



Diverse soil respiration responses to extreme precipitation patterns in arid and semiarid ecosystems

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ARTICLE INFO

Keywords:

Extreme precipitation patterns
Soil respiration
Water stress
N and maize straw

ABSTRACT

Projected increases in the frequency and magnitude of extreme precipitation profoundly impact terrestrial ecosystems. However, the response of soil respiration to changing precipitation patterns has not been systematically investigated, especially in arid and semi-arid areas. Precipitation amounts of 300 and 600 mm (T300 and T600) were set to simulate normal and extremely wet summers, respectively, and were individually conducted by wetting soils in a series of sub-events—10 or 100 mm (P10, P100)—over equal time intervals. Maize straw (1300 kg ha⁻¹) and N fertilization (200 kg N ha⁻¹) were applied in parallel to extend our simulation to natural cropland conditions. Soil respiration pulses were observed after T300-P100, and inhibited effects occasionally occurred 1 day after T600-P100, primarily because frequent and harsh storms in T600-P100 induced saturation stress on soil respiration. Cumulative soil respiration in T600 was greater than that in T300, owing to prolonged suitable water conditions for soil respiration. Similarly, for the same total precipitation amount, P100 produced 40–44% more soil respiration than P10. Applying N and maize straw did not change response trends but produced different magnitudes of response to changing precipitation patterns. Maize straw significantly stimulated soil respiration, and this effect became more evident in P100 with improved water conditions, producing a 122–185% increase in cumulative soil respiration. Nitrogen slightly inhibited soil respiration; this effect was enhanced when maize straw was also added but was insignificant. Cumulative soil respiration was significantly correlated with β -D-glucosidase and soil microbial biomass carbon content. Such soil respiration responses highlight the need to accurately account for soil respiration contributions when projecting global carbon cycling in future climate scenarios.

1. Introduction

Extreme precipitation events are predicted to increase both in frequency and magnitude with global warming (Fischer and Knutti, 2015; Donat et al., 2016; IPCC, 2013). Hydrological cycles intensified by extreme precipitation may profoundly impact terrestrial carbon cycling dynamics (Zhao et al., 2016; Ru et al., 2018). As the second largest C flux between the atmosphere and the biosphere, soil respiration is strongly influenced by extreme precipitation (Knapp et al., 2008; Chen et al., 2017; Liu et al., 2018). Lack of water from precipitation is the primary constraint on biological activities in arid and semiarid regions, which account for one third of the earth surface (Wang et al., 2019; Liu et al., 2018; Trumbore and Czimczik, 2008). Therefore, the effect of extreme

precipitation on soil respiration in arid and semiarid regions must be evaluated.

The effect of extreme, frequent, and prolonged precipitation events on soil respiration has been extensively studied (Thomey et al., 2011; Unger et al., 2010; Liu et al., 2018). Studies reported controversial results on whether extreme precipitation reduced (Liu et al., 2018; Harper et al., 2005) or increased (Thomey et al., 2011; Vargas et al., 2014) soil respiration. Heavy precipitation increased and suppressed soil respiration under initial dry and humid conditions, respectively (Li et al., 2018; Rey et al., 2017; Harper et al., 2005). The differences may correlate with varied substrate availability and C-degrading extracellular enzymes, which are influenced by the diffusion capacity response to precipitation under different initial soil moisture conditions (Knapp et al., 2009; Ren

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<https://doi.org/10.1016/j.apsoil.2021.103928>

Received 8 September 2020; Received in revised form 30 January 2021; Accepted 5 February 2021

Available online 16 February 2021

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et al., 2017). Extreme precipitation is frequently associated with more intense individual events and extreme droughts (Knapp et al., 2017), which may lead to soil water saturation or over-dried soil conditions. Thus, stresses derived from over-wetness and drought inhibit soil respiration owing to limitations on soil microbial activity and substrate diffusion (Liu et al., 2019). However, most studies primarily addressed variations in total precipitation (Liu et al., 2016), and the effect of extreme precipitation patterns on soil respiration—including frequency, intensity, and sub-events—remains limited.

The Loess Plateau contains typical arid and semiarid regions; >70% of crops are planted in rain-fed areas and are particularly sensitive to precipitation change (Jiang et al., 2015). Although annual total precipitation on the Loess Plateau has shown no obvious variations in recent years, precipitation distribution has changed (Sun et al., 2016). The frequency and intensity of extreme precipitation have increased (Chen et al., 2012; Fu et al., 2013; Wang et al., 2014), and an extreme rainstorm (>100 mm) affected an area of 6126 km² in July 26, 2017 (He et al., 2018). Extreme precipitation events considerably impact carbon cycling on the Loess Plateau, especially during the summer wet season. However, the effects of extreme precipitation patterns on soil respiration remain unclear. At the present study, we hypothesized that 1) different soil respiration responses to extreme precipitation patterns primarily depend on altered enzyme activity caused by changing water availability and 2) that the addition of carbon and Nitrogen (N) may enhance soil respiration responses to extreme precipitation patterns. Therefore, our objectives were 1) to identify how soil respiration responds to extreme precipitation patterns and 2) to determine if the addition of N and straw influence the response of soil respiration to extreme precipitation patterns.

2. Materials and methods

2.1. Site description

This study was carried out at the State Key Agro-Ecological Experimental Station on the Loess Plateau in Changwu County, Shaanxi province, China (35°13' N, 107°40' E, 1220 m a.s.l.). The region has a sub-humid continental monsoon climate with a mean temperature of 9.2 °C (1957–2014). The Mean annual precipitation is 584 mm, approximately 60% of which falls between July–September (Changwu Meteorological Station). The soil was classified as loam developed from loess deposits (IUSS Working group WRB, 2015). Soil collected at the

study site in 2016 at a depth of 0–20 cm had a field capacity of 27.3–30.9%, permanent wilting point of 11.7–15.6%, and bulk density of 1.3 g cm⁻³ (Huang et al., 2003).

