Characteristics of Surface CO2 Flux Variations in Sandy Loam Soils under Different Land Use Types in the Loess Region: A Case Study of the Qingliangsigou Watershed (Postprint)

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Date: 2021-08-12T00:00:00+00:00

Abstract

Using the LI-8100A automated soil carbon flux measurement system, surface soil CO2 flux was measured in the Qingliangsi Gully watershed of the loess hilly and gully region in northwestern Shanxi, to investigate the spatiotemporal variation characteristics of CO2 flux, CO2 flux characteristics under different land use types, and the influence of environmental factors on CO2 flux, providing a supplement to research on surface soil CO2 flux in small watershed areas of the loess hilly and gully region in northwestern Shanxi. The results show that: (1) CO2 flux exhibited unimodal variation during the growing season, reaching its daily minimum around sunrise and its daily maximum between 16:00 and 22:00; during the non-growing season, it showed irregular variation. (2) The CO2 flux of cropland was lower than that of abandoned grassland and jujube forest land; the seasonal CO2 flux relationship was as follows: August had the highest CO2 flux, May had the second highest, and November had the lowest. (3) Surface soil CO2 flux is closely related to factors such as photosynthetically active radiation, atmospheric temperature, soil temperature, soil moisture content, soil organic matter, and soil texture; scientific land use practices can effectively enhance soil carbon sequestration capacity.

Full Text

Study on Variation Characteristics of Surface CO2 Flux in Sandy Loam Soil Under Different Land Use Types in the Loess Region: A Case Study of the Qingliangsi Ditch Watershed

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Abstract

This study measured surface soil CO_2 fluxes in the Qingliangsi ditch watershed of the Loess Hills and Gullies region in northwestern Shanxi using an LI-8100A soil carbon flux automatic measurement system. The research explored the spatiotemporal variation characteristics of CO_2 flux, flux patterns under different land use types, and the influence of environmental factors on CO_2 flux, thereby supplementing existing research on surface soil CO_2 fluxes in small watershed areas of the Loess Hills and Gullies region in northwestern Shanxi. Results indicate that: (1) CO_2 flux exhibited unimodal variation during the growing season, reaching daily minimum values around sunrise and daily maximum values between 16:00-22:00; during the non-growing season, variation patterns were irregular. (2) Farmland CO_2 flux was lower than that of waste grassland and jujube forest land. (3) Seasonal CO_2 flux relationships showed August > May > November. (4) Surface soil CO_2 flux was closely correlated with photosynthetic active radiation, atmospheric temperature, soil temperature, soil moisture content, soil organic matter, and soil texture. Scientific land use practices can effectively enhance soil carbon sequestration capacity.

Keywords: soil CO_2 flux; spatiotemporal variation characteristics; influencing factors; land use type; loess hilly gully area; northwestern Shanxi

Introduction

Soil CO_2 flux represents a critical component of the carbon cycle and has become essential content in current global warming research. As a key hub connecting soil and atmospheric carbon pools, even minor changes in soil CO_2 flux significantly impact global carbon cycling and balance. The Loess Plateau, located in arid and semi-arid climate zones with deep loess deposits, abundant soil resources, and large carbon storage capacity, represents an extremely ecologically sensitive region in China with unstable surface carbon emissions. As a transitional zone between semi-arid and semi-humid regions, the Loess Plateau features diverse land use patterns. Unreasonable land use practices affect the carbon sequestration capacity of soil and vegetation, exacerbating unstable surface carbon emissions. Currently, large-scale "Grain for Green" programs implemented in the Loess Plateau represent concrete measures to adjust unreasonable land use patterns for ecological construction. Scientific land use practices can increase soil carbon sequestration capacity, thereby mitigating global warming.

Analysis shows that soil respiration rates are determined by the combined effects of multiple influencing factors, with soil temperature and moisture playing dominant roles. Since temperature is a key factor regulating many ecological processes, multiple aspects of soil carbon cycling are directly or indirectly affected by temperature, and soil respiration increases with rising temperature. Soil moisture also significantly affects soil respiration, though in more complex ways, as both excessively high and low moisture content can inhibit soil respiration. Soil organic matter serves as an important substrate for soil respiration and positively correlates with soil respiration rates. Land use patterns affect atmospheric CO_2 content, and different land use types have varying effects on soil respiration. Farmland ecosystems, as areas with intensive human activity, can inhibit soil CO_2 release to the atmosphere, playing a positive role in mitigating global warming.

