Characteristics of Water-Heat Fluxes and Their Main Influencing Factors in Vineyards of Arid Desert Oases in Northwest China: Postprint

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Abstract

To enhance scientific understanding of farmland surface processes and improve agricultural water management in arid oasis regions, this study employed eddy covariance technique and utilized energy balance observational data from a vineyard during the growing season to analyze variation characteristics of water and heat fluxes at different temporal scales, as well as the effects of dry advection and canopy conductance (Gc) on water and heat fluxes across different growth stages. Furthermore, we applied path analysis to investigate the influence pathways and magnitude of environmental factors on latent heat flux (LE). The results indicate: (1) At the daily scale, LE exhibited multi-peak patterns of varying degrees, while the remaining water and heat fluxes generally displayed single-peak patterns. Overall, across all growth stages, daytime net radiation (Rn) > LE > sensible heat flux (H) > soil heat flux (G). G exhibited a significant lag relative to Rn. (2) Throughout the entire growing season, LE and H accounted for 86% and 14% of daytime available energy (Rn–G), respectively, demonstrating that LE consistently represented the primary consumer of available energy in the vineyard during daytime. The contribution of dry advection to daytime LE ranged from 5%~59%, with an average contribution of 28% across the entire growing season; the influence of Gc on LE exhibited dynamic variation throughout the growing season and was more pronounced during the shoot growth stage and leaf fall stage than during the middle growth stage. (3) LE was predominantly influenced by Rn, with vapor pressure deficit (VPD) and air temperature (Ta) exerting similar influence magnitudes second only to Rn. Path analysis revealed that Rn primarily affected LE through direct effects, whereas VPD and Ta mainly exerted indirect effects on LE via Rn. In conclusion, water and heat fluxes in vineyards of the arid desert oasis region of northwestern China exhibited distinct diurnal and seasonal variation

characteristics, with environmental factors exerting significant influences that differed in both magnitude and pathway.

Full Text

Characteristics and Influencing Factors of Water and Heat Fluxes over a Vineyard in an Arid Desert Oasis Region of Northwest China

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Abstract: To improve scientific understanding of farmland surface processes and agricultural water management in arid oasis regions, this study analyzed water and heat flux characteristics at different temporal scales and examined the influence of arid advection and canopy conductance (Gc) on these fluxes across different growth stages. Based on energy balance observations from a vineyard during the 2017 growing season using eddy covariance technology, we quantified the dynamic responses of water and heat fluxes to environmental factors through path analysis. The results indicate: (1) At the daily scale, latent heat flux (LE) exhibited multiple peaks of varying degrees, while other flux components showed unimodal patterns. Overall, net radiation (Rn) > LE > sensible heat flux (H) > soil heat flux (G) during daytime across all growth stages, with G showing a pronounced lag relative to Rn. (2) Across the entire growing season, LE and H accounted for 86% and 14% of daytime available energy (Rn-G), respectively, demonstrating that LE was consistently the primary consumer of available energy in the vineyard. The contribution of arid advection to daytime LE ranged from 5% to 59%, with a seasonal average of 28%. The influence of Gc on LE varied dynamically throughout the season, with stronger effects during the new shoot and leaf-fall stages compared to mid-season phases. (3) LE was predominantly influenced by Rn, followed by vapor pressure deficit (VPD) and air temperature (Ta), which had similar influence magnitudes. Path analysis revealed that Rn primarily affected LE through direct pathways, whereas VPD and Ta mainly exerted indirect effects on LE via Rn. In summary, water and heat fluxes in vineyards of the arid desert oasis region in Northwest China display significant diurnal and seasonal variations, with environmental factors exerting distinct influences that differ in both magnitude and pathway.

