Net Carbon Exchange and Its Influencing Factors in Oasis Vineyards of the Northwestern Arid Region: Postprint

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Abstract

Investigating the carbon budget dynamics and carbon source-sink formation mechanisms of oasis agricultural ecosystems in arid regions is crucial for guiding carbon sequestration and emission reduction in oasis agriculture. Based on CO2 flux data and related environmental factors observed by the eddy covariance system in a vineyard at the Dunhuang arid oasis, this study estimates the total carbon budget of the vineyard during the 2019 growing season (May-October), and simultaneously investigates the diurnal and seasonal dynamics of net ecosystem carbon exchange (NEE) and its responses to leaf area index (LAI), photosynthetically active radiation (PAR), vapor pressure deficit (VPD), and air temperature (Ta). The results show that: (1) During the growing season, the cumulative values of net ecosystem carbon exchange (NEE), ecosystem respiration (Re), and gross primary productivity (GPP) in the vineyard were -647.3, 883.2 g C·m-2, and 1530.5 g C·m-2, respectively, with an Re/GPP ratio of 57.7%, indicating low carbon consumption intensity and a strong carbon sink process. (2) The seasonal variation of NEE during the growing season exhibited a unimodal pattern (peaking in July), similar to the seasonal variation of air temperature. This indicates that under the basic condition of sufficient water supply, air temperature has a significant influence on NEE. (3) NEE during the growing season was comprehensively affected by biophysical factors such as LAI, PAR, VPD, and Ta. Throughout the growing season, PAR was the environmental factor most highly correlated with NEE, increasing carbon sequestration by driving photosynthesis. LAI first increased and then decreased during the growing season, which correspondingly affected photosynthetic carbon fixation, thereby causing NEE to exhibit a trend of first decreasing and then increasing. Meanwhile, maintaining VPD within a suitable range (20–35 hPa) can effectively enhance its carbon sequestration capacity.

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Full Text

Net Carbon Exchange and Its Influencing Factors of Oasis Vineyards in Northwest Arid Region of China

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Abstract

Studying carbon budget dynamics and the formation mechanisms of carbon sources and sinks in oasis agricultural ecosystems in arid regions is crucial for guiding carbon sequestration and emission reduction in oasis agriculture. Based on eddy covariance system observations of CO_2 fluxes and related environmental factors in a vineyard within the Dunhuang arid oasis, this study estimated the total carbon budget during the growing season (May–October) and investigated the daily and seasonal dynamics of net ecosystem exchange (NEE) and its responses to leaf area index (LAI), photosynthetically active radiation (PAR), vapor pressure deficit (VPD), and air temperature (Ta). The results showed that during the growing season, the cumulative values of NEE, ecosystem respiration (Re), and gross primary productivity (GPP) were 883.2 g $C \cdot m^{-2}$ and 1530.5 g $C \cdot m^{-2}$, respectively. The Re/GPP ratio was 57.7%, indicating relatively low carbon consumption intensity and a strong carbon sink process. NEE exhibited a single-peak pattern during the growing season, peaking in July, which closely mirrored the seasonal variation in air temperature. This suggests that under conditions of adequate water supply, air temperature exerts a significant influence on NEE. Throughout the growing season, NEE was affected by the combined effects of biophysical factors including LAI, PAR, VPD, and Ta. PAR was the most highly correlated environmental factor with NEE, enhancing carbon sequestration by driving photosynthesis. LAI increased initially and then decreased during the growing season, which correspondingly affected photosynthetic carbon fixation and caused NEE to first decline and then rise. Additionally, maintaining VPD within a suitable range (20–35 hPa) could effectively improve the carbon sequestration capacity of the vineyard.

