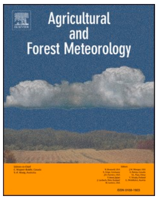
Agricultural and Forest Meteorology 304-305 (2021) 108426

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Impacts of land use conversion on the response of soil respiration to precipitation in drylands: A case study with four-yearlong observations

Wenhao Sun [a], Xining Zhao [b,c,*], Xiaodong Gao [b,c], Weiyu Shi [d], Qiang Ling [a], Kadambot H. M. Siddique [e]

[a] *Key laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A & F University, Yangling 712100, Shaanxi Province, PR China*
[b] *Institute of Soil and Water Conservation, Northwest A & F University, Yangling 712100, Shaanxi Province, PR China*
[c] *Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, Yangling 712100, Shaanxi Province, PR China*
[d] *School of Geographical Sciences, Southwest University, Chongqing, China*
[e] *Univ Western Australia, UWA Inst Agr, LB 5005, Perth, WA, 6001, Australia*

ARTICLE INFO

Keywords:
CO_2
Temperature sensitivity
Q_{10}
Precipitation regime
Land use conversion
Afforestation

ABSTRACT

Soil respiration (Rs) in drylands is strongly influenced by precipitation. However, there is a lack of long-term studies on how land-use conversion impact the Rs's responds to precipitation variations. In situ Rs, soil moisture and soil temperature were monitored in cropland, and cropland converted jujube orchard, grassland and shrubland in the semiarid Loess Plateau, China for four years with significant interannual precipitation variation. Q_{10}-soil moisture relationships were quantified by selecting observations within limited range of soil moisture. As soil moisture increased, Rs was found to be markedly suppressed in cropland and jujube orchard with great disturbance, with volumetric water content exceeding 0.15 and 0.16, respectively, but increased in grassland and shrubland with few disturbances. Q_{10} became saturated as soil moisture increased in cropland, and was linearly correlated with soil moisture in jujube orchard, grassland and shrubland. Q_{10} was least sensitive to soil moisture variation in shrubland, which was characterized by a nitrogen-fixing shrub. The interannual variation in mean growing season Rs (MGR) was positively correlated with mean soil moisture. The difference in MGR between land-use types was significant except during the extreme drought year: converting cropland to jujube orchard saw a reduction in MGR by 5–18%, while converting cropland to grassland and shrubland saw an increase in MGR by 16–53% and 67–126%, respectively. This corresponded with a greater sensitivity of MGR to soil moisture in grassland and shrubland. These results suggest a greater response of soil carbon emission in the land-use applied with afforestation or restoration to the enhanced soil moisture as precipitation intensify, compared to agricultural land-use.

1. Introduction

Soil respiration (Rs) is the second-largest terrestrial source of carbon (C) flux, estimated to emit approximately 64–98 pg C year^{-1} (Bond--Lamberty 2018). Even a small variation in Rs has a huge influence on the global terrestrial C budget (Bond-Lamberty and Thomson 2010). Land-use conversion makes a major contribution to greenhouse gas emissions and has a significant impact on Rs (Edenhofer et al., 2014; Raich and Schlesinger 1992; Sheng et al., 2010). Evidence suggests that future precipitation regimes will undergo significant change across a wide range of habitats, which will therefore have a profound effect on Rs and the terrestrial C balance (Fay et al., 2008; Liu et al., 2016). Thus, research on how Rs and different types of land use interact with varied precipitation will enhance our understanding of future C cycles.

Precipitation is an important driver of ecosystem structure and function (Heisler and Weltzin 2006), especially in drylands, which cover 41% of the earth's surface (Maestre et al., 2012). For most dryland ecosystems, water availability regulated by precipitation is the primary limiting factor for multiple soil biogeochemical processes and intra- and interannual variation in Rs (Austin et al., 2004; Huxman et al., 2004). Land-use conversion processes, which usually involve vegetation change and specific management regimes, can significantly influence Rs (Hu

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* Corresponding author at: No. 26, Xinong Road, Yangling, Shaanxi, 712100, China.
E-mail addresses: zxn@nwafu.edu.cn, xiningz@aliyun.com (X. Zhao).

https://doi.org/10.1016/j.agrformet.2021.108426
Received 27 June 2020; Received in revised form 3 April 2021; Accepted 4 April 2021
Available online 21 April 2021
0168-1923/

et al., 2018; Sheng et al., 2010; Zhang et al., 2015). The species composition, structure and physiological characteristics of the vegetation strongly influence the soil microclimate, the amount and quality of detritus available in the soil, and the aboveground photosynthetic supply for roots, which are key factors in determining the soil substrate pool and root respiration and influence the Rs response to precipitation (Anaya et al., 2012; Arredondo et al., 2018; Sponseller 2007). For example, Shi et al. (2011) found that land use afforested with exotic tree with higher litter quality result in greater response of Rs to the precipitation during the early growing season than native trees. They also suggest that the different tree species displayed different physiological activities also contributes in a differential response of Rs. The interaction between land-use type and precipitation regimes is also significant. Arredondo et al. (2018) found that a shift in grass composition altered not only soil moisture and soil temperature, but also their influence on the Rs response to a manipulated precipitation decrease. Munson et al. (2010) and Sun et al. (2018) both found that a larger precipitation event is related to significant differences in Rs response between different land-use types other than smaller precipitation. However, most of these studies collected data over short time periods with only a few precipitation events, or using water manipulation method. A more complete picture of the influence of real-world precipitation on seasonal and interannual soil C efflux is needed across different land-use types.

Soil moisture and soil temperature have been intensively studied because of their close relationship with Rs. They affect the rate of gas diffusion, substrate availability, soil microbial activities and root systems, all influencing the Rs. Previous studies have suggested that land-use conversion can change the sensitivity of Rs to soil moisture and soil temperature (Hu et al., 2018; Sheng et al., 2010; Shi et al., 2011; Sun et al., 2018), resulting in significant spatial heterogeneity in the Rs response to precipitation. Moreover, the apparent temperature sensitivity of Rs (Q_{10}) is influenced by water availability as a result of the interactive effect of soil moisture and soil temperature. For example, enhanced precipitation or soil moisture increases Q_{10} by alleviating the limitation of substrate availability (Huang et al., 2018; Yu et al., 2019), and vice versa (Huang et al., 2018; Suseela et al., 2012; Yuste et al., 2003). A positive correlation between Q_{10} and precipitation was seen by Liu et al. (2016) in water manipulation experiments from different sites across the world. In contrast, several studies conducted in wetter climates suggest that higher soil moisture may depress Q_{10} by limiting gas diffusion (Chen et al., 2018; Dörr and Münnich 1987). Despite such significant variations in in situ Q_{10}, a fixed Q_{10} value of 2 or 1.5 is used in many C cycle ecosystem models (Meyer et al., 2018), leading to significant bias in predicting future C cycles under a probably more extreme precipitation regime. Moreover, an interactive effect between precipitation and land-use type has been illustrated by Jia et al. (2014), who reported that the Q_{10} response to water addition differed depending on grass type, while Q_{10} in fallow grassland was unchanged. Thus, quantitative studies exploring the relationships between Q_{10} and precipitation or soil moisture under different land-use types are needed.

Previous studies on Q_{10} under different soil moisture conditions are mostly based on lab incubations (Hamdi et al., 2013) or in situ experiments (Liu et al., 2016; Suseela et al., 2012). Soil incubations disturb the soil structure and only measure heterotrophic respiration, which is different from the Rs in vegetated natural systems (Hamdi et al., 2013; Herbst et al., 2016; Liu et al., 2002). Field experiments are less convenient for testing Q_{10} across a wide range of soil moisture conditions. Moreover, field observation is usually accompanied by significant soil moisture variations, and the negative correlation between soil water and soil temperature may result in underestimation of Q_{10} (see Fig. S1 and its explanations in the supplementary materials). In conclusion, a suitable method is needed to test accurate Q_{10} based on situ data across a wide range of soil moisture conditions, meanwhile reducing the influence of soil moisture variations on Q_{10} calculations.

China's Loess Plateau, which covers an area of 640, 000 km^2 and is mostly characterized by drylands, suffers from severe soil erosion and land degradation as a result of inappropriate farming. The Grain for Green Project initiated in 1999 aimed to solve the ecological problems by converting low-quality croplands to grassland, shrubs, forests or orchards (PRC 2003; Zhao et al., 2015). These afforestation or restoration practice enhances soil C and soil C efflux (Shi et al., 2014; Zhang et al. 2015) and changes the short-term response of Rs to precipitation events (Shi et al., 2011; Sun et al., 2018). However, the seasonal and interannual influence of precipitation on Rs is still unknown. In this study, in situ growing season Rs was monitored in cropland, jujube orchard, grassland and shrubland for 4 years. We treated the cropland as the pre-conversion status and treated the other 3 land-uses, originated from cropland, as the after-conversion status. By comparing Rs between these two status across the wide range of precipitation variation during those 4 years, we examined the individual and interact effect of precipitation regime and land-use conversion on Rs. We hypothesize that land use conversion involving afforestation or restoration in Loess Plateau would (1) enhance the Rs and Q_{10} response to soil moisture variation, (2) enhance annual growing season Rs, and the enhancement depends on precipitation regimes.