2.2. Experimental design

A simulated experiment was established on bare loess soil from the semi-arid Chinese Loess Plateau in 2016. Precipitation patterns were designed according to daily precipitation data from 1981 to 2014, which was supplied by the Changwu Meteorological Station. The mean precipitation during the rainy season was 313 mm, with maximum and minimum of yearly precipitation of 608 and 120.7 mm, respectively (Fig. 1). The most frequent precipitation events produced between 5 and 10 mm (Fig. 1). Two patterns with total precipitation amounts of 300 and 600 mm were performed to simulate typical and extremely wet summers, respectively. The total precipitation amounts were evenly distributed within ca. 2 months by the sub-events (P10 and P100). Four groups of soil pots were set corresponding to the four precipitation patterns: T600-P10, T600-P100, T300-P10, T300-P100. Each precipitation pattern was triplicated. All precipitation simulations were conducted after 19:00 to avoid high daytime evaporation.

Soil samples were collected from a fallow crop land at a depth of 0–20 cm, naturally air-dried and sieved through a 2 mm filter to remove plant residue and roots. The initial water content was controlled at 12%. Nitrogen fertilization and crop residue return are commonly managed in the Loess Plateau region (Fan et al., 2005; Duan et al., 2010); therefore, we included control (no fertilizer or straw), N addition, and straw addition treatments to maintain consistency with local agriculture management. For the N addition treatments, 3.2 g of NH₄NO₃ was mixed with the soil to simulate traditional local field fertilization of 200 kg N ha⁻¹; for the maize straw addition treatments, 80 g of crushed maize straw was mixed with soil according to the field straw returning ratio of 1:200. Each pot was subsequently filled with 16 kg of soil with a bulk density controlled at 1.3 g cm⁻³ (32 cm diameter and 20 cm height). The pots were buried under a rain shed to keep the soil temperature close to that of the field (Fig. 2).

2.3. Measurements of soil respiration, temperature, and moisture

Soil respiration, moisture, temperature measurements were performed from June to August 2016. For soil respiration measurement, one polyvinyl chloride (PVC) collar (20 cm diameter × 12 cm height)

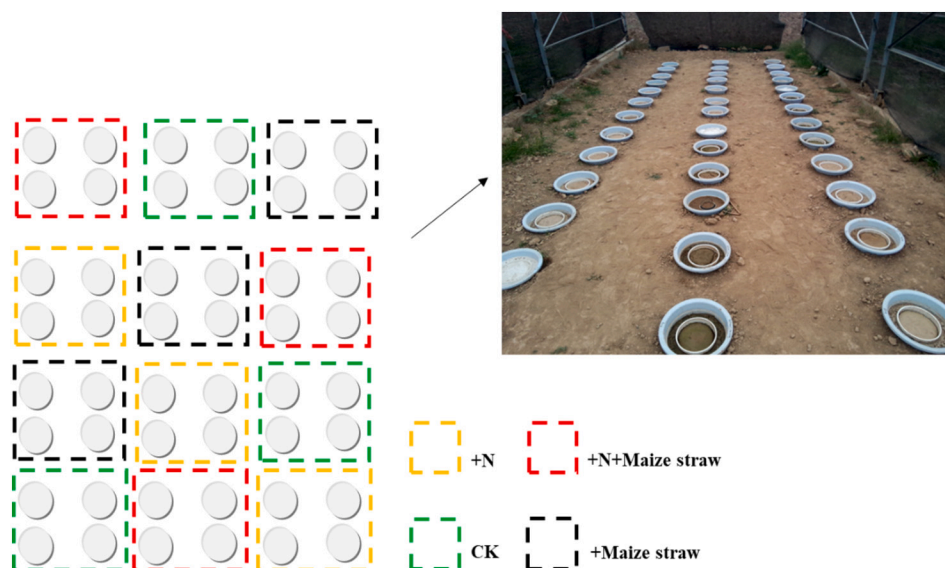


Fig. 1. Layout of incubation pots under a rain shed.

