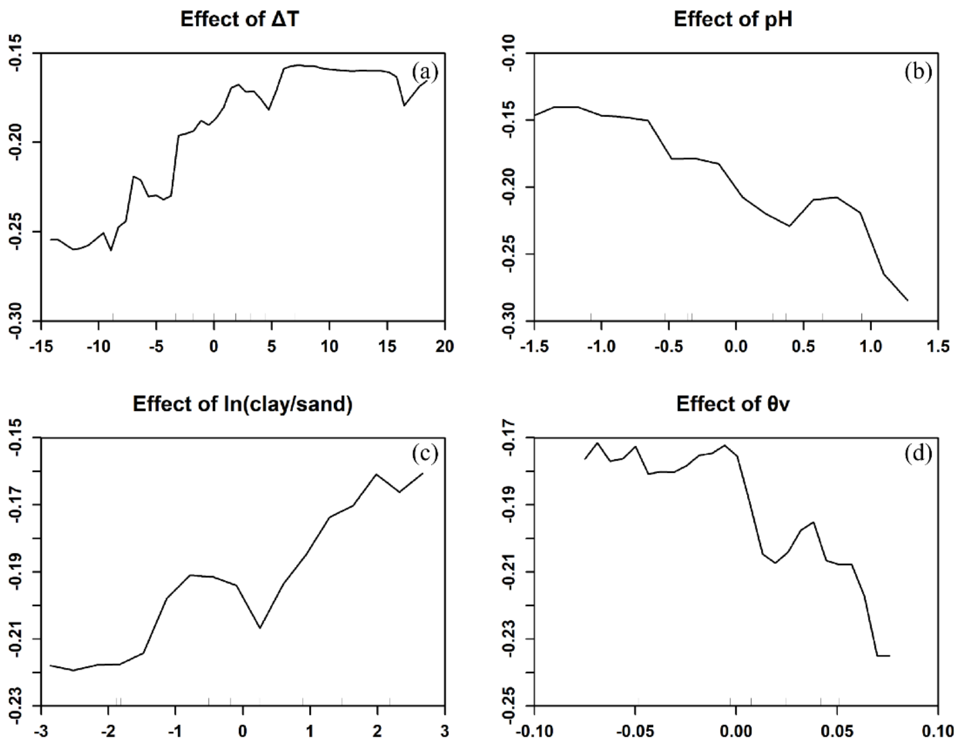

Figure 5: Partial dependence plots from random forest model illustrating the marginal effects of key environmental variables on nocturnal soil CO_2 flux (Fs) in desert ecosystems. The horizontal axes represent standardized values of environmental predictors (ΔT): air-soil temperature difference; pH: soil pH; (θv): volumetric soil water content; ln(sand/clay): Soil texture), and vertical axes denote the predicted response of soil CO_2 flux driven by each single variable.

To explicitly quantify the unique versus interactive contributions of the four environmental factors to Fs variation, we performed Hierarchical Partitioning (HP). The total explained variation (adjusted R^2) was 39.8%. As shown in Fig. 6, the unique contributions of individual factors were: pH (40.6%) >ΔT (25.2%) > θv (22.3%) > ln(sand/clay) (11.8%). Among all factor pairs, the interaction between ΔT and θv exhibited the largest positive shared contribution, explaining 18.51% of the variance. All four factors made significant contributions to Fs. By contrast, other pairwise interactions were either weak or constrained by collinearity, yielding negative adjusted R^2 values.

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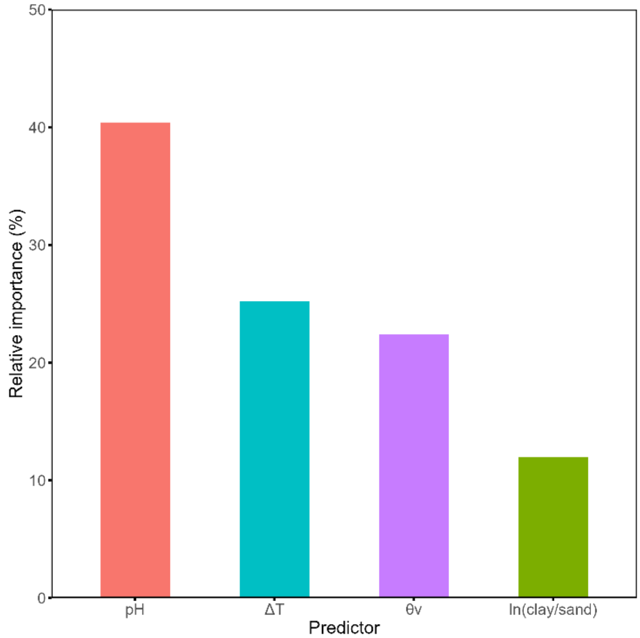

Figure 6: Relative importance (%) of environmental variables for nocturnal soil CO_2 flux in desert ecosystems.

3.3 Regression Relationships Between Fs and Environmental Variables

Negligible correlations were found with Ta (Fig. 7a) or Ts (Fig. 7b) individually. Soil electrical conductivity (Fig. 7c) showed no significant effect on Fs ($p > 0.05$) and was therefore excluded from subsequent analyses (c).