Keywords: Oasis vineyard; Eddy covariance system; Net ecosystem exchange; Influencing factors

Terrestrial ecosystems serve as a critical link for material and energy exchange between the atmosphere and land surface. In recent years, with increasing atmospheric CO_2 concentrations, carbon exchange in terrestrial ecosystems has attracted growing attention. The development of eddy covariance technology has enabled long-term, continuous monitoring of ecosystem CO_2 fluxes, establishing it as the standard method for directly measuring carbon fluxes in terrestrial ecosystems with high measurement precision. Currently, this technology has been widely applied in carbon cycle research across various terrestrial ecosystems and serves as the primary technical approach for the global FLUXNET observation network. The FLUXNET network encompasses over 40°S–70°N, though observation density remains relatively sparse in global arid and semi-arid regions. Arid and semi-arid zones account for approximately 41% of global land surface area, and their expansion due to climate change makes ecosystem carbon exchange processes in these regions particularly vulnerable to natural and anthropogenic disturbances. Previous carbon exchange studies in China' s arid and semi-arid areas have primarily focused on desert shrublands, grasslands, and other ecosystems with relatively low leaf area, aboveground biomass, and net primary productivity. For instance, Liu et al. measured annual and interannual variations in NEE in a saline desert ecosystem on the southern edge of the Gurbantunggut Desert using eddy covariance methods. Jia et al. quantified annual cumulative NEE, GPP, and ecosystem respiration (Re) in a semiarid shrubland on the southern edge of the Mu Us Desert and analyzed carbon flux dependencies on biophysical factors across multiple timescales. Wu et al. estimated the total carbon sequestration of *Haloxylon ammodendron* plantations in the Minqin oasis-desert ecotone. Other studies have examined carbon flux variations in irrigated oasis agricultural ecosystems unique to northwest China, such as maize and cotton croplands. Dunhuang City, a traditional grain and cotton production base in northwestern China, has been adjusting its agricultural structure in recent years by expanding fresh grape cultivation, with vineyard area reaching 83.3 km^2 by 2017. The widespread planting of grapes has altered the underlying surface and will inevitably impact regional carbon cycling. Therefore, clarifying the net carbon exchange between oasis vineyards and the atmosphere, identifying its influencing factors, and estimating the carbon sequestration capacity of vineyards are essential for assessing the carbon source-sink capacity of irrigated oasis agricultural ecosystems in northwest China.

1.1 Study Area Overview

The study area is located in the Nanhu Oasis, approximately 70 km southwest of Dunhuang City in Gansu Province. This region is classified as an extreme arid zone with annual sunshine duration of 3115–3247 h and total annual solar radiation ranging from 5903.4 to 6309.5 $MJ \cdot m^{-2}$, providing ample light and heat conditions for crop growth. The mean annual temperature is approximately 9.3°C. Although annual potential evapotranspiration is high (about 2500 mm), the area benefits from stable irrigation water from the Danghe Reservoir. Soil types are predominantly sandy loam with relatively high nutrient content. Leveraging these advantages in light, heat, water, and soil resources, the region has become one of China' s most suitable areas for grape cultivation outside Xinjiang. In the Nanhu Oasis, the primary crop is seedless white grapes (*Vitis vinifera*). We selected a typical seedless white grape plot (450 m × 160 m) within the core study area, with vine spacing of 2.5 m and row spacing of 3.0 m.

1.2.1 Observation Methods

An eddy covariance system was installed in the study plot, consisting of a three-dimensional ultrasonic anemometer (R3-50, Gill Instruments) and an open-path CO_2/H_2O gas analyzer (LI-7500, LI-Cor), mounted at a height of 4.5 m. The system measured latent heat, sensible heat, and CO_2 fluxes. The prevailing wind direction in this region is northeasterly, with a flux source area length of approximately 250 m during daytime unstable atmospheric conditions and 150 m during nighttime stable conditions, ensuring that the primary flux source area remained within the core vineyard plot throughout the day. An automatic meteorological station was also installed to monitor air temperature (Ta), precipitation (Rainfall), photosynthetically active radiation (PAR), relative humidity (RH), and soil water content (SWC). Air temperature and humidity were measured at 2.5 m and 3.0 m heights using HMP60 sensors (Vaisala, Finland). PAR was measured with an LI-190R quantum sensor (LI-Cor). Precipitation was recorded with a TE525 tipping-bucket rain gauge (Texas Electronics). Soil temperature and moisture sensors (Decagon) were installed at 5 cm, 20 cm, and 50 cm depths. All data were recorded by a CR1000 data logger (Campbell Scientific) at 30-minute intervals.