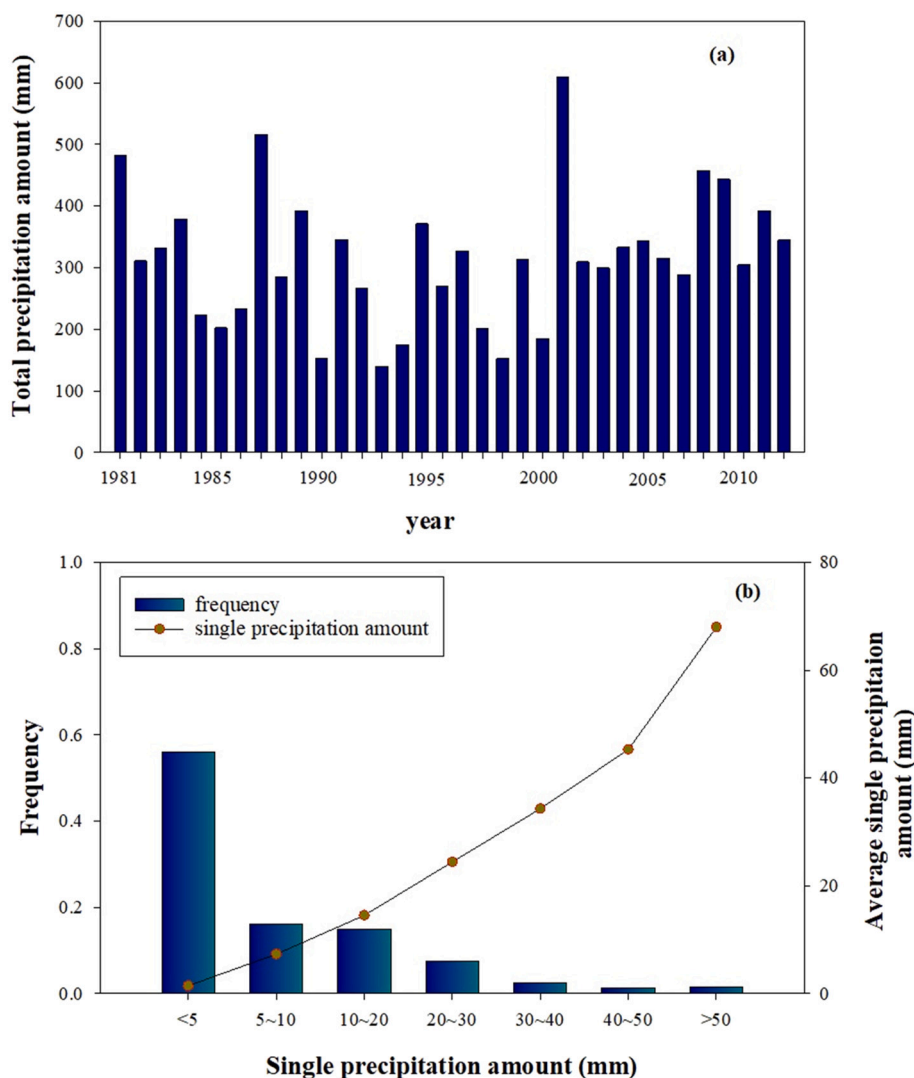


Fig. 2. Rainy season precipitation distribution during (July–September) from 1981 to 2014: (a) total precipitation amount during the rainy season; (b) distribution of single precipitation amounts.

was inserted to a depth of 10 cm into the middle of each soil pot. Soil respiration was monitored using an automated and closed soil CO₂ flux system equipped with a 20 cm diameter portable chamber (Li-8100, Lincoln, NE, USA). Measurements were conducted from 9:00–11:00 to ensure the comparability and representativeness of soil respiration (Iqbal et al., 2010). Each measurement was conducted twice, with a 90 s enclosure period and a 30 s delay between measurements. Two or more measurements were taken to reduce any variation between the two measurements larger than 15%. Soil respiration measurements were continuously conducted after each precipitation simulation to collect the daily variation of soil respiration under different precipitation patterns.

Soil temperature and moisture were measured with a Li-Cor thermocouple probe and a Theta Probe ML2X with a HH2 water content meter (Delta-T Devices, Cambridge, England) at a 5 cm depth, respectively.

2.4. Soil sampling and analysis

Soil samples were collected from the pots after the simulation experiments to obtain basic soil properties. The samples were stored at 4 °C before soil microbial biomass carbon content (SMBC), nitrate (NO₃-N), ammonium (NH₄-N), and enzyme activity (β -D-xylosidase, β -D-

glucosidase, cellobiohydrolase) measurements. SMBC was measured using the chloroform fumigation-extraction method (Vance et al., 1987). The NO₃-N and NH₄-N contents were first extracted with KCl, then determined by colorimetry (Bran & LuebbeIIAutoAnalyser) (Fernández-Escobar et al., 2009). Three C-degrading enzyme activities were determined following a microplate fluorimetry method (Trap et al., 2012).

2.5. Data analysis

A statistic equation was used to calculate the cumulative respiration:

$$X = R_s \times 3600 \times 24 \times 12 \times 10^{-6} \quad (1)$$

$$\text{CO}_2 - C \text{ (g}\cdot\text{m}^{-2}) = \sum_{i=1}^n X_i \quad (2)$$

where X is daily soil respiration, R_s is measured soil respiration ($\mu\text{mol (m}^2\text{s)}^{-1}$), 12 is the molar mass of CO₂-C (g mol^{-1}), 3600 and 24 are conversion coefficient of time, i is the first measurement of soil respiration rate, and n is the monitoring number.

The statistical analysis was conducted in SPSS 20.0 software. Data were checked for normality with the Shapiro–Wilks test. Because soil

respiration rates were not normally distributed, a non-parametric Mann–Whitney U test was conducted to assess the effect of N, straw addition and changing precipitation patterns. A one-way analysis of variation (ANOVA) and a least significant difference (LSD) multiple comparison ($p < 0.05$) were performed to assess differences in microbial properties and cumulative soil respiration among precipitation patterns (mean \pm SD, $n = 3$). Statistical significance was defined as $p < 0.05$. Spearman analysis was performed to explore the relationship between soil respiration and SMBC, $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, $\beta\text{-D-xylosidase}$, $\beta\text{-D-glucosidase}$ and cellobiohydrolase. All figures were generated in Sigmaplot 12.5 software.

2.6. Definition of water stress on soil respiration

The expected effect of soil moisture on soil respiration involves drought stress in low moisture conditions and saturation stress in high moisture conditions (Smith, 2002). The soil used for this study was from the Loess Plateau and had a wilting point of 11.7–15.6% and field capacity of 27.3–30.9% (Huang et al., 2003). We found that soil respiration was inhibited while soil moisture content was lower than $\sim 15\%$ and defined 15–28% as a suitable water content range (Zhang et al., 2013; Yan et al., 2013). For soil moisture out of this range, we defined existing stress on soil respiration as drought ($<15\%$) and saturation ($>28\%$) stresses, respectively.

The water stress duration was calculated as follows:

$$\text{Water stress duration (D)} = \text{drought stress duration (d}_1\text{)} \\ + \text{saturation stress duration (d}_2\text{)}$$

3. Results

3.1. Soil respiration response to precipitation patterns

Regularly precipitation and subsequent soil moisture measurements reveal different fluctuations with different precipitation patterns (Fig. 3). Soil moisture is basically synchronized with precipitation events. Soil moisture in P10—accompanied by strong evaporation during the monitoring period—was relatively stable with average values of 8.4% and 6.8% in T600 and T300, respectively. However, a sharp increase in soil moisture occurred immediately after the P100 precipitation simulation. Soil moisture fluctuated from 8.9–29.8% to 5.9–26.5% in T600 and T300, respectively.