Keywords: arid area; grape; water and heat fluxes; arid advection; path analysis; influencing factors

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Farmland ecosystems represent one of the most important terrestrial ecosystems. Due to their specialized functions, they are strongly influenced by human activities throughout crop production cycles (e.g., irrigation and tillage), making them complex hydrological systems involving water, heat, and material exchanges with intricate interactions between hydrological and ecological cycles (Monteith et al., 2008). Water and heat flux transport processes in farmland are inextricably linked to crop physiological processes and environmental conditions (Zhao et al., 2018). Investigating these flux characteristics is crucial for understanding farmland-atmosphere interactions and for rational allocation and efficient utilization of water resources (Wilson et al., 2002). Currently, the eddy covariance (EC) method is widely recognized as the standard approach for studying energy, water vapor, and carbon dioxide exchange between the surface and atmosphere (Baldocchi, 2003).

China' s arid inland regions in the Northwest receive minimal precipitation and represent typical water-scarce areas. Grape is a major economic crop in the arid oasis regions of Northwest China and has been extensively planted in recent years (Sun, 2018). Although the region' s abundant sunlight conditions satisfy grape growth requirements, cultivation demands substantial irrigation water to meet crop water needs, creating an urgent conflict between high water demand and resource scarcity. Managers have planted poplar trees as shelterbelts around vineyards to reduce unnecessary water loss (McNaughton, 1988). However, shelterbelts also consume water, and without proper understanding of surface water and heat flux processes in arid oasis farmland, water resources may still be wasted (Ding et al., 2014). Meanwhile, advection effects between oasis and desert environments further complicate energy exchange processes and environmental factors in vineyards (Ding et al., 2015). Quantifying the impact of advection effects on water and heat fluxes in arid region vineyards requires further research, as this is essential for correctly understanding farmland surface processes in arid oasis areas.

Both physiological and environmental factors significantly influence water and heat fluxes. Canopy conductance (Gc) represents the most important crop physiological factor affecting farmland water and heat fluxes, reflecting the integrated crop response to environmental conditions and serving as a key parameter in latent heat flux models (Monteith et al., 2008). However, few studies have quantified the control characteristics of Gc on vineyard water and heat fluxes in arid inland regions. Regarding environmental factor impacts, most current research employs simple correlation or multiple regression analysis (Yang et al., 2014; Feng et al., 2018; Zheng et al., 2020), yet these methods cannot reveal the influence pathways of environmental factors on water and heat fluxes. Path analysis decomposes correlation coefficients into direct and indirect path coefficients, enabling standardized comparison without units and thereby reflecting both the degree of influence and relative importance of independent variables on dependent variables (Zhang et al., 2016).

Based on these considerations, this study selected a seedless white vineyard in Nanhu Town, Dunhuang City, Gansu Province, as the research site. Using water and heat flux data measured by an EC system during the 2017 growing season, we aimed to: (1) reveal the variation and partitioning characteristics of water and heat fluxes in Northwest China arid region vineyards across different growth stages; (2) quantify the impacts of Gc and arid advection on water and heat fluxes; and (3) clarify the influence mechanisms of environmental factors on water and heat fluxes using path analysis.

1.1 Study Area Description

The experiment was conducted during the 2017 growing season (May-October) in a vineyard located in the desert oasis region of Nanhu Town, Dunhuang City, Gansu Province, China. The site is positioned at 94°06 E, 39°55 N, with an annual mean temperature of 9-10 °C, annual precipitation of 36.9 mm, and elevation of 1,100-1,300 m (Wang, 2019). The study area features a warm temperate arid climate with distinct seasons, long sunshine hours, low precipitation, and strong evaporation. Soils are intrazonal, primarily meadow and saline soils, with extensive wetland areas distributed throughout the region, receiving water supply from seepage recharge of the Dang River channel.

The experimental plot (450 m × 160 m) is located in the southwestern part of the Dunhuang Nanhu Oasis. Seedless white grape is the main economic crop, planted with spacing of approximately 1 m between plants and 3 m between rows. Grapes mature once annually, with the growing season typically extending from late April/early May to late September/early October. The entire growing season can be divided into five stages: new shoot stage (DOY 121-147), flowering and fruiting stage (DOY 148-171), fruit filling stage (DOY 172-222), coloring and maturity stage (DOY 223-262), and leaf-fall stage (DOY 263-283). To ensure normal grape growth, manual flood irrigation was applied approximately every 25 days, maintaining relatively sufficient soil moisture.

