Antecedent water condition determines carbon exchange response to extreme precipitation events across global drylands

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Received: 26 January 2021 / Accepted: 1 July 2022 / Published online: 11 July 2022
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Abstract
The global hydrological cycle is predicted to be intensified under the warming climate, with more extreme precipitation events and longer dry spell in between. Here, we evaluated how extreme precipitation events (EPEs) with antecedent dry (dry-EPEs) and wet (wet-EPEs) water conditions influence carbon exchange along gradient of arid, semi-arid, and sub-humid ecosystems based on eddy covariance datasets. After EPEs, ecosystem respiration and gross primary productivity (GPP) were stimulated by pulses of soil moisture in arid and semi-arid regions, but suppressed by decreased soil temperature in sub-humid region. Antecedent water condition determined asynchronous response of ecosystem respiration and GPP to EPEs, and therefore fluctuations in net carbon balance. Net carbon uptake capacity was enhanced immediately following wet-EPEs because of more rapid and greater response of GPP than respiration. However, after dry-EPEs, net carbon uptake capacity decreased immediately and increased thereafter because the response of GPP to dry-EPEs lagged behind ecosystem respiration. More antecedent precipitation further stimulated accumulative net carbon uptake. In general, the accumulated net carbon uptake within 3 weeks after wet-EPEs was two times and seven times of that after dry-EPEs in arid and semi-arid region, respectively. In sub-humid region, ecosystems acted as a carbon sink after wet-EPEs, but as a carbon source after dry-EPEs. We conclude that antecedent water conditions and local climate regimes need to be considered when interpreting the response of carbon exchange to EPEs in dryland ecosystems.

1 Introduction
Drylands cover around 40% of the Earth’s land surface and account for large mass of global net primary production (Shen et al. 2016). Drylands determine the interannual variations in terrestrial carbon sink because they are highly sensitive to climate variation, especially precipitation (Ahlström et al. 2015; Bunting et al. 2017). Precipitation constrains biological and physical processes in drylands and occurs as episodic events (‘pulses’) separated by periods of low water availability (Collins et al. 2014). Extreme precipitation pulses can have a global effect on the trend and interannual variability of drylands carbon uptake (Ahlström et al. 2015). Frequency of extreme precipitation events (EPEs) has increased, and the dry spell between the precipitation pulses is longer than before (Giorgi et al. 2019). It is important to understand how ecosystem carbon exchange responds to EPEs as global drylands experience major shift of precipitation patterns, in order to better estimate future variability of global carbon sink.

Some studies have examined biome-scale responses of carbon exchange to EPEs using in situ observations. Both precipitation intensity and frequency are important controls of ecosystem processes in drylands because EPEs after an extended dry spell can lead to rapid mineralization and pulses of photosynthesis and respiration with different magnitudes and response time (Huxman et al. 2004; Nielsen and Ball 2015). A large, but short-term increased respiration immediately after a precipitation pulse was widely observed across drylands (Sun et al. 2017). The magnitude of soil respiration pulse following rewetting of dry soil has been shown to be dependent on the frequency of dry–wet cycles before EPEs (Yan et al. 2010; Liu et al. 2017, 2019). The increase of carbon assimilation is slower but lasts longer than that of respiration (Chen et al. 2009). However, the
effects of EPEs and antecedent water condition on subsequent net ecosystem carbon balance are not well understood.

Various researches reported biome specific effects of shifted precipitation regimes on net carbon balance. For example, increases in plant productivity and net carbon uptake was reported in a desert shrubland site, because EPEs increase soil moisture and stimulate plant water uptake significantly (Zhang et al. 2019). A temperate grassland was reported to be carbon neutral after EPEs, which could be attributed to the ecosystem resilience to EPEs and the quick recovery of carbon exchange (Hao et al. 2017). A Mediterranean grassland showed net carbon release after EPEs because soil respiration was the only component significantly stimulated by precipitation pulses (López-Ballesteros et al. 2016). It seemed that local climate regimes determine the sensitivity of carbon exchange to fluctuations in soil water availability induced by EPEs (Vicente-Serrano et al. 2013). However, the response of carbon exchange to EPEs in diverse drylands has not been evaluated in a more integrated way.