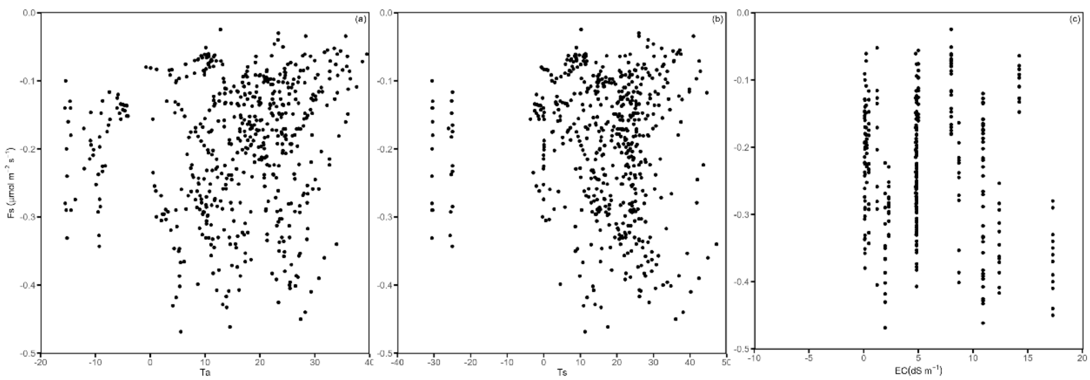

Figure 7: Scatter plots of soil CO_2 flux (Fs) versus air temperature (Ta) (a), soil temperature (Ts) (b), and soil electrical conductivity (EC) (c) in global desert regions.

The CO_2 uptake rate responds differently to environmental factors. Specifically, the CO_2 uptake rate increases (approaches zero) with increasing ΔT (Fig. 8a). Fs was significantly negatively correlated with soil pH ($P < 0.001$) (Fig. 8b), indicating that CO_2 uptake increases with rising soil pH. Additionally, a significant quadratic relationship was detected between Fs and θv ($P < 0.001$) (Fig. 8c). Over the observed θv range, Fs decreased with increasing θv, suggesting enhanced CO_2 uptake at higher soil water content. Meanwhile, CO_2 uptake rate also increases with ln(sand/clay) ($P < 0.001$) (Fig. 8d).

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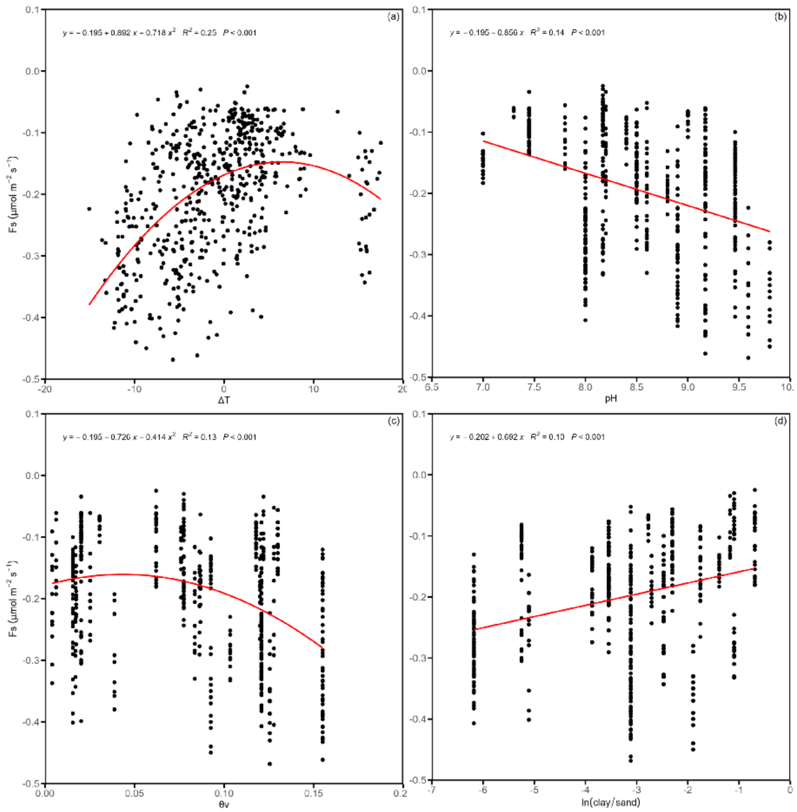

Figure 8: Relationships between nocturnal soil CO_2 influx (Fs) and environmental factors in desert ecosystems. (a) Air-soil temperature difference (ΔT); (b) soil pH; (c) soil moisture (θv); (d) ln(sand/clay).

205 **3.4 Direct and Indirect Effects of ΔT, θv, pH, and ln(clay/sand) on Fs (SEM)**

To disentangle the causal pathways through which environmental factors influence Fs, we constructed a structural equation model (SEM) based on a priori hypotheses informed by the RF and VPA results. The structural equation model explained 40% of the variation in Fs. The SEM revealed that nighttime Fs was directly driven by ΔT, soil pH, ln(sand/clay), and θv (Fig. 9). Among these, ΔT exhibited only a direct effect (standardized path coefficient = 0.249). Soil pH had a direct effect of −0.44 on Fs and an indirect effect of −0.092 via soil water content. And ln(sand/clay) showed indirect effects of −0.265 on the ΔT and −0.163 on θv, as well as a direct effect of −0.265 on Fs. θv had an indirect effect on ΔT with a standardized path coefficient of -0.363, and a direct effect on Fs of -0.304.