Leaf area index (LAI), defined as the total leaf area per unit ground area, characterizes plant growth status and canopy development. LAI was measured using an LAI-2200 plant canopy analyzer (LI-Cor). Flux data were preprocessed using EddyPro software, including outlier removal, coordinate rotation correction, frequency response correction, and WPL density correction. Data quality was assessed using quality flags (Q) after processing. Gaps in flux data caused by negative NEE values, rainfall events (\$$\pm 30 minutes), anddataoutsidethevalidrangeof - 41to20 \mu mol \cdot m^{\text{\{-2\}} \cdot s}$\{-1\}\$ were filled using the REddyProc package (https://www.bgc-jena.mpg.de/bgi/index.php/Services/REddyProcWeb). Gap-filling followed these steps: (1) A friction velocity threshold was calculated using the moving point method and breakpoint detection ($u^* = 0.084\ m \cdot s^{-1}$), and flux data during periods of weak turbulence (especially at night) were excluded. The overall valid flux rate was 68.3%, with daytime validity at 85.5% and nighttime at 51.0%. (2) The marginal distribution sampling method was used for gap-filling. The most common partitioning method uses nighttime NEE data to establish a temperature-response relationship for ecosystem respiration, then separates NEE into Re and GPP components using the equation NEE = Re - GPP, where NEE is net ecosystem exchange, Re is ecosystem respiration, and GPP is gross primary productivity (units: $mol \cdot m^{-2} \cdot s^{-1}$).

Nighttime ecosystem respiration (Re) responds to temperature following the Lloyd-Taylor equation: Re = R_{ref} × exp[E_0 × (1/(T_{ref} - T_0) - 1/(Ta - T_0))], where R_{ref} is ecosystem respiration at reference temperature ($mol \cdot m^{-2} \cdot s^{-1}$), E_0 is activation energy ($KJ \cdot mol^{-1}$), Ta is air temperature (°C), T_{ref} is reference temperature (°C), and T_0 is a constant (-46.02°C). Daytime Re was estimated using the nighttime temperature-response relationship and the

Lloyd-Taylor equation. The relationship between daytime NEE and PAR was fitted using a rectangular hyperbola model for PAR > 10 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$: NEE = ($\alpha$ × PAR × A_{max}) / (α × PAR + A_{max}) - R_e,d, where A_{max} is the maximum photosynthetic rate at infinite PAR ($\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), α is initial light use efficiency ($\text{mol} \cdot \text{mol}^{-1}$), and R_e,d is daytime ecosystem respiration ($\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). Nighttime ecosystem respiration temperature sensitivity (Q_{10}) was calculated as: $Q_{10} = \exp(10 \times \beta)$, where β is a fitted parameter.

2.1 Dynamics of Physiological and Environmental Factors During the Growing Season

LAI in the study area showed a trend of increasing initially and then decreasing, reaching its maximum of 3.9 $\text{m}^2 \cdot \text{m}^{-2}$ in July. Air temperature (Ta) varied stably, with daily average Ta gradually rising after grape emergence in early May, peaking at 20.2°C in July, and then gradually declining after August. The average Ta during the growing season was 18.5°C. Daily average PAR was relatively stable, reaching its maximum of 1878 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ at 13:00. PAR declined significantly at the end of August due to cloudy and rainy weather conditions. VPD, an important factor affecting photosynthesis, showed seasonal variation with higher values in June and July, peaking at 26.70 hPa, and gradually declining after July. Precipitation was scarce (42.9 mm total) and heavily influenced by agricultural flood irrigation, causing sudden increases during emergence, budding, flowering, two fruiting periods, and pre-burial stages. The increment during the two fruiting periods was smaller than other stages because excessive water during fruit ripening affects sugar accumulation.

2.2 Carbon Budget Dynamics During the Growing Season

Carbon flux variations in the vineyard during the growing season are shown in Figure 2. NEE values were positive in early May, indicating the vineyard was a carbon source. After mid-May, NEE became negative, showing a strong carbon sink process. NEE and GPP showed consistent fluctuations, with NEE reaching its maximum daily value of -16.4 g $\text{C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ on July 4. Cumulative values for the growing season were 883.2 g $\text{C} \cdot \text{m}^{-2}$ for NEE and 1530.5 g $\text{C} \cdot \text{m}^{-2}$ for GPP, demonstrating a strong carbon sink process. The Re/GPP ratio was 57.7%. Monthly cumulative carbon budgets showed that NEE, Re, and GPP all exhibited slow initial change, followed by rapid change, then slow change again—directly related to phenological stages. During early and late growth stages, vegetation physiological activity was weak, resulting in smaller carbon flux values. In June and July, during vigorous growth, carbon flux cumulative values were larger, but carbon consumption intensity was lower (51.0% and 54.7%, respectively).