Eddy covariance technique can continuously monitor ecosystem carbon exchange with high temporal resolution, which can capture the immediate response of the ecosystem to the precipitation events. The growth of global networks of carbon fluxes observation (e.g., FLUXNET) enables integrated researches on how carbon exchange responds to precipitation variation across global drylands. Based on this, we performed an integrated analysis to detect how and to what extent diurnal carbon fluxes and net carbon balance fluctuated after EPEs and regulated by different antecedent water conditions across global drylands gradient.

2 Data and methods

2.1 Screening the sites along the aridity gradient

The FLUXNET2015 dataset (CC-BY-4.0 Data, ‘FULLSET’) was provided by the FLUXNET portal. Site-level aridity index was extracted from the CGIAR-CSI Global-PET dataset (Trabucco and Zomer 2018). Eddy covariance flux tower sites located in drylands were filtered according to the classification scheme of United Nations Environment Programme (UNEP); arid sites with the aridity index from 0.03 to 0.2, semi-arid sites with aridity index from 0.2 to 0.5, and sub-humid sites with aridity index from 0.5 to 0.65. As a result, there are six arid sites, 28 semi-arid sites and 34 sub-humid sites in FLUXNET2015 datasets selected along the aridity gradient.

In addition to the sites included in the FLUXNET2015, we have measured carbon exchange over a semi-arid grassland in East Asia since 2010. The field site is located in Songnen Plain (Tongyu site), Jilin Province, China (44.34°N, 122.92°E, el. 184 m) (Table S1). A 20-m tower was established as an observation platform. A detailed description of the instrumentation can be found in Zhao et al. (2019). At the site, measurements of air CO₂/H₂O density (IRGA, LI-7500, LI-COR Inc., Lincoln, NE, USA) and three-dimensional wind speed (CSAT3, Campbell Scientific Inc., Logan, UT, USA) are recorded at a frequency of 10 Hz. Meteorological data, including air temperature (HMP45C, Vaisala Inc., Helsinki, Finland), photosynthetically active radiation (LI190R, LI-COR Inc., Lincoln, NE, USA), soil water content, and temperature (CS616, Campbell Scientific Inc.) are recorded simultaneously with CO₂ and H₂O fluxes in 30-min intervals.

2.2 Data processing and quality control

For FLUXNET 2015 dataset, half-hourly eddy covariance (EC) data were quality controlled, friction velocity filtered and gap-filled following the standardized protocols (Papale et al. 2006). In this study, to avoid major errors resulted from gap-filling, daily NEE data with QC flags less than 90%, meaning the ratio of measured values, were discarded. Soil moisture (SWC), soil temperature (Ts), and photosynthetic photon flux density (PPFD) data were used in this study. We adopted soil moisture tagged SWC_F_MDS_1 and soil temperature tagged TS_F_MDS_1, meaning soil moisture, and temperature of the shallowest layer.

For eddy covariance measurements at Tongyu site, coverances were computed every half-hour to generate fluxes and quality controlled following the FLUXNET standardized protocols as described in Zhao et al. (2019). The half-hour NEE at Tongyu site was partitioned into ecosystem respiration (Re) and gross primary productivity (GPP) after applying data gap filling techniques, and then calculated to mean daily fluxes. GPP is derived by subtracting NEE from ecosystem respiration. Thus, negative NEE values denote the pathway of carbon from the atmosphere to ecosystem while positive values represent the carbon pathway from ecosystem to atmosphere. Daily NEE data with QC flags less than 90% were discarded. We adopted soil temperature and moisture recorded at the shallowest layer of 2 cm.

2.3 Extreme precipitation events filtration and classification

In this study, an individual EPE for each site was defined as a series of precipitation less than 3 days, with precipitation intensity greater than the 90th percentile of all the precipitation events during observation. Response of carbon exchange to an individual EPE may be confounded by leaf area and photosynthetic capacity at different phenological period (Huxman et al. 2004). For example, carbon exchange is more responsive in the early growing season than that in the...
late growing season (Guo et al. 2016). Therefore, we chose EPEs occurring during the middle growing season, which was defined as the period with daily gross primary production (GPP) greater than half of the difference between annual maximum and minimum daily GPP, to minimize the effects of leaf area and phenology on carbon exchange after EPEs. The annual cycle was calculated from January to December, and from July to June of next year for sites located in the Northern and Southern Hemispheres, respectively.