Soil respiration can be defined as soil surface CO_2 flux, comprising both autotrophic and heterotrophic respiration, and is influenced by environmental factors including temperature, moisture, light, and organic matter throughout the process. The complex control mechanisms of soil respiration and their interactions across multiple spatiotemporal scales make soil respiration mechanisms increasingly complex. Regarding the main influencing factors of soil respiration, previous research has focused on single vegetation types or single ecosystems. This study takes the Qingliangsi ditch watershed in the Loess Hills and Gullies region as the research object, systematically analyzing soil CO_2 fluxes under different land use types in the Loess region of northwestern Shanxi using the LI-8100A soil carbon flux automatic measurement system. By combining temporal and spatial scales in the study area and comprehensively examining environmental factors, this research analyzes variation characteristics of surface soil CO_2 flux to assess the impact of soil respiration on carbon sinks. Understanding the response and variation patterns of CO_2 flux to land use and climate factors provides an important foundation for ecological construction and land use structure optimization in this region, which is significant for implementing reasonable farmland management measures and land use practices to mitigate and even improve climate warming.

1.1 Study Area Overview

The study area is the Qingliangsi ditch watershed, located in the central-eastern Loess Plateau, east of the Yellow River, with terrain sloping from north to south. As a first-level tributary on the eastern bank of the Yellow River, it is administratively part of Lin County, Lüliang City, Shanxi Province, with geographical coordinates of 110°55 E and 37°45 -38°5 N. The watershed is primarily covered by loess, with developed hills and gullies, relatively simple loess stratigraphy, clear watershed boundaries, and appropriate watershed scale. Severe soil and water loss has resulted in fragmented terrain with crisscrossing gullies, making it a typical Loess Hills and Gullies region. The area has a continental monsoon climate with distinct seasons, synchronized rainfall and heat, and abundant sunlight. Spring is dry, windy, and rainless, while summer is hot with concentrated rainfall. Annual sunshine hours range 2487-2872 h, average annual temperature is 9.5°C, and average annual precipitation is only 437 mm.

Based on hydrological stations, meteorological stations, and observation feasibility in the study area, three observation zones (upstream, midstream, and downstream) were selected in the Qingliangsi ditch watershed. Through data collection for the Loess region of northwestern Shanxi and investigation of the Qingliangsi ditch watershed, local land use types mainly include farmland (planting corn and potatoes), forest land (dominated by jujube and apricot trees), and abandoned grassland (excluding construction land). Therefore, three typical land use types were selected within the observation zones: waste grassland, farmland, and jujube forest land. Specifically, these include waste grassland (Zhangguocun upstream) and farmland (Zhangguocun upstream), jujube forest land (Qingliangsi Village midstream), and jujube forest land (Yangjiapo Village downstream).

1.2 Research Methods

This study examined surface soil CO_2 fluxes under different land use types in the Qingliangsi ditch watershed of Lin County, Shanxi. An LI-8100A carbon flux automatic measurement system was used to conduct measurements of surface soil CO_2 fluxes in farmland, jujube forest land, and waste grassland during both growing and non-growing seasons. Annual precipitation and temperature anomaly data were collected and plotted [Figure 9: see original paper]. The 2019 annual precipitation was 442.5 mm and annual average temperature was 9.39°C, approximately equal to the 1989-2019 average. As shown in the figure, 2019 was representative without extreme climate conditions, so observations were conducted in 2019.

All observation zones were measured seasonally, with each zone observed continuously for 3 days per season across two hydrological years. Considering that spring in the study area is dry, windy, and rainless while summer is hot with concentrated rainfall, and autumn/winter have lower atmospheric temperatures, observation times were selected on clear days with normal climatic conditions and no recent precipitation impact. This selection excluded precipitation effects on soil moisture content. Daily climate conditions were compared with historical meteorological data to avoid abnormal effects of excessively high or low atmospheric temperatures on soil CO_2 flux. Clear weather was also the basic condition for observing photosynthetic active radiation. Observations were conducted during daytime in November, December, and January due to nighttime atmospheric temperatures being below the instrument' s minimum operating temperature.

