



Asynchronous responses of CO₂ fluxes to hydrological anomalies in a subalpine peatland: evidence from hysteresis and lagged responses

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Abstract. Ecosystem-atmosphere CO₂ exchange in peatlands is highly sensitive to hydrological changes. However, continuous observations of how drought-induced hydrological anomalies and subsequent recovery affect the response pathways and timescales of CO₂ fluxes remain limited. The 2022 extreme drought in the Yangtze River Basin provided a valuable observational window for this study. Based on continuous eddy covariance (EC) measurements from 2021 to 2023, we characterized annual CO₂ source-sink status and, using the growing season (May–September) as the primary analysis window, compared variations in CO₂ flux components across different hydrological stages and analyzed their diel hysteresis and day-scale lagged responses to hydrological and temperature variables. The results showed that extreme drought shifted the Dajiuhu peatland from a CO₂ sink in 2021 ($-353.20 \text{ g C m}^{-2} \text{ yr}^{-1}$) to a weak CO₂ source in 2022 ($5.36 \text{ g C m}^{-2} \text{ yr}^{-1}$). During the growing season, gross primary productivity (GPP) declined more strongly than ecosystem respiration (Reco). Drought also altered diel hysteresis patterns in CO₂ flux responses. At the day scale, net ecosystem exchange (NEE) showed short lags to hydrological variables but relatively longer lags to temperature variables. This study provides continuous observational evidence of both asynchronous CO₂ flux responses to hydrological disturbances and drought legacy effects in a subalpine peatland.

1 Introduction

Peatland ecosystems are a key component of the global terrestrial carbon pool (Gallego-Sala et al., 2018). Although peatlands cover only about 3% of the global land area, they store 500-700 Gt of carbon (Yu et al., 2010; Zhang et al., 2025), accounting for approximately one-third of the global soil carbon pool (Dargie et al., 2017; Page et al., 2011). This carbon storage function depends on high water tables and long-term anoxic conditions (Huang et al., 2021; Koch et al., 2023), which enable peatlands to act as effective long-term carbon sinks (Loisel et al., 2021; Temmink et al., 2022). Accordingly, hydrological conditions strongly influence the stability of peatland carbon stocks. When the water table declines, increased



oxygen availability can accelerate soil carbon decomposition, leading to carbon loss from peatlands (Ma et al., 2022) and weakening their CO₂ sink capacity (Evans et al., 2021; Yang et al., 2025b). In some cases, this process can even turn peatlands into CO₂ sources (Salimi et al., 2021; Tiemeyer et al., 2016; van der Poel et al., 2025; Wood et al., 2025).
35 Therefore, changes in peatland CO₂ fluxes not only reflect ecosystem carbon balance but also indicate carbon-cycle responses to hydrological changes, including shifts in water table depth (WTD) and soil water content (SWC). Understanding how drought-related hydrological anomalies affect terrestrial ecosystems remains an important topic in Earth system science (Piao et al., 2019).

Traditionally, in studies of CO₂ fluxes, the net CO₂ exchange between terrestrial ecosystems and the atmosphere is
40 commonly represented by net ecosystem exchange (NEE), which reflects the combined effects of gross primary productivity (GPP) and ecosystem respiration (Reco) (Spielmann et al., 2019). Previous studies have shown that CO₂ exchange and its component fluxes respond differently depending on drought severity (Lund et al., 2012). During water-table drawdown or soil drying, the balance between GPP and Reco can be disrupted (Kane et al., 2021), and the greater sensitivity of GPP to extreme drought is often an important factor explaining changes in the CO₂ sink function of peatlands (Kang et al., 2018;
45 McDonald et al., 2023). These differential responses among CO₂ flux components suggest that GPP and Reco may become decoupled under different hydrological conditions or across different timescales. Separating NEE into GPP and Reco therefore provides a basis for assessing which component contributes more to changes in net CO₂ exchange and for comparing their response pathways under hydrological anomalies.

Ecosystem CO₂ fluxes are not controlled only by current environmental conditions. Memory effects arising from antecedent
50 climate, moisture, and vegetation states can also influence their dynamics, but are often overlooked in traditional prediction frameworks. Previous studies have separately examined ecosystem memory effects, lag effects of hydrological disturbances in peatlands, and diel dynamics of CO₂ fluxes. At seasonal timescales, drought-induced hydrological anomalies may continue to affect CO₂ release from peatlands after the drought event has ended (Boonman et al., 2025; Limpens et al., 2008). Such persistence may reflect drought legacy effects (Kane et al., 2021), indicating that hydrological recovery does not
55 necessarily imply synchronous recovery of carbon-cycle processes (Loisel and Gallego-Sala, 2022). Kalhori et al. (2024) found that a rewetted peatland became a stronger CO₂ sink one year after drought and interpreted this delayed response as a lag effect linked to drought-induced changes in vegetation growth status. In addition to these carry-over effects from seasonal to annual timescales, peatland CO₂ exchange also shows clear temporal structure at the diel scale. Liu et al. (2024a) reported day–night differences and hysteresis in CO₂–H₂O coupling pathways in the Dajiuhu peatland, suggesting that
60 hydrological controls on CO₂ fluxes may vary with diel phase and hydrological status. However, continuous observational evidence remains limited on whether NEE, GPP, and Reco simultaneously exhibit diel path dependence and day-scale lag effects under natural hydrological anomalies. This gap may lead to an underestimation of the persistent effects of hydrological anomalies on CO₂ fluxes during drought events and subsequent recovery.

Addressing this gap requires a peatland site with long-term monitoring records and a distinct hydrological anomaly event.

65 From a global observational perspective, peatland CO₂ flux observations are still concentrated mainly in high-latitude and



northern peatland regions (Pallandt et al., 2024; Zhao et al., 2024), whereas continuous flux observations in high-elevation peatlands remain relatively scarce. Eddy covariance (EC) measurements, widely used in peatland studies, provide continuous ecosystem-scale observations of gas exchange between the land surface and the atmosphere and are well suited for capturing flux dynamics during natural hydrological anomalies (Schrier-Uijl et al., 2010; Zhao et al., 2024). The Dajiuhu peatland in central China is a well-preserved typical subalpine peatland in the subtropical region. The site is characterized by favorable hydrological conditions throughout the year (Yang et al., 2025a) and generally functions as a CO₂ sink (Liu et al., 2024a). Notably, the Yangtze River Basin experienced an extreme drought in 2022 that was unprecedented since 1961 (Zhang et al., 2024), during which river and lake water levels in the Dajiuhu region declined markedly. Together, the continuous EC observations and synchronous hydrometeorological records at Dajiuhu peatland provide a valuable natural observational window for examining peatland CO₂ flux responses to hydrological anomalies.

To identify asynchronous CO₂ flux responses to natural hydrological anomalies in the Dajiuhu subalpine peatland, this study used 2021–2023 EC-based CO₂ flux and hydrometeorological data to address three main questions: (1) how the CO₂ source-sink status and flux components varied across different hydrological periods; (2) whether CO₂ flux components exhibited diel hysteresis and day-scale lagged responses to environmental variables; (3) whether the effects of extreme drought on CO₂ fluxes and their temporal responses persisted during subsequent recovery. We hypothesized that: (1) sustained growing-season water deficit would weaken peatland CO₂ uptake, with GPP being more sensitive to extreme drought than Reco and thereby shifting NEE toward a net CO₂ source; (2) extreme drought would reorganize the diel hysteresis and day-scale lagged responses of NEE, GPP, and Reco to hydrological and temperature variables, with inconsistent temporal response patterns across flux components and environmental drivers; (3) drought effects would persist into the subsequent recovery period, such that CO₂ uptake capacity and its temporal responses would not immediately return to normal conditions. This study advances previous work by jointly examining changes in CO₂ source-sink status and flux components, together with the diel hysteresis and day-scale lagged responses of NEE, GPP, and Reco to hydrological and temperature variables across different hydrological periods. This integrated framework enables the concurrent assessment of response magnitude, response pathways, response timescales, and post-drought persistence, thereby providing continuous observational evidence of asynchronous CO₂ flux responses to hydrological anomalies and advancing understanding of peatland carbon sink stability under hydrological disturbances.

2 Materials and methods

2.1 Study site

The Dajiuhu peatland in Shennongjia, Hubei Province, China (31°24'51"–31°32'30" N, 109°58'35"–110°07'32" E), is a subalpine enclosed karst basin surrounded by mountains. The basin covers approximately 16 km², with a mean annual precipitation of about 1550–1560 mm. It contains a series of interconnected natural lakes, and surface runoff within the basin ultimately drains through an underground karst cave system (Li et al., 2016). The EC flux tower is located within the



Dajiuhu peatland (31°28'44.45" N, 110°00'14.61" E) at an elevation of approximately 1758 m (Fig. 1), and the monitored area covers approximately 100 × 100 m. The area surrounding the EC tower is characterized by thick peat deposits of approximately 3.5 m, persistently wet soils, and vegetation dominated by *Sphagnum palustre*. As the site lies within a National Wetland Park, cultivation and grazing are strictly prohibited, and direct human disturbance is minimal.