For most drylands, precipitation is concentrated during the middle growing season. The response of carbon exchange to EPEs may be confounded by subsequent precipitation. To get the sequence of carbon exchange pulse after each EPE, we selected the events without subsequent precipitation at least for 3 weeks. During this period, if there were data gaps resulted from the filtration of NEE QC flags mentioned in Sect. 2.1 and 2.2, the events were discarded. Finally, we filtered 24 extreme precipitation events (Table S2) from 21 sites, including 8 events at 6 arid sites, 9 events at 9 semi-arid sites, and 7 events at 6 sub-humid sites (Fig. 1, Table S1).

We further classify the events into two groups according to antecedent water conditions. For the events with soil moisture observation, one-way analysis of variance (ANOVA) was used to compare differences in soil moisture within 3 weeks before and after the events. If soil moisture was high and did not increase significantly further after EPEs, these events are identified with sufficient antecedent precipitation and named ‘wet-EPEs’ hereafter. For the events without soil moisture observation, we identify wet-EPEs with antecedent precipitation events greater than the central precipitation events. Otherwise, the events were thought without sufficient antecedent precipitation and were named as dry-EPEs (Table S2).

2.4 Analysis of event responses and controls

In order to minimize the effects of random variability in observations, we applied Savitzky-Golay filter to daily NEE, ecosystem respiration and GPP, and multiple controlling factors, including soil moisture, soil temperature, and PPFD. We calculated 7-day mean NEE, ecosystem respiration, GPP, and environmental factors prior to the events as the pre-event level. Positive pulsed NEE (ΔNEE) indicates decreased net carbon sequestration capacity in response to the events, and vice versa. To quantify the influence of EPEs on carbon exchange, we defined the number of days required for ecosystem respiration and GPP to recover to its pre-event level as response duration. The response duration of NEE is determined by ecosystem respiration and GPP because NEE dynamics is the result of the balance of ecosystem respiration and GPP. The time-integrated amount of NEE, ecosystem respiration, and GPP during the response duration was calculated as accumulative pulsed NEE, ecosystem respiration, and GPP after the events. Stepwise multiple regression was used to analyze the relationships of diurnal NEE, ecosystem respiration, and GPP with concurrent changes in environmental variables.

3 Results

3.1 Climate factors following extreme precipitation events

Soil moisture increased immediately and peaked on the third day after EPEs in arid and semi-arid regions (Fig. 2a-d). In comparison, soil moisture was more strongly stimulated by dry-EPEs than wet-EPEs (Table 1). The peak soil moisture
after dry-EPEs was about four and three times of the peak soil moisture after wet-EPEs in arid and semi-arid region, respectively. Antecedent precipitation determined the response of soil moisture to extreme precipitation events in sub-humid region (Fig. 2e, f). Soil moisture increased after dry-EPEs until about 20 days after the events, but maintained a slight decrease even 30 days after wet-EPEs. In arid and semi-arid regions, pulse of soil moisture lasted for about 6 days, much shorter than that in sub-humid region. Soil temperature and PPFD decreased after EPEs. Greater
decrease of soil temperature was observed in arid region than that in semi-arid and sub-humid regions.

3.2 Carbon flux changes in response to extreme precipitation events

Ecosystem respiration increased in response to EPEs in arid and semi-arid regions but decreased in sub-humid regions, with different response time, duration, and magnitude. In arid region, on the day of dry-EPEs, ecosystem respiration increased by about 116.0%, then peaked on the second day after dry-EPEs, and recovered to pre-level about 6 days after dry-EPEs (Fig. 2a). In semi-arid region, ecosystem respiration responded to EPEs slower than that in arid region, without significant difference with the pre-level on the day of EPEs (Fig. 2c). Ecosystem respiration peaked about 4 days after dry-EPEs, and recovered to pre-level about 8 days after dry-EPEs. The peak value of ΔRe in semi-arid region was significantly higher than that in arid region. In sub-humid region, ecosystem respiration was suppressed by about 77.3% on the day of the dry-EPEs, and remained lower than the pre-event level until 12 days after the EPEs (Fig. 2e).

The ecosystem respiration responded to wet-EPEs in different way compared to dry-EPEs. In arid region, wet-EPEs increased ecosystem respiration on the day of the events, and the pulse lasted only for about 2 days (Fig. 2b). In semi-arid region, ecosystem respiration peaked about 6 days after wet-EPEs, and recovered to the pre-event level about 10 days after wet-EPEs, which lasted longer than that in arid region. In sub-humid region, ecosystem respiration was more suppressed after wet-EPEs than that after dry-EPEs. Though the duration was similar, the negative peak value of ecosystem respiration was about 2.4 times greater than that after dry-EPEs (Fig. 2f).