Field in-situ observation procedures and parameter settings: First, the soil ring of the short-term survey chamber was buried at the sample point, exposing 2 cm above ground, then the chamber was gently placed horizontally on the soil ring. Sample points were selected on uniform, flat ground surfaces, avoiding areas with insect holes, cracks, or rills. Vegetation and litter within the soil ring were cut and removed to minimize human impact on observation results. At each CO_2 flux measurement point, a Delta-T Theta soil moisture probe was inserted 30 cm deep to measure soil temperature and moisture.

During May, August, and November, daytime observations were conducted at each sample point every 0.5 hours, with three replicate measurements. Observation duration was set to 120 s, chamber closure and measurement start time was set to 15 s, pre-closure mixing time was set to 10 s, and post-opening mixing time was set to 5 s. Photosynthetic active radiation was measured using the LI-190R sensor configured with the LI-8100A soil carbon flux automatic measurement system. Soil temperature was measured using the sensor configured with the LI-8100A system. Atmospheric temperature was measured using a liquid metal mercury thermometer. All data were recorded at 0.5-hour intervals.

Soil samples collected in the field underwent particle size analysis using a Mastersizer 2000 laser particle size analyzer after pretreatment to remove carbonates and organic matter. Soil organic matter content in 0-30 cm soil samples was determined using chemical titration, and soil moisture content was measured using the drying method.

1.3 Data Processing and Quality Control

The CO_2 flux data obtained from the LI-8100A soil carbon flux automatic measurement system were calculated from measured data and corrected, with final data precision within 1.5% of readings. The measurement range was -1 to 370 $\mathrm{mol \cdot mol^{-1}}$, with total drift <0.15 $\mathrm{mol \cdot mol^{-1}}$ and zero drift <0.1 $\mathrm{mol \cdot mol^{-1}}$. The calculation formula is as follows:

$$F = \frac{P \cdot V \cdot (C_0 - C_t)}{S \cdot (t - t_0)}$$

where F is the CO_2 emission flux; V is volume; P is initial pressure (kPa); C_0 is initial CO_2 molar fraction ($\mathrm{mol \cdot mol^{-1}}$); C_t is CO_2 molar fraction after moisture correction at time t ($\mathrm{mol \cdot mol^{-1}}$); S is measured soil area (cm^2); and t is time (s).

Since the LI-8100A system automatically performs flux calculations, CO_2 flux observation data only required strict screening at hourly intervals to eliminate obvious outliers caused by instrument malfunction or human operation errors.

Additionally, for three replicate measurements of the same dataset, standard error was calculated using the formula $SE = \frac{SD}{\sqrt{n}}$, with the principle of excluding data points greater than 2×SE from the time series. Observation data were retained to two decimal places. On this basis, FluxCV software was used to calculate the coefficient of variation for data with smaller time values, and LI-8100 File Viewer 3.1.0 software was used for data processing and quality control. Excel and Origin 2016 were used for mapping.

2 Results and Analysis

As shown in the data, CO_2 flux in Qingliangsi farmland varied from 0.51-1.86 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ with an average concentration of 1.04 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$; Zhangguocun farmland varied from 0.37-2.40 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ with an average of 1.78 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$; Yangjiapo jujube forest land varied from 2.09-3.61 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ with an average of 2.78 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$; and Zhangguocun waste grassland varied from 1.92-2.90 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ with an average of 2.33 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ [Figure 3: see original paper].

All observation zones showed regular unimodal variation in CO_2 flux, with minimum values occurring at the same time (around sunrise). After sunrise, flux gradually increased, reaching daily peaks between 16:00-22:00, then gradually decreased. The average concentration was 3.91 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. Due to rainy weather in August, Qingliangsi farmland CO_2 flux data could not be monitored, simultaneously affecting photosynthetic active radiation data. In November, lower temperatures and dormant herbaceous layers resulted in overall low CO_2 flux levels with irregular variation patterns.

Observation data from the four zones showed average concentrations of 0.44 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ for Qingliangsi farmland, 0.29 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ for Yangjiapo jujube forest land, 0.50 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ for Zhangguocun waste grassland, and 0.49 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ for Zhangguocun farmland.