Soil respiration and soil moisture varied concomitantly (Fig. 3). With a lower soil moisture in P10, soil respiration rates were relatively stable at approximately 1.47 (T600-P10) and 1.32 (m^2s^{-1}) (T300-P10). Compared with P10, soil respiration rate was 41% higher in P100 ($p < 0.05$). It fluctuated between 0.82 and 4.73 $\mu\text{mol}(\text{m}^2\text{s})^{-1}$ with an average respiration rate of 2.08 $\mu\text{mol}(\text{m}^2\text{s})^{-1}$ in T600. The average soil respiration rates when soil moisture exceeded field capacity (28%) or fell below the wilting point (15%) were always lower than that at soil moisture between 15% and 28% ($1.27\text{--}1.84$ $\mu\text{mol}(\text{m}^2\text{s})^{-1}$ vs. $2.35\text{--}3.32$ $\mu\text{mol}(\text{m}^2\text{s})^{-1}$). Soil respiration rates followed similar patterns in T300, ranging from $0.59\text{--}4.42$ $\mu\text{mol}(\text{m}^2\text{s})^{-1}$ with an average value of 1.86 $\mu\text{mol}(\text{m}^2\text{s})^{-1}$ and peaked the day after precipitation events.

3.2. Magnitude of straw- and N-influenced soil respiration response to precipitation patterns

Straw addition significantly amplified soil respiration response

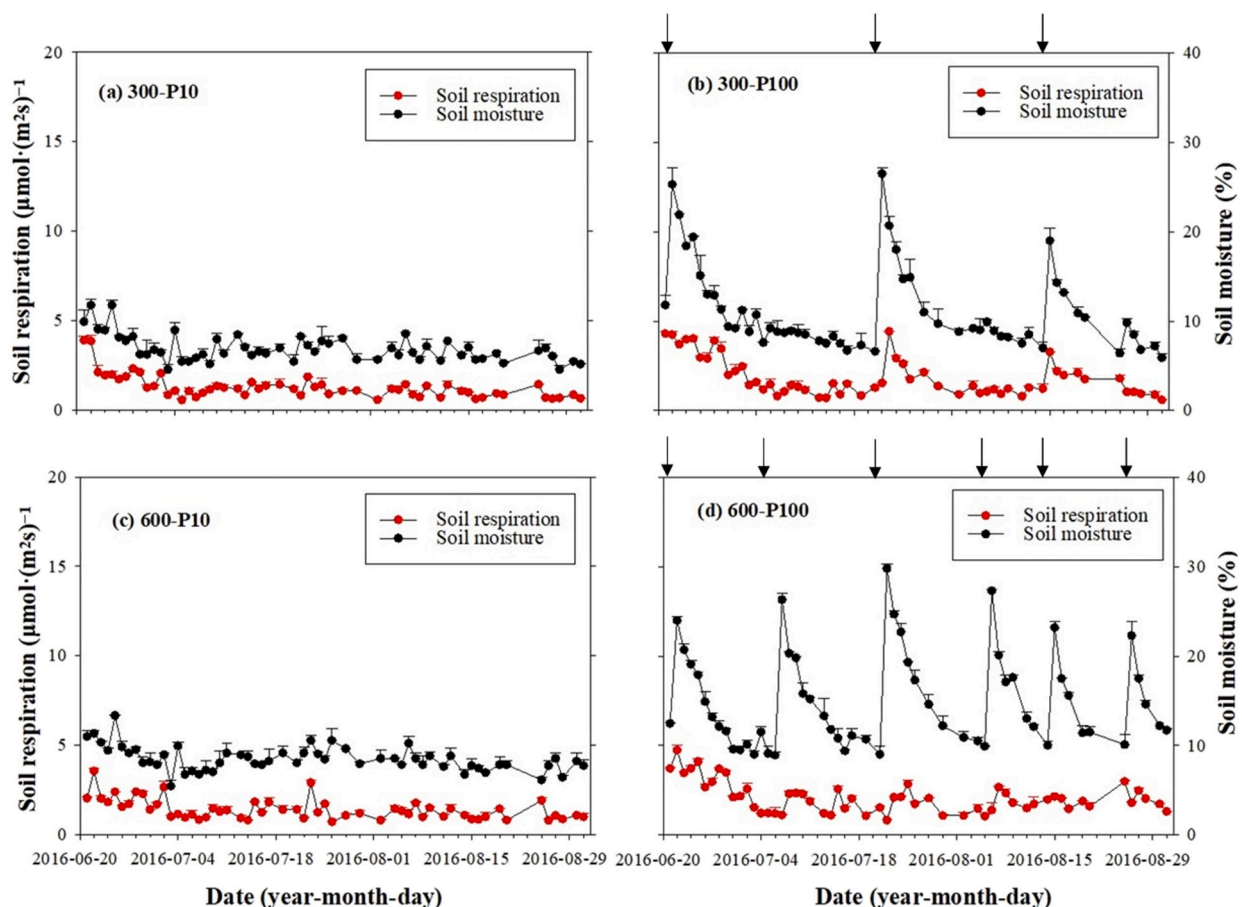


Fig. 3. Variation of soil respiration and moisture with four precipitation patterns.