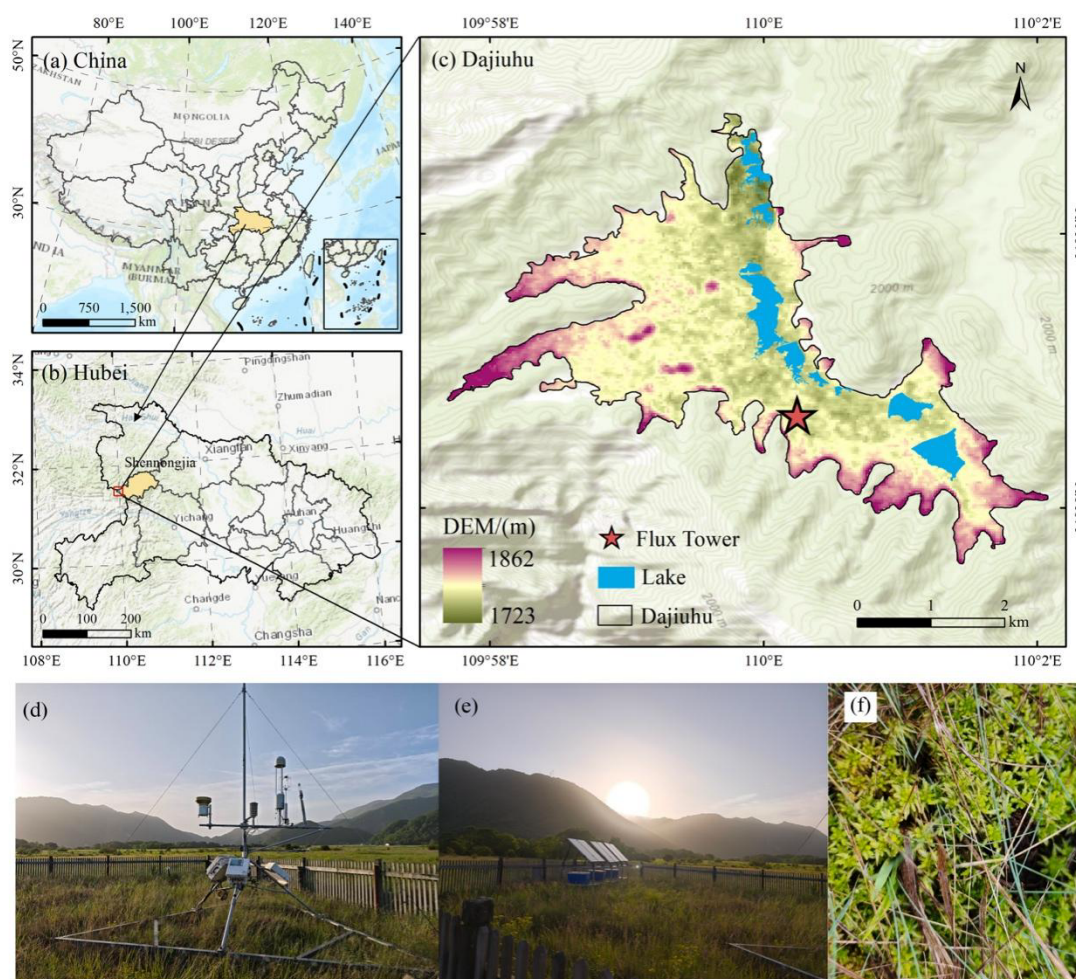


Figure 1: (a and b) Location of the study area in China and Hubei Province. (c) The topographic setting of the Dajiuhu peatland and the position of the flux tower. (d) Eddy covariance flux tower. (e) Environmental photo around the flux tower. (f) Photo of *Sphagnum palustre*.

2.2 Eddy covariance measurements and flux data processing

Our research group established a flux observation platform in the Dajiuhu peatland and has conducted long-term continuous in situ observations there since August 2015. The EC flux tower was installed approximately 3 m above the ground and was equipped with an open-path eddy covariance system developed by LI-COR. The main instruments included a three-dimensional sonic anemometer (Gill, USA), an open-path CO₂/H₂O infrared gas analyzer (LI-7500, LI-COR, USA), a



biometeorological observation system (Biomet-103, LI-COR, USA), a datalogger (9210, Sutron, USA), and a SmartFlux module for online flux calculation. The sonic anemometer and gas analyzer were used to measure high-frequency turbulent signals and fluctuations in CO₂ and H₂O concentrations at a sampling frequency of 10 Hz. The biometeorological system recorded environmental variables at 30 min intervals, including air temperature (Ta), soil temperature (Ts), relative humidity (RH), friction velocity (u*), precipitation, photosynthetic photon flux density (PPFD), vapor pressure deficit (VPD), and soil water content (SWC) at soil depths of 10, 20, and 30 cm, providing auxiliary data for flux calculation.

Before analysis, EC data were preprocessed, quality controlled, gap-filled, and partitioned. Raw data were first processed in EddyPro (version 7.0.6) and assigned quality classes of 0, 1, or 2, representing high-quality, acceptable-quality, and poor-quality data, respectively. Further processing was conducted because instrument malfunction, abrupt weather changes, and other environmental disturbances can cause missing or unreliable observations. Quality control was performed in Tovi (version 2.9.1): CO₂ flux data with a quality class of 2 were removed, classes 0 and 1 were retained, and outliers were identified and removed using theoretically reasonable ranges and the median ±10 interquartile range criterion. Storage correction was then applied using the Tovi storage correction module, and the corrected CO₂ flux was defined as NEE for subsequent analysis. Gap filling was performed using REddyProcWeb online (<https://bgc.iwww.mpg.de/5624884/Data-Formats>). NEE data with $u^* < 0.15 \text{ m s}^{-1}$ were removed, and missing values were filled using marginal distribution sampling (MDS), which estimates missing NEE values from available observations under similar meteorological conditions by considering flux–meteorology covariation and temporal autocorrelation (Reichstein et al., 2005).

Gap-filled NEE was further partitioned into GPP and Reco using the daytime partitioning method (Lasslop et al., 2010). Negative NEE values indicate CO₂ uptake from the atmosphere by the ecosystem, whereas positive values indicate CO₂ release from the ecosystem to the atmosphere. Here, GPP represents photosynthetic CO₂ uptake, Reco represents respiratory CO₂ release, and the three fluxes follow $NEE = Reco - GPP$.

2.3 Water table depth measurements

Groundwater level was continuously monitored using a water level logger (Levellogger M20, Solinst, Canada) installed in a PVC observation tube approximately 1 m from the EC flux tower. The recording interval was set to 30 min, consistent with the flux tower observations. Because the logger records raw pressure values, the data were corrected for atmospheric pressure before calculating water table depth (WTD). The calculation formula is as follows:

$$WTD = L - (H - H_a) - h \quad (1)$$

where H denotes the raw value recorded by the logger, H_a denotes the water-equivalent height corresponding to atmospheric pressure at the installation site, L denotes the cable length used to install the logger, and h denotes the height of the PVC tube above the ground surface. Both L and h were measured in the field. Larger WTD values indicate a deeper water table and drier peatland conditions.



2.4 Definition of hydrological periods and analysis window

Site-observed hydrological conditions were used as the primary basis for defining the hydrological periods. Previous research identified an extreme drought in the Yangtze River Basin in 2022 (Zhang et al., 2024), providing the regional context for assessing local hydrological conditions at the Dajiuhu peatland. At the site scale, hydrological status was assessed by jointly considering precipitation, WTD, and SWC_10 cm during the same analysis window. Lower precipitation, deeper WTD, and lower shallow SWC were interpreted as indicating stronger water stress. May–September was selected as the primary analysis window because it covers the main growing season of the Dajiuhu peatland, better captures the responses of CO₂ fluxes and their components to hydrological anomalies, and minimizes interference from seasonal transitions in interpreting these responses. Accordingly, May–September 2022 was defined as the Stressed period, whereas the same windows in 2021 and 2023 were defined as the Normal and Recovery periods, respectively.

2.5 Hysteresis analysis

For each period, CO₂ flux components and environmental variables were averaged by hour of day to obtain 24 points representing the mean diel cycle. These points were connected chronologically from 00:00 to 23:00 to form the mean diel response trajectory. Diel hysteresis was considered present when CO₂ flux values differed at similar levels of an environmental variable at different times of day.

For each response trajectory, the corresponding environmental variable and CO₂ flux component were then transformed using min-max normalization. The 24 normalized hourly points were connected sequentially to form a closed polygon, and the hysteresis area was calculated. For each variable combination, z_{min} and z_{max} used in this normalization were determined jointly from the 72 hourly points across the three periods, ensuring comparability of hysteresis areas among periods. The calculations were performed as follows:

$$z'_i = \frac{z_i - z_{min}}{z_{max} - z_{min}}, \quad (2)$$

$$A = \frac{1}{2} \left| \sum_{i=1}^n (x'_i y'_{i+1} - x'_{i+1} y'_i) \right|, \quad (3)$$

where z_i denotes the original variable value, z'_i denotes the normalized value. z_{min} and z_{max} are the minimum and maximum values of the corresponding variable, respectively. A denotes the normalized hysteresis area. x'_i and y'_i are the normalized environmental variable and normalized CO₂ flux component corresponding at hour i , respectively, with $n = 24$. To close the trajectory, $x'_{n+1} = x'_1$ and $y'_{n+1} = y'_1$ were used in the calculation.