3.1 Spatiotemporal Variation of CO_2 Flux Under Different Land Use Types

Different land use patterns affect the intensity of human activities and natural processes, thereby influencing carbon cycling. Seasonal variation patterns of CO_2 flux concentrations under different land use types were consistent, all showing August > May > November, with farmland CO_2 flux being the lowest [Figure 3: see original paper]. This may be related to temperature and photosynthetic active radiation effects on plant respiration rates.

The order of CO_2 flux from high to low was Yangjiapo jujube forest land, Zhangguocun waste grassland, Zhangguocun farmland, and Qingliangsi farmland. Farmland CO_2 flux was smaller than that of waste grassland and forest ecosystems, indicating that reasonable land use measures have a certain carbon fixation effect on soil. This aligns with Wang et al. [14], who found that scientific land use practices can increase carbon sequestration capacity.

At the daily scale, minimum values for all four observation zones appeared around sunrise. Qingliangsi farmland and Zhangguocun farmland showed consistent patterns, with CO_2 flux increasing after sunrise and reaching maximum values between 16:00-18:00 before gradually decreasing. Yangjiapo jujube forest land and Zhangguocun waste grassland showed similar patterns, but their maximum values appeared at 18:00-20:00 and 20:00-22:00, respectively. The overall average CO_2 flux concentration in May was close to that in August, while Zhangguocun waste grassland showed slightly higher concentration than jujube forest land and farmland. This demonstrates that reasonable management measures are important for carbon balance, and improved management can promote carbon absorption in waste grassland ecosystems [15].

CO_2 flux average concentrations among the three land use types of Zhangguocun farmland, Qingliangsi farmland, and Yangjiapo jujube forest land differed by only 0.1 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, showing no significant differences. In November, CO_2 flux concentrations dropped sharply, with maximum values less than 0.5 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ and all showing irregular variation patterns, indicating that plant senescence in the non-growing season significantly affects CO_2 flux. Zhangguocun waste grassland showed the largest variation amplitude, with an average concentration of 3.42 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

3.2 Correlation Analysis of Photosynthetic Active Radiation, Temperature, Soil Moisture, Soil Particle Size, and Soil Organic Matter with CO_2 Flux

3.2.1 Influence of Photosynthetic Active Radiation on Surface Soil CO_2 Flux Photosynthetic active radiation is closely related to CO_2 flux. As Fan et al. [16] noted, not only is this relationship close, but photosynthetic active radiation affects CO_2 flux primarily by influencing surface soil temperature and altering vegetation photosynthesis rates—directly affecting photosynthesis and indirectly affecting community carbon flux through stomatal conductance.

In May (representing spring), Yangjiapo jujube forest land CO_2 flux showed weak negative correlation with photosynthetic active radiation, while Qingliangsi farmland, Zhangguocun waste grassland, and Zhangguocun farmland showed significant positive correlation, with CO_2 flux increasing as photosynthetic active radiation increased. In August (representing summer), all observation zones showed weak positive correlation with photosynthetic active radiation. Due to more rainy days in summer, photosynthetic active radiation values were generally smaller. Zhangguocun farmland showed the largest span of photosynthetic active radiation, closely positively correlated with CO_2 flux. In November (representing autumn-winter), photosynthetic active radiation decreased significantly compared to spring and summer, and CO_2 flux also decreased markedly. Plant death in the non-growing season reduced the correlation between photosynthetic active radiation and CO_2 flux.

3.2.2 Influence of Temperature on Surface Soil CO_2 Flux As shown in [Figure 5: see original paper], atmospheric temperature, soil temperature, and photosynthetic active radiation all showed significant positive correlation with CO_2 flux. Changes in 30 cm soil temperature followed atmospheric temperature changes but with a lag. When atmospheric temperature reached daily peaks (14:00-16:00), soil temperature peaks occurred later. CO_2 flux changes were consistent with soil temperature changes, reaching daily peaks when soil temperature peaked, then showing significant decline. After sunrise, surface soil CO_2 flux rose rapidly, reaching daily peaks between 16:00-22:00, followed by slow decline. When soil temperature exceeded atmospheric temperature, CO_2 flux began to decrease, indicating that temperature increases within suitable ranges enhance soil microbial activity, thereby increasing soil respiration rates, while exceeding certain ranges causes microbial deactivation and decreased soil respiration rates.