2. Materials and methods

2.1. Study site

The experiment was conducted in the small catchment area of Yuanzegou (37°15′N, 110°21′E), Qingjian County, Shaanxi Province, China. This catchment is situated in a loess hilly-gully area, in the north-central region of the Loess Plateau. The area has a semiarid continental climate with a mean annual precipitation of 505 mm, 70% of which falls in August, September and October. The mean annual temperature is 8.6 °C, with mean monthly temperatures ranging from −6.5 °C in January to 22.8 °C in July. The catchment area covers 0.58km^2, at altitudes varying from 876 to 1082 m. The soil texture is silt loam, classified as Inceptisols according to the USDA, with a textural composition of 12.62% clay, 68.9% silt and 18.2% sand, and is relatively uniform across the catchment area (Zhao et al., 2015). Current land-use in the catchment includes cropland, jujube orchard, shrubland and grassland, which are all common across the Loess Plateau following the implementation of the Grain for Green Project in 1999 (Zhang et al. 2015; Zhao et al., 2015). All the jujube orchard, grassland and shrubland in the catchment area were originally cropland, correspondingly with an age of 9 years, 20 years and 20 years since conversion. We obtained information on land-use history and afforestation by interviewing local farmers and the details were provided by Sun et al. (2018). To explore the effect of land use on Rs, four slopes corresponding to the four land-use types with similar stand conditions were selected for the experimental sites. The distance between sites was less than 0.5 km to minimize soil homogeneity. Soil characteristics and fine root biomass measurements from

Table 1
Soil organic carbon (SOC), carbon:nitrogen (C:N) ratio, bulk density (BD) in the top 10 cm, and fine root biomass, for different land-use types within the small Yuanzegou catchment, Loess Plateau, China.

Land-use type	SOC (g kg^{-1})	C:N ratio	BD (g cm^{-3})	Fine root biomass (g m^{-2})
Cropland	2.08 ± 0.12c	10.9 ± 0.05b	1.42 ± 0.02a	43 ± 4c
Jujube orchard	2.78 ± 0.45bc	10.3 ± 0.12b	1.44 ± 0.03a	44 ± 10c
Grassland	3.33 ± 0.11b	11.9 ± 0.14b	1.36 ± 0.00b	68 ± 10bc
Shrubland	5.07 ± 0.37a	15.8 ± 0.10a	1.36 ± 0.01b	102 ± 6a

Values are means ± standard error of four plots from each land-use type, and when followed by the same letter within each column do not differ according to a least significant difference (LSD) test (p<0.05).

each site are presented in Table 1. Cropland had been planted with *Setaria italica* (L.) Beauv., *Zea mays* L., *Vigna radiata* (L.) Wilczek and *Solanum tuberosum* L.. Jujube orchard had been planted with the Jujube tree (*Ziziphus jujuba* Mill.), a traditional economic fruit tree species in the study area. Grassland was dominated by *Artemisia sacrorum* Ledeb. ex Hook.f., *Artemisia scoparia* Waldst. et Kit. and *Setaria viridis* (L.) Beauv., as a result of ecological succession after the original cropland was abandoned, with canopy cover averaging 70%. Shrubland was planted with *Caragana korshinskii* Kom. for soil and water conservation. Both cropland and jujube orchard were rainfed, receiving conventional agriculture practice. Fertilizer was applied during sowing in cropland and before the growing season in the jujube orchard every year. Shallow tillage (above 10 cm) was applied mainly for weed control. The frequency of the weed control was determined by the status that weed grew. Conversely, both the grassland and shrubland received no human intervention since the land-use was converted.

2.2. Rs and environmental factors

For each land-use type, four permanent plots of 2 *m* × 2 m were established. The plots were distributed randomly with a 6-m gap between them and placed between vegetation patches. To measure the rate of Rs, a collar made of polyvinyl chloride, 21 cm in diameter and 10 cm in height, was inserted into the soil to a depth of about 3 cm in each plot two days before the first measurement, and left in situ throughout the study period. The above-ground portion of live plants within the collars was cut before measurements were taken. Field surveys were made routinely from 2015 to 2018, about three times a month, to measure in situ Rs and related environmental factors. Extra observations (every one or two days) were made after precipitation events to capture pulse dynamics for Rs. On each observation day, measurements were taken between 9:00 and 11:00 to provide approximate daily means. All measurements were made within 2 h, minimizing the effect of daily variation. Rs was measured using a LI-8100 (LI-COR, USA) equipped with a portable chamber (Model 8100–103). Environmental factors, including soil temperature and soil moisture, were measured near each collar at the same time as the Rs. Soil temperature was measured at a depth of 10 cm using a thermocouple probe, while soil volumetric water content (VWC) was measured using a time domain reflectometry moisture meter (TDR200, Spectrum, USA) at 0–5 cm. Climatic variables, including air temperature, wind speed and precipitation, were recorded by an automatic weather station at the center of the catchment area, near the four land-use sites.

2.3. Data analysis and statistics

Mean Rs, soil temperature, soil moisture values were used in regression analyses. The relationships between Rs and soil moisture were fitted with a parabola equation:

$$\mathrm{Rs} = a\mathrm{SM}^2 + b\mathrm{SM} + c \tag{1}$$

Where SM is the soil moisture, *a, b*, and *c* are the parameters.

Relationships between Rs and soil temperature were fitted with an exponential equation:

$$Rs = a\exp(bST) \tag{2}$$

Where ST is the soil temperature, *a* and *b* are the parameters.

The parameter b was then used to calculate Q_{10} using the following equation:

$$Q_{10} = \exp(10b) \tag{3}$$

The mean growing season Rs, soil temperature and soil moisture were calculated using the following equation:

$$y = \frac{1}{2(t_n - t_1)} \sum_{i=1}^{n} (t_{i+1} - t_i)(x_i + x_{i+1}) \tag{4}$$

where *y* is the mean Rs, soil temperature or soil moisture of each year, *t* is the sampling date (Julian day), *x* is the Rs, soil temperature or soil moisture value measured at each sampling date, *i* is the sampling number for each observation, and *n* is the total sampling number.

All data were tested for normal distribution before statistical analysis. The relationship between Q_{10} calculated for each growing season and mean soil moisture (arithmetic mean) was analyzed using linear regression. The relationships between mean growing season Rs (MGR) and soil moisture, and between MGR, soil moisture and soil temperature were analyzed using single factor and multiple linear regression, respectively.

The differences in mean Rs, soil temperature and soil moisture between land-use type and observation year were analyzed using a repeated measures ANOVA (RMANOVA), with the year as the within-subjects variable, and land-use type as the between-subjects factor. Where their interaction proved significant, a year by year and a land-use by land-use ANOVA were performed and differences between factor levels were analyzed by an LSD test. Before the RMANOVA analysis, Mauchly's sphericity test was applied and suggested the data met the sphericity criterion. All of the analyses were carried out using Excel and Orignlab.

2.4. Quantifying Q_{10}-soil moisture relationship

Based on Eq. (3), we developed a new method to evaluate the Q_{10}–soil moisture relationship. By selecting observations within a restricted range of soil moisture values, we tested the relationships between the Q_{10} and mean soil moisture calculated from these observations. The detailed procedure is listed as follows:

Step 1 All observations were ranked by soil moisture values in ascending order, and the rank numbers from 1 to N was assigned to each observation. N is the total number of observations.

Step 2 We defined sample size (S) as the number of the observations used in each Q_{10} and mean soil moisture calculation. In this study, S was tested with values ranging from 8 to 50. For each S, steps 3 to step 5 were performed successively.

Step 3 Mean soil moisture values were generated by using a moving average method applying to previous ranked observations. For the *n*th calculation of mean soil moisture ($n = 1$ to N-$S + 1$), observations with the rank number from *n* to $n + S$-1 were used. The detailed calculation equation for each mean can be expressed as:

$$\overline{SW_n} = \frac{1}{S} \sum_{i=n}^{n+S-1} sw_i \tag{5}$$

Where $\overline{\mathrm{SW}_n}$ is the mean soil moisture of *n*th moving average calculation, sw_i is the soil moisture from the previously ranked observations, the subscript *i* indicates the rank number.

Step 4 For each $\overline{\mathrm{SW}_n}$, a $\overline{Q_{10_n}}$ was calculated using Eq. (3) based on the same observations (observations with the rank number from *n* to $n + S$-1). The p-value, R^2 of each $\overline{Q_{10_n}}$ calculation was recorded. The moisture range of the observations for each $\overline{Q_{10_n}}$, evaluated by Δsw_n, was also recorded:

$$\Delta sw_n = sw_{n+S-1} - sw_n \tag{6}$$

Where Δsw_n is the difference between the highest and lowest soil moisture value from the observations used in Q_{10n} calculation, *sw* represent soil moisture from previously ranked observation and the subscript indicates the rank number.

Step 5 The $\overline{Q_{10_n}}$ is treated approximately as the Q_{10} value when soil moisture quals to $\overline{\mathrm{SW}_n}$ in following analysis.

The median of Δsw_n increased from 0.01∼0.02 to 0.08∼0.1 (volumetric water content) as S rose from 8 to 50 (Fig. S2). Thus, the soil moisture variation which used in the Q_{10} calculation is restricted in our study, especially when S was small.

The Q_{10}-SM moisture calculation was done by R, with the detailed R script provided in supplementary files.