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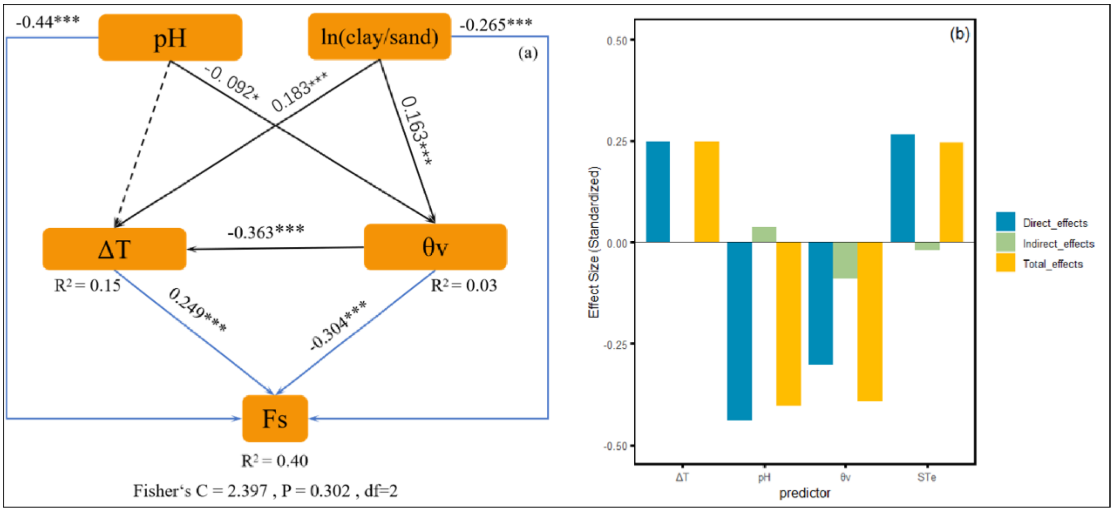

Figure 9: Structural equation model (SEM) illustrating the relationships between Fs and environmental drivers (a), and the corresponding standardized direct, indirect, and total effects (b). Path coefficients are displayed along the lines, where solid and dotted lines denote statistically significant and non-significant pathways, respectively. Significance is marked with asterisks: ***P < 0.001, **P < 0.01, *P < 0.05.

4 Discussion

4.1 Nocturnal soil CO_2 influx, NEE, and soil respiration rate in desert regions

Across 563 observations from global deserts, the mean nocturnal soil CO_2 influx (Fs) was −0.195 μmol m^{-2} s^{-1} (−72.84 g C m-2 yr-1). To assess its ecological significance, we compared this value with reported net ecosystem exchange (NEE) in the desert ecosystems. Mean NEE value measured in the Sonoran, Qaidam Basin, Badain Jaran, Chihuahuan and Tabernas Deserts was −280.8 g C m^{-2} a^{-1} (Ming et al., 2025). NEE acrossed five typical sandy land including the Songnen, Hulunbuir, Horqin, Otindag, and Mu Us Sandy Lands, ranged from −130.68 to −216.14 g C m^{-2} yr^{-1} (Huishi Du, 2025). In the present study, mean annual cumulative nocturnal soil CO_2 influx across global deserts was −72.84 g C m^{-2} yr^{-1}, equivalent to about 25%–50% of reported desert ecosystem NEE, indicating that nocturnal soil CO_2 influx was an important component of carbon absorption in desert ecosystems.

Furthermore, we compared the mean Fs obtained in the study with published nocturnal soil respiration rates. The mean soil respiration rates were measured as 1.46, 0.97, 0.33, 2.45, 1.96, 1.70, and 0.90 μmol m^{-2} s^{-1}1 for the Chihuahuan, Great Basin, Mojave, Sagebrush steppe, Sonoran, Polar semi desert, and Polar desert, respectively (Cable et al., 2011). These flux estimates generally did not account for nocturnal CO_2 influx. If this nocturnal CO_2 uptake component were fully considered, the soil respiration rate in desert regions would theoretically increase by 10% – 35%. This comparison intimated that future soil respiration studies should be recommended to fully account for nocturnal soil CO_2 influx. Otherwise, respiration rates could be significantly underestimated, distorting our understanding of desert carbon cycling. Together, the comparisons with

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NEE and soil respiration suggested that nocturnal negative CO_2 influx was a non-negligible component of carbon cycling in arid regions.

The mean Fs values for the Central Asian Desert Area, Circum Mediterranean Desert Area, North American Desert Area, Southern African Desert Area, and Antarctic Desert Area were ranged from −0.138 to −0.224 μmol m^{-2} s^{-1} (Fig. 2), respectively. Among these, CO_2 uptake rate was highest in the Central Asian Desert Area and lowest in the North American Desert Area. These regional differences likely arose from spatial variations in temperature, moisture conditions, and soil properties across desert.

4.2 Responses of Fs to Environmental Factors

In this study, the integrated analysis identified ΔT as one of the main direct factors associated with nocturnal soil CO_2 influx (Fig. 8a), whereas neither Ta nor Ts alone showed a significant relationship with Fs (Fig. 7). The results that soil CO_2 influx strengthened with increasing ΔT aligned with observations from a range of desert regions, including the Gurbantunggut, Taklamakan, Mu Us, Negev, and Chihuahuan Deserts (Hamerlynck et al., 2013; Ma et al., 2015; Yang et al., 2020a; Gao et al., 2021; Bekin and Agam, 2023). During the exchange between soil air and atmospheric air, cold air enriched with CO_2 entered the soil, while warm air with lower CO_2 content was released into the atmosphere, the net exchange between the ground and the atmosphere was manifested as the transfer of atmospheric CO_2 into the soil, resulting in CO_2 uptake by the soil. However, the relationship was not linear. Partial dependence plots from both polynomial regression and random forest (Fig. 5) showed that, when ΔT exceeded a certain threshold, the response of Fs levelled off and other limiting factors began to dominate the CO_2 exchange between soil and atmosphere.