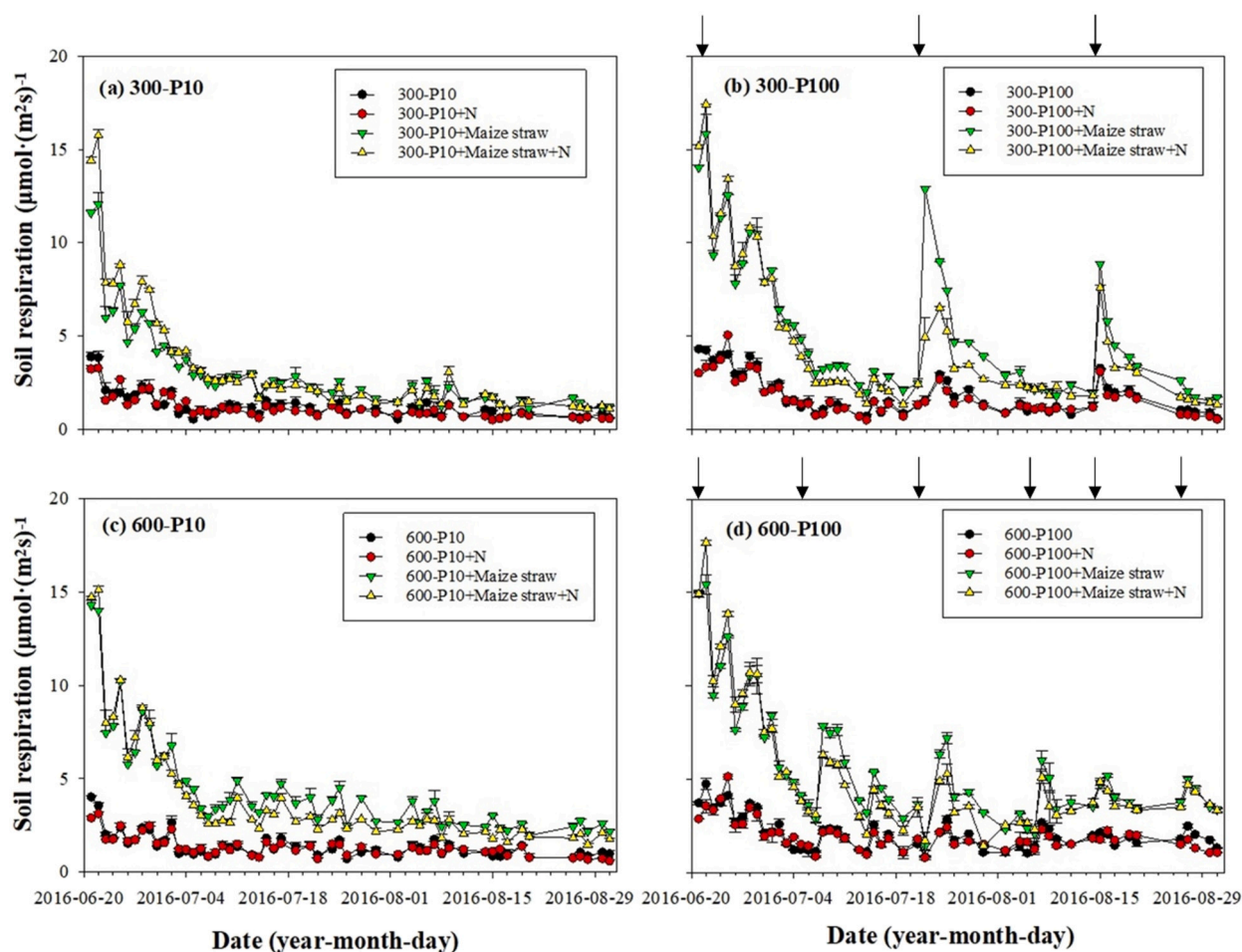


Fig. 4. Dynamic response of soil respiration to N and maize straw addition with four precipitation patterns.

patterns to different precipitation patterns ($p < 0.05$, Fig. 4). P10 soil respiration was significantly stimulated in the initial period and limited under low water conditions with average values of 3.23 (T600-P10) and 1.99 (300-P10) $\mu\text{mol} (\text{m}^2\text{s})^{-1}$. However, the P100 soil response pattern was significantly stimulated with an amplified fluctuation range of 0.67–15.84 $\mu\text{mol} (\text{m}^2\text{s})^{-1}$. Additionally, the average soil respiration during the study period was trebled compared with that of the non-straw addition treatment (T600: 5.66 vs. 2.12 $\mu\text{mol} (\text{m}^2\text{s})^{-1}$; T300: 5.13 vs. 1.85 $\mu\text{mol} (\text{m}^2\text{s})^{-1}$).

N addition showed relatively minor effect on soil respiration and did not change soil respiration response patterns to precipitation (Fig. 4, $p > 0.05$). The average soil respiration rates were reduced by 3%, 5%, 11%, and 9% for T600-P10, T600-P100, T300-P10, and T300-P100, respectively. This inhibition effect was slightly enhanced with straw addition under an improved water condition in T600 (T600-P10: 9%, T600-P100: 6%), but did not reach a significant level ($p > 0.05$).

3.3. Cumulative soil respiration and its relationship with soil biochemical properties

Cumulative soil respiration was sensitive to changing precipitation patterns, and increased precipitation caused higher cumulative respiration (Fig. 5). For the same sub-event, cumulative respiration from T600 events was greater than that of T300 ($p < 0.05$), with an increase rate of 15% and 18% for P10 and P100, respectively; for the same total precipitation amount, P100 produced 40–44% more soil respiration than P10 ($p < 0.05$). Similarly, cumulative soil respiration increased by 122–185% with straw addition ($p < 0.05$). P100 produced higher

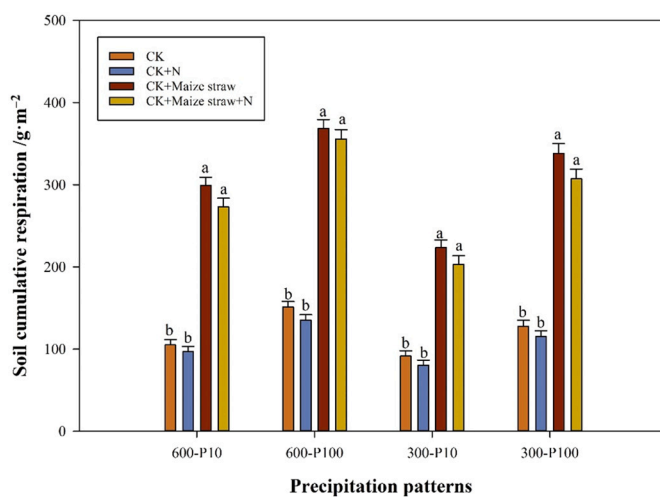


Fig. 5. Cumulative soil respiration for different precipitation patterns.

cumulative respiration than P10 treatments, but the difference between P10 and P100 decreased to 23% in T600 and increased to 51% in T300. Moreover, N showed a relative minor effect on cumulative soil respiration with and without straw addition (P10: 8%–12%, P100: 4%–10%, $p > 0.05$).