The response time, peak value and duration of GPP after EPEs were quite different from respiration. In arid region, GPP was not significantly different from the pre-event level on the day of dry-EPEs, but then increased and peaked on the fourth day, and recovered to the pre-event level about 9 days after dry-EPEs (Fig. 2a). In semi-arid region, GPP was suppressed within 2 days after dry-EPEs (Fig. 2c). GPP increased thereafter and became higher than the pre-event level, peaked about 6 days after dry-EPEs and recovered to pre-event level about 10 days after the EPEs. The peak value of GPP in semi-arid region was about 1.5 times of that in arid region. GPP in sub-humid region decreased after dry-EPEs, and the negative peak value was higher than ecosystem respiration (Fig. 2e).

Wet-EPEs induced longer and higher magnitude of GPP response than that of ecosystem respiration. In arid region, GPP peaked on the day of the events with a peak value about 1.8 times of ecosystem respiration (Fig. 2b). The pulse duration was about 9 days, which was much longer than the pulse duration of ecosystem respiration. In semi-arid region, GPP responded to wet-EPEs slower than that in arid region (Fig. 2d). GPP increased gradually after wet-EPEs and peaked about 5 days after wet-EPEs, but the peak value of ΔGPP was about two times of that in arid region. In sub-humid region, GPP was suppressed and the peak value was about half of ecosystem respiration (Fig. 2f).

Under the asynchronous responses of ecosystem respiration and GPP, NEE increased after dry-EPEs, and then decreased in all regions (Fig. 2a, c, and e). ΔNEE peaked at 0.25 ± 0.15 gCm⁻² day⁻¹, 0.56 ± 0.28 gCm⁻² day⁻¹, and 0.42 ± 0.63 gCm⁻² day⁻¹ in arid, semi-arid, and sub-humid regions, respectively (Table 2). The magnitude of positive pulsed NEE was significantly higher in semi-arid and sub-humid region than that in arid region. The duration of positive pulsed NEE increased with local humidity, and was significantly longer in sub-humid region, about 7.67 ± 2.52 days. The magnitude and duration of negative pulsed NEE was not significantly different among all regions. After wet-EPEs, the fluctuation pattern of NEE was quite different from that after dry-EPEs. NEE decreased

Table 1 Mean extreme precipitation events intensity, antecedent precipitation intensity within 3 weeks before the events, and mean magnitude and duration of SWC, Ts, and PPFD pulses (mean ± SD)

|                      | Dry-EPEs         | Wet-EPEs         |
|----------------------|------------------|------------------|
|                      | Arid             | Semi-arid        | Sub-humid |
|                      | Arid             | Semi-arid        | Sub-humid |
| Extreme precipitation (mm) | 45.4 ± 27.1a     | 42.4 ± 15.0a     | 19.2 ± 9.4b |
| Antecedent precipitation (mm) | 15.3 ± 14.4a     | 27.6 ± 21.6b     | 7.6 ± 6.6c |
| Magnitude of ΔSWC (%) | 4.0 ± 1.4a       | 4.6 ± 3.4a       | 1.8 ± 1.2b |
| Duration of SWC pulse (day) | 6.8 ± 0.8a       | 6.4 ± 0.6a       | 13.0 ± 8.9b |
| Magnitude of ΔTs (°C) | 3.1 ± 1.7a       | 0.7 ± 0.4b       | 1.6 ± 1.5c |
| Duration of Ts pulse (day) | 8.3 ± 5.0a       | 5.7 ± 2.5b       | 8.0 ± 7.9a |
| Magnitude of ΔPPFD (μmolm⁻² s⁻¹) | 104.9 ± 66.3a | 66.8 ± 67.0b | 51.3 ± 44.5b |
| Duration of PPFD pulse (day) | 5.0 ± 2.4a       | 4.0 ± 1.8a       | 9.0 ± 4.0b |

Different letters behind the numbers indicate significant differences (P < 0.05) among arid, semi-arid, and sub-humid regions.
immediately after wet-EPEs in all regions (Fig. 2b, d, f). The magnitude of the negative ΔNEE peak was not significantly different among different regions, but the duration decreased from arid region to sub-humid region, and was significantly shorter in sub-humid region (Table 2).