2.3 Average Diurnal Variation of Monthly Carbon Budget During the Growing Season

Monthly average diurnal variations of NEE, Re, and GPP showed distinct patterns (Figure 4). NEE exhibited a single-peak pattern across all months, with daily average NEE ranging from -3.2 to -0.4 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, indicating gradually strengthening carbon sink capacity from May to July, followed by gradual weakening. Re showed similar trends, peaking in July. GPP diurnal variation showed an inverted single-peak pattern, also peaking in July and then declining. At night, NEE was positive (carbon emission), while after sunrise, photosynthetic carbon fixation began. When photosynthesis exceeded respiration, NEE turned negative, showing net carbon absorption. The transition times from positive to negative NEE varied by month: May at 06:30, June at 06:00, July and August at 05:30, and September and October at 06:00. The afternoon transition from negative to positive occurred at 20:00 in May, 20:30 in June, 19:30 in July, 19:00 in August and September, and 18:30 in October. These differences were primarily due to variations in sunrise/sunset times across months.

2.4 Relationship Between NEE and LAI During the Growing Season

The relationship between NEE and LAI during the growing season was linear (Figure 5), with the fitted line explaining 54% of the variation. As LAI increased, NEE decreased significantly. The slope of the fitted line was -2.4 g $\text{C} \cdot \text{m}^{-2}$ per unit increase in LAI, indicating the change in NEE per unit increase in leaf area index.

2.5 Relationship Between NEE and Environmental Factors

2.5.1 Daytime NEE and PAR Correlation analysis between daytime NEE and environmental factors during the growing season showed that PAR, as the primary driver of photosynthesis, was the most important factor affecting ecosystem carbon cycling (Table 1). PAR had the highest negative correlation with NEE across the entire growing season ($r = -0.52$, $p < 0.01$), with correlation coefficients gradually increasing month by month, reaching a maximum of -0.61 in July. The relationship between daytime NEE and PAR was fitted using a rectangular hyperbola model (Figure 6), which explained 13–54% of the variation in NEE across different months. Monthly goodness-of-fit varied consistently with correlation strength. The weak response in October was mainly due to declining temperature and PAR and plant leaf senescence, reducing vegetation CO_2 uptake. Across all months, NEE showed a decreasing trend with increasing PAR, though considerable scatter existed around the fitted curves.

Photosynthetic curve fitting parameters for the growing season are shown in Table 2. Maximum photosynthetic rate (A_{max}) ranged from 7.91 to 30.58 $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, peaking in July and reaching its minimum in October. Initial light use efficiency (α), which reflects the ability to utilize weak light, ranged from 0.051 to 0.170 $\text{mol} \cdot \text{mol}^{-1}$, with higher values in June and July (0.119 and

0.170 mol · mol^{-1}, respectively) and lower values in May and October (0.051 and 0.057 mol · mol^{-1}, respectively). Daytime ecosystem respiration peaked in July at 4.5 mol · m^{-2} · s^{-1}.

2.5.2 Daytime NEE and VPD VPD reflects air dryness and directly controls leaf and canopy conductance, indirectly affecting photosynthesis and NEE. The relationship between daytime NEE and VPD showed that NEE initially decreased and then increased with rising VPD across the growing season (Figure 7). The optimal VPD range for the vineyard was 20–35 hPa. Both excessively high and low VPD values inhibited photosynthesis.

2.5.3 Nighttime NEE and Ta The relationship between ecosystem respiration and temperature is typically described by an exponential equation. Nighttime NEE values equal ecosystem respiration. To investigate the response of Re to temperature, we analyzed the exponential relationship between nighttime NEE and Ta (Table 3). Temperature explained 35–72% of the variation in nighttime NEE across months, with respiration increasing exponentially with Ta. Nighttime ecosystem respiration temperature sensitivity (Q_{10}) showed clear seasonal variation, peaking at 2.0 in summer months (July–August) and reaching a minimum of 1.4 in May.