1.2 Eddy Flux and Environmental Factor Measurements

Latent heat flux (LE) and sensible heat flux (H) were measured using an eddy covariance (EC) system, which operates reliably under complex and harsh weather conditions to provide accurate measurements. The instrument was installed in the center of the experimental plot at 4 m height, satisfying the flux footprint requirements. Four soil heat flux plates (HFP01SC, Hukseflux, Netherlands) were installed 5 cm below the ground surface, with soil heat flux (G) calculated by averaging data from four directional sensors. Daytime net radiation (Rn) was measured using a radiometer (NR01, Hukseflux, Netherlands). All observed data were processed and stored by a data logger (CR1000, Campbell, USA) at 30-minute intervals. Raw EC data were processed and corrected using Eddy Pro 6.0 software. When daily data gaps were less than 2 hours, linear interpolation was applied; for larger gaps, artificial neural networks (ANN) were used for gap-filling (Zhang et al., 2014). Processed data were then used for energy balance closure analysis (Figure 1), achieving a closure rate of 87%, which is comparable to previous vineyard studies under similar conditions (Ferreira et al., 2012).

A small automatic weather station was installed at the site to measure and record environmental factors including canopy air temperature (Ta, °C), canopy relative humidity (RH, %), wind speed (WS, $m \cdot s^{-1}$), and soil volumetric water content (VWC, $m^3 \cdot m^{-3}$). Air temperature and humidity were measured using a temperature and humidity sensor (HHMP60, Vaisala, Finland); wind speed was measured with a 2D anemometer (5103, R. M. Young, USA); and VWC was measured using soil moisture sensors (ML2x, Delta T, UK).

1.3 Index Calculations

The contribution rate of advection to LE (Rad) was calculated using the following equation (McNaughton, 1976):

$$Rad = \frac{LE - LE_{eq}}{LE}$$

where LE_{eq} is the latent heat flux required for equilibrium evaporation from available energy, i.e., LE without advection effects, calculated as:

$$LE_{eq} = \frac{\Delta}{\Delta + \gamma}(Rn - G)$$

where Δ is the slope of the saturation vapor pressure-temperature curve ($kPa \cdot °C^{-1}$) and γ is the psychrometric constant ($kPa \cdot °C^{-1}$).

The Bowen ratio (β) was calculated as:

$$\beta = \frac{H}{LE}$$

To quantify the dynamic control degree of Gc on LE, Jarvis & McNaughton (1986) introduced the decoupling coefficient (Ω) to characterize the response of LE to Gc:

$$\Omega = \frac{\Delta + \gamma}{\Delta + \gamma(1 + Gc/Ga)}$$

where Gc is canopy conductance and Ga is aerodynamic conductance ($mm \cdot s^{-1}$), both calculated as follows (Monteith et al., 2008):

$$Gc = \frac{LE \cdot \gamma}{\rho \cdot Cp \cdot VPD}$$

$$Ga = \frac{u_*^2}{WS}$$

where VPD is vapor pressure deficit (kPa), WS is wind speed ($m \cdot s^{-1}$), ρ is air density ($kg \cdot m^{-3}$), Cp is specific heat of air at constant pressure ($MJ \cdot kg^{-1} \cdot °C^{-1}$), and u_* is friction velocity ($m \cdot s^{-1}$).