2.6 Lagged response analysis

For each of the three periods, daily data were detrended using ordinary least-squares linear regression to reduce the influence of shared seasonal trends on lagged correlation results. The residual series was used as the detrended variable. The calculations were as follows:



$$X_t = a + bt + \varepsilon_t, \quad (4)$$

$$X_t^d = X_t - (a + bt), \quad (5)$$

where X_t denotes the original variable value on day t , $a + bt$ denotes the fitted linear trend, and X_t^d denotes the detrended variable value.

After obtaining the detrended daily series, the main lag-analysis window was set to 0–30 days. Assuming that changes in environmental variables preceded CO₂ flux responses, the CO₂ flux component series was shifted backward relative to the environmental variable series by one day at a time to construct paired series at each lag. Spearman rank correlation coefficients were calculated for lags of 0–30 days, and the lag with the maximum absolute correlation coefficient was defined as the peak lag. An additional lag window of 0–60 days was used to test the robustness of the main lag results. Spearman rank correlation analysis and significance testing were performed in OriginPro 2024.

2.7 Statistical analysis

Differences in CO₂ flux components and environmental variables among hydrological periods were analyzed using the non-parametric Kruskal-Wallis test. When the overall difference was significant, pairwise comparisons were further performed using Dunn's post hoc test, with p values adjusted for multiple comparisons using the Holm method. The Kruskal-Wallis test and Holm correction were performed in R, and Dunn's post hoc test was implemented using the FSA package. The significance level for all statistical tests was set at $p < 0.05$. The location map of the study area was produced using ArcMap 10.8, and all other figures were plotted using OriginPro 2024.

3 Results

3.1 Temporal dynamics of hydrological anomalies and CO₂ exchange

In the multi-year meteorological context shown in Fig. S1, annual precipitation in 2022 was relatively low, while May–September precipitation was the lowest and mean air temperature during the same period was the highest among the years shown (641.7 mm and 20.71 °C, respectively). At the annual scale (Fig. 2), precipitation in 2022 was 1238.4 mm, representing decreases of 36.7% and 42.1% compared with 2021 (1957.0 mm) and 2023 (2139.4 mm), respectively. Annual cumulative NEE was −353.20, 5.36, and −66.80 g C m^{−2} yr^{−1} in 2021, 2022, and 2023, respectively. During May–September, the precipitation deficit in 2022 was pronounced (Fig. 2e; Table S1), with cumulative precipitation reaching only 641.7 mm, 57.4% and 55.4% lower than that in the same period of 2021 (1505.1 mm) and 2023 (1440.1 mm), respectively. During May–September 2022, mean WTD increased to 31.15 cm, higher than that in the same period of 2021 (19.73 cm) and 2023 (25.21 cm). SWC₁₀ cm decreased to 0.567 m³ m^{−3}, lower than that during the same period in 2021 (0.584 m³ m^{−3}) and 2023 (0.575 m³ m^{−3}). The deeper WTD and lower SWC₁₀ cm did not represent isolated short-term fluctuations but occurred simultaneously during the 2022 drought period. Cumulative NEE was −414.94 g C m^{−2} in the Normal period but

only $-32.55 \text{ g C m}^{-2}$ in the Stressed period, indicating a 92.2% weakening of net CO_2 uptake relative to the Normal period. In the Recovery period, cumulative NEE recovered to $-93.46 \text{ g C m}^{-2}$ but remained much lower than that in the Normal period (Table S1).

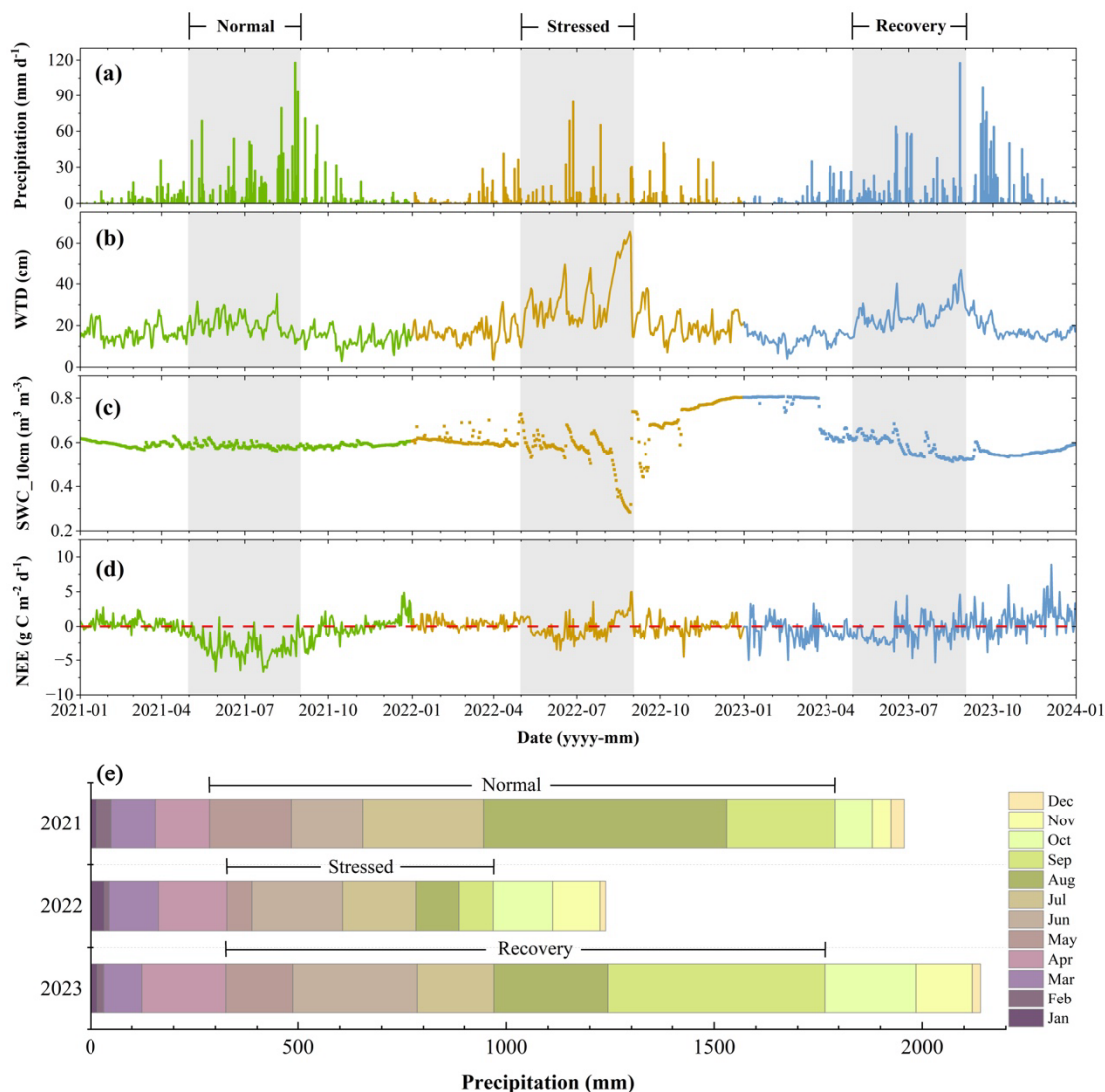


Figure 2: Temporal dynamics of precipitation, WTD, SWC_10 cm and NEE during 2021-2023. Daily variations in (a) precipitation, (b) WTD, (c) SWC_10 cm and (d) NEE, and (e) monthly and annual precipitation totals. Grey shaded areas indicate the three hydrological stages: Normal, Stressed and Recovery. The red dashed line in panel (d) indicates $\text{NEE} = 0$; negative NEE values represent CO_2 uptake by the ecosystem, whereas positive values represent CO_2 release to the atmosphere.

3.2 Stage-dependent differences in hydrology and CO_2 flux components

Kruskal–Wallis tests showed significant overall differences in WTD, SWC_10 cm, and CO_2 flux components among the three hydrological periods (Table S2). Dunn–Holm pairwise comparisons further indicated that WTD showed the clearest



separation among periods, with significant differences between all pairs of periods. WTD in the Stressed period was higher than that in the Normal and Recovery periods, while WTD in the Recovery period was lower than that in the Stressed period but remained significantly higher than that in the Normal period (Fig. 3a). In contrast, SWC₁₀ cm showed weaker separation among periods. Although the overall difference was significant (Kruskal–Wallis, $P = 0.041$), Dunn–Holm comparisons showed that SWC₁₀ cm in the Stressed period did not differ significantly from that in either the Normal period ($P = 0.382$) or the Recovery period ($P = 0.210$); the only significant pairwise difference occurred between the Normal and Recovery periods ($P = 0.038$). Thus, period differences in shallow SWC were weaker than those in WTD and did not clearly distinguish the three hydrological periods.