3. Results

3.1. *Meteorological conditions and soil microclimate*

The total growing season precipitation (GP) for the 4 years ranged from 267 to 455 mm during 2015–2018, and was plotted among historical data (1979–2014) expressed by exceedance probability in Fig. 1. The exceedance probability was calculated by the same method used by Kotowski and Kaźmierczak (2013). The lowest GP occurred in 2015, which was the third driest year for the past 40 years. The GP for 2016, of 378 mm, was similar to the average value for 40 years, of 400 mm. Precipitation during 2017 and 2018 was similar, being 440 mm and 445 mm, respectively. However, significant variations in monthly precipitation occurred compared with the historical meteorological data for the past 40 years (Fig. 2). Noticeably, in July 2015, there was an extreme drought, with the monthly precipitation representing the minimum value for 40 years, as indicated by the box plot. The mean growing season air temperatures during 2015–2018 were 20 °C, 20 °C, 22 °C and 18 °C, respectively. RMANOVA suggests the effect of year, land use and their interactions significantly influenced the mean growing season soil moisture and temperature (MGR) ($p<0.05$) (Table 2). The mean growing season soil moisture for the four land-use types varied synchronously, increasing from 2015 to 2018 (Fig. 3a). The lowest mean growing season soil temperature was found in 2016, apart from in grassland (Fig. 3b). The interannual variations in mean growing season soil temperature were smallest for grassland, as indicated by a lowest coefficient of variation of 3% compared with other land-use types (7%−8%).

3.2. *The response of rs to soil moisture and soil temperature influenced by land-use conversion*

Rs-soil moisture remained similar as cropland converted into jujube orchard, but changed significantly owing to the conversion to grassland and jujube orchard (Fig. 4). Apparent suppression of Rs in high soil moisture conditions occurred in jujube orchard, which was similar to cropland, and was absent in grassland and shrubland. The response of Rs to soil moisture was also limited by low soil temperature. After excluding soil moisture values lower than 15 °C, significant parabola correlations were found between Rs and soil moisture ($p<0.05$). The fitting function suggested thresholds of soil volumetric water content (VWC) for maximum Rs was remained similar as cropland converted into jujube orchard, which was 15% for cropland and 16% for jujube orchard. However, the threshold significantly increased to 20% and 25% due to the conversion to grassland and shrubland, respectively.

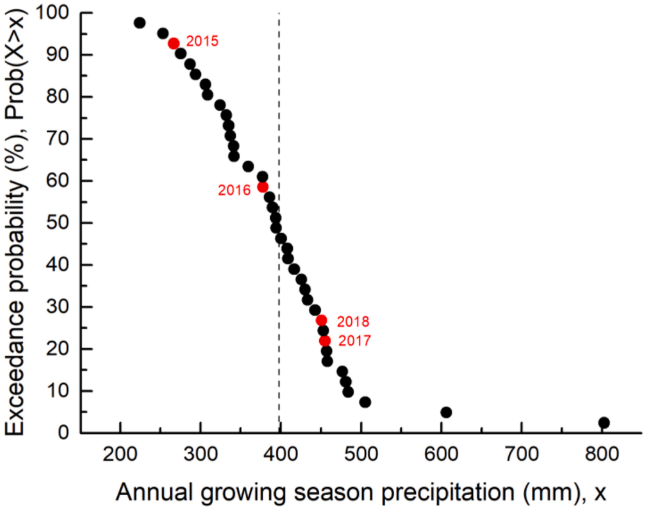

Fig. 1. Exceedance probability distribution of the annual growing season precipitation values. Red circles indicate the annual growing season precipitation during this experiment (2015–2018) and black circles show the historical records from 1979 to 2014. The dotted line indicates the average value of the growing season precipitation from 1979 to 2018.

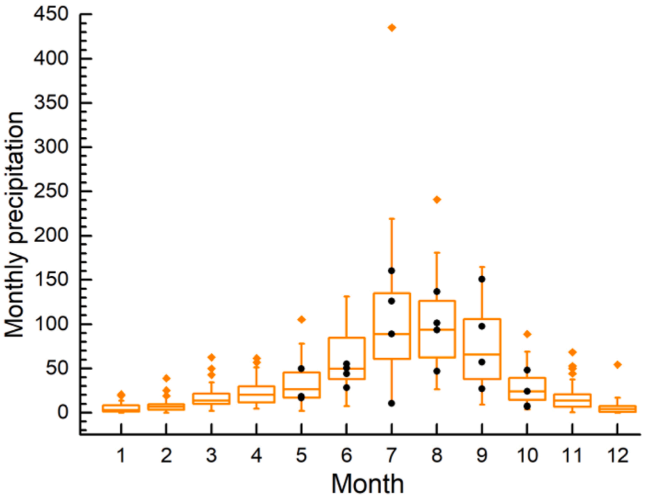

Fig. 2. Monthly variation in precipitation from 2015 to 2018 (black dots) and historical records from 1979 to 2014 (orange box plots).

Table 2
Results from RMANOVA (land use type as between-subject factor and year as within-subject factor) for each variable. ($n = 4$).

Source of variation	F	p-value	generalized eta squared
Mean growing season Rs			
Land-use (L)	40.4	1.51e-06	0.803
Year (Y)	82.9	3.13e-16	0.805
$Y \times L$	8.4	1.25e-06	0.556
Mean growing season soil temperature			
Land-use (L)	9.8	2.00e-03	0.588
Year (Y)	756.2	1.49e-32	0.963
$Y \times L$	10.3	1.16e-07	0.519
Mean growing season soil moisture			
Land-use (L)	61.9	1.43e-07	0.839
Year (Y)	66.8	8.80e-15	0.787
$Y \times L$	7.5	4.31e-06	0.555

3.3. *Relationships between Q_{10} and soil moisture influenced by land-use conversion*

The growing season Q_{10} values over the 4 years ranged from 0.65 to 2.0 across the land-use types, and were all positively correlated with soil moisture ($p<0.01$) (Fig. 5). To quantify the Q_{10}-soil moisture relationships by land-use type further, we enlarged the data set for Q_{10} calculations by including all 126 observations from the 4 years and applying our new methodology. The results showed that the Q_{10} values generally increased with increasing soil moisture across the four land-use types (Fig. 6), in agreement with the Q_{10}-soil moisture relationships seen at the scale of growing season (Fig. 5). Higher R^2 values for Q_{10} were generally accompanied by higher soil moisture values, which also suggested that the influence of soil temperature on Rs increased with increasing soil moisture. The Q_{10}-soil moisture relationships were fitted with a quadratic function for cropland ($p<0.01$), and with linear

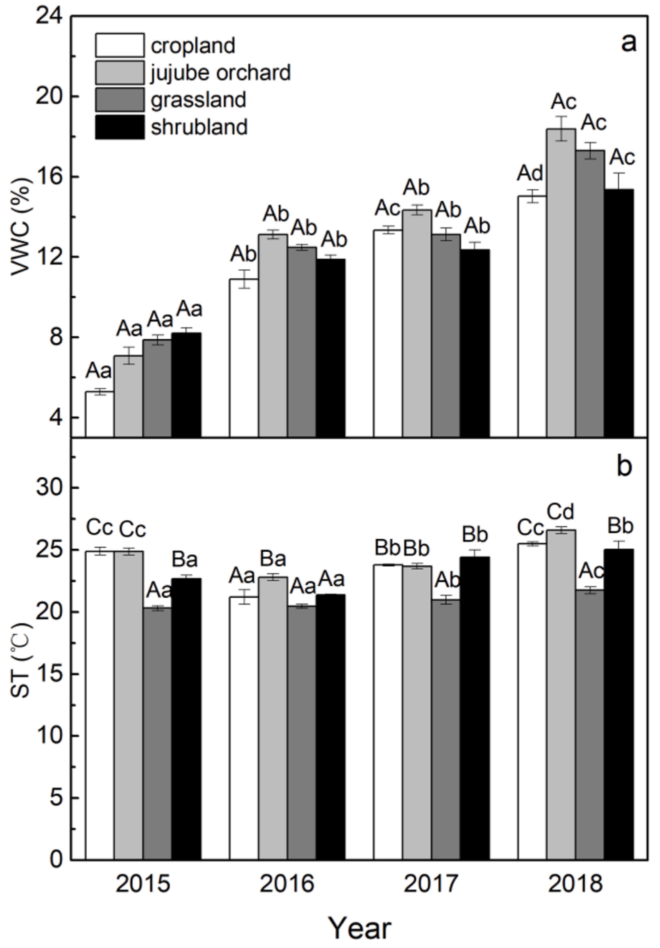

Fig. 3. Mean growing season soil volumetric water content (VWC) (a) and soil temperature (ST) (b) at a soil depth of 5 cm for different land-use types. The error bar indicates the standard error. Different lowercase and uppercase letters indicate significant differences between years for the same land-use type, and between land-use types for the same year, respectively (LSD test, $p<0.05$).

equations for the other land-use types ($p<0.01$). A slight suppression effect on Q_{10} was found for cropland when soil VWC was higher than 17% and Q_{10} was limited to 2.1, while there was no evident suppression with higher soil moisture as cropland converted into other land-use types. Converting to shrubland didn't increase the sensitivity Q_{10} in response to soil moisture, as the Q_{10} value derived from the regression function was 2.0 for shrubland, when the VWC was 20%, and the limitation of water availability largely alleviated, similar to that for cropland when suppression occurred (2.0). Converting to jujube orchard and grassland increase the sensitivity of Q_{10} in response to soil moisture, as the Q_{10} value increase to 2.2 and 2.6 when the VWC was 20%, respectively. The regression slope of the linear relationships was 7.3 and 7.4 by converting to grassland and jujube orchard, respectively, much higher than converting to shrubland (2.7).