1.4 Path Analysis

Path analysis decomposes correlation coefficients between causal variables into direct effects (direct path coefficients) and indirect effects (indirect path coefficients) to investigate data structures of causal relationships and analyze the direct and indirect importance of independent variables on dependent variables (Kozak et al., 2006). This study employed structural equation modeling, which integrates factor analysis and linear regression statistical techniques to identify, estimate, and validate causal models. Initially considered environmental factors included Rn, Ta, VPD, WS, precipitation, and VWC. Stepwise regression analysis was used to screen major environmental factors (those passing significance tests), and path analysis was subsequently applied to evaluate the direct and indirect effects of key environmental variables (Rn, Ta, VPD, and WS) on LE.

2.1 Environmental Condition Variations

Figure 2 shows seasonal variations of environmental factors during the experimental period. Precipitation events were infrequent and minimal throughout the growing season, with only one event exceeding 10 mm occurring at the end of July. Small precipitation events (<10 mm) had minimal impact on soil water content (VWC), while effective precipitation events (>10 mm) noticeably affected VWC. Additionally, due to regular irrigation in the study area, VWC exhibited periodic declining characteristics, reaching a maximum value of 0.28 $m^3 \cdot m^{-3}$ after irrigation. Vapor pressure deficit (VPD) showed an overall decreasing trend across the growing season, with the lowest average in October (0.74 kPa) and highest in May (1.81 kPa). Air temperature (Ta) generally increased then decreased, peaking in July (23.55 °C) and reaching its minimum in September (9.5 °C). Wind speed (WS) remained relatively stable overall but exhibited large diurnal fluctuations, with maximum and minimum values of 1.23 $m \cdot s^{-1}$ and 0.11 $m \cdot s^{-1}$, respectively. Atmospheric relative humidity (RH) increased then decreased throughout the growing season, with maximum and minimum values of 55.5% in July and 30.0% in May, respectively. Grape physiological factors are also crucial for interpreting water and heat flux variations. Leaf area index (LAI) increased from 0.80 $m^2 \cdot m^{-2}$ in early growth to 4.10 $m^2 \cdot m^{-2}$ in mid-season, then gradually declined toward the end of the growing season. Canopy conductance (Gc) showed similar variation patterns, increasing from 1.3 $mm \cdot s^{-1}$ in early growth to 12.2 $mm \cdot s^{-1}$ in mid-season (Figure 2e).

2.2 Water and Heat Flux Variation Characteristics

Daily-scale averaging of Rn, LE, H, and G for each growth stage revealed diurnal variation patterns (Figure 3). LE curves showed varying degrees of multiple peaks across growth stages but exhibited a unimodal pattern for the entire growing season, primarily due to temporal misalignment of LE peak occurrence among stages. Rn, H, and G generally displayed unimodal patterns. All energy components were positive during daytime and near-zero or negative at night, though the timing of sign conversion differed among growth stages. LE maximum values fluctuated substantially, occurring between 11:30–14:30, with specific timing at 14:30 for new shoot stage, 13:30 for flowering and fruiting and filling stages, 13:00 for maturity stage, and 14:00 for leaf-fall stage. Maximum values ranged from 261.8 to 517.6 $\mathrm{W \cdot m^{-2}}$, with stage-specific values of 339.3, 517.6, 496.9, 472.2, and 261.8 $\mathrm{W \cdot m^{-2}}$, respectively. For the entire growing season, the maximum LE occurred at 13:30, reaching 456.3 $\mathrm{W \cdot m^{-2}}$. Notably, nighttime LE remained positive, ranging from 3.0 to 46.1 $\mathrm{W \cdot m^{-2}}$, likely due to high VPD caused by dry conditions. During the new shoot stage, LE values were relatively small and similar to H, while substantial differences between LE and H were observed in other stages.