3 Discussion

During the 2018 growing season, the vineyard' s cumulative NEE and GPP were 883.2 g C · m^{-2} and 1530.5 g C · m^{-2}, respectively. Compared with other arid region ecosystems, the vineyard demonstrated strong carbon sink capacity. For example, the *Haloxylon ammodendron* plantation in the Minqin oasis-desert ecotone sequestered only 34.4 g C · m^{-2} during the growing season, while the Horqin meadow wetland fixed 209.0 g C · m^{-2}. The Gurbantunggut Desert shrubland showed NEE ranging from -25.1 to -223.6 g C · m^{-2} across three growing seasons, and the cotton field under mulched drip irrigation in the Korla oasis had NEE of -209.0 g C · m^{-2}. Although interannual variations in net carbon uptake were substantial in these ecosystems, all were significantly lower than the vineyard. The differences in annual carbon sequestration capacity primarily relate to whether water was fully irrigated and to lower leaf area, aboveground biomass, and net primary productivity in those ecosystems. The vineyard' s Re/GPP ratio of 57.7% reflects relatively low carbon consumption intensity, compared with 84.7% reported for the Horqin meadow wetland and 67.9–78.9% for the Korla cotton field.

The seasonal variation of NEE showed a single-peak pattern, differing from the double-peak pattern reported in some studies. For instance, research on a coniferous plantation in Jiangxi' s Qianyanzhou showed double peaks in July and September, mainly due to drought-induced reductions in GPP during the peak growing season. Similarly, Wu et al. reported a double-peak curve for *Haloxylon ammodendron* in Minqin, with reduced carbon sequestration in July due to low precipitation and continuous high-temperature drought. Although this study' s vineyard is located in an arid region, its position in an oasis with stable irrigation water (monthly flood irrigation) prevented prolonged water stress. Carrana et al. demonstrated that under high temperatures, water deficit is the primary cause of reduced carbon sequestration. Therefore, maintaining VPD within the optimal range of 20–35 hPa enables more efficient water and nutrient cycling, thereby enhancing carbon sequestration capacity. Nighttime ecosystem respiration temperature sensitivity (Q_{10} = 1.4-2.0) was higher than that reported for the Horqin meadow ecosystem (Q_{10} = 1.3), suggesting the vineyard may be more sensitive to climate warming.

NEE variation is determined by both photosynthesis and respiration, thus influenced by combined biophysical factors. LAI determines the ecosystem' s potential to capture light energy for photosynthesis, and this study found a strong linear relationship between NEE and LAI. PAR, as the main driver of photosynthesis in terrestrial ecosystems, significantly affects carbon cycling processes. PAR showed the highest correlation with NEE across the growing season (r = -0.52). Daytime NEE and PAR followed a rectangular hyperbola relationship, with better model performance in June–July during vigorous growth and weaker performance in early and late season. The fitted maximum photosynthetic rate and initial light use efficiency were higher than those reported for deciduous broadleaf forests in Beijing's Songshan Mountains and mixed forests in Badaling at similar latitudes, primarily due to abundant light and high canopy coverage in the study area. VPD affects photosynthesis by regulating stomatal opening and closing; both excessively high and low VPD values inhibit photosynthesis. Although this study focused on an irrigated orchard in an arid region where water variation significantly affects grape growth and flux processes, further investigation of carbon exchange differences before and after irrigation remains an important future direction.

4 Conclusion

During the 2018 growing season, the vineyard' s cumulative NEE, Re, and GPP were 883.2 g $C \cdot m^{-2}$ and 1530.5 g $C \cdot m^{-2}$, respectively, with an Re/GPP ratio of 57.7%. The vineyard functioned as a strong carbon sink. Compared with other arid region ecosystems, the vineyard' s carbon consumption intensity was relatively low. NEE showed a single-peak pattern during the growing season, peaking in July and following similar seasonal variation as air temperature, indicating that under adequate water supply conditions, air temperature significantly influences NEE.

NEE was affected by the combined effects of biophysical factors including LAI, PAR, VPD, and Ta. PAR showed the highest correlation with NEE throughout the growing season, enhancing carbon sequestration by driving grape photosynthesis. LAI increased initially and then decreased, affecting photosynthetic carbon fixation and causing NEE to decline and then rise. Maintaining VPD within a suitable range (20–35 hPa) effectively improved carbon sequestration capacity.

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