3.4. *MGR influenced by land-use conversion*

RMANOVA suggests the effect of year, land use and their interactions significantly influenced the mean growing season soil respiration (MGR) ($p<0.05$) (Table 2). Converting cropland to other three land-uses resulted no significant change in MGR during the extreme drought year (2015) (Fig. 7, $p<0.05$). During 2016–2018, converting cropland to jujube orchard only reduced MGR by 5%−18% ($p<0.05$ only in 2017), while converting cropland to grassland and shrubland increased MGR by 16%−53% ($p<0.05$ in 2016 and 2017) and 67%−126% ($p<0.05$ during 2016–2018), respectively. Interannual variation was also significant for all land-use types ($p<0.05$). The single factor linear regression suggested that MGR was positively correlated with soil moisture for all land-use types (Table 3). The effect of soil moisture on MGR increased by converting cropland to other land-uses and the increment was followed the order of jujube orchard<grassland<shrubland, indicating an increase in sensitivity of MGR in response to variation in soil moisture, which was similar to the effect of soil moisture seen by multiple linear regression between MGR, soil moisture and soil temperature (Table 3). The multiple linear regression suggested that soil moisture and soil temperature explained 68% and 58% of the interannual MGR variation for cropland and jujube orchard, distinctly higher than the 30% and 26% explained solely by soil moisture. In contrast, the R^2 values were similar between single factor and multiple linear regressions from grassland and shrubland. These results suggest that soil temperature played a distinct role in interannual MGR variation before land use conversion, and after converting into jujube orchard, but not after converting into grassland and shrubland.

4. Discussion

4.1. *The role of soil moisture and soil temperature in Rs under precipitation variations*

In arid and semiarid regions, precipitation induces significant fluctuations in soil moisture and soil temperature in the surface layer, where roots, microorganisms and nutrients are most concentrated, driving temporal variations in Rs (Liu et al., 2002; Munson et al., 2010; Qi et al., 2014). During the 4 years of our experiment, a wide range in precipitation (Fig. 1, Fig. 2) was accompanied by significant fluctuations in both soil temperature (8.9 °C-33.7 °C, mean values across the four land-use types) and VWC (1.6%−28.6%). However, on average soil temperature only explained 11% of the total variation in Rs, as indicated by quadratic functions, while soil moisture explained 30% of the Rs variation, as indicated by exponential functions. On the one hand, as the primary limiting factor for the dryland C cycle, soil moisture is closely related to the substrate diffusion rate that controls soil microbial biomass and their metabolic activities, and the plant growth and belowground C allocation that regulates rhizosphere respiration (Norton et al., 2008; Zhang et al. 2015). On the other hand, variations in soil temperature are relatively small during the growing season and its influence is frequently limited by low water availability, especially during drought periods, as has been reported by many researchers, such as Shi et al. (2011) and Sun et al. (2018). Our results emphasize the significant role that soil moisture plays in Rs-precipitation relationships during the growing season on the semiarid Loess Plateau. Our results also suggest significant interactions occur between soil moisture and soil temperature that then influence Rs. The Rs response to soil moisture was enhanced by high soil temperature and limited by low soil temperature in all land-use types (Fig. 4). Similar interactions have also reported for manipulation experiments (e.g. interactions between water addition treatments and warming treatments) (Flanagan et al., 2013; Harper et al., 2005; Zhou et al., 2006). Compared with more temperature- or moisture-driven ecosystems, this significant interaction in semiarid ecosystems, as exemplified by our sites, may lead to a larger response to a combination of increased precipitation and warmer climate.

4.2. *The Rs-soil moisture relationship influenced by land-use conversion*

Our result suggest land-use conversion could change the Rs-soil moisture relationship, however, depending on types of conversion. Comparing to cropland, Rs significantly enhanced under high soil moisture condition after converting to grassland and shrubland, which supports our hypothesis on Rs-soil moisture relationship. However, significant suppression of Rs was found after converting to jujube orchard, similar to cropland, which was against our hypothesis (Fig. 4).

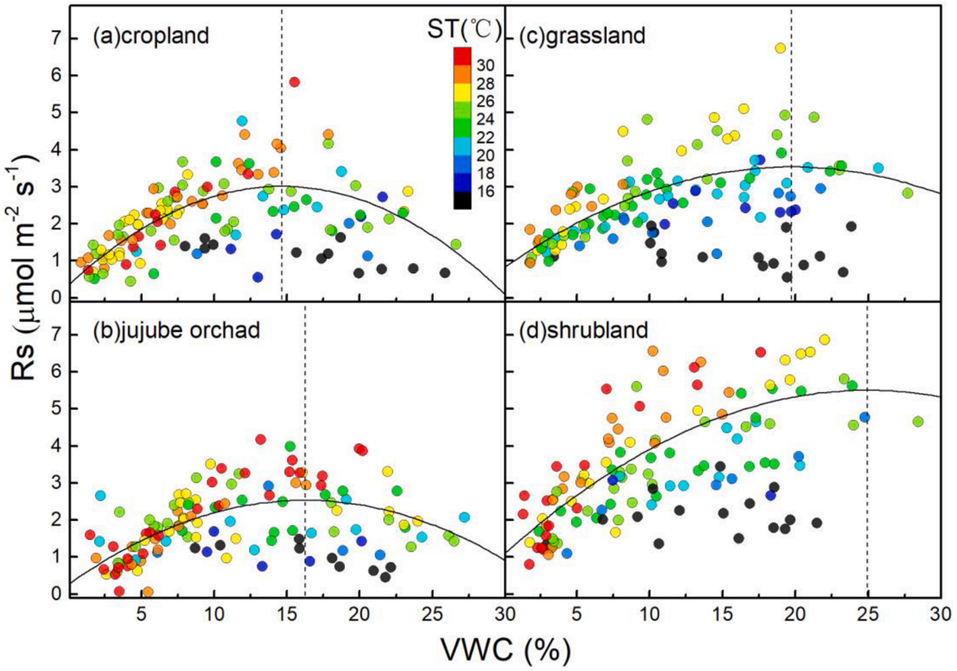

Fig. 4. The relationships between soil respiration (Rs) and soil volumetric water content (VWC) at a soil depth of 5 cm for different land-use types. The color of the circle indicates the soil temperature (ST) at 5 cm. The black curve suggests the fitted function and the dotted line suggests the VWC threshold for maximum Rs.

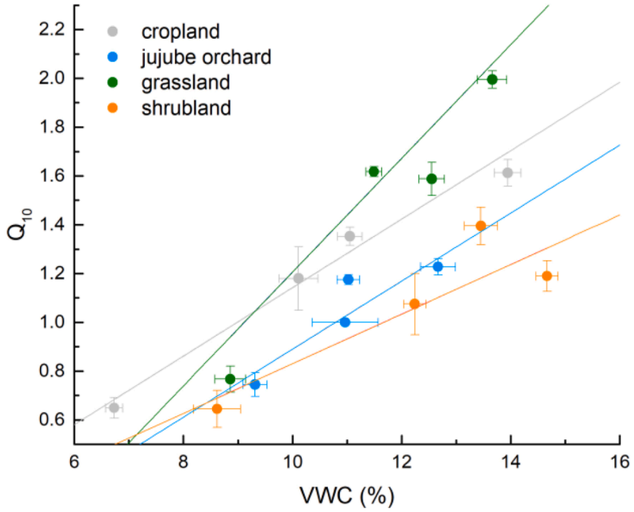

Fig. 5. The relationships between growing season temperature sensitivity (Q_{10}) and the mean growing season soil volumetric water content (VWC) at a soil depth of 5 cm for different land-use types. The black curve is the fitted line using linear function.

This is similar to the short-term results from Sun et al. (2018), and may be caused by oxygen availability and carbon dioxide generation and transportation, which are limited by high soil moisture (Han et al., 2018). At our sites, although the hill slopes were well drained and soil moisture in the soil surface decreased quickly after precipitation events because of the semiarid climate, high soil moisture was still detected immediately after some heavy precipitation. Higher bulk densities were found in both cropland and jujube orchard (Table 1), suggesting lower soil porosities in these land-use types; anaerobic conditions are more likely to occur in these land-use types compared with grassland and shrubland. Similar results reported from Loess Plateau suggest cropland and orchard have higher bulk density than other land uses (Han et al., 2010; Li et al., 2013; Zhang et al. 2015). Agriculture practices, including tillage, fertilization, and weed-control, reduce vegetation cover and root biomass of the land, disturbs the surface soil, rise the chance of soil erosion and compaction through the raindrop impact and result in soil crust with high bulk density (Epstein and Grant, 1967 Paustian et al., 2000). Conversely, converting to grassland and shrubland decrease the bulk density (Table 1). A higher root distribution in these two restoration systems also provides more channels for water to infiltrate deeper into the soil, leading to better aeration. A higher fine root biomass and soil organic matter (SOM) content in grassland and shrubland (Table 1) may also contribute more to the response of both autotrophic and heterotrophic respiration under higher soil moisture conditions. This was especially significant in shrubland, where the most intensive response of Rs to variations in soil moisture (Fig. 4) was accompanied by the highest fine root biomass and SOM content (Table 1).