Peak H values ranged from 47.5 to 223.2 $\mathrm{W \cdot m^{-2}}$, occurring between 13:00–14:30, with stage-specific values of 223.2, 92.9, 47.5, 67.8, and 137.9 $\mathrm{W \cdot m^{-2}}$. For the entire growing season, H peaked at 13:30 with a value of 89.0 $\mathrm{W \cdot m^{-2}}$. As another energy expenditure component of Rn, G showed relatively flat variation with small values, peaking between 24.9–58.9 $\mathrm{W \cdot m^{-2}}$ and generally being negative at night. Stage-specific average G values were 5.1, 1.9, 2.6, 0.4, and -1.3 $\mathrm{W \cdot m^{-2}}$, indicating that G can be approximated as zero at daily scales. The duration of positive Rn values across growth stages first increased then decreased, reaching a maximum of 12.5 hours during the filling stage and 11.5 hours for the entire growing season. Rn peaks occurred between 14:00–14:30, ranging from 449.1 to 604.8 $\mathrm{W \cdot m^{-2}}$, with stage-specific values of 604.8, 588.2, 584.3, 542.1, and 449.1 $\mathrm{W \cdot m^{-2}}$. These variations were primarily influenced by solar elevation, cloud cover, and underlying crop growth conditions. For the entire growing season, Rn peaked at 14:00 with a value of 572.1 $\mathrm{W \cdot m^{-2}}$. Except during the new shoot stage, Rn peak occurrence lagged behind LE by approximately 1 hour, reaching 2.5 hours during leaf-fall stage. A similar lag pattern existed between Rn and H, while G lagged Rn by an average of approximately 2.5 hours.

To avoid nighttime measurement errors caused by small LE and humidity gradient magnitudes, seasonal variation analysis of water and heat fluxes and advection effects was limited to daytime (Li & Yu, 2007) (Rn>0). As shown in Figure 4, Rn increased from 316.10 to 372.11 $\mathrm{W \cdot m^{-2}}$ during the new shoot, flowering, and filling stages, then decreased during maturity and leaf-fall stages. During the new shoot and flowering stages, rapid grape growth with new branches and leaves led to rapid LE increase from 117.82 to 180.56 $\mathrm{W \cdot m^{-2}}$, while H showed a clear decreasing trend to near-zero values, indicating that most Rn was converted to LE during this period. During the filling and maturity stages, H remained near-zero while LE consistently dominated Rn, showing responsive variations to Rn and environmental changes. During leaf-fall stage, LE gradually decreased as leaves senesced while H recovered. Except during the new shoot stage when vineyard ground cover was incomplete, G fluctuated near-zero across other stages, allowing some solar radiation to reach the ground surface. Notably, G did not recover during leaf-fall stage but instead decreased, likely due to reduced Rn and Ta.

Seasonal variations of LE/(Rn–G), H/(Rn–G), and β are shown in Figure 5 and Table 1. LE/(Rn–G) was relatively low during new shoot (0.75) and leaf-fall (0.70) stages but approached 1.0 during the three middle growth stages, with a seasonal average of 0.86. In contrast, H/(Rn–G) showed opposite seasonal trends, rapidly decreasing from 0.45 during new shoot stage to near-zero during middle stages, then recovering during leaf-fall stage. Consequently, β exhibited seasonal variation consistent with H, decreasing from 0.60 during new shoot stage to near-zero, then increasing to 0.35 during leaf-fall stage. LE/(Rn–G) > 1 or H/(Rn–G) < 0 indicates that the grape canopy consumed all available energy plus additional sensible heat flux for water evaporation, representing arid sensible heat advection (McNaughton, 1976; Li & Yu, 2007). Throughout the growing season, 42 days exhibited LE/(Rn–G) > 1 or H/(Rn–G) < 0, suggesting that vineyard water and heat fluxes were influenced not only by physiological and environmental factors but also by arid advection requiring further investigation.

2.3.1 Canopy Conductance Effects on Water and Heat Fluxes

The dynamic response and sensitivity of LE to Gc [i.e., (dLE/LE)/(dGc/Gc) = 1-Ω] varied substantially throughout the growing season, decreasing from 0.75 in early new shoot stage to 0.40 during filling stage, then increasing to 0.70 during leaf-fall stage (Figure 6). These results indicate stronger stomatal control on LE during early and late growing stages compared to mid-season. Monteith & Unsworth (2008) proposed that for canopies well-coupled with the atmosphere (1-$\Omega > 0.5$), stomata control water loss, whereas weakly-coupled canopies show poor stomatal control with transpiration primarily dependent on radiant energy. Considering the dramatic LAI variation throughout the season (Figure 2e), the dynamic nature of 1-Ω appears reasonable.