In November, soil temperature changed with atmospheric temperature, rising slowly after sunrise and reaching daily peaks at 16:00-18:00, then gradually declining. However, CO_2 flux showed irregular variation at the daily scale, with maximum values appearing at sunrise and gradually decreasing, reaching minimum values when atmospheric temperature peaked, then slightly increasing. Overall winter CO_2 flux variation amplitude was small, fluctuating only between 0.2-0.4 $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$. Temperature affects not only soil microbial activity and community structure but also plant photosynthesis and root respiration rates [17]. The combination of temperature decrease and plant death in the non-growing season significantly affected soil CO_2 flux, resulting in low flux concentrations. This aligns with Fan et al. [18], who found that excessively high or low temperatures limit soil respiration and that temperature cannot permanently increase soil respiration.

3.2.3 Soil Particle Size Distribution Characteristics and Their Influence on CO_2 Flux The climate in the Loess Hills and Gullies region of northwestern Shanxi is drier with less rainfall compared to typical Loess regions such as the Guanzhong Plain and Weibei dry plateau. Consequently, soil texture is coarser, and sandy soil types dominate the region (except for exposed bedrock and gravel floodplains), making sandy loam texture representative and typical of the northwestern Loess region.

The study area is mainly distributed with dark loessial soil (Heilutu), widely distributed in northwestern China' s Loess erosion region and the primary soil type in this area [19]. Dark loessial soil distribution extends west to Linxia-Lanzhou, south to Tianshui-Baoji-Hancheng, east to Taiyuan-Datong, and north to Lanzhou-Jingbian-Datong. Dark loessial soil is classified into typical, clay, light, and meadow subtypes, plus black loam soil. The dark loessial soil in the study area belongs to the clay subtype.

Soil particle size distribution is often overlooked in CO_2 flux research. Different soil textures show significant differences in CO_2 flux. Accurately understanding

CO_2 flux variation characteristics under different textures provides important guidance for efficient land use and carbon emission control, making in-depth study of soil texture effects on CO_2 flux necessary. Surface soil samples collected from observation zones were analyzed using a laser particle size analyzer, with particle size data plotted in a triangular diagram [Figure 6: see original paper]. According to the Shepard classification, monitoring points showed similar particle size levels, with comparable distribution characteristics across profiles.

Based on particle size distribution characteristics of Zhangguocun farmland and Qingliangsi farmland surface soils, clay and silt content features were similar, with combined clay and silt content accounting for 53.14% and 54.31% of total content, respectively. Sand content in Yangjiapo jujube forest land and Zhangguocun waste grassland exceeded 52.00%, accounting for 50.47% of total content. In the Loess Hills and Gullies region, clay volume fraction is relatively low, with silt and sand dominating [20]. Farmland soil types belong to sandy silt, while waste grassland and jujube forest land belong to silty sand. The study area' s soil texture is sandy loam, representing both the northwestern Loess Hills and Gullies region and applicable to most of the Loess Plateau based on dark loessial soil distribution.

Chen et al. [21] found that soil texture is closely related to soil gas diffusion rates, affecting both plant root and soil microbial O_2 acquisition and CO_2 release from biological respiration. Therefore, land use types with higher sand content promote CO_2 release and accelerate gas diffusion rates. Consequently, farmland CO_2 flux was smaller than that of jujube forest land and waste grassland. Biological factors closely related to CO_2 flux play important controlling roles. Chen et al. [22] found that near field capacity is the optimal moisture state for CO_2 flux, and soil respiration is inhibited when soil is too dry or too wet.

Average soil particle size across the four observation zones from largest to smallest was: Yangjiapo jujube forest land, Zhangguocun waste grassland, Zhangguocun farmland, and Qingliangsi farmland, consistent with the order of CO_2 flux magnitude, indicating that soil texture significantly affects carbon emissions. When soil is more compact, gas release is inhibited, increasing soil carbon sequestration. Farmland soil particle size was smaller than that of jujube forest land and waste grassland, suggesting that effective long-term land use types may alter soil texture. Soils with good texture, having higher proportions of clay and silt, show stronger water-holding capacity, higher soil organic matter content, and faster decomposition rates, resulting in higher respiration rates [23].