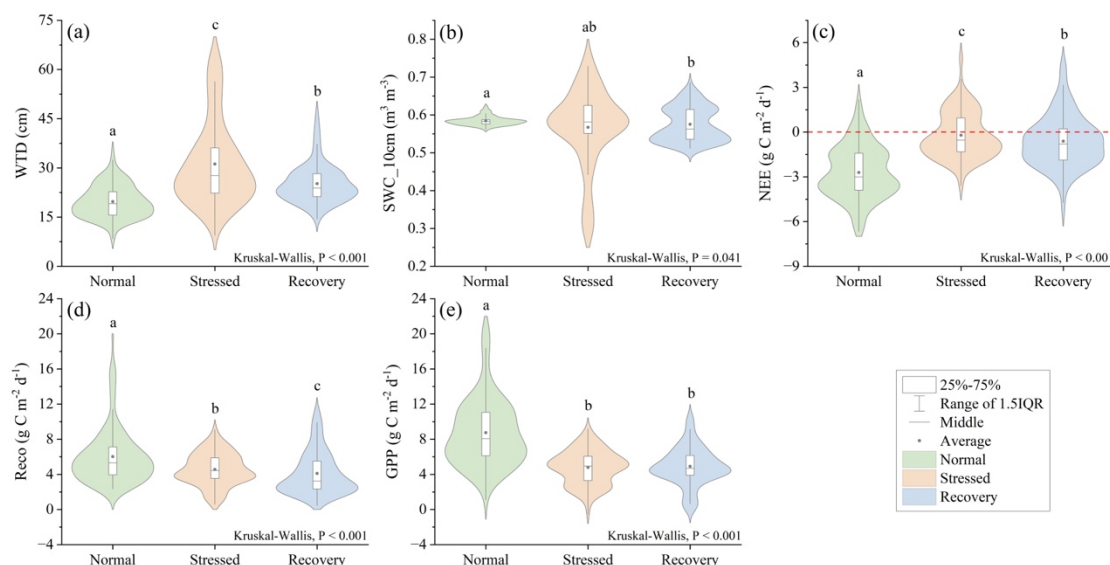


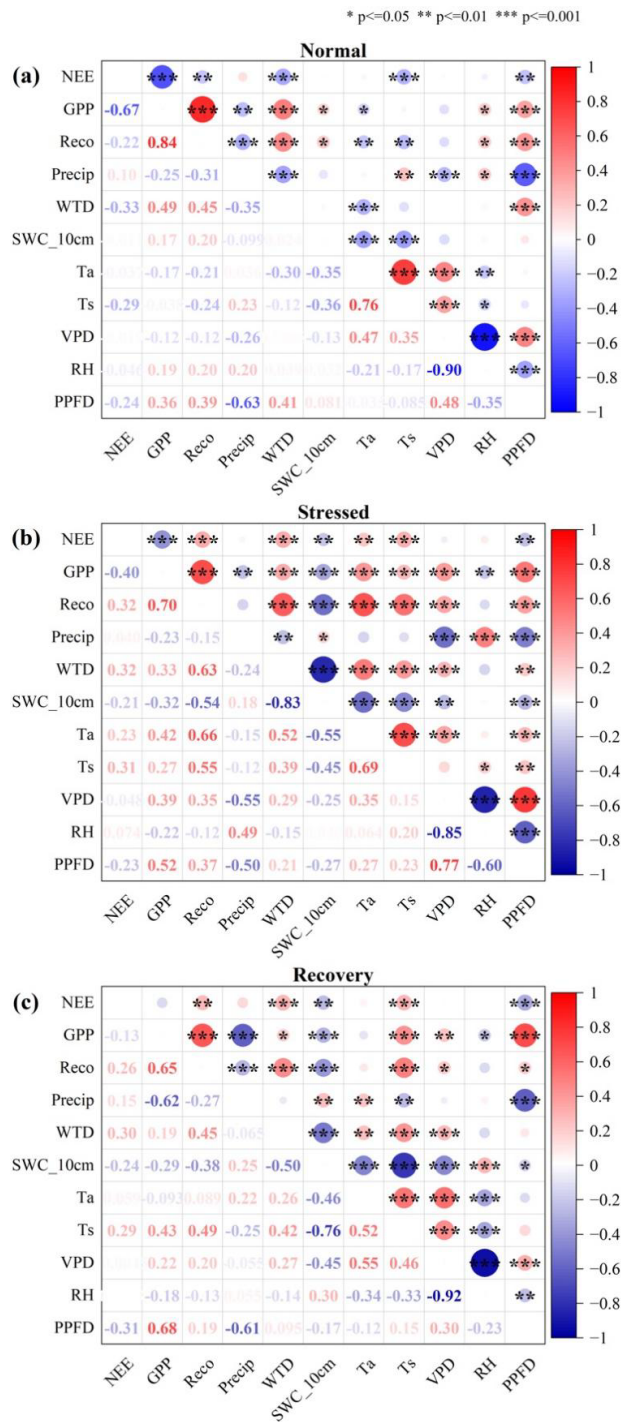
Figure 3: Distributions of hydrological variables and CO₂ flux components across hydrological stages. Distributions of (a) WTD, (b) SWC₁₀ cm, (c) NEE, (d) GPP and (e) Reco during the Normal, Stressed and Recovery periods. Different lowercase letters indicate significant differences among periods based on Dunn–Holm post hoc comparisons ($P < 0.05$).

NEE differed significantly among the three periods (Kruskal–Wallis, $P < 0.001$), with all pairwise comparisons being significant (Table S2). NEE was mainly distributed in the negative range during the Normal period, shifted markedly toward 0 during the Stressed period, and was intermediate during the Recovery period (Fig. 3c). GPP was significantly lower in both the Stressed and Recovery periods than in the Normal period (Dunn–Holm, both $P < 0.001$), with no significant difference between the Stressed and Recovery periods ($P = 0.877$). Cumulative GPP decreased by 45.3%, from 1337.17 g C m⁻² in the Normal period to 732.03 g C m⁻² in the Stressed period and remained low in the Recovery period (750.52 g C m⁻²; Table S3). Reco also differed among periods, and all pairwise comparisons were significant. Cumulative Reco decreased by 24.2%, from 922.23 to 699.48 g C m⁻² between the Normal and Stressed periods (Table S3).



3.3 Shifts in flux–environment relationships across different hydrological stages

235 Drought and subsequent recovery altered the relationships between relevant environmental variables and CO₂ flux components (Fig. 4). During the Normal period, NEE was most strongly and significantly correlated with GPP ($r = -0.67$), whereas its correlation with Reco was weak and not significant ($r = -0.22$). NEE was also significantly negatively correlated with WTD ($r = -0.33$), Ts ($r = -0.29$), and PPFD ($r = -0.24$). Meanwhile, GPP and Reco were strongly and positively correlated with each other ($r = 0.84$), and both were significantly positively correlated with WTD (GPP: $r = 0.49$; Reco: $r = 0.45$).



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Figure 4: Shifts in relationships between CO₂ flux components and environmental variables across hydrological stages. Abbreviations: NEE, net ecosystem exchange; GPP, gross primary productivity; Reco, ecosystem respiration; Precip, precipitation; WTD, water table depth; SWC_10 cm, soil water content at 10 cm depth; Ta, air temperature; Ts, soil temperature; VPD, vapor



pressure deficit; RH, relative humidity; PPFD, photosynthetic photon flux density. Lower-left values indicate Spearman correlation coefficients, and upper-right circles indicate the direction and strength of correlations. Red and blue indicate positive and negative correlations, respectively. The darker the colour and the larger the dot, the stronger the correlation.

During the Stressed period, the correlation structure shifted markedly. The negative correlation between NEE and GPP weakened to $r = -0.40$, whereas NEE became significantly positively correlated with Reco ($r = 0.32$). The relationship between NEE and WTD also shifted from a significant negative correlation in the Normal period to a significant positive correlation ($r = 0.32$), and NEE became significantly correlated with SWC_10 cm ($r = -0.21$). NEE also showed significant positive correlations with both Ta ($r = 0.23$) and Ts ($r = 0.31$). During this period, GPP was significantly positively correlated with WTD, PPFD, and Ta ($r = 0.48, 0.52$, and 0.42 , respectively), but negatively correlated with SWC_10 cm ($r = -0.32$). Reco showed similar but stronger relationships with hydrological and temperature variables, with positive correlations with WTD, Ta, and Ts ($r = 0.63, 0.66$, and 0.55 , respectively) and a negative correlation with SWC_10 cm ($r = -0.54$). In addition, VPD became significantly positively correlated with both GPP and Reco ($r = 0.39$ and 0.35 , respectively).

During the Recovery period, some correlations did not return to the Normal-period pattern. The correlation between NEE and GPP weakened further and became non-significant ($r = -0.13$), whereas NEE remained significantly positively correlated with Reco ($r = 0.26$). NEE also remained significantly positively correlated with WTD and negatively correlated with SWC_10 cm ($r = 0.30$ and -0.24 , respectively), and was significantly positively correlated with Ts ($r = 0.29$). The GPP–PPFD correlation increased to the highest value among the three periods ($r = 0.68$), and GPP was also significantly positively correlated with Ts ($r = 0.43$). Reco remained significantly positively correlated with WTD and Ts ($r = 0.45$ and 0.49 , respectively). Positive correlations of VPD with GPP and Reco persisted but weakened ($r = 0.22$ and 0.20 , respectively), with lower significance levels than in the Stressed period.

3.4 Diel hysteresis of CO₂ flux components in response to environmental variables

Hysteresis analysis focused on hydrology-related variables (WTD and SWC_10 cm) and temperature-related variables (Ta and Ts), with VPD and PPFD included as supplementary atmospheric variables. Figure 5 shows that the diel trajectories between CO₂ flux components and hydrology-related variables did not follow the same path in the forward and return directions, and that loop shapes and period-related changes differed among flux components. NEE and GPP formed closed hysteresis loops with both WTD and SWC_10 cm, showing similar loop shapes but opposite directions (Figs. 5a–5f, 5j–5o). In comparison, Reco also formed closed loops, but their extent and period-related changes differed from those of NEE and GPP (Figs. 5g–5i, 5p–5r).