2.3.2 Arid Advection Effects on Water and Heat Fluxes

To accurately understand arid advection impacts on water and heat fluxes, we calculated the advection contribution rate to LE (Rad), as shown in Figure 7 and Table 1. The contribution of arid advection to latent heat flux ranged from 5% to 59%, averaging 28% across the entire growing season. The flowering and fruiting stage had the most advection days (14 d), while the new shoot stage exhibited the highest advection intensity (34%).

2.3.3 Environmental Factor Influence Mechanisms on Water and Heat Fluxes

Table 2 shows that due to combined direct and indirect effects of environmental factors, the ranking of influence on LE (by correlation coefficient) was consistently Rn > Ta > VPD > WS across the first four growth stages and the entire season. During leaf-fall stage, the ranking was Rn > VPD > Ta > WS, with minimal difference between VPD and Ta effects. Net radiation consistently represented the most important environmental factor affecting LE, followed by VPD and Ta, while WS had the smallest impact.

Direct and indirect path coefficients represent the degree of influence exerted by environmental factors on LE through direct and indirect pathways, respectively. Table 2 indicates that the absolute values of direct path coefficients varied across growth stages, primarily reflecting differences between Ta and VPD. Except during the new shoot stage when Ta exceeded VPD, VPD was greater than Ta in all other periods. However, Rn consistently showed the largest direct path coefficient and WS the smallest across all stages and the entire season, demonstrating that Rn had the strongest direct effect on half-hourly LE while WS had the weakest direct effect. Furthermore, only Rn exhibited direct path coefficients larger than the sum of indirect path coefficients across all growth stages, indicating that Rn primarily influenced half-hourly LE through direct effects, whereas other factors mainly exerted indirect influences. The indirect effects of Rn on LE occurred primarily through interactions with Ta and VPD, while Ta, VPD, and WS all influenced LE through Rn.

3 Discussion

At the daily scale, LE curves showed multiple peaks across growth stages, primarily because excessively high Ta at midday caused moderate stomatal closure in grape leaves, entering a "midday depression" state that reduced transpiration and LE (Zhang et al., 2007; Huang et al., 2019). The unimodal pattern of LE diurnal variation across the entire growing season resulted from temporal misalignment of LE peaks among growth stages. Diurnal variations of Rn, H, and G generally showed unimodal patterns, with H showing distinct differences across growth stages while G remained consistently flat—findings consistent with previous studies across various underlying surfaces (Ding et al., 2014; Zheng et al., 2020; Yu et al., 2020). The stable lag of G relative to Rn was also identified by Huang et al. (2019). All energy components were positive during daytime and near-zero or negative at night, except for LE, with timing of sign conversion differing among growth stages due to varying environmental conditions.

At the seasonal scale, the average LE/(Rn–G) of 86% indicates that LE was the primary consumer of available energy, consistent with studies on wheat in the North China Plain (Lei, 2010), irrigated corn in the United States (Suyker et al., 2008), and corn fields in Northwest China arid regions (Ding et al., 2014; Zhang et al., 2016). However, these results differ from studies on vineyards in different geographical environments (Zheng et al., 2020; Yu et al., 2020), where H dominated energy partitioning. These discrepancies may arise from: (1) sufficient irrigation in our study area leading to greater grape transpiration; (2) favorable local light conditions creating strong transpiration pull; (3) arid advection effects enabling grape canopies to utilize sensible heat for evaporation; and (4) vineyard canopy structure effects on energy partitioning (Kool et al., 2016). This highlights the importance of environmental conditions and cultivation techniques on water and heat flux distribution. Our study also found significant arid advection effects, with Rad ranging from 5% to 59% and averaging 28% across the season. Kool et al. (2018) reported a seasonal average Rad of 8% for drip-irrigated vineyards in Israel' s arid region, likely due to differences in geography and irrigation technology. In well-irrigated alfalfa fields in arid regions, advection contributions ranged from 28% to 90% (Prueger et al., 1996)—substantially greater than in our study area—demonstrating that water supply and planting density significantly affect advection contributions to water and heat fluxes (Kool et al., 2018). Nevertheless, our results show considerable similarity to studies in similar environments, with Rad ranges of 1%–50%.