The Spearman's correlation coefficients between soil biochemical properties showed that cumulative soil respiration was significantly

Table 1Soil biochemical properties (SMBC, NO₃-N, NH₄-N, β-D-xylosidase, β-D-glucosidase and cellobiohydrolase) for different precipitation patterns at the end of the experiment

		SMBC (mg kg ⁻¹)		NO ₃ -N (mg kg ⁻¹)		NH ₄ -N (mg kg ⁻¹)		β-D-xylosidase (nmol g ⁻¹ h ⁻¹)		β-D-glucosidase (nmol g ⁻¹ h ⁻¹)		cellobiohydrolase (nmol g ⁻¹ h ⁻¹)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
600-P10	CK ^a	131.64	7.59	7.30	1.64	0.33	0.07	13.36	1.91	13.39	1.65	7.10	0.90
	+N ^b	104.61	8.52	15.63	0.71	0.18	0.05	20.09	0.73	31.24	3.29	16.79	0.83
	+M ^c	158.92	5.80	0.44	0.11	0.22	0.04	32.11	1.12	50.49	2.03	17.86	3.72
	+N + M ^d	207.01	7.20	6.47	0.56	0.22	0.08	45.78	2.70	92.83	10.33	21.03	3.15
600-P100	CK	133.32	6.15	12.40	1.50	0.16	0.03	8.30	0.82	22.63	4.26	4.83	1.20
	+N	49.86	3.88	34.85	2.21	0.18	0.04	21.23	1.69	38.88	4.89	4.73	0.78
	+M	234.66	8.81	1.28	0.11	0.15	0.04	46.08	4.94	54.24	9.65	16.58	2.76
	+N + M	233.32	6.88	14.67	0.50	0.23	0.02	14.50	0.88	43.41	3.15	13.15	2.71
300-P10	CK	127.72	3.76	6.28	0.45	0.15	0.03	17.10	1.05	33.43	3.38	10.57	2.26
	+N	114.12	8.62	13.89	0.95	0.16	0.06	25.81	2.44	32.41	2.69	18.06	1.25
	+M	156.79	4.95	0.79	0.09	0.29	0.03	28.21	2.70	48.29	4.26	20.05	3.04
	+N + M	145.59	5.46	6.38	0.48	0.27	0.02	26.01	1.40	88.06	3.52	24.71	4.24
300-P100	CK	145.24	5.74	12.21	0.54	0.20	0.02	12.33	0.79	39.92	1.27	5.50	0.89
	+N	141.32	6.74	30.80	1.35	0.19	0.06	24.01	1.39	58.38	2.08	15.41	1.27
	+M	222.12	9.48	2.72	0.19	0.37	0.07	16.37	0.58	43.31	4.37	9.75	1.05
	+N + M	216.17	6.95	15.98	0.82	0.21	0.04	35.10	2.82	59.07	5.55	35.91	2.32

SMBC: soil microbial biomass carbon.

^a Treatment without nitrogen and straw addition^b Treatment with nitrogen addition^c Treatment with straw addition^d Treatment with both nitrogen and straw addition

correlated with β-D-glucosidase ($p < 0.05$) and SMBC ($p < 0.01$, Table 2). Soil biochemical properties varied considerably with different precipitation patterns at the end of the incubation (Table 1). Under the same total precipitation amount, SMBC, soil enzyme activity, and NO₃-N were generally greater in P100. SMBC increased by 14% (127.72 vs. 145.59 mg kg⁻¹) in T300-P100 ($p > 0.05$), whereas SMBC was similar in P10 and P100 under T600 (131.64 vs. 133.32 mg kg⁻¹) ($p > 0.05$). β-glucosidase was 20–69% higher (T300: 33.43 vs. 39.92, $p > 0.05$; T600: 13.39 vs. 22.63 nmol g⁻¹ h⁻¹, $p < 0.05$) and NO₃-N concentration was 70–90% higher (T300: 6.28 vs. 12.21, $p < 0.05$; T600: 7.30 vs. 12.40 mg·kg⁻¹, $p < 0.05$) in P100 compared to P10. For the same sub-event, changes in total precipitation amount had no significant effect on SMBC, NO₃-N, or NH₄-N concentrations ($p > 0.05$), and soil enzyme activity decreased in T600. β-D-xylosidase, β-D-glucosidase, and cellobiohydrolase varied by 22–33% (P10: 17.10 vs. 13.36 and P100: 12.33 vs. 8.3 nmol g⁻¹ h⁻¹, $p > 0.05$), 43–60% (P10: 33.43 vs. 13.39 and P100: 39.92 vs. 22.63 nmol g⁻¹ h⁻¹, $p < 0.05$), and 12–33% (P10: 10.57 vs. 7.10 and P100: 5.50 vs. 4.83 nmol g⁻¹ h⁻¹, $p > 0.05$) in T600 compared to T300.