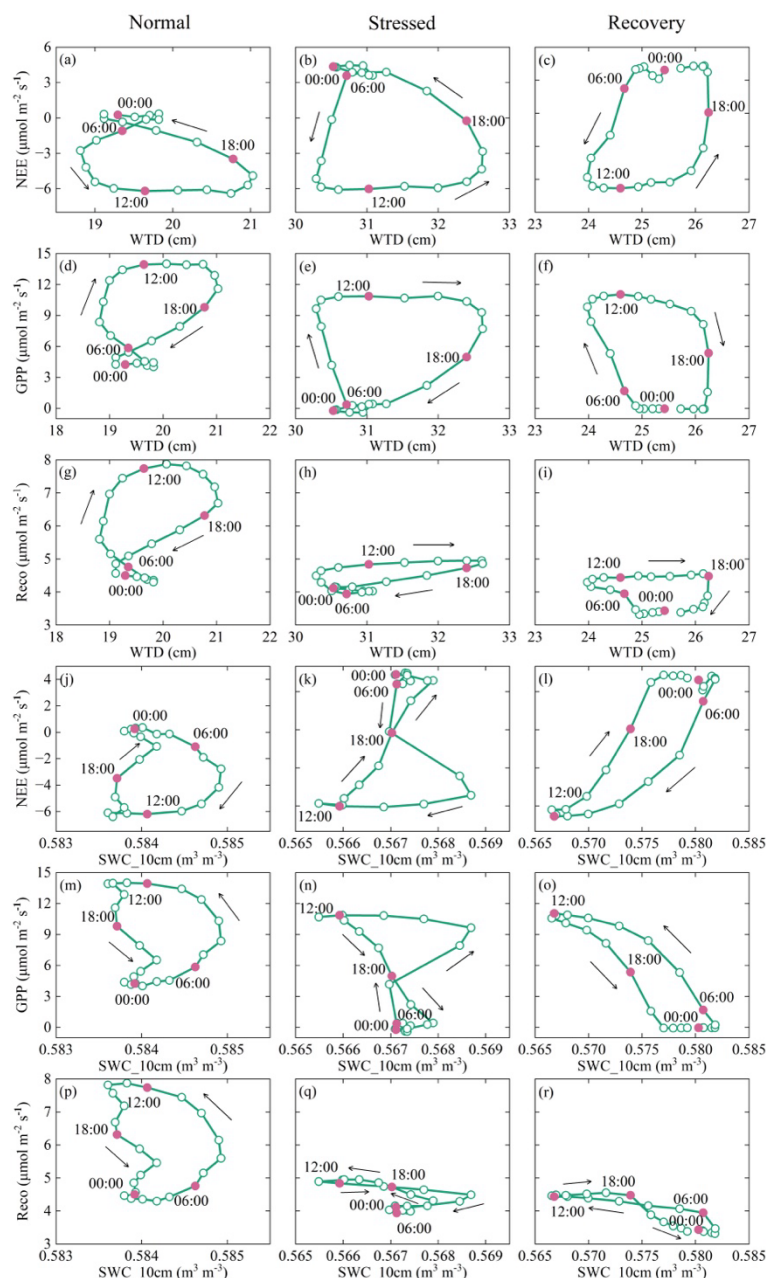


Figure 5: Diel hysteresis between CO₂ flux components and hydrological variables across the three hydrological stages. Panels (a–i)
show relationships between WTD and NEE, GPP and Reco, respectively; panels (j–r) show relationships between 10 cm soil water
content (SWC) and NEE, GPP and Reco, respectively. Trajectories were constructed from 24 hourly mean values, connected
chronologically, and shown in original units. Arrows indicate diel progression. Filled circles indicate representative time points
(00:00, 06:00, 12:00 and 18:00).



Compared with the more compact trajectories in the Normal period, WTD–NEE and WTD–GPP formed more expanded closed paths in the Stressed and Recovery periods, indicating stronger diel path separation. In contrast, WTD–Reco showed the opposite pattern, with markedly smaller hysteresis loops in the Stressed and Recovery periods. SWC–NEE and SWC–GPP showed eight-shaped loops in the Stressed period (Figs. 5k, 5n), and SWC–Reco showed similar eight-shaped loops in the Stressed and Recovery periods (Figs. 5q–5r). By contrast, all three SWC-related trajectories in the Normal period showed single closed loops.

To quantify the degree of path separation, normalized hysteresis areas were calculated for each loop (Table 1). Larger areas indicate stronger diel path separation and more asynchronous responses of CO₂ flux components to environmental variables, whereas smaller areas indicate greater overlap between the diel trajectories. The WTD–NEE area increased from 0.053 in the Normal period to 0.110 in the Stressed period and 0.117 in the Recovery period. A similar increase was observed for WTD–GPP, from 0.061 to 0.092 and 0.094, respectively. In contrast, WTD–Reco areas were lower in the Stressed and Recovery periods (0.017 and 0.029, respectively) than in the Normal period (0.063). For SWC-related loops, path separation of NEE and GPP was strongest in the Recovery period. The areas of SWC–NEE and SWC–GPP increased to 0.259 and 0.175, respectively, much higher than those in the Normal period (0.024 and 0.029) and Stressed period (0.031 and 0.025). The SWC–Reco area did not show the same Recovery-period maximum but was instead highest in the Normal period (0.032).

Table 1. Normalized hysteresis areas between CO₂ flux components and hydrological variables. Normalized hysteresis areas were calculated after applying one shared min–max range to the pooled 24 hourly points across the Normal, Stressed and Recovery periods for each variable pair.

Variable pair	Normal	Stressed	Recovery
WTD-NEE	0.053	0.110	0.117
WTD-GPP	0.061	0.092	0.094
WTD-Reco	0.063	0.017	0.029
SWC-NEE	0.024	0.031	0.259
SWC-GPP	0.029	0.025	0.175
SWC-Reco	0.032	0.002	0.022

Diel path differences in CO₂ flux components were not limited to hydrology-related variables but were also observed for temperature-related variables (Fig. 6). Ta–NEE and Ta–GPP showed clear closed trajectories in all three periods, with loop expansion increasing from the Normal period to the Stressed and Recovery periods. Similar to the hydrology-related hysteresis patterns, NEE and GPP showed similar loop shapes but opposite directions in their temperature-related trajectories (Figs. 6a–6f, 6j–6o). Reco-related hysteresis showed different period-specific patterns. Ta–Reco formed almost no clear hysteresis loop in the Stressed period (Fig. 6h), suggesting weak diel hysteresis in the response of Reco to Ta. In the Recovery period, Ta–Reco showed a eight-shaped loop (Fig. 6i), and Ts–Reco showed eight-shaped loops in the Stressed and Recovery periods (Figs. 6q–6r).

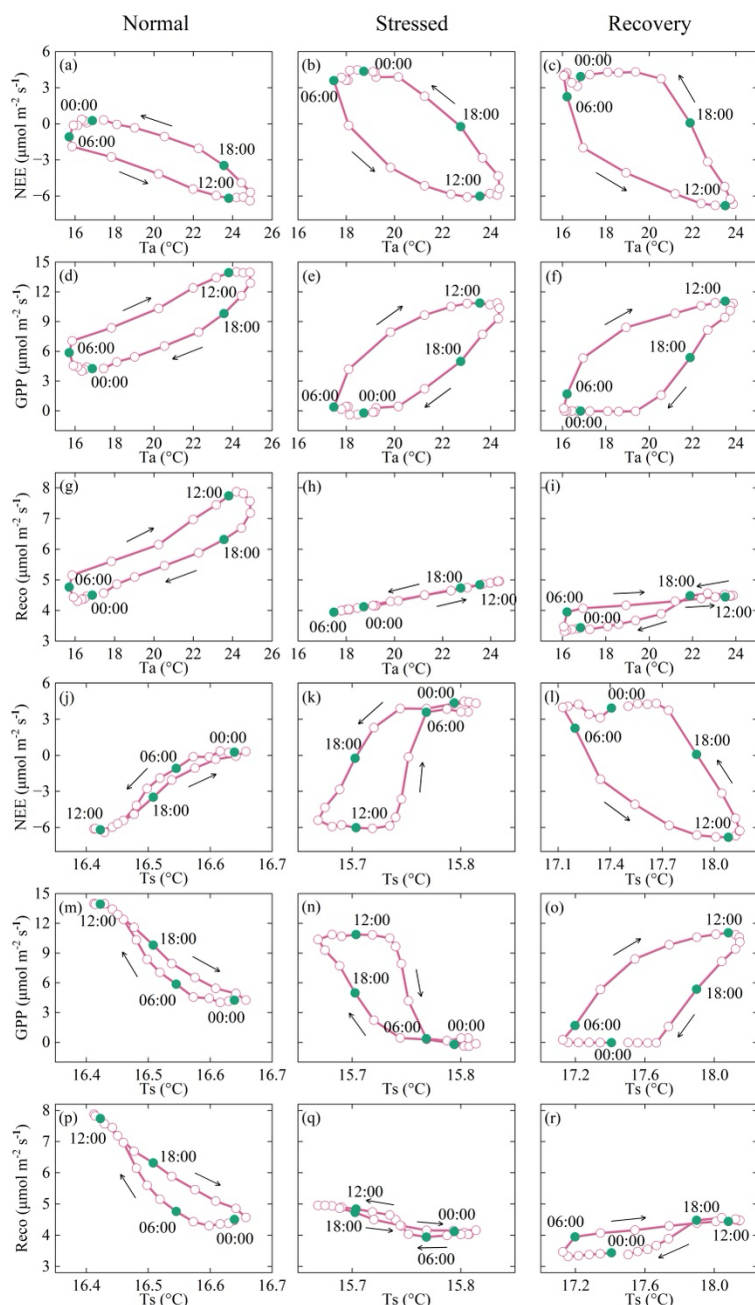


Figure 6: Diel hysteresis between CO₂ flux components and temperature variables across the three hydrological stages. Panels (a–i) show relationships between Ta and NEE, GPP and Reco, respectively; panels (j–r) show relationships between Ts and NEE, GPP and Reco, respectively. Trajectories were constructed from 24 hourly mean values, connected chronologically, and shown in original units. Arrows indicate diel progression. Filled circles indicate representative time points (00:00, 06:00, 12:00 and 18:00).