Soil pH was identified as the predictor affecting Fs, with its variable importance in the random forest model (Fig. 5) and its independent contribution in VPA analysis both reaching significant levels (Fig.6). Fs was significantly negatively correlated with soil pH (Fig. 8b), meaning higher alkalinity can enhance CO_2 uptake. The relationship could be attributed to the dissolution equilibrium described by Henry's law (Zeebe and Wolf-Gladrow, 2001) and the subsequent reactions:

$$\mathrm{CO_2(g) \rightleftharpoons CO_2(aq)}, \quad \text{(R1)}$$

$$\mathrm{CO_2(aq) + H_2O \rightleftharpoons H_2CO_3}\ , \quad \text{(R2)}$$

$$\mathrm{H_2CO_3 \rightleftharpoons H^+ + HCO_3^-}\ , \quad \text{(R3)}$$

$$\mathrm{HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}}\ , \quad \text{(R4)}$$

$$\mathrm{Ca^{2+} + CO_3^{2-} \longrightarrow CaCO_3(s)\downarrow}\ , \quad \text{(R5)}$$

In high-pH environments, lower H^+ concentrations in soil solution promoted the dissolution of gaseous CO_2, and this process enlarged the CO_2 gradient at the air-soil interface and thereby promoted soil CO_2 uptake. Under alkaline conditions, dissolved CO_2 ultimately dissociated bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). Continued H^+ consumption during

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dissociation shifted the dissolution equilibrium toward further gaseous CO_2 uptake. In arid soils with abundant Ca^{2+} and Mg^{2+}, CO_3^{2-} could precipitate as carbonates (Monger et al., 2015), thereby driving the equilibrium toward the right.

Fs was significantly negatively correlated with θv ($R^2 = 0.1$, $P < 0.001$), suggesting stronger soil CO_2 influx occurring at higher soil water content conditions. Desert soils are typically arid, and small changes in water content could substantially affect liquid-phase transport of CO_2 (Soper et al., 2017; Tucker et al., 2017; Bekin et al., 2025). This phenomenon likely resulted from the role of soil moisture in CO_2 dissolution. Water films coating soil particles enhanced the surface area available for gas dissolution and reactions (Richards and Kump, 2003), promoting the transition of CO_2 into the liquid phase. A slight increase in soil moisture could significantly enhance CO_2 uptake, as because the thickness of the adsorbed water film increased with increasing soil water content (Bojana and Borut, 2016), thereby promoting soil CO_2 absorption.

Soil porosity also significantly influenced Fs (Fig. 8d), with higher sand content (i.e., coarser texture) leading to stronger soil CO_2 uptake. Sandy desert soils typically had high porosity and aeration, which reduced gas diffusion resistance (Yabuki and Kitaya, 1984) and facilitated soil CO_2 exchange. Higher porosity also provided more space for gas retention, enabling CO_2 to reside in soil pores and thus further promoting CO_2 uptake by soil.

Our SEM results further revealed a complex network of direct and indirect pathways among these environmental factors (Yu et al., 2023). Among the variables included in the model, ΔT emerged as an important direct factor, with a positive direct effect (path coefficient = 0.2741), highlighting the key role of thermal convection. θv exhibited a significant negative direct effect on Fs (path coefficient = −0.304) and exerted an indirect effect through ΔT. Soil pH had the strongest negative direct effect on Fs (standardized path coefficient = −0.44), indicating that increasing soil alkalinity served as a direct chemical driving force for CO_2 uptake. In addition, pH produced an indirect effect via soil moisture, although its total effect remained dominated by the direct pathway. In contrast, ln(clay/sand) showed a negative direct effect on Fs (−0.2655), but its influence was largely indirect, mediated through θv and ΔT, resulting in a relatively small total effect. These results suggested that nocturnal CO_2 uptake in dryland soils should be a multi factor synergistically regulated process, yet its core driving forces can be attributed to two main mechanisms: physical and chemical.

4.3 Generation mechanism of nocturnal soil CO_2 flux in Deserts

Previous studies in different desert regions had referred the various mechanisms underlying nocturnal soil CO_2 influx. In the Mu Us Desert, thermal convection driven by the air-soil temperature difference was identified as a key mechanism (Liu et al., 2015b). In the Tabernas and Negev Deserts, studies showed that water vapor adsorption and the formation of thin water films under alkaline conditions promoted CO_2 dissolution and carbonate precipitation (Lopez-Canfin et al., 2022b; Bekin and Agam, 2023). However, these single-factor perspectives had largely overlooked the complex interactions among multiple environmental factors.

https://doi.org/10.5194/egusphere-2026-4692
Preprint. Discussion started: 26 August 2026

By integrating the results of our analysis with previous findings, we proposed a comprehensive physico chemical mechanism framework to elucidate the possible generation processes of nocturnal atmospheric CO_2 uptake by dryland soils (Fig. 10). In the physical transport process, thermal convection driven by the temperature difference acted as the primary physical driving force, continuously delivering CO_2 into the soil. A portion of the CO_2 entering soil pores was temporarily stored in the gas phase, particularly in highly porous sandy soils. The remaining CO_2 entering the soil dissolved in surface water films under alkaline conditions at the chemical level. It dissociated into HCO_3^- and CO_3^{2-} due to low H^+, and then precipitated as carbonates with Ca^{2+} and Mg^{2+}. Soil water films and soil pH acted as the respective sites for CO_2 dissolution and reaction, continuously leading to a net consumption of the incoming CO_2. The physical transport and chemical fixation processes described above operated in concert and jointly controlled the rate of nocturnal CO_2 influx in desert soils.