### 3.3 Environmental regulations of carbon fluxes in response to EPEs

The relationships between diurnal carbon fluxes and environmental factors were analyzed to understand how EPEs induced carbon fluxes dynamics. The relationships between carbon fluxes and multiple controlling factors are represented by the results of a stepwise multiple linear regression analysis in Table S3, and summarized in Fig. 3. For arid and semi-arid regions, soil moisture dominated carbon fluxes dynamics after EPEs (Fig. 3a, d). Carbon flux in sub-humid regions are not significantly sensitive to the soil moisture, which was only negatively correlated with GPP after dry-EPEs (Fig. 3a). NEE, ecosystem respiration and GPP in sub-humid regions declined significantly with decreasing soil temperature (\( p < 0.05 \)), regardless of antecedent water availability (Fig. 3b, e). PPFD following EPEs only had influences on GPP, and thus determined the sign of NEE fluctuations in semi-arid and sub-humid regions (Fig. 3c, f). Significant positive relationships between PPFD and GPP induced negative relationships between PPFD and NEE, indicating enhanced carbon uptake capacity with increasing PPFD following EPEs in semi-arid and sub-humid regions.

### 3.4 Accumulative carbon fluxes in response to EPEs along aridity gradient

To assess changes of carbon balance in response to EPEs, we analyzed accumulative pulsed ecosystem respiration, GPP and NEE of the pulse events following EPEs along aridity gradient (Fig. 4). The response of accumulative pulsed carbon exchanges to EPEs was influenced by local aridity index. Following the EPEs with similar precipitation intensity and antecedent precipitation, accumulative pulsed respiration and GPP decreased with increasing aridity index, positive in regions with aridity index lower than 0.5, but mostly negative in regions with aridity index higher than 0.5 (Fig. 4a-d). Compared with respiration, accumulative pulsed GPP tracked more closely to the variations in aridity index. Under the balance of respiration and GPP, accumulative pulsed NEE increased with local aridity index, ranged from negative to positive with the increase in aridity index (Fig. 4e, f). Variations in NEE in the regions with aridity index lower than 0.4 was generally negative, indicating increased net carbon uptake capacity, but was mostly positive in the regions with aridity index higher than 0.4. Accumulative pulsed NEE after the events in arid, semi-arid, and sub-humid region were \(-2.23 \pm 1.81 \text{ gCm}^{-2}, -1.39 \pm 1.21 \text{ gCm}^{-2}, \) and \(-0.35 \pm 1.48 \text{ gCm}^{-2} \), respectively.

Higher intensity EPEs enabled more accumulative pulsed ecosystem respiration and GPP than lower intensity ones (Fig. 4a, c). In regions with aridity index lower than 0.4, accumulative pulsed GPP generally increased more than respiration. Thus, higher intensity EPEs stimulated more net carbon uptake (negative NEE) in the regions with aridity index lower than 0.4, but reduced net carbon release (positive NEE) in the regions with aridity index higher than 0.4 (Fig. 4e).

Antecedent precipitation also led to fluctuations of carbon fluxes along the aridity gradient. Accumulative ecosystem respiration showed negative relationships with antecedent precipitation (Fig. 4b), and more antecedent precipitation decreased accumulative carbon release by ecosystem respiration. Accumulative pulsed GPP showed no significant pattern with varied antecedent precipitation (Fig. 4d). EPEs with more antecedent precipitation tended to enhance net carbon uptake in drier region, and depress net carbon release in wetter region (Fig. 4f).
Fig. 3 Schematic diagram of how diurnal NEE, GPP and Re varied within 15 days after EPEs to soil water content (SWC), soil temperature (Ts) and photosynthetic photon flux density (PPFD). (a), (b) and (c) illustrate responses of carbon fluxes to SWC, Ts and PPFD after dry-EPEs, separately. (d), (e) and (f) illustrate responses of carbon fluxes after wet-EPEs. Circles indicate no statistically significant relationship ($p > 0.05$) between carbon fluxes response and other factors. Ascending (descending) arrows indicate a statistically significant positive (negative) relationship ($p < 0.05$) between carbon fluxes responses and other variables. Red, orange and green arrow or circle in each subplot represent arid, semi-arid and sub-humid sites, respectively. The numbers on the right side of each subplot denote the partial correlation coefficients between carbon fluxes (NEE, GPP and Re) and environmental factors (SWC, Ts and PPFD) for arid (red), semi-arid (orange) and sub-humid (green) sites. * and ** denote $p < 0.05$ and $p < 0.01$, respectively.
Fig. 4 Accumulative pulsed Re (a, b), GPP (c, d) and NEE (e, f) following EPEs along the aridity gradient specified by the aridity index. Values shown in each box are means across all events characterized by respective EPEs intensity, antecedent precipitation and aridity index