4.3. *The Q_{10}-soil moisture relationship influenced by land-use conversion*

Q_{10} is a key factor characterizing the response of Rs to variations in soil temperature. It is also an important ecological parameter in ecosystem C cycle models and is widely used to predict Rs in response to global warming, as a variable strongly influenced by soil moisture. Commonly, Q_{10} is calculated from seasonal or annual Rs and temperature data from a wide range of soil water conditions. However, this method does not shed light on the interaction between soil moisture and soil temperature that influences the Q_{10} value, as found in our research when the negative Rs-soil temperature relationships observed in July and August 2015 produced a Q_{10} lower than 1 (Fig. S3). Similar negative relationship can be found in many semiarid regions or during drought periods (Davidson et al., 1998; Felton et al., 2018), which can be explained by the following mechanisms. (1) soil moisture generally controls Rs positively; (2) the response of Rs to soil temperature is limited by low soil moisture; and (3) soil moisture and soil temperature are negatively correlated. A negative Q_{10} value therefore reflects the sensitivity of soil moisture and the covariance between soil moisture and soil temperature rather than actual “temperature sensitivity”, and Q_{10} should be relatively low or approaching 1, but not blow 1, under specific soil moisture conditions. Our results suggest that Q_{10} calculations should be used with caution in in situ experiments when environmental factors

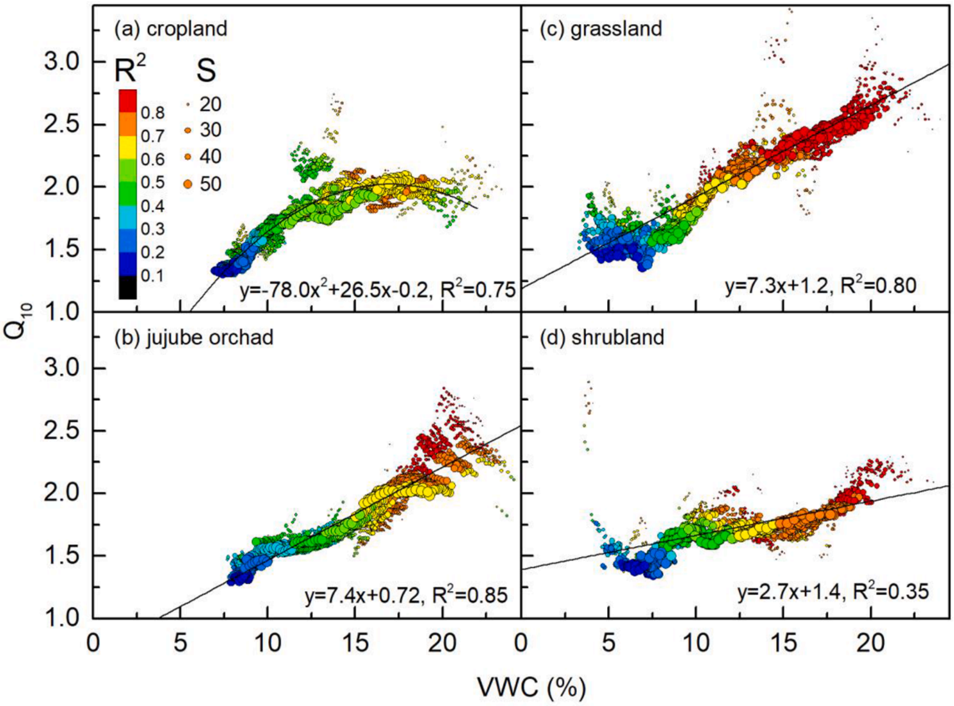

Fig. 6. The relationship between temperature sensitivity (Q_{10}) and soil volumetric water content (VWC) for different land-use types. The size of the circle indicates the sample size (S) for each Q_{10} calculation. The color of the circle indicates the R^2 for each Q_{10} calculation. The black curve/line indicates the fit between Q_{10} and soil moisture content.

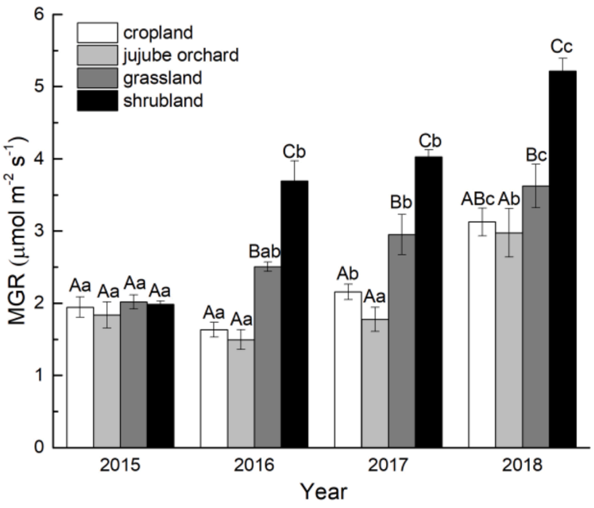

Fig. 7. Mean growing season soil respiration (MGR) values during 2015–2018 for different land-use types. The error bar indicates the standard error. Different lowercase and uppercase letters indicate significant differences between years for the same land-use type, and between land-use types for the same year, respectively (LSD test, $p<0.05$).

have strong covariations, especially when dealing with data with a large variance in soil moisture, as is quite common in arid and semiarid ecosystems and during dry seasons. These results also imply that even when the Q_{10} value falls above zero, it can still be underestimated because of these mechanisms (Fig. S1). Applying our new methodology, restricting soil moisture to a smaller range (Fig S2), can reduce the influence of variation in soil moisture and allow us to analyze the in-situ relationship between Q_{10} and soil moisture. Moreover, Q_{10} calculated based on short-term data (monthly or seasonally) is strongly influenced by plant growth, which is related to the specific seasonal growing stage (Janssens and Pilegaard 2003). The influence of seasonality on our Q_{10}-soil moisture relationships is reduced because our method uses data from across the whole growing season for each Q_{10} calculation.

Our results generally suggested a positive relationship between Q_{10} and soil moisture for all four land-use types (Fig. 6), which is consistent with previous field experiments indicating that increased water availability increases Q_{10} (Liu et al., 2016; Yu et al., 2019; Yuste et al., 2003) while drought suppresses Q_{10} (Wang et al., 2014). This is because, as soil moisture increases, the rate of diffusion of extracellular enzymes produced by microbes to break down organic matter, and of soluble C substrates that can be assimilated by microbial cells, is also increased (Davidson et al., 2006). Higher water availability is also related to higher C accumulation and allocation, enhancing rhizosphere respiration, which is reported to have higher Q_{10} (Hill et al., 2015). Several studies, such as those by Dörr and Münnich (1987) and Chen et al.

Table 3
Linear regression between mean growing season soil respiration (MGR) and soil moisture (SM), and multiple linear regressions between MGR and SM and soil temperature (ST).

Land-use type	Linear regression (df=14)				Multiple linear regression (df=13)				
	Effect of SM	Intercept	R^2	p	Effect of SM	Effect of ST	Intercept	R^2	p
Cropland	9.0 ± 3.6	1.2 ± 0.4	0.30	0.03	8.6 ± 2.6	0.21±0.05	−3.8 ± 1.3	0.68	<0.01
Jujube orchard	8.4 ± 3.8	0.9 ± 0.5	0.26	0.04	5.2 ± 3.1	0.27±0.09	−5.4 ± 2.0	0.58	<0.01
Grassland	17.3 ± 3.0	0.6 ± 0.4	0.71	<0.01	21.6 ± 4.0	−0.29±0.18	6.1 ± 3.5	0.75	<0.01
Shrubland	41.3 ± 4.5	−1.2 ± 0.6	0.86	<0.01	41.0 ± 5.8	0.01±0.09	−1.4 ± 1.9	0.94	<0.01

(2018), suggest Q_{10} may also be depressed by high water content, which in our study was only found in cropland, where the suppression of Rs was most significant (Fig. 4a, Fig. 6a). Our results imply that the suppression of Q_{10} under high soil moisture is less significant in arid regions. Moreover, the water threshold for Q_{10} suppression may be higher than Rs, as also reported for the Mediterranean region by Reichstein et al. (2002).

Land-use conversion can induce significant Q_{10} variation (Chang et al., 2016; Hu et al., 2018; Sheng et al., 2010; Shi et al., 2014), but how the Q_{10}-soil moisture relationship changes is rarely reported. In our experiments, we found that converting to jujube orchard and grassland increase the sensitivity of Q_{10} in response to soil moisture, supported our hypothesis. Such increase was due to the absence of Q_{10} suppressed under high soil moisture conditions in these two land uses, as previously discussed. Against our hypothesis, we also found that converting to shrubland didn't increase the sensitivity of Q_{10} in response to soil moisture, different from grassland and jujube orchard. This was partly because the Q_{10} in shrubland was less limited by low soil moisture, as indicated by the intercept of the regression equation (1.4), which was higher than that for jujube orchard (0.72) and grassland (1.2). Similarly, the Rs in shrubland was less limited by drought, as indicated by the intercept of the Rs-soil moisture relationship (1.1), which was higher than that for cropland (0.4), jujube orchard (0.3) and grassland (0.8). All of these results may relate to the *C. korshinskii* afforestation of shrubland, as this is a highly drought-tolerant species and is widely used in the region (Ning et al., 2016; Zhang et al., 2017). *C. korshinskii* has a deep root system and a plasticity for using water sources from different soil layers; this means its physiological activity may be less limited by drought (Gao et al., 2018), maintaining a higher Rs rate for its rhizosphere through its well-developed root system in the surface soil layer (Table 1). Another reason for the reduced sensitivity of Q_{10} in shrubland is that Q_{10} values were low when drought stress was alleviated. When soil moisture was 20%, the regression results suggested that the Q_{10} in shrubland was lower than in jujube orchard, and equal to the low, suppressed value in cropland. It has been reported that Q_{10} is positively correlated with soil organic carbon (SOC) and fine root biomass during land-use conversion (Sheng et al., 2010; C. Zhang et al. 2015), which contradicts the low Q_{10} found in shrubland, which was accompanied by the highest SOC values and fine root biomass (Table 1). Several earlier studies have also reported that intensively managed agriculture practices (as in cropland and jujube orchard) can enhance Q_{10} (Adewopo et al., 2015; Chang et al., 2016; Sheng et al., 2010), because the breakdown of soil aggregates and the release of aggregate-protected C can enhance decomposition and increase soil microbial activity (Zimmermann et al., 2012). However, the influence of this process may be limited in cropland and jujube orchard because of the low SOC content. Thus, a possible explanation of our results may be related to specific substrate conditions in shrubland. Compared with recalcitrant SOM, labile compounds usually have low Q_{10} values because of their low activation energy (Davidson and Janssens 2006), resulting in the different Q_{10} values for different land-use types reported in various studies (Meyer et al., 2018; Wang et al., 2018). In our experiment, the soil carbon:nitrogen (C:N) ratio value for shrubland was 15.8, which was higher than the other land-use types and similar to values reported elsewhere for the Loess Plateau (Jia et al., 2010; Zhang et al., 2011; Zhang et al., 2018). However, as a nitrogen (N)-fixing leguminous shrub, *C. korshinskii* litter is reported to have significantly higher quantities of labile compounds (Zhang et al., 2018; Zhao et al., 2006). As suggested by Davidson and Janssens (2006), these labile compounds from fresh plant residue may count little towards the total amount of SOM, but have a significant influence on Q_{10} because of its significantly higher decomposition rate. The change in microbial composition and soil enzyme activity during land-use conversion may also have a significant influence on Q_{10} (Wang et al., 2018; Yang et al., 2017; X. Zhang et al. 2015). Moreover, autotrophic and heterotrophic Rs may contribute differentially to the total Q_{10} of different land-use types (Hu et al., 2018). Thus, the differential response of Q_{10} in our experiments included both autotrophic and heterotrophic components, which need to be studied further by partitioning the different components of Rs.