SMBC and soil enzyme activity were notably greater with maize straw addition (Table 1). Treatments with maize straw addition showed a 21–76% increase in SMBC ($p < 0.05$); the increase was much larger in P100 during the same total precipitation event (T600: 21% vs. 76%; T300: 23% vs. 56%). β-D-xylosidase, β-D-glucosidase, and cellobiohydrolase activities were 33–455%, 9–277%, and 77–243% greater in treatments with maize straw addition, respectively (T600-P10, T600-P100, T300-P10: $p < 0.05$; T300-P100: $p > 0.05$). NO₃-N concentrations were increased by 114–181% with N addition ($p < 0.05$), and this increase was relatively minor with the combined straw- and N- addition ($p > 0.05$).

4. Discussion

4.1. Effect of changing precipitation pattern on soil respiration

Our findings indicated that precipitation pattern changes significantly affect soil respiration. Soil respiration was consistently inhibited in P10 with limited microbial activity and substrate diffusion in over-dried soil conditions (Fig. 3a,c) (Manzoni et al., 2012). However, P100—with an amplified hydrological cycle—showed diverse impacts

on soil respiration (Fig. 3b,d), including a rapid and substantial increase in soil respiration on the first day after the precipitation events, which then gradually decreased until the next precipitation event. This phenomenon was extensively observed in a variety of ecosystems (Chen et al., 2008; Vargas et al., 2012; Thomey et al., 2011). Less frequent and larger precipitation events may lead to deeper water infiltration and longer water retention (Knapp et al., 2008), which could improve diffusion and labile organic substrate availability and increase microbial biomass and activity, thus increase C mineralization (Borken and Matzner, 2009; Moyano et al., 2013). Furthermore, when comparing the stimulation effects on soil respiration rates after T300-P100 and T600-P100, we found that the response of soil respiration to P100 is greater for T300 with a 30-day drought period than for T600 with a 15-day drought period. This finding suggested that the soil respiration response to precipitation events largely depends on antecedent soil water conditions; prolonged drought conditions before precipitation may increase the responsiveness of microbial turnover and enhance soil C mineralization (Meisner et al., 2017).

Heavy precipitation cycles produced over-dried and over-saturated water stress on soil respiration (Fig. 3b,d). Over-saturated water stress usually occurred on the first day after precipitation and primarily depended on the initial water conditions. For humid antecedent soil conditions, heavy precipitation may decrease soil respiration. These results agree with those of several studies (Cable et al., 2008; Lei and Han, 2020). Saturated soil can produce frequent anoxic conditions and limit oxygen transport, further restricting soil respiration (De-Campos et al., 2012; Felton et al., 2019). Over-dried water stress occurred during prolonged dry periods between precipitation events; inhibited soil respiration rates were primarily affected by the constrained substrate-microbe interaction in low water conditions (Felton et al., 2019).

In our study, cumulative soil respiration showed a good correlation with the duration of precipitation-induced water stress (Figs. 6–7). For the same total precipitation amount, soil respiration remained under drought stress throughout incubation under P10, and P100 significantly increased the duration of suitable water conditions. Improved water conditions may trigger microbial activity and improve substrate diffusion and availability, thus enhancing carbon mineralization after each precipitation event (Huang et al., 2015; Williams and Potts, 2003). Likewise, during the same sub-event, T600 showed higher cumulative soil respiration. This result was consistent with that of several previous

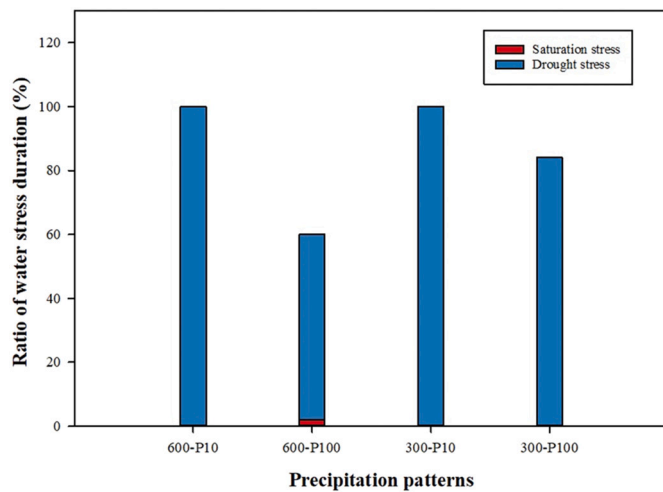


Fig. 6. Ratio of water stress duration for different precipitation patterns.

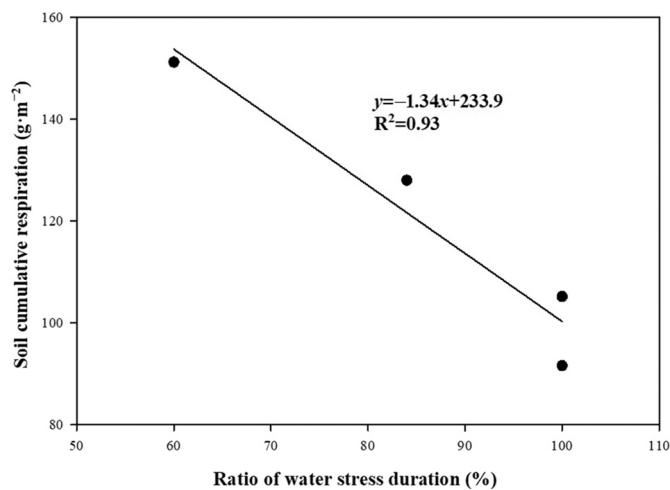


Fig. 7. Relationship between cumulative soil respiration and the ratio of water stress duration.

studies (Huxman et al., 2004; Yan et al., 2014); more precipitation enhances water percolation, which triggers soil respiration. Therefore, increased water availability explains the greater soil respiration for higher total precipitation amounts or larger single precipitation events. Additionally, the higher cumulative soil respiration of T300-P100 (than of T600-P10) highlighted the importance on soil respiration of the precipitation amount and soil water conditions induced by shifting precipitation patterns. Considering frequent heavy precipitation events and prolonged dry periods on the Loess Plateau, these findings highlight the unignorable influence of changing precipitation patterns on soil C flux under future climate scenarios.