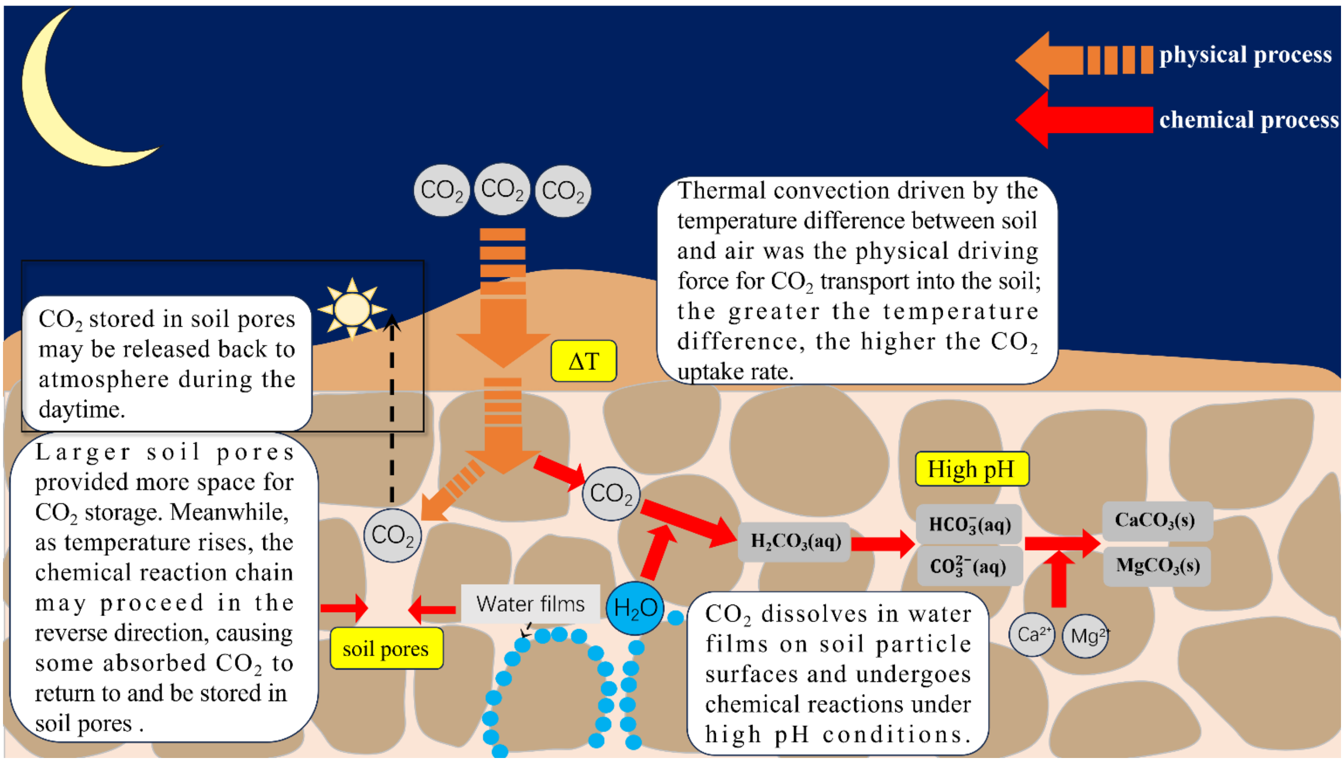

Figure 10: Conceptual framework illustrating the key mechanisms driving nocturnal soil CO_2 influx.

However, the physico-chemical framework proposed above remained primarily theoretical and has not yet been empirically verified. The future research could use ^{13}C isotopic labeling to test the physico-chemical framework proposed in this study. This would track the partitioning of labeled carbon between soil gas and liquid phases under controlled conditions of temperature difference, moisture, pH, and texture.

Information about the Supplement

Due to the large volume of data, the complete dataset is provided as a Supplement to this article.

Code and data availability

Data will be made available on request.

Author contributions

Yuan Huang: Writing (original draft preparation); Investigation; Formal analysis; Zhenyu Zhao: Methodology; Zimu Li: Formal analysis; Meixuan Pan: Writing (original draft preparation); Yang Gao: Funding acquisition; Methodology; Jiabin Liu: Funding acquisition; Investigation.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research was supported by the National Natural Science Foundation of China (No.32371965; No. 32101596)

https://doi.org/10.5194/egusphere-2026-4692
Preprint. Discussion started: 26 August 2026

References

Andrew David, T., Stephen Robert, H., and Andrew John, D.: Soil respiration at five sites along the Kalahari Transect: Effects of temperature, precipitation pulses and biological soil crust cover, Geoderma, 167-168, 284-294, https://doi.org/10.1016/j.geoderma.2011.07.034, 2011.