4 Discussion

4.1 Effect of antecedent water condition on carbon exchange pulses

The influence of precipitation intensity on carbon exchange have been widely reported (Chen et al. 2009; Williams et al. 2009; Zeppel et al. 2014; Guo et al. 2016). This study demonstrated that antecedent water condition determined response pattern of carbon exchange to the extreme precipitation events. Accumulation of respiration substrates were highly influenced by antecedent water conditions prior to extreme precipitation events. In arid and semi-arid regions, most plant and microbes decreased physiological activity, rather than using the limited water and resources to maintain activity under dry condition, thus more litters and nutrients were accumulated (Austin et al. 2004; Wang et al. 2018).

Once dry-EPEs occurred, soil surface re-wetting increases microbial activity (Barnard et al. 2015), and available litter and nutrients provide organic carbon to allow immediate respiration pulse (Kim et al. 2012; Ma et al. 2012). However, plant carbon assimilation was provoked afterwards when water infiltrated deeper for plant roots to absorb. Thus, response of GPP to dry-EPEs lagged about 2–3 days behind ecosystem respiration. Then, GPP increased gradually and GPP pulse lasted longer than respiration because plants can utilize deeper soil water even after surface soil water dries out (Chen et al. 2009). In sub-humid region, temperature was important in controlling carbon exchange (Tiemoko et al. 2020). Ecosystem respiration and GPP fluctuated following soil temperature well, thus decreased after EPEs. After dry-EPEs, ecosystem respiration decreased more slightly than GPP because more soil organic carbon and nutrients needed for ecosystem respiration were accumulated before the events (Austin et al. 2004; Inglima et al. 2009), relieving the stress of decreased soil temperature to some extent. Thus, dry-EPEs cause immediately increase in net carbon uptake capacity across all drylands.

Carbon balance change after wet-EPEs were different from that after dry-EPEs. Soil moisture was high before the events and was not stimulated significantly by wet-EPEs compared with dry-EPEs (Table S2). The accumulation of soil organic matters, litters and nutrients for respiration before wet-EPEs are less than dry-EPEs (Austin et al. 2004; Wang et al. 2018). In arid and semi-arid regions, plant characteristics are adapted to the persistent wet condition, including the new growth of roots and leaves, resulting in more rapid and greater response of photosynthesis than respiration to wet-EPEs (Chen et al. 2009; Munson et al. 2010). Thus net carbon uptake capacity increased once the events occurred, and decreased with the gradually declining GPP. Similarly, respiration in sub-humid region was dramatically suppressed after wet-EPEs because of increased consumption of soil organic carbon and nutrients needed for ecosystem respiration under antecedent sufficient water condition (Austin et al. 2004; Inglima et al. 2009).

As accumulative pulsed GPP did not show clear relationship with antecedent precipitation, the diverse responses of respiration to dry-EPEs and wet-EPEs determined the accumulative pulsed NEE after EPEs (Fig. 4b). More carbon was released by respiration subject to drying before EPEs than constantly wet soils. Dry periods between precipitation events are projected to be extended with the increasing frequency of EPEs in the coming decades (Kirchmeier-Young and Zhang 2020), which indicates that net carbon uptake capacity may be weakened by prolonged antecedent dry spell.