As seen in Fig. 6, several Q_{10} values were found to be significantly greater or lower when comparing values predicted by the fitting functions, mostly calculated from small data sets (e.g. sample size$\leq$30). Smaller sample sizes are not usually sufficient for precise fitting results, even when the p-value suggests significance. If one or several outliers incidentally are significantly correlated with each other, those correlations may make a greater contribution to the fit with smaller sample sizes. This is implied by our results: when the sample sizes were smaller, the R^2 for the Q_{10} fit was greatly increased. Both of these effects can be alleviated as the number of observations increases, and each fit can have an efficient sample size by using limited variation in soil moisture. We strongly recommend researchers using high-frequency automatic monitoring data to apply our method.

4.4. *Interannual MGR influenced by land use conversion*

In arid and semiarid ecosystems, precipitation regimes can have a significant influence on soil moisture dynamics, resulting in different responses of Rs that contribute greatly to interannual patterns of C emission. In our experiments, the interannual variations of MGR were positively correlated with the mean growing season soil moisture for all land-use types (Table 3), as has been seen in other studies (Liu et al., 2016). The interannual variations in mean growing season soil moisture were also synchronous for all land-use types, suggesting a similar impact of precipitation regimes and other associated climatic factors. In particular, the lowest soil moisture values for all land-use types occurred during the extreme drought year (2015) (Fig. 3a), significantly limiting the MGR (Fig. 7). However, the soil moisture did not respond linearly as precipitation regimes changed, in contrast with previous water manipulation experiments (Liu et al., 2016). The mean growing season soil VWC values for all land-use types displayed smaller increases (0.00–0.02, absolute value, similar as follow) as the precipitation increased between 2016 and 2017 (+77 mm), but larger increases (0.02–0.04) when the precipitation fell between 2017 and 2018 (−5 mm). These interannual variations were consistent with the MGR, which increased by 0.28–0.52 μmol m^{-2} s^{-1} in the four land-use types between 2016 and 2017 but was lower than that from 2017 to 2018 (0.67–1.20 μmol m^{-2} s^{-1}). The dynamic of soil moisture at the surface layer is sensitive to both precipitation input and the amount of evapotranspiration. The mean air temperature was low in 2016 and 2018 (20 °C) compared with 2017 (22 °C), which may have resulted in a lower amount of evapotranspiration. Further examination suggested the cumulative potential evapotranspiration during the growing season estimated using the Penman-Monteith equation (Allen et al., 1998) increased by 116 mm from 2016 to 2017, and decreased by 150 mm from 2017 to 2018. The higher potential evapotranspiration in 2017 suggests favorable weather conditions for evapotranspiration, which may have reduced the difference in mean growing season soil moisture between 2016 and 2017 and increased those differences between 2017 and 2018. Knapp et al. (2008) also suggest that the change in evaporation as a result of variation in precipitation has a significant effect on water availability and influences soil C fluxes. The MGR values of cropland and jujube orchard in 2016 were not significantly different compared with 2015 (Fig. 7), even though the precipitation and soil moisture values increased. This may be partly because of the greater drop in soil temperature between 2015 and 2016 in cropland and jujube orchard (a decrease of 3.7 °C and 2.1 °C, respectively) compared with grassland and shrubland (a decrease of −0.2 °C and 1.3 °C, respectively) (Fig. 3b). The influence of soil temperature was also reflected in the multiple regression results, indicating that the effect of soil temperature was higher in cropland and jujube orchard compared with grassland and shrubland (Table 3). Our results suggest that not only the volume of precipitation but also other related climatic factors may have a large influence on the interannual variation in C fluxes, highlighting how soil moisture and soil temperature respond to different precipitation regimes play a key role in the C cycle.

The influence of land-use conversion type was also significant for the MGR, which increased by 16%~53% as converting to grassland and 67%~126% as converting to shrubland during 2016~2018 (Fig. 7). These increments in MGR were consistent with the higher SOM content, soil porosity and fine root biomass found in grassland and shrubland (Table 3), implying greater soil aeration and substrate supply are favorable conditions for Rs. Our results are consistent with the positive correlation between Rs and SOM and fine root biomass reported by Zhang et al. (2015) and Shi et al. (2014). Revegetation in degraded farmland is usually accompanied by an improvement in the physical properties of the soil, nutrient status and microbial properties (Zhang et al., 2011), creating favorable conditions for soil microorganisms to respond to changes in precipitation. Decreases in bulk density at the soil surface layer (Li and Shao 2006; Zhang et al., 2011), enhancement of SOM (Jia et al., 2010; Liu et al., 2012; Zhang et al., 2011) and fine root biomass (Zhang et al. 2015) caused by revegetation have been reported in other research from across Loess Plateau, consistent with our results. Soil microbial biomass and microbial entropy were also elevated following a reported increase in SOM during restoration (Jia et al., 2005), which may enhance the response of MGR to greater water availability. Different agricultural management usually lead to different response of Rs (Drewitt et al., 2009; Wagai et al., 1998). Intensive management like tillage and clipping can result in soil degradation, including soil erosion, nutrient loss and aggravation of the soil's physical properties (Paustian et al., 2000), limiting the response of Rs. Moreover, we found improved MGR after conversion from cropland to grassland and shrubland was highly dependent on precipitation input, which was markedly limited during the extreme drought year (Fig. 7). MGR rose more as soil moisture was increased by greater precipitation input in grassland and shrubland compared with cropland and jujube orchard, because of the greater sensitivity of MGR to variation in soil moisture (Table 3). These differences in soil C emission by land-use type conversion will be exaggerated under more extreme precipitation regimes, which needs to be considered when considering future C cycles.

5. Conclusion

Precipitation drives soil C fluxes by regulating soil moisture and soil temperature in a semiarid region, but the influence is dependent on land-use type. No significant change was found in Rs-soil moisture relationships as cropland converting to jujube orchard, as the Rs suppressed at high soil moisture level in both land-uses. Conversely, converting to grassland and shrubland enhanced the Rs in response to high soil moisture, as a result of better soil aeration and substrate condition. The sensitivity of Q_{10} in response to soil moisture enhanced by converting to jujube orchard and grassland, but not enhanced in shrubland, which had been afforested with an N-fixing shrub and had litter input with a higher quality substrate. Positive MGR-soil moisture relationships were found with all land-use types. The sensitivity of MGR in response to mean growing season soil moisture was enhanced by converting to grassland and shrubland but not in jujube orchard. Our results implies the change of Rs and Q_{10} in response to soil moisture is depend on the types of land-use conversion, which play a great role in soil C emission response to different precipitation regimes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was jointly supported by the National Key Research and Development Program (2016YFC0400204), the National Natural Science Foundation of China (41771316), CAS "Youth Scholar of West China" Program (XAB 2018A04), the Natural Science Funds for Distinguished Young Scholar of Shaanxi Province (2021JC-19), the Shaanxi Innovative Research Team for Key Science and Technology (No. 2017KCT-15), and the '111' Project (No. B12007).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2021.108426.

References

Adewopo, J.B., Silveira, M.L., Xu, S., Gerber, S., Sollenberger, L.E., Martin, T., 2015. Management intensification effects on autotrophic and heterotrophic soil respiration in subtropical grasslands. Ecol. Indic. 56, 6–14. https://doi.org/10.1016/j.ecolind.2015.03.025.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao, Rome 300, D5109.

Anaya, C.A., Jaramillo, V.J., Martinez-Yrizar, A., Garcia-Oliva, F., 2012. Large rainfall pulses control litter decomposition in a tropical dry forest: evidence from an 8-year study. Ecosystems 15, 652–663. https://doi.org/10.1007/s10021-012-9537-z.