3.2.4 Influence of Soil Moisture Content and Soil Organic Matter on CO_2 Flux Soil moisture content is an environmental factor affecting surface soil CO_2 flux, influencing vegetation growth, root distribution, and microbial activity. Overall, topsoil moisture content varied across months, with May at 12%-15%, August at 19%-21%, and November at 10%-13%. Individually, Yangjiapo jujube forest land showed the highest moisture content in August, opposite to other sites due to geographical factors causing rainwater to flow to the lower-elevation Yangjiapo observation zone during summer rainfall increases. During the growing season, soil moisture content was lower in May but CO_2 flux was higher. In the non-growing season, soil moisture remained around 10%-13%, with smaller variation in CO_2 flux, indicating that soil moisture inhibits CO_2 flux variation—lower moisture content corresponded to higher CO_2 flux. This may be because high soil moisture limits litter decomposition and water infiltration into soil pores, thereby hindering soil respiration [24]. The optimal moisture content for sandy loam is generally 12%-15%, and since the study area' s moisture content was relatively low, CO_2 flux was smaller, consistent with Chen et al. [22].

Soil organic matter is closely related to soil CO_2 flux, with different organic matter content significantly affecting soil respiration. Soil respiration is influenced by active organic matter components, and soil organic matter content positively correlates with soil respiration rate [25]. Organic matter content across the four observation zones fluctuated around 10-15 $g \cdot kg^{-1}$, generally similar. Yangjiapo jujube forest land and Zhangguocun waste grassland showed organic matter content of 12.3 $g \cdot kg^{-1}$ and 11.8 $g \cdot kg^{-1}$, respectively, higher than farmland organic matter content (10.5 $g \cdot kg^{-1}$). CO_2 flux showed a relatively obvious positive correlation with organic matter content characteristics. In May, farmland organic matter content increased slightly compared to August, but with small variation. Yangjiapo jujube forest land organic matter content (12.3 $g \cdot kg^{-1}$) increased significantly, while Zhangguocun waste grassland organic matter content (11.8 $g \cdot kg^{-1}$) decreased significantly. Zhangguocun farmland CO_2 flux was lower than the other three sites, while the other three sites showed smaller variation amplitude. This occurred because during the growing season, temperature and photosynthetic active radiation had greater influence on CO_2 flux than soil organic matter.

In November, Yangjiapo jujube forest land organic matter decreased by about 11.2%, while Qingliangsi farmland increased significantly to about 11.2%. Overall, Zhangguocun waste grassland and Zhangguocun farmland showed lower CO_2 flux, while Yangjiapo jujube forest land and Qingliangsi farmland showed higher CO_2 flux, consistent with organic matter variation trends. This indicates that in the non-growing season, microbial deactivation and plant senescence cause temperature and photosynthetic active radiation to have less influence on CO_2 flux than soil organic matter, which becomes the dominant factor.

4 Conclusions

(1) The diurnal variation pattern of surface soil CO_2 flux in the study area showed unimodal variation during the growing season, reaching daily maximum values between 16:00-22:00 and daily minimum values around sunrise; during the non-growing season, variation patterns were irregular.

(2) The spatiotemporal characteristics of CO_2 flux showed that farmland CO_2 flux was lower than that of waste grassland and jujube forest land, indicating that reasonable land use measures have positive effects on carbon emissions. Seasonal CO_2 flux relationships were August > May > November, related to sufficient precipitation, warm and suitable climate, and vegetation growth period in August, with soil root and microbial respiration rates being faster.

(3) Photosynthetic active radiation and atmospheric temperature affect soil temperature, and all three showed significant positive correlation with CO_2 flux. Land use type and moisture content also affect soil texture, with scientific land use types reducing soil porosity and thereby improving soil carbon sequestration capacity. High soil moisture content inhibits surface soil CO_2 flux; organic matter is not the dominant factor during the growing season but occupies a dominant position during the non-growing season, showing negative correlation with CO_2 flux.

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Note: Figure translations are in progress. See original paper for figures.