Ball, B. A. and Virginia, R. A.: Controls on diel soil CO_2 flux across moisture gradients in a polar desert, Antarctic Science, 27, 527-534, https://doi.org/10.1017/S0954102015000255, 2015.

Ball, B. A., Virginia, R. A., Barrett, J., Parsons, A. N., and Wall, D. H.: Interactions between physical and biotic factors influence CO_2 flux in Antarctic dry valley soils, Soil Biology and Biochemistry, 41, 1510-1517, https://doi.org/10.1016/j.soilbio.2009.04.011, 2009.

Bekin, N. and Agam, N.: Rethinking the deployment of static chambers for CO_2 flux measurement in dry desert soils, Biogeosciences, 20, 3791-3802, https://doi.org/10.5194/bg-20-3791-2023, 2023.

Bekin, N., Ashilenje, D., Chehbouni, A., Bouchaou, L., Kool, D., and Agam, N.: Pioneering evidence of the dynamics of water vapor and CO_2 fluxes in Sahara Desert soils, Journal of Geophysical Research: Biogeosciences, 130, e2025JG009193, https://doi.org/10.1029/2025JG009193, 2025.

Bojana, D. and Borut, M.: Determining the thickness of adsorbed water layers on the external surfaces of clay minerals based on the engineering properties of soils, Applied Clay Science, 123, 279-284, https://doi.org/10.1016/j.clay.2015.12.029, 2016.

Cable, J. M., Ogle, K., Lucas, R. W., Huxman, T. E., Loik, M. E., Smith, S. D., Tissue, D. T., Ewers, B. E., Pendall, E., and Welker, J. M.: The temperature responses of soil respiration in deserts: a seven desert synthesis, Biogeochemistry, 103, 71-90, https://doi.org/10.1007/s10533-010-9448-z, 2011.

Fa, K.-Y., Zhang, Y.-Q., Wu, B., Qin, S.-G., Liu, Z., and She, W.-W.: Patterns and possible mechanisms of soil CO_2 uptake in sandy soil, Science of the Total Environment, 544, 587-594, https://doi.org/10.1016/j.scitotenv.2015.11.163, 2016.

Fa, K., Lei, G., Zhang, Y., and Liu, J.: Carbon exchange process between atmosphere and soil in desert soils, Advances in Earth Science, 33, 464, https://doi.org/10.11867/j.issn.1001-8166.2018.05.0464, 2018a.

Fa, K., Zhang, Y., Lei, G., Wu, B., Qin, S., Liu, J., Feng, W., and Lai, Z.: Underestimation of soil respiration in a desert ecosystem, Catena, 162, 23-28, https://doi.org/10.1016/j.catena.2017.11.019, 2018b.

Fa, K. Y., Liu, J. B., Zhang, Y. Q., Wu, B., Qin, S. G., Feng, W., and Lai, Z. R.: CO_2 absorption of sandy soil induced by rainfall pulses in a desert ecosystem, Hydrological processes, 29, 2043-2051, https://doi.org/10.1002/hyp.10350Digital, 2015.

FAO and IIASA: Harmonized World Soil Database version 2.0, FAO; IIASA, Rome, Italy ; Laxenburg, Austria ;, 69 pp., https://doi.org/10.4060/cc3823en, 2023.

Gao, Y., Zhao, Z., Zhang, Y., and Liu, J.: Response of abiotic soil CO_2 flux to the difference in air-soil temperature in a desert, Sci Total Environ, 785, 147377, https://doi.org/10.1016/j.scitotenv.2021.147377, 2021.

Hamerlynck, E. P., Scott, R. L., Sánchez-Cañete, E. P., and Barron-Gafford, G. A.: Nocturnal soil CO_2 uptake and its relationship to subsurface soil and ecosystem carbon fluxes in a Chihuahuan Desert shrubland, Journal of Geophysical Research: Biogeosciences, 118, 1593-1603, https://doi.org/10.1002/2013JG002495, 2013.

Huishi Du, W. Q., Hasi Eerdun: Carbon sequestration in typical sandy lands of China from 1982 to 2024： Patterns, evolution and driving forces., Journal of Desert Research, 45, 59-69, https://doi.org/10.7522/j.issn.1000-694X.2025.00016, 2025.

Islam, W., Naveed, H., Zhihao, Z., Du, Y., Zhang, Y., Alshaharni, M. O., Khan, K. A., and Zeng, F.: Desert ecosystems as carbon frontiers: innovations in sequestration and climate adaptation strategies, Biological Reviews, 101, 615-643, https://doi.org/10.1111/brv.70096, 2026.