4.2. Effect of straw and N on the response of soil respiration to extreme precipitation patterns

The amplified soil respiration after heavy precipitation cycles and straw addition (Fig. 4) illustrated the synergistic effects of straw and optimum water conditions. Firstly, straw addition significantly stimulated the response of soil respiration to precipitation events (Fig. 4), together with the increased SMBC and soil enzyme activity (Table 1). Straw addition provided soil with additional substrates and activated microbial activity, thus stimulating C decomposition (Duong et al., 2009; Bending et al., 2002). This stimulation effect was intensified in

P100 with improved water conditions, where straw addition to P100 significantly amplified the fluctuation range of soil respiration (Fig. 4, $p < 0.05$). This result suggested that the external C supply may strongly amplify the response of soil respiration to changing precipitation patterns, especially with increased large precipitation events in arid and semiarid ecosystems.

Conversely, N addition showed minor influence on soil respiration with changing precipitation patterns (Fig. 4), agreeing with several previous studies. Chen et al. (2017) partitioned soil respiration components and found that soil microbial respiration was unresponsive to N fertilization. Likewise, Su et al. (2016) proposed that a combination of water and N addition did not generate synergistic soil respiration effects. On the one hand, improved water conditions after precipitation events could increase N availability to compensate for higher N requirements (Austin et al., 2004); on the other hand, precipitation events may significantly increase dissolved organic carbon content, which is generally considered to be labile carbon and is more easily to be decomposed, suggesting a low N demand (Su et al., 2016), thus N addition may have a limited role on soil respiration.

Straw and N addition initially had a slightly positive effect on soil respiration than did straw addition alone (Fig. 4), probably because N addition increased hydrolytic enzymes activities—such as β -D-glucosidase and β -D-xylosidase (Table 1)—and promoted the decomposition of labile organic matter (Knorr et al., 2005). However, as the labile organic matter was gradually consumed, the positive effect weakened and began to negatively affect soil respiration. Several mechanisms have been discussed in previous studies: N may inhibit soil respiration by decreasing C-degrading enzyme activities (Waldrop and Zak, 2006) or altering the composition of the microbial community (Fierer et al., 2012). Because the soil analysis showed opposite results on soil enzyme activities, we assume that the latter mechanism may explain the inhibitory effect on soil respiration. Further studies will be conducted to identify the effect of precipitation-induced N on soil respiration changes in the composition of the microbial community.

4.3. Influencing factors of soil respiration with extreme precipitation patterns

Cumulative soil respiration was significantly correlated with β -D-glucosidase and SMBC (Table 2). For the same total precipitation event, P100 significantly increased β -glucosidase compared to P10, suggesting that altered precipitation-induced changes in soil water availability are an important driver for microbial activities, which control soil respiration (Ren et al., 2017). Similarly, SMBC was higher in P100 compared to P10 under T300, proving that P100 microbial activity increased. These results agree with the higher cumulative soil respiration variation under P100 compared with that of P10. However, under the same sub-event, T600 treatments showed enhanced cumulative soil respiration but reduced soil enzyme activity. More frequent heavy precipitation event cycles in T600 could produce over-saturated water conditions that restrain the activity of extracellular enzymes because of limited O₂ availability (Chen et al., 2017), which was reported as an ‘enzymatic

Table 2

Spearman's rank correlation coefficients between soil biochemical properties (i. e. cellobiohydrolase, β -D-xylosidase, β -D-glucosidase, SMBC, and NO₃-N, NH₄-N) and cumulative soil respiration.

Soil biochemical properties	R	p
β -D-Xylosidase (XL)	0.376	0.151
Cellobiohydrolase (CEL)	0.215	0.425
β -D-Glucosidase (GLU)	0.588*	0.017
Soil microbial biomass carbon (SMBC)	0.806**	0.000
NO ₃ -N	-0.335	0.204
NH ₄ -N	0.354	0.179

* Represents significant effects at $p < 0.05$.

** Represents significant effects at $p < 0.01$.

latch' mechanism (Freeman et al., 2001). However, the more frequent T600 precipitation cycles may stimulate soil respiration after each precipitation event and contribute to higher cumulative soil respiration during the entire incubation period.

Soil respiration is profoundly affected by the size and the frequency of extreme precipitation. Ignoring these factors may largely underestimate regional carbon emissions. Thus, scenarios incorporating the impact of extreme precipitation on soil respiration should be considered when using carbon models to predict the carbon budget of an ecosystem under climate change.

5. Conclusions

This study suggests diverse responses of soil respiration to extreme precipitation patterns in arid and semi-arid regions and that the stimulation or inhibition of precipitation events primarily depends on precipitation size and the antecedent soil water conditions. Cumulative soil respiration was sensitive to precipitation pattern changes. Large but less frequent precipitation events largely increased cumulative soil respiration compared to the small frequent precipitation events under the same total precipitation amount. For the same sub-event, the increase in total precipitation amount also presented with higher cumulative soil respiration in the same time period. Considering the strong wet and dry cycles during the summer rainy season on the Loess Plateau, these results strongly indicate the possibility of greater C loss with the changing precipitation scenarios, especially in case of frequent storms and erratic precipitation patterns. Furthermore, although water availability is the most important factor controlling soil respiration, the amplified response with straw addition suggested that soil respiration might show a greater response to changing precipitation events with different agriculture management. This strong response of soil respiration to altered extreme precipitation patterns suggests that global climate change is likely to have important ramifications for carbon cycling in the xeric environments.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

Acknowledgements

This work was funded by National Natural Science Foundation of China [No. 41830751], and China Postdoctoral Science Foundation [No. 2018M643755]. The contributions of Qiqi Sun, Lanlan Du, and Xin Gao in maintaining the plots and collecting samples are gratefully acknowledged. The authors also highly appreciate all the research facilities provided by Changwu Experimental Station.

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