Normalized hysteresis areas further quantified temperature-related diel path separation (Table 2). Consistent with the trajectories in Fig. 6, the normalized areas of Ta–NEE and Ta–GPP increased across the three periods. The Ta–NEE area



increased from 0.246 in the Normal period to 0.368 in the Stressed period and 0.462 in the Recovery period, while the Ta–GPP area increased from 0.259 to 0.289 and 0.329, respectively. In contrast, the Ta–Reco area was close to 0 in the Stressed period and remained low in the Recovery period (0.060). In the Recovery period, the areas of Ts–NEE and Ts–GPP reached 0.215 and 0.155, respectively. These values were clearly higher than those in the Normal period (0.005 and 0.008) and Stressed period (0.019 and 0.015). The Ts–Reco area was nearly 0 in the Stressed period, consistent with the Ta–Reco pattern.

Table 2. Normalized hysteresis areas between CO₂ flux components and temperature variables. Normalized hysteresis areas were calculated after applying one shared min–max range to the pooled 24 hourly points across the Normal, Stressed and Recovery periods for each variable pair.

Variable pair	Normal	Stressed	Recovery
Ta-NEE	0.246	0.368	0.462
Ta-GPP	0.259	0.289	0.329
Ta-Reco	0.210	0.000	0.060
Ts-NEE	0.005	0.019	0.215
Ts-GPP	0.008	0.015	0.155
Ts-Reco	0.013	0.000	0.033

In addition to hydrology-related and temperature-related variables, VPD and PPFD were significantly correlated with some CO₂ flux components (Fig. 4) and were therefore included as supplementary variables in the analysis of diel response trajectories (Fig. S2; Table S4). In VPD-related and PPFD-related hysteresis, NEE and GPP still showed similar loop shapes but opposite directions (Figs. S2a–S2f, S2j–S2o). VPD-related hysteresis was mainly enhanced in the Stressed period, with VPD–NEE and VPD–GPP forming clear closed loops and reaching areas of 0.452 and 0.349, respectively, both higher than those in the Normal period (0.115 and 0.118) and Recovery period (0.341 and 0.260). In contrast, VPD–Reco formed almost no clear hysteresis loop in the Stressed period (Fig. S2h), with an area of only 0.017. PPFD-related hysteresis was generally weak, especially for PPFD–NEE and PPFD–GPP, whose trajectories nearly overlapped in the Stressed and Recovery periods (Figs. S2k–S2l, S2n–S2o). The PPFD–GPP area decreased progressively from 0.112 in the Normal period to 0.016 in the Stressed period and 0.004 in the Recovery period.

3.5 Lagged responses of CO₂ flux components to environmental variables

Based on the clear differences in hydrological and temperature-related hysteresis among the three hydrological periods, we further identified day-scale lagged responses of CO₂ flux components to hydrological and temperature variables. Interpretation of the lag results was mainly based on detrended results within the 0–30 d main window, while the raw (non-detrended) results were presented for comparison. Within the 0–30 d main window, peak lags between CO₂ flux components and hydrological variables were generally short (Table 3), mostly ranging from 0 to 4 d. For WTD–NEE, detrended peak lags were 0 d in the Normal and Recovery periods. In the Stressed period, however, WTD–NEE showed a stronger 4 d



lagged correlation ($\rho = 0.440$, $P < 0.001$). SWC–NEE also showed a significant 4 d lag in the Stressed period ($\rho = -0.310$, $P < 0.001$), whereas no significant lagged correlation was observed in the Normal or Recovery period. These results indicate that short-term lagged responses of NEE to hydrological variables were clearest during drought, with a stronger correlation for WTD–NEE. In the 0–60 d sensitivity analysis, WTD–NEE peak lags remained consistent with the 0–30 d results across the three periods, at 0, 4, and 0 d, respectively (Table S5). By contrast, SWC–NEE in the Recovery period showed a 46 d peak lag only under the extended window ($\rho = 0.278$, $P < 0.05$).

Table 3. Lagged responses of CO₂ flux components to hydrological variables within the 0–30 d window. Positive lag values indicate that CO₂ flux components responded after changes in environmental variables. Detrended results were used as the main basis for interpretation. p-values are presented as significance classes (<0.001 , <0.01 , <0.05 , ns), where ns indicates $p \geq 0.05$.

Variable pair	Period	Raw			Detrended		
		peak lag (d)	peak ρ	p	peak lag (d)	peak ρ	p
WTD-NEE	Normal	3	-0.332	<0.001	0	-0.251	<0.01
	Stressed	4	0.391	<0.001	4	0.44	<0.001
	Recovery	0	0.3	<0.001	0	0.178	<0.05
SWC-NEE	Normal	2	-0.033	ns	0	0.087	ns
	Stressed	12	-0.347	<0.001	4	-0.31	<0.001
	Recovery	0	-0.245	<0.01	1	0.041	ns
WTD-GPP	Normal	3	0.5	<0.001	0	0.334	<0.001
	Stressed	0	0.327	<0.001	0	0.355	<0.001
	Recovery	1	0.196	<0.05	0	0.251	<0.01
SWC-GPP	Normal	2	0.193	<0.05	2	0.098	ns
	Stressed	0	-0.325	<0.001	0	-0.285	<0.001
	Recovery	5	-0.311	<0.001	0	-0.53	<0.001
WTD-Reco	Normal	0	0.448	<0.001	0	0.318	<0.001
	Stressed	0	0.63	<0.001	0	0.638	<0.001
	Recovery	4	0.468	<0.001	2	0.434	<0.001
SWC-Reco	Normal	2	0.219	<0.01	2	0.176	<0.05
	Stressed	0	-0.542	<0.001	0	-0.48	<0.001
	Recovery	0	-0.381	<0.001	0	-0.359	<0.001

GPP responses to hydrological variables were closer to synchronous. WTD–GPP showed significant 0 d lags in all three periods ($\rho = 0.334$, 0.355 , and 0.251). SWC–GPP also showed significant 0 d lags in the Stressed and Recovery periods ($\rho = -0.285$ and -0.530 , respectively). Reco also responded over short lags, with WTD–Reco and SWC–Reco lags generally within 0–2 d. In the Stressed period, both relationships showed strong peak correlations at these short lags (WTD–Reco: $\rho =$



0.638; SWC–Reco: $\rho = -0.480$). The main lag results for GPP and Reco remained consistent under the 0–60 d extended window, indicating robust synchronous or short-delay responses to hydrological variables (Table S5).

Compared with hydrological variables, temperature variables showed longer peak lags with CO₂ flux components, mainly for NEE (Table 4). The clearest pattern occurred in the Stressed period, when both Ta–NEE and Ts–NEE showed significant 16 d lags, with correlations of $\rho = 0.249$ ($P < 0.01$) and $\rho = 0.422$ ($P < 0.001$), respectively. In the Recovery period, NEE still showed a 13 d lag with Ts ($\rho = 0.178$, $P < 0.05$), suggesting partial recovery but not a full return to the same-day response observed in the Normal period (0 d, $\rho = -0.433$, $P < 0.001$). The 0–60 d sensitivity analysis showed that the 16 d lags of Ta–NEE and Ts–NEE in the Stressed period remained unchanged under the extended window (Table S6), indicating that this prolonged temperature-related lag was robust.

Table 4. Lagged responses of CO₂ flux components to temperature variables within the 0–30 d window. Positive lag values indicate that CO₂ flux components responded after changes in environmental variables. Detrended results were used as the main basis for interpretation. p-values are presented as significance classes (<0.001, <0.01, <0.05, ns), where ns indicates $p \geq 0.05$.