Jasoni, R. L., Smith, S. D., and Arnone III, J. A.: Net ecosystem CO_2 exchange in Mojave Desert shrublands during the eighth year of exposure to elevated CO_2, Global Change Biology, 11, 749-756, https://doi.org/10.1111/j.1365-2486.2005.00948.x, 2005.
Kim, M., Lopez-Canfin, C., Lázaro, R., Sánchez-Cañete, E. P., and Weber, B.: Unravelling the main mechanism responsible for nocturnal CO_2 uptake by dryland soils, Sci Total Environ, 926, 171751, https://doi.org/10.1016/j.scitotenv.2024.171751, 2024.
Lancaster, N.: Deserts, in: Geomorphology and Global Environmental Change, edited by: Slaymaker, O., Spencer, T., and Embleton-Hamann, C., Cambridge University Press, Cambridge, 276-296, DOI: 10.1017/CBO9780511627057.011, 2009.
Lefcheck, J. S.: piecewiseSEM: Piecewise structural equation modelling in r for ecology, evolution, and systematics, Methods in ecology and evolution, 7, 573-579, https://doi.org/10.1111/2041-210X.12512, 2016.
Li, X., Duan, H., and Yang, X.: A comprehensive China topsoil dataset of high-resolution microstructure, topographical characteristics and physical properties, Scientific Data, 13, 769, https://doi.org/10.1038/s41597-026-07049-x, 2026.
Liu, J., Fa, K., Zhang, Y., Wu, B., Qin, S., and Jia, X.: Abiotic CO_2 uptake from the atmosphere by semiarid desert soil and its partitioning into soil phases, Geophysical Research Letters, 42, 5779-5785, https://doi.org/10.1002/2015GL064689Digital, 2015a.
Liu, J., Feng, W., Zhang, Y., Jia, X., Wu, B., Qin, S., Fa, K., and Lai, Z.: Abiotic CO_2 exchange between soil and atmosphere and its response to temperature, Environmental Earth Sciences, 73, 2463-2471, https://doi.org/10.1007/s12665-014-3595-9, 2015b.
Liu, Y., Yang, F., Liu, X., Yang, P., Ma, H., Zheng, X., Yang, X., Abudukad, S., Gao, J., and Zhang, F.: Warming Enhances CO_2 Flux from Saline–Alkali Soils by Intensifying Moisture–Temperature Interactions in the Critical Zone, Land, 14, 1964, https://doi.org/10.3390/land14101964, 2025.
Lopez-Canfin, C., Lázaro, R., and Sánchez-Cañete, E. P.: Water vapor adsorption by dry soils: A potential link between the water and carbon cycles, Sci Total Environ, 824, 153746, https://doi.org/10.1016/j.scitotenv.2022.153746, 2022a.
Lopez-Canfin, C., Lázaro, R., and Sánchez-Cañete, E. P.: Disparate responses of soil-atmosphere CO_2 exchange to biophysical and geochemical factors over a biocrust ecological succession in the Tabernas Desert, Geoderma, 425, 116067, https://doi.org/10.1016/j.geoderma.2022.116067, 2022b.
Ma, J., Li, Y., and Liu, R.: The abiotic contribution to total CO_2 flux for soils in arid zone, Biogeosciences Discussions, 12, 11217-11244, https://doi.org/10.5194/bgd-12-11217-2015, 2015.
Ma, J., Wang, Z., Tang, L., and wang, Y.: Effect of soil abiotic processes on soil CO_2 flux in saline/alkaline soils (in Chinese), Arid Land Geography, 37, 555-560, https://doi.org/10.13826/j.cnki.cn65-1103/x.2014.016, 2014.
Ming, W., Xu, T., Xiao, J., Liu, S., Xu, Z., and Lin, J.: Responses and shifting drivers of ecosystem carbon fluxes under drought conditions, Ecological Indicators, 179, 114283, https://doi.org/10.1016/j.ecolind.2025.114283, 2025.
Monger, H. C., Kraimer, R. A., Khresat, S. e., Cole, D. R., Wang, X., and Wang, J.: Sequestration of inorganic carbon in soil and groundwater, Geology, 43, 375-378, https://doi.org/10.1130/G36449.1, 2015.
Mordhorst, A., Peth, S., and Horn, R.: Influence of mechanical loading on static and dynamic CO_2 efflux on differently textured and managed Luvisols, Geoderma, 219, 1-13, https://doi.org/10.1016/j.geoderma.2013.12.020, 2014.
Parsons, A. N., Barrett, J., Wall, D. H., and Virginia, R. A.: Soil carbon dioxide flux in Antarctic dry valley ecosystems, Ecosystems, 7, 286-295, https://doi.org/10.1007/s10021-003-0132-1, 2004.
Posit team: RStudio: Integrated Development Environment for R, Posit Software, PBC [code], 2025.
R Core Team: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing [code], 2025.
Richards, P. L. and Kump, L. R.: Soil pore-water distributions and the temperature feedback of weathering in soils, Geochimica et cosmochimica acta, 67, 3803-3815, https://doi.org/10.1016/S0016-7037(03)00270-9, 2003.
Romero-Mujalli, G., Hartmann, J., Börker, J., Gaillardet, J., and Calmels, D.: Ecosystem controlled soil-rock pCO_2 and carbonate weathering–Constraints by temperature and soil water content, Chemical Geology, 527, 118634, https://doi.org/10.1016/j.chemgeo.2018.01.030, 2019.
Sagi, N., Zaguri, M., and Hawlena, D.: Soil CO_2 influx in drylands: a conceptual framework and empirical examination, Soil Biology and Biochemistry, 156, 108209, https://doi.org/10.1016/j.chemgeo.2018.01.030, 2021.
Shanhun, F. L., Almond, P. C., Clough, T. J., and Smith, C. M.: Abiotic processes dominate CO_2 fluxes in Antarctic soils, Soil Biology and Biochemistry, 53, 99-111, https://doi.org/10.1016/j.soilbio.2012.04.027, 2012.

https://doi.org/10.5194/egusphere-2026-4692
Preprint. Discussion started: 26 August 2026

Soper, F. M., McCalley, C. K., Sparks, K., and Sparks, J. P.: Soil carbon dioxide emissions from the Mojave desert: Isotopic evidence for a carbonate source, Geophysical Research Letters, 44, 245-251, https://doi.org/10.1002/2016GL071198Digital, 2017.