Grape physiological and environmental factors represent the two main aspects influencing vineyard LE. Regarding physiological factors, we found dynamic Gc effects on LE throughout the season: stronger Gc control during early and late stages and weaker control during mid-season. This occurs because during early and late stages, lower LAI or senescing leaves result in drier or rougher surfaces with minimal VPD differences between leaf surfaces and above-canopy air, strengthening Gc control on LE. Conversely, during mid-season, large VPD differences between leaf surfaces and above-canopy air weaken Gc control (Steduto & Hsiao, 1998; Monteith & Unsworth, 2008). Regarding environmental factors, path analysis revealed that LE was primarily influenced by Rn, followed by VPD and Ta with similar influence magnitudes. Rn directly affected LE, while VPD and Ta mainly exerted indirect effects through Rn, consistent with Zhang et al. (2016). Solar radiation drives changes in Ta and RH, increases leaf temperature, enlarges vapor pressure differences between leaf interior and exterior, enhances transpiration rates, and induces stomatal opening/closing, making it the most important environmental factor affecting LE (Gong et al., 2018). VPD represents the combined effect of temperature and relative humidity, serving as an important indicator of air dryness that directly affects stomatal opening and grape transpiration, making it another crucial environmental factor (Qiu et al., 2018) that primarily influences LE indirectly through Rn. Path analysis clearly demonstrates the complex interaction pathways among environmental factors, consistent with natural conditions where environmental factors mutually influence each other. Furthermore, Zhang et al. (2018) identified pathway contributions of latent heat flux influencing factors at different temporal scales using path analysis, revealing that environmental factor effects differ across temporal scales. Therefore, further research is needed on environmental factor influence mechanisms on water and heat fluxes.

4 Conclusions

Based on water and heat flux data measured by an eddy covariance system and path analysis methods, this study analyzed variation characteristics and influencing factors of water and heat fluxes in a vineyard in the arid oasis region of Northwest China. The main conclusions are:

(1) At the daily scale, LE showed multiple peaks of varying degrees across growth stages, while other components generally exhibited unimodal patterns. Maximum peaks were 604.8 $W \cdot m^{-2}$ for Rn, 517.6 $W \cdot m^{-2}$ for LE, 223.2 $W \cdot m^{-2}$ for H, and only 58.9 $W \cdot m^{-2}$ for G. Nighttime LE remained positive while other components were negative. G showed a stable lag relative to Rn.

(2) Across the entire growing season, LE was consistently the primary consumer of available energy in the vineyard, with LE and H accounting for 86% and 14% of daytime available energy, respectively. Arid advection contributions to daytime LE ranged from 5% to 59%, averaging 28% across the season and showing particularly strong effects during the flowering and fruiting stage. Arid advection could explain more than half of the energy imbalance at daily scales. Therefore, the influence of arid advection on water and heat fluxes in this region cannot be ignored.

(3) The influence of Gc on LE varied dynamically throughout the growing season, with stronger effects during new shoot and leaf-fall stages compared to mid-season. LE was primarily affected by Rn (correlation coefficient > 0.82), followed by VPD and Ta with similar influence magnitudes, while WS had the weakest effect. Rn mainly influenced LE through direct pathways, whereas VPD and Ta primarily exerted indirect effects on LE via Rn.

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