Variable pair	Period	Raw			Detrended		
		peak lag (d)	peak ρ	p	peak lag (d)	peak ρ	p
Ta–NEE	Normal	0	-0.037	ns	0	-0.201	<0.05
	Stressed	12	0.397	<0.001	16	0.249	<0.01
	Recovery	0	0.059	ns	0	-0.138	ns
Ts–NEE	Normal	0	-0.287	<0.001	0	-0.433	<0.001
	Stressed	30	0.672	<0.001	16	0.422	<0.001
	Recovery	0	0.294	<0.001	13	0.178	<0.05
Ta–GPP	Normal	6	-0.232	<0.01	30	0.341	<0.001
	Stressed	1	0.43	<0.001	1	0.575	<0.001
	Recovery	23	-0.191	<0.05	14	-0.183	<0.05
Ts–GPP	Normal	14	-0.242	<0.01	30	0.254	<0.05
	Stressed	0	0.265	<0.001	0	0.601	<0.001
	Recovery	1	0.436	<0.001	0	0.618	<0.001
Ta–Reco	Normal	7	-0.266	<0.01	30	0.295	<0.01
	Stressed	3	0.684	<0.001	1	0.689	<0.001
	Recovery	30	0.23	<0.05	0	-0.012	ns
Ts–Reco	Normal	7	-0.324	<0.001	7	-0.225	<0.01
	Stressed	5	0.561	<0.001	0	0.723	<0.001
	Recovery	2	0.492	<0.001	1	0.444	<0.001



In contrast, GPP and Reco showed maximum lagged correlations with temperature variables mainly at 0–1 d in the Stressed period. Ta–GPP showed a significant 1 d lag ($\rho = 0.575$, $P < 0.001$), whereas Ts–GPP showed a 0 d lag ($\rho = 0.601$, $P < 0.001$). In the Recovery period, Ts–GPP remained at 0 d ($\rho = 0.618$, $P < 0.001$), while Ta–GPP showed a 14 d peak lag ($\rho = -0.183$, $P < 0.05$). The 30 d lags of Ta–GPP and Ts–GPP in the Normal period were located at the boundary of the 0–30 d window and were therefore not emphasized as main ecological response times. Reco showed a different pattern from NEE: the Ts–Reco lag was longest in the Normal period (7 d, $\rho = -0.225$, $P < 0.001$), shortened to 0 d in the Stressed period ($\rho = 0.723$, $P < 0.001$), and remained short in the Recovery period (1 d, $\rho = 0.444$, $P < 0.001$). In the Stressed period, Ta–Reco and Ts–Reco showed the same lag times as GPP, at 1 d and 0 d, respectively, but with stronger correlations. The 0–60 d sensitivity analysis confirmed that the longer NEE–temperature lags in the Stressed period (16 d) and the shorter GPP/Reco–temperature lags (0–1 d) remained robust under the extended window (Table S6).

4 Discussion

4.1 Effects of extreme drought on peatland CO₂ sink function

The Dajiuhu peatland acted as a CO₂ sink in 2021 and 2023 (-353.20 and -66.80 g C m⁻² yr⁻¹, respectively), but shifted to a CO₂ source in 2022 (5.36 g C m⁻² yr⁻¹). This source–sink shift occurred under extreme drought conditions, with markedly reduced precipitation, a deeper water table, and lower soil moisture, indicating that the growing-season hydrological anomaly in 2022 strongly weakened the CO₂ sink function of the Dajiuhu peatland. GPP decreased by 45.3% from the Normal to Stressed period, whereas Reco decreased by 24.2% (Fig. 3; Table S3), suggesting that the 2022 source shift was mainly driven by reduced GPP under sustained growing-season water deficit. These results supported our first hypothesis by showing that the weakening of CO₂ uptake during drought was mainly associated with a larger reduction in GPP than in Reco. Spearman correlations further revealed changes in the relationships between NEE and its component fluxes (Fig. 4). In the Normal period, NEE was strongly correlated with GPP ($r = -0.67$) but weakly and non-significantly correlated with Reco. In the Stressed period, the NEE–GPP correlation weakened ($r = -0.40$), whereas NEE became significantly positively correlated with Reco ($r = 0.32$), indicating that the relationships of GPP and Reco with NEE were altered under drought. Similar patterns were reported by Minkinen et al. (2018), who attributed drought-year weakening of the CO₂ sink to simultaneous declines in summer GPP and Reco, with a larger decline in GPP. Some studies also suggest that declines in GPP under drought conditions are a key factor in the reduced CO₂ sink capacity of peatlands (Lund et al., 2012; McDonald et al., 2023). However, other studies have shown that drought effects on peatland CO₂ exchange may instead be driven mainly by enhanced Reco, often linked to increased peat aeration and aerobic decomposition after water-table drawdown (Kwon et al., 2022; Lund et al., 2012). GPP and Reco may also increase simultaneously under drought conditions (Beyer et al., 2021). Although CO₂ flux observations and drought-response evidence remain limited for subtropical subalpine peatlands such as Dajiuhu, studies from low-latitude mountain peatlands outside China provide useful regional comparisons. Water-table decline has been shown to alter carbon exchange in these mountain peatlands, with enhanced ecosystem



395 respiration as an important response (Planas-Clarke et al., 2020). This differs from the Dajiuhu result, where Reco did not increase during drought, suggesting that CO₂ responses to hydrological change in such peatlands may vary with dominant vegetation type and near-surface water supply.

For the Dajiuhu peatland, where *Sphagnum palustre* is the dominant vegetation, its water-acquisition strategy may provide a plausible explanation for the observed decline in GPP under drought. Because *Sphagnum palustre* lacks vascular tissue and
400 roots that actively obtain water from deeper soil, its tissue water content is mainly maintained by precipitation, surface absorption, and capillary rise (Schipperges and Rydin, 1998; Weston et al., 2015), making it sensitive to near-surface water deficit (Kokkonen et al., 2024). In this study, precipitation in the Stressed period was 57.4% lower than in the Normal period, while WTD deepened significantly and shallow SWC declined (Fig. 2). This hydrological combination may have reduced direct rainfall input to *Sphagnum palustre*, weakened capillary water supply from wetter peat below, and lowered the
405 buffering capacity of shallow peat against surface water fluctuations. These conditions may have limited the ability of *Sphagnum palustre* to maintain suitable tissue water content. Once *Sphagnum palustre* water content falls below the suitable range, photosynthesis and net CO₂ uptake can decline markedly (Bengtsson et al., 2020). Under sustained growing-season water deficit, *Sphagnum palustre* may therefore have more frequently remained below this range, turning periods with strong carbon uptake potential into periods of low uptake efficiency. Lund et al. (2012) also showed that sustained drought
410 beginning in the early growing season can dry *Sphagnum* and continuously reduce photosynthetic rates and biomass accumulation.

Although peat drying can generally increase oxygen entry and aerobic decomposition, thereby enhancing CO₂ release, such an increase in cumulative Reco was not observed in the Dajiuhu peatland. This pattern may be related to the multiple sources of Reco. Reco includes plant autotrophic respiration, rhizosphere respiration, and microbial heterotrophic respiration, all of
415 which can be strongly influenced by vegetation dynamics (Rankin et al., 2022). When drought causes a marked decline in GPP, reduced vegetation activity may weaken plant respiration and decrease recent photosynthate supply to rhizosphere and microbial processes (Barba et al., 2018), potentially limiting increases in both autotrophic and heterotrophic respiration. In addition, shallow soil water deficit may constrain surface peat decomposition (Minkinen et al., 2018) and the heterotrophic component of Reco by limiting microbially mediated processes. Extreme drought has been shown to reduce soil
420 heterotrophic respiration by altering the abundance of soil microbial functional groups (Kang et al., 2022), suggesting that the heterotrophic component of Reco may also be constrained by drought-induced changes in microbial function. When near-surface peat becomes excessively dry, reduced water-film connectivity may limit the diffusion of soluble substrates to microbial cells, reduce enzyme–substrate contact, and weaken microbial metabolic activity (Moyano et al., 2013; Ghezzehei et al., 2019). This substrate-diffusion limitation can also affect extracellular enzyme-mediated organic matter decomposition
425 and subsequent microbial metabolism (Bonnett et al., 2017), and may alter microbial metabolic efficiency and microbial biomass allocation in peatlands (Jiang et al., 2025). Therefore, near-surface water deficit may have partly offset the decomposition-enhancing effect of deeper WTD and increased peat aeration, thereby limiting the increase in Reco during drought. Because this study did not include component-specific measurements to distinguish plant autotrophic respiration,

rhizosphere respiration, and microbial heterotrophic respiration, the above interpretation should be regarded as a possible mechanistic explanation based on the observed flux patterns and previous studies.

4.2 Changes in diel response pathways of CO₂ flux components under drought disturbance

The asynchronous responses of CO₂ flux components under drought disturbance were reflected not only in cumulative fluxes, but also in hourly diel pathways. Although the NEE–GPP relationship weakened during the Stressed period, NEE remained linked to GPP, while CO₂ flux components became more strongly constrained by combined hydrological and thermal conditions (Fig. 4). Diel hysteresis analysis showed that NEE and GPP had similar but oppositely directed trajectories with hydrological and temperature variables, whereas Reco showed distinct patterns (Figs. 5 and 6), indicating that hourly NEE variation was closer to the diel response of GPP. Larger WTD- related and Ta-related hysteresis areas in the Stressed and Recovery periods, and maximum shallow SWC- and Ts-related areas mainly in the Recovery period (Tables 1 and 2), suggest that NEE/GPP responses became more asynchronous during and after drought and were influenced by earlier diel states, not only by instantaneous environmental conditions. In contrast, weak PPFD-related hysteresis (Table S4; Fig. S2) suggests that PPFD was unlikely to be the main driver of diel hysteresis in GPP and NEE.