Arredondo, T., Delgado-Balbuena, J., Huber-Sannwald, E., García-Moya, E., Loescher, H. W., Aguirre-Gutiérrez, C., Rodriguez-Robles, U., 2018. Does precipitation affects soil respiration of tropical semiarid grasslands with different plant cover types? Agric. Ecosyst. Environ. 251, 218–225. https://doi.org/10.1016/j.agee.2017.09.034.

Austin, A.T., Yahdjian, L., Stark, J.M., Belnap, J., Porporato, A., Norton, U., Ravetta, D. A., Schaeffer, S.M., 2004. Water pulses and biogeochemical cycles in arid and semiarid ecosystems. Oecologia 141, 221–235. https://doi.org/10.1007/s00442-004-1519-1.

Bond-Lamberty, B., 2018. New techniques and data for understanding the global soil respiration flux. Earths Future 6, 1176–1180. https://doi.org/10.1029/2018EF000866.

Bond-Lamberty, B., Thomson, A., 2010. Temperature-associated increases in the global soil respiration record. Nature 464, 579–582. https://doi.org/10.1038/nature08930.

Chang, S.X., Shi, Z., Thomas, B.R., 2016. Soil respiration and its temperature sensitivity in agricultural and afforested poplar plantation systems in northern Alberta. Biol. Fertil. Soils 52, 629–641. https://doi.org/10.1007/s00374-016-1104-x.

Chen, H., Zou, J., Cui, J., Nie, M., Fang, C., 2018. Wetland drying increases the temperature sensitivity of soil respiration. Soil Biol. Biochem. 120, 24–27. https://doi.org/10.1016/j.soilbio.2018.01.035.

Davidson, E.A., Belk, E., Boone, R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Glob. Chang. Biol. 4, 217–227. https://doi.org/10.1046/j.1365-2486.1998.00128.x.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173. https://doi.org/10.1038/nature04514.

Davidson, E.A., Janssens, I.A., Luo, Y., 2006. On the variability of respiration in terrestrial ecosystems: moving beyond Q10. Glob. Chang. Biol. 12, 154–164. https://doi.org/10.1111/j.1365-2486.2005.01065.x.

Dörr, H., Münnich, K.O., 1987. Annual variation in soil respiration in selected areas of the temperate zone. Tellus Ser. B-Chem. Phys. Meteorol. 39, 114–121. https://doi.org/10.1111/j.1600-0889.1987.tb00276.x.

Drewitt, G., Wagner-Riddle, C., Warland, J., 2009. Isotopic CO2 measurements of soil respiration over conventional and no-till plots in fall and spring. Agric. For. Meteorol. 149, 614–622. https://doi.org/10.1016/j.agrformet.2008.10.009.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., et al., IPCC, 2014. Summary For Policymakers, In: Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Eds Edenhofer, O. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 6–9.

Epstein, E., Grant, W.J., 1967. Soil losses and crust formation as related to some soil physical properties. Soil Sci. Soc. Am. J. 31 (4), 547–550. https://doi.org/10.2136/sssaj1967.03615995003100040032x.

Fay, P.A., Kaufman, D.M., Nippert, J.B., Carlisle, J.D., Harper, C.W., 2008. Changes in grassland ecosystem function due to extreme rainfall events: implications for responses to climate change. Glob. Chang. Biol. 14, 1600–1608. https://doi.org/10.1111/j.1365-2486.2008.01605.x.

Felton, A.J., Knapp, A.K., Smith, M.D., 2018. Carbon exchange responses of a mesic grassland to an extreme gradient of precipitation. Oecologia. https://doi.org/10.1007/s00442-018-4284-2.

Flanagan, L.B., Sharp, E.J., Letts, M.G., 2013. Response of plant biomass and soil respiration to experimental warming and precipitation manipulation in a Northern

Great Plains grassland. Agric. For. Meteorol. 173, 40–52. https://doi.org/10.1016/j.agrformet.2013.01.002.

Gao, X., Zhao, X., Li, H., Guo, L., Lv, T., Wu, P., 2018. Exotic shrub species (Caragana korshinskii) is more resistant to extreme natural drought than native species (Artemisia gmelinii) in a semiarid revegetated ecosystem. Agric. For. Meteorol. 263, 207–216. https://doi.org/10.1016/j.agrformet.2018.08.029.

Hamdi, S., Moyano, F., Sall, S., Bernoux, M., Chevallier, T., 2013. Synthesis analysis of the temperature sensitivity of soil respiration from laboratory studies in relation to incubation methods and soil conditions. Soil Biol. Biochem. 58, 115–126. https://doi.org/10.1016/j.soilbio.2012.11.012.

Han, F., Hu, W., Zheng, J., Du, F., Zhang, X., 2010. Estimating soil organic carbon storage and distribution in a catchment of Loess Plateau, China. Geoderma 154 (3–4), 261–266. https://doi.org/10.1016/j.geoderma.2009.10.011.

Han, G., Sun, B., Chu, X., Xing, Q., Song, W., Xia, J., 2018. Precipitation events reduce soil respiration in a coastal wetland based on four-year continuous field measurements. Agric. For. Meteorol. 256-257, 292–303. https://doi.org/10.1016/j.agrformet.2018.03.018.

Harper, C.W., Blair, J.M., Fay, P.A., Knapp, A.K., Carlisle, J.D., 2005. Increased rainfall variability and reduced rainfall amount decreases soil CO_2 flux in a grassland ecosystem. Glob. Chang. Biol. 11, 322–334. https://doi.org/10.1111/j.1365-2486.2005.00899.x.

Heisler, J.L., Weltzin, J.F., 2006. Variability matters: towards a perspective on the influence of precipitation on terrestrial ecosystems. New Phytol. 172, 189–192. https://doi.org/10.1111/j.1469-8137.2006.01876.x.

Herbst, M., Tappe, W., Kummer, S., Vereecken, H., 2016. The impact of sieving on heterotrophic respiration response to water content in loamy and sandy topsoils. Geoderma 272, 73–82. https://doi.org/10.1016/j.geoderma.2016.03.002.

Hill, P.W., Garnett, M.H., Farrar, J., Iqbal, Z., Khalid, M., Soleman, N., Jones, D.L., 2015. Living roots magnify the response of soil organic carbon decomposition to temperature in temperate grassland. Glob. Chang. Biol. 21, 1368–1375. https://doi.org/10.1111/gcb.12784.

Hu, S., Li, Y., Chang, S.X., Li, Y., Yang, W., Fu, W., Liu, J., Jiang, P., Lin, Z., 2018. Soil autotrophic and heterotrophic respiration respond differently to land-use change and variations in environmental factors. Agric. For. Meteorol. 250-251, 290–298. https://doi.org/10.1016/j.agrformet.2018.01.003.

Huang, S., Ye, G., Lin, J., Chen, K., Xu, X., Ruan, H., Tan, F., Chen, H.Y.H, 2018. Autotrophic and heterotrophic soil respiration responds asymmetrically to drought in a subtropical forest in the Southeast China. Soil Biol. Biochem. 123, 242–249. https://doi.org/10.1016/j.soilbio.2018.04.029.

Huxman, T.E., Snyder, K.A., Tissue, D., Leffler, A.J., Ogle, K., Pockman, W.T., Sandquist, D.R., Potts, D.L., Schwinning, S., 2004. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. Oecologia 141, 254–268. https://doi.org/10.1007/s00442-004-1682-4.

Janssens, I.A., Pilegaard, K., 2003. Large seasonal changes in Q10 of soil respiration in a beech forest. Glob. Chang. Biol. 9, 911–918. https://doi.org/10.1046/j.1365-2486.2003.00636.x.

Jia, G., Cao, J., Wang, C., Wang, G., 2005. Microbial biomass and nutrients in soil at the different stages of secondary forest succession in Ziwulin, northwest China. For. Ecol. Manage. 217, 117–125. https://doi.org/10.1016/j.foreco.2005.05.055.

Jia, G., Liu, B., Wang, G., Zhang, B., 2010. The microbial biomass and activity in soil with shrub (Caragana korshinskii K.) plantation in the semi-arid loess plateau in China. Eur. J. Soil Biol. 46, 6–10. https://doi.org/10.1016/j.ejsobi.2009.10.002.

Jia, X., Shao, M., Wei, X., Li, X., 2014. Response of soil CO_2 efflux to water addition in temperate semiarid grassland in northern China: the importance of water availability and species composition. Biol. Fertil. Soils 50, 839–850. https://doi.org/10.1007/s00374-014-0901-3.

Knapp, A.K., Beier, C., Briske, D.D., Classen, A.T., Luo, Y.Q., Reichstein, M., Smith, M.D., Smith, S.D., Bell, J.E., Fay, P.A., Heisler, J.L., Leavitt, S.W., Sherry, R., Smith, B., Weng, E.S., 2008. Consequences of more extreme precipitation regimes for terrestrial ecosystems. Bioscience 58, 811–821. https://doi.org/10.1641/B580908.

Kotowski, A., Kaźmierczak, B., 2013. Probabilistic models of maximum precipitation for designing sewerage. J. Hydrometeorol. 14, 1958–1965. https://doi.org/10.1175/JHM-D-13-01.1.

Li, M., Zhang, X., Pang, G., Han, F., 2013. The estimation of soil organic carbon distribution and storage in a small catchment area of the Loess Plateau. Catena 101, 11–16. https://doi.org/10.1016/j.catena.2012.09.012.

Li, Y.Y., Shao, M.A., 2006. Change of soil physical properties under long-term natural vegetation restoration in the Loess Plateau of China. J. Arid Environ. 64, 77–96. https://doi.org/10.1016/j.jaridenv.2005.04.005.

Liu, L., Wang, X., Lajeunesse, M.J., Miao, G., Piao, S., Wan, S., Wu, Y., Wang, Z., Yang, S., Li, P., Deng, M., 2016. A cross-biome synthesis of soil respiration and its determinants under simulated precipitation changes. Glob. Chang. Biol. 22, 1394–1405. https://doi.org/10.1111/gcb.13156.

Liu, Y., Wei, X., Guo, X., Niu, D., Zhang, J., Gong, X., Jiang, Y., 2012. The long-term effects of reforestation on soil microbial biomass carbon in sub-tropic severe red soil degradation areas. For. Ecol. Manage. 285, 77–84. https://doi.org/10.1016/j.foreco.2012.08.019.

Liu, X., Wan, S., Su, B., Hui, D., Luo, Y., 2002. Response of soil CO2 efflux to water manipulation in a tallgrass prairie ecosystem. Plant Soil 240 (2), 213–223. https://doi.org/10.1023/A:1015744126533.

Maestre, F.T., Salguero-Gómez, R., Quero, J.L., 2012. It is getting hotter in here: determining and projecting the impacts of global environmental change on drylands. Philos. Trans. R. Soc. B 367, 3062–3075. https://doi.org/10.1098/rstb.2011.0323.

Meyer, N., Welp, G., Amelung, W., 2018. The temperature sensitivity (Q10) of soil respiration: controlling factors and spatial prediction at regional scale based on environmental soil classes. Global. Biogeochem. Cycles 32, 306–323. https://doi.org/10.1002/2017GB005644.

Munson, S.M., Benton, T.J., Lauenroth, W.K., Burke, I.C., 2010. Soil carbon flux following pulse precipitation events in the shortgrass steppe. Ecol. Res. 25, 205–211. https://doi.org/10.1007/s11284-009-0651-0.

Ning, P., Wang, J., Zhou, Y., Gao, L., Wang, J., Gong, C., 2016. Adaptional evolution of trichome in Caragana korshinskii to natural drought stress on the Loess Plateau, China. Ecol. Evol. 6, 3786–3795. https://doi.org/10.1002/ece3.2157.

Norton, U., Mosier, A.R., Morgan, J.A., Derner, J.D., Ingram, L.J., Stahl, P.D., 2008. Moisture pulses, trace gas emissions and soil C and N in cheatgrass and native grass-dominated sagebrush-steppe in Wyoming, USA. Soil Biol. Biochem. 40, 1421–1431. https://doi.org/10.1016/j.soilbio.2007.12.021.

Paustian, K., Six, J., Elliott, E.T., Hunt, H.W., 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48, 147–163. https://doi.org/10.1023/A:1006271331703.

PRC (2003): http://www.gov.cn/gongbao/content/2003/content_62531.htm.

Qi, Y.C., Liu, X.C., Dong, Y.S., Peng, Q., He, Y.T., Sun, L.J., Jia, J.Q., Cao, C.C., 2014. Differential responses of short-term soil respiration dynamics to the experimental addition of nitrogen and water in the temperate semi-arid steppe of Inner Mongolia, China. J. Environ. Sci. 26 (4), 834–845. https://doi.org/10.1016/S1001-0742(13)60509-4.

Raich, J.W., Schlesinger, W.H., 1992. The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. Tellus Ser. B-Chem. Phys. Meteorol. 44, 81–99. https://doi.org/10.1034/j.1600-0889.1992.t01-1-00001.x.

Reichstein, M., Tenhunen, J.D., Roupsard, O., Ourcival, J.M., Rambal, S., Miglietta, F., Peressotti, A., Pecchiari, M., Tirone, G., Valentini, R., 2002. Severe drought effects on ecosystem CO2 and H2O fluxes at three Mediterranean evergreen sites: revision of current hypotheses? Glob. Chang. Biol. 8, 999–1017. https://doi.org/10.1046/j.1365-2486.2002.00530.x.

Sheng, H., Yang, Y.S., Yang, Z.J., Chen, G.S., Xie, J.S., Guo, J.F., Zou, S.Q., 2010. The dynamic response of soil respiration to land-use changes in subtropical China. Glob. Chang. Biol. 16, 1107–1121. https://doi.org/10.1111/j.1365-2486.2009.01988.x.

Shi, W.Y., Tateno, R., Zhang, J.G., Wang, Y.L., Yamanaka, N., Du, S., 2011. Response of soil respiration to precipitation during the dry season in two typical forest stands in the forest–grassland transition zone of the Loess Plateau. Agric. For. Meteorol. 151, 854–863. https://doi.org/10.1016/j.agrformet.2011.02.003.

Shi, W.Y., Yan, M.J., Zhang, J.G., Guan, J.H., Du, S., 2014. Soil CO2 emissions from five different types of land use on the semiarid Loess Plateau of China, with emphasis on the contribution of winter soil respiration. Atmos. Environ. 88, 74–82. https://doi.org/10.1016/j.atmosenv.2014.01.066.

Sponseller, R.A., 2007. Precipitation pulses and soil CO_2 flux in a Sonoran Desert ecosystem. Glob. Chang. Biol. 13, 426–436. https://doi.org/10.1111/j.1365-2486.2006.01307.x.

Sun, W.H., Zhao, X.N., Ling, Q., Li, H.C., Gao, X.D., 2018. Revegetation modifies patterns of temporal soil respiration responses to extreme-drying-and-rewetting in a semiarid ecosystem. Plant Soil. https://doi.org/10.1007/s11104-018-3835-y.

Suseela, V., Conant, R.T., Wallenstein, M.D., Dukes, J.S., 2012. Effects of soil moisture on the temperature sensitivity of heterotrophic respiration vary seasonally in an old-field climate change experiment. Glob. Chang. Biol. 18, 336–348. https://doi.org/10.1111/j.1365-2486.2011.02516.x.

Wang, R., Sun, Q., Wang, Y., Zheng, W., Yao, L., Hu, Y., Guo, S., 2018. Contrasting responses of soil respiration and temperature sensitivity to land use types: cropland vs. apple orchard on the Chinese Loess Plateau. Sci. Total Environ. 621, 425–433. https://doi.org/10.1016/j.scitotenv.2017.11.290.

Wagai, R., Brye, K.R., Gower, S.T., Norman, J.M., Bundy, L.G., 1998. Land use and environmental factors influencing soil surface CO_2 flux and microbial biomass in natural and managed ecosystems in southern Wisconsin. Soil Biol. Biochem. 30, 1501–1509. https://doi.org/10.1016/S0038-0717(98)00041-8.

Wang, Y., Hao, Y., Cui, X.Y., Zhao, H., Xu, C., Zhou, X., Xu, Z., 2014. Responses of soil respiration and its components to drought stress. J. Soils Sediments 14, 99–109. https://doi.org/10.1007/s11368-013-0799-7.

Yang, Y., Dou, Y., Huang, Y., An, S., 2017. Links between Soil Fungal Diversity and Plant and Soil Properties on the Loess Plateau. Front. Microbiol. 8 https://doi.org/10.3389/fmicb.2017.02198.

Yu, C., Wang, J., Shen, Z., Fu, G., 2019. Effects of experimental warming and increased precipitation on soil respiration in an alpine meadow in the Northern Tibetan Plateau. Sci. Total Environ. 647, 1490–1497. https://doi.org/10.1016/j.scitotenv.2018.08.111.

Yuste, J.C., Janssens, I.A., Carrara, A., Meiresonne, L., Ceulemans, R., 2003. Interactive effects of temperature and precipitation on soil respiration in a temperate maritime pine forest. Tree Physiol. 23, 1263–1270. https://doi.org/10.1093/treephys/23.18.1263.

Zhang, C., Liu, G., Xue, S., Wang, G., 2015a. Changes in rhizospheric microbial community structure and function during the natural recovery of abandoned cropland on the Loess Plateau, China. Ecol. Eng. 75, 161–171. https://doi.org/10.1016/j.ecoleng.2014.11.059.

Zhang, C., Xue, S., Liu, G., Song, Z., 2011. A comparison of soil qualities of different revegetation types in the Loess Plateau, China. Plant and Soil 347, 163–178. https://doi.org/10.1007/s11104-011-0836-5.

Zhang, J., Chen, G., Zhao, P., Zhou, Q., Zhao, X., 2017. The abundance of certain metabolites responds to drought stress in the highly drought tolerant plant Caragana korshinskii. Acta Physiol. Plantarum 39, 116. https://doi.org/10.1007/s11738-017-2412-y.

Zhang, W., Gao, D., Chen, Z., Li, H., Deng, J., Qiao, W., Han, X., Yang, G., Feng, Y., Huang, J., 2018. Substrate quality and soil environmental conditions predict litter decomposition and drive soil nutrient dynamics following afforestation on the Loess

Plateau of China. Geoderma 325, 152–161. https://doi.org/10.1016/j.geoderma.2018.03.027.

Zhang, X., Zhang, Y., Sha, L., Wu, C., Tan, Z., Song, Q., Liu, Y., Dong, L., 2015b. Effects of continuous drought stress on soil respiration in a tropical rainforest in southwest China. Plant Soil 394, 343–353. https://doi.org/10.1007/s11104-015-2523-4.

Zhang, Y.J., Guo, S.L., Liu, Q.F., Jiang, J.S., Wang, R., Li, N.N., 2015c. Responses of soil respiration to land use conversions in degraded ecosystem of the semi-arid Loess Plateau. Ecol. Eng. 74, 196–205. https://doi.org/10.1016/j.ecoleng.2014.