4.2 The response of carbon exchange to EPEs along drylands gradient

Based on integrated analysis, this study showed that the accumulatively pulsed NEE shifted from negative to positive with the increase of aridity index, indicating net carbon uptake capacity of drier region benefited more from EPEs than wetter region. Magnitude and duration of NEE pulses after EPEs determined the accumulative net carbon uptake after the EPEs (Huxman et al. 2004). Duration of NEE pulses was determined by the duration of ecosystem respiration and GPP fluctuation (Fig. 2). After dry-EPEs, the duration of declining net carbon uptake capacity got longer with local aridity index. Response of GPP to EPE was more delayed than ecosystem respiration in semi-arid region than arid region, resulting in longer duration of decreased net carbon uptake capacity once dry-EPEs occurred (Table 2). That was attributed to the higher sensitivity of GPP to precipitation pulse in arid vegetation than that in semi-arid vegetation (Zhao et al. 2022), leading to quicker response of GPP in arid region. In sub-humid region, GPP decreased much more than ecosystem respiration, and the duration of declining net carbon uptake capacity was the longest among all the regions. After wet-EPEs, the longest duration of enhanced carbon uptake capacity occurred in arid region, but the shortest occurred in sub-humid region. That was likely attributed to the more soil microbial biomass or nutrient in wetter region than that in drier region (Campo and Merino 2016; Wang et al. 2016), resulting in longer lasting pulses of increased ecosystem respiration. In sub-humid region, although ecosystem respiration decreased following decreased soil temperature after wet-EPEs, it recovered
rapidly after the events, resulting in the shortest rising pulses of the net carbon uptake. The magnitude of NEE pulse was also determined by the magnitude difference between ecosystem respiration and GPP. After dry-EPEs, the maximum difference between ecosystem respiration and GPP in semi-arid region was greater than that in arid region, resulting in larger magnitude of pulsed positive NEE in semi-arid region and contributing to larger net carbon capacity decrease in semi-arid region. That might be attributed to more soil respiratory substrates (Campo and Merino 2016; Wang et al. 2016) in semi-arid region and greater pulsed ecosystem respiration once dry-EPEs occurred. However, the sensitivity of carbon assimilation to EPEs was lower in semi-arid region than arid region (Vicente-Serrano et al. 2013), leading to slower response of GPP to dry-EPEs and the magnitude difference between ecosystem respiration and GPP was enlarged. There was more soil respiratory substrates in sub-humid region and the much less decrease in ecosystem respiration than GPP caused greater magnitude of positive pulsed NEE than semi-arid and arid regions after dry-EPEs. The magnitudes of negative pulsed NEE after dry-EPEs and wet-EPEs along the aridity index were not significant (Table 2).

Although we applied more integrated approaches to investigate carbon exchange responses to EPEs in global drylands, this analysis is based on limited extreme precipitation events due to limited number of observations in drylands and the strict criteria of events screening. More observations with high spatial and temporal resolution are needed to covering more complex global dryland types. Besides, this study focuses on carbon exchange dynamics after each single EPE. The effects of EPEs on carbon exchange may decline with successive drying and rewetting cycles, possibly as a result of a limited pool of labile substrates (Kim et al. 2012). Thus, long-term studies are needed to investigate how drylands carbon uptake capacity shifts after repetitive dry–wet cycles.

5 Conclusions
The results from this study suggest that extreme precipitation events led to fluctuations in respiration and GPP by triggering soil moisture pulse in arid and semi-arid region, but largely by suppressing soil temperature in sub-humid region. Antecedent water condition determined the response pattern of carbon exchange to EPEs. Dry condition before EPEs induced immediate pulses of carbon release, which was almost absent if there was sufficient antecedent precipitation. Accumulative pulsed carbon exchange had negative relationships with antecedent precipitation. Net carbon uptake capacity benefits more from the events in drier regions than wetter region, because of shorter duration of decreased net carbon uptake capacity and lower positive NEE magnitude after dry-EPEs, and longer duration of increased net carbon uptake capacity after wet-EPEs. Frequency of EPEs increased with longer dry spell between the events. Further observations and experiments on impacts of extreme precipitation events and antecedent water condition across global drylands are needed to get in-depth insight into how carbon uptake capacity of drylands changes under shifting precipitation regime.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00704-022-04134-0.

Acknowledgements We thank FLUXNET for the data supports for this study.

Authors’ contributions Huichen Zhao provided the idea, performed the analysis, and drafted the paper. Xiyan Xu and Gensuo Jia guided the analysis and revised the paper. Anzhi Zhang and Hesong Wang maintained flux observation at Tongyu site and helped to improve the paper.

Funding This study is funded by Strategic Priority Research Program of Chinese Academy of Sciences, CASEarth (XDA19030401).

Data availability Aridity index was extracted from the CGIAR-CSI Global-PET Dataset: http://www.cgiar-csi.org/data/global-aridity-and-pet-database. FLUXNET dataset are extracted at http://fluxnet.fluxdata.org/data/fluxnet2015-dataset. Datasets of Tongyu sites are available from the corresponding author on reasonable request.

Declarations

Competing interest The authors declare that they have no competing interest.

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