Daytime NEE variation is largely controlled by light-driven GPP (Järveoja et al., 2018). When diel GPP fluctuations exceed those of Reco, NEE can retain the trajectory features of GPP while showing a mirrored pattern because of their opposite flux directions. Our results therefore suggest that diel hysteresis in NEE and GPP was more likely associated with the regulation of photosynthetic CO₂ fixation by water status and thermal conditions than by PPFD. PPFD provides the direct energy input for photosynthesis and usually drives rapid diel GPP responses, whereas water status and temperature can alter the physiological state of *Sphagnum palustre* and the near-surface peat layer. *Sphagnum* photosynthesis is limited by both excessive wetness and excessive drying (Strack and Price, 2009), while the temperature effect on *Sphagnum* photosynthesis depends strongly on water status (Jassey and Signarbieux, 2019). Thus, morning and afternoon periods under similar hydrothermal conditions may differ in *Sphagnum palustre* water content, evaporative water loss, and thermal stress. This provides a plausible explanation for the diel hysteresis of GPP and NEE responses to hydrological and thermal variables.

Reco was more strongly constrained by hydrothermal conditions during the Stressed period, and this constraint appeared closer to a synchronous response. Thus, Reco did not show the clear diel pathway divergence observed for GPP and NEE. This difference may reflect the integration of multiple respiration sources within Reco. Previous peatland studies have shown that Reco can exhibit bimodal diel patterns, partly because of diel differences in autotrophic and heterotrophic contributions (Järveoja et al., 2020). In addition, autotrophic and heterotrophic respiration may differ in the direction and magnitude of hysteresis relative to temperature, and changes in moisture conditions can further modify the hysteretic behavior of these respiratory components (Song et al., 2015). Therefore, when different respiratory components are integrated into ecosystem-scale Reco, the hysteretic signal of an individual component may be attenuated or partly offset. Meanwhile, soil moisture can regulate the balance between soil CO₂ production and transport by altering CO₂ diffusivity and thermal diffusion processes (Phillips et al., 2011), and soil CO₂ diel hysteresis may also be weakened or nearly eliminated under lower SWC (Riveros-



Iregui et al., 2007). Taken together, the less distinct diel pathway divergence of Reco during the Stressed period likely reflected the ecosystem-scale net effect of different respiratory processes integrated with soil CO₂ production–transport dynamics.

465 Studies on diel hysteresis in peatland CO₂ fluxes remain limited. Liu et al. (2024a) found clear day–night differences and hysteresis in CO₂–H₂O coupling in the Dajiuhu peatland, suggesting that local CO₂ exchange does not simply vary instantaneously with environmental variables. The present study further shows, using continuous flux observations, that subalpine peatland CO₂ fluxes exhibit diel hysteresis and that NEE, GPP, and Reco respond asynchronously at the diel scale under drought disturbance.

470 4.3 Day-scale lagged responses of CO₂ flux components to environmental variables across hydrological periods

Lag analysis further showed that the asynchronous response of CO₂ fluxes to hydrological anomalies extended from diel hysteresis to day-scale response timing. During the Stressed period, NEE showed significant 4 d lags with both WTD and shallow SWC, whereas GPP and Reco responded mainly within 0–2 d (Table 3), suggesting a short cross-day delay in NEE but more same-day or short-delay responses in its component fluxes. Temperature-related lags were longer, with significant
 475 16 d lags for Ta–NEE and Ts–NEE, while GPP and Reco responded to Ta and Ts mainly within 0–1 d (Table 4). Together, the diel hysteresis and lag results supported our second hypothesis that drought reorganized the diel and day-scale responses of NEE, GPP, and Reco, with response patterns differing among flux components and environmental drivers. Because NEE responses to hydrological disturbance are jointly influenced by photosynthesis, ecosystem respiration, decomposition processes, and CO₂ transport (Han et al., 2015), under sustained hydrological deficit, GPP may be rapidly limited by the
 480 water status and photosynthetic activity of *Sphagnum palustre*, whereas Reco may be regulated by vegetation activity, substrate supply, an expanded aerobic peat layer, and temperature conditions. When GPP and Reco differ in response direction and magnitude, NEE, as their net result, may show a more pronounced short-term lag than either component flux. Compared with previous studies, the 4 d short-term lags between NEE and hydrological variables under drought conditions are not unusual, but they may reflect peatland-specific response characteristics. Helfter et al. (2015) similarly showed that
 485 hydrological changes in peatlands may take several days to be reflected in CO₂ fluxes during drought and reported 0–5 d lags in Reco responses to WTD. Similar short lags have also been observed in water-limited ecosystems, Wohlfahrt et al. (2008) found a 3–4 d lag between water input and NEE in a desert ecosystem, with shorter lags at higher SWC. Under drought conditions, hydrological variables may more directly represent water limitation, allowing NEE responses to WTD and SWC to emerge over relatively short timescales. By contrast, temperature variables may reflect slower ecological adjustment
 490 processes associated with combined thermal stress and water limitation, including sustained effects on phenology (Richardson et al., 2010), vegetation growth (Reddy et al., 2004), and photosynthetic capacity (Li et al., 2021). This interpretation is consistent with Zhang et al. (2015), who found persistent and relatively long temperature-related lagged effects on CO₂ exchange, whereas moisture effects were mostly immediate.



It should be acknowledged that the lag analysis reflects correlations between environmental variables and CO₂ fluxes under temporal offsets, rather than causal mechanisms. Although detrending and the 0–60 d sensitivity analysis improved interpretive robustness, they could not fully separate the independent effects of environmental variables and vegetation states during drought. In addition, because Reco was derived from EC-based flux partitioning and represents ecosystem-scale respiration, its lagged responses should be interpreted as integrated net responses rather than component-specific lag patterns.

4.4 Asynchronous responses during the recovery of CO₂ sink function after drought

Results from the Recovery period showed that the effects of the 2022 extreme drought on CO₂ fluxes in the Dajiuhu peatland did not fully disappear with the recovery of moisture conditions. This incomplete recovery was reflected in weakened CO₂ sink strength, continued deviation of some diel hysteresis pathways, and incomplete recovery of some day-scale lagged response patterns. These recovery patterns supported our third hypothesis that drought effects would persist into the subsequent recovery period, with CO₂ uptake capacity and temporal responses not immediately returning to Normal-period conditions. We suggest that CO₂ sink strength and response structure recovered more slowly than hydrological conditions, reflecting a legacy effect of extreme drought on peatland CO₂ flux processes. Although previous studies have shown that drought effects on peatlands can persist after the event ends (Kalhori et al., 2024; Kane et al., 2021), our results further suggest that such legacy effects may involve persistent deviations in flux response pathways and response timing, not only weakened CO₂ sink strength.

This has important implications for assessing the stability of peatland CO₂ sink function. Global peatland carbon sinks are vulnerable to future climate change, and extreme drought risks may further increase. Even when peatlands recovering from hydrological anomalies regain net CO₂ sink function, hydrological processes, biodiversity, and peat soil structure may remain incompletely recovered, potentially weakening their resilience to future disturbances (Loisel and Gallego-Sala, 2022). Therefore, drought legacy effects should be considered when assessing hydrological-anomaly impacts on peatland CO₂ sink function, in order to better evaluate peatland CO₂ sink stability under more frequent future climate extremes. However, because this study was based on a single site and a single extreme drought event, whether drought legacy effects show consistent patterns across other low-latitude mountain peatlands and different drought events remains to be further tested. Given the remaining regional and peatland-type gaps in peatland flux observations (Zhao et al., 2024) and the limited understanding of regional differences in high-altitude peatland carbon cycling (Gaffney et al., 2025), future work could build on the long-term observations at Dajiuhu and include other low-latitude mountain peatlands with long-term observation capacity for regional comparisons, using comparable analysis windows, flux-partitioning procedures, and hydrometeorological variables. Further integration of EC-based CO₂ flux observations with multi-scale process measurements, including vegetation water status, respiration components, and microbial processes (Dyukarev et al., 2021), would help better constrain the mechanistic interpretation of NEE, GPP, and Reco responses to drought and recovery.



525 5 Conclusions

This study showed that the 2022 extreme drought substantially weakened the CO₂ sink function of the Dajiuhu peatland, shifting it from a stable CO₂ sink to a weak CO₂ source. The weakened NEE during this period was mainly associated with reduced GPP. Although the ecosystem returned to a CO₂ sink after drought, its sink strength remained much lower than the pre-drought level. Drought-induced hydrological anomalies also altered the response relationships between CO₂ flux
530 components and hydrological and temperature variables, leading to asynchronous diel pathways and day-scale responses of NEE, GPP, and Reco. NEE showed short lags to hydrological variables but longer lags to temperature variables, indicating temporal offsets in the effects of different environmental variables on NEE. The drought effects persisted into the subsequent Recovery period, suggesting a drought legacy effect. These findings highlight the need to account for post-drought legacy effects when evaluating peatland CO₂ sink stability under increasing hydrological extremes.

535 Data availability

The processed CO₂ flux and hydrometeorological data used to support the findings of this study are available from the corresponding author upon request. The administrative boundary data (<https://doi.org/10.12078/2023010103>, <https://doi.org/10.12078/2023010101>; Xu, 2023a, b) were sourced from the Resources and Environment Science Data Center (RESDC) of the Chinese Academy of Sciences.

540 Author contributions

LW: Conceptualization, methodology, investigation, formal analysis, writing–original draft, writing–review and editing. JG: Project administration, funding acquisition, supervision, writing–review and editing. SY: Methodology, formal analysis, writing–review and editing. ZL: Methodology, data curation. XL: data curation. All authors reviewed and approved the final manuscript.

545 Competing interests

The contact author has declared that none of the authors has any competing interests.

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