Tucker, C. L., McHugh, T. A., Howell, A., Gill, R., Weber, B., Belnap, J., Grote, E., and Reed, S. C.: The concurrent use of novel soil surface microclimate measurements to evaluate CO_2 pulses in biocrusted interspaces in a cool desert ecosystem, Biogeochemistry, 135, 239-249, https://doi.org/10.1007/s10533-017-0372-3, 2017.

Vargas, R., Carbone, M. S., Reichstein, M., and Baldocchi, D. D.: Frontiers and challenges in soil respiration research: from measurements to model-data integration, Biogeochemistry, 102, 1-13, https://doi.org/10.1007/s10533-010-9462-1, 2011.

Wang, Z.-y., Xie, J.-b., Wang, Y.-g., and Li, Y.: Soil inorganic CO_2 flux in relation to soil pH and electric conductivity in saline/alkaline soils (in Chinese), Chinese Journal of Ecology, 32, 2552, https://doi.org/10.13292/j.1000-4890.2013.0278, 2013.

Wang, Z.-Y., Xie, J.-B., Wang, Y.-G., and Li, Y.: Biotic and abiotic contribution to diurnal soil CO_2 fluxes from saline/alkaline soils. , Scientific Reports, 10, 5396, https://doi.org/10.1038/s41598-020-62209-2, 2020.

Wankmüller, F. J. P., Delval, L., Lehmann, P., Baur, M. J., Cecere, A., Wolf, S., Or, D., Javaux, M., and Carminati, A.: Global influence of soil texture on ecosystem water limitation, Nature, 635, 631-638, https://doi.org/10.1038/s41586-024-08089-2, 2024.

Wickham, H.: ggplot2: Elegant Graphics for Data Analysis, Springer-Verlag New York2016.

Wu, Y.-H., Wu, Y.-F., Fan, L.-W., Yu, Z.-T., and Khodadadi, J.: Thermal conductivity of soil: A review on the vast experimental data and predictive models, International Journal of Thermal Sciences, 208, 109486, https://doi.org/10.1016/j.ijthermalsci.2024.109486, 2025.

Xie, J., Li, Y., Zhai, C., Li, C., and Lan, Z.: CO_2 absorption by alkaline soils and its implication to the global carbon cycle, Environmental Geology, 56, 953-961, https://doi.org/10.1007/s00254-008-1197-0, 2009.

Yabuki, K. and Kitaya, Y.: Studies on the Control of Gaseous Environment in the Rhizosphere (1) Changes in CO_2 concentration and gaseous diffusion coefficient in soils after irrigation, Journal of Agricultural Meteorology, 40, 1-7, https://doi.org/10.2480/agrmet.40.1, 1984.

Yang, F., Ali, M., Zheng, X., He, Q., Yang, X., Huo, W., Liang, F., and Wang, S.: Diurnal dynamics of soil respiration and the influencing factors for three land-cover types in the hinterland of the Taklimakan Desert, China, Journal of Arid Land, 9, 568-579, https://doi.org/10.1007/s40333-017-0060-0, 2017.

Yang, F., Huang, J., He, Q., Zheng, X., Zhou, C., Pan, H., Huo, W., Yu, H., Liu, X., and Meng, L.: Impact of differences in soil temperature on the desert carbon sink, Geoderma, 379, 114636, https://doi.org/10.1016/j.geoderma.2020.114636, 2020a.

Yang, F., Huang, J., Zhou, C., Yang, X., Ali, M., Li, C., Pan, H., Huo, W., Yu, H., and Liu, X.: Taklimakan desert carbon-sink decreases under climate change, Sci. Bull, 65, 431-433, https://doi.org/10.1016/j.scib.2019.12.022, 2020b.

Yates, E. L., Detweiler, A. M., Iraci, L. T., Bebout, B. M., McKay, C. P., Schiro, K., Sheffner, E. J., Kelley, C. A., Tadić, J. M., and Loewenstein, M.: Assessing the role of alkaline soils on the carbon cycle at a playa site., Environmental Earth Sciences, 70, 1047-1056, https://doi.org/10.1007/s12665-012-2194-x, 2013.

Yu, T., Han, T., Feng, Q., Chen, W., Zhao, C., Li, H., and Liu, J.: Divergent response to abiotic factor determines the decoupling of water and carbon fluxes over an artificial C4 shrub in desert, Journal of Environmental Management, 344, 118416, https://doi.org/10.1016/j.jenvman.2023.118416, 2023.

Yue, P., Cui, X., Gong, Y., Li, K., Goulding, K., and Liu, X.: Impact of elevated precipitation, nitrogen deposition and warming on soil respiration in a temperate desert, Biogeosciences, 15, 2007-2019, https://doi.org/10.5194/bg-15-2007-2018, 2018.

Zeebe, R. E. and Wolf-Gladrow, D.: CO_2 in seawater: equilibrium, kinetics, isotopes, Gulf Professional Publishing2001.

Zhang, Z.-S., Li, X.-R., Nowak, R. S., Wu, P., Gao, Y.-H., Zhao, Y., Huang, L., Hu, Y.-G., and Jia, R.-L.: Effect of sand-stabilizing shrubs on soil respiration in a temperate desert, Plant and Soil, 367, 449-463, https://doi.org/10.1007/s11104-012-1465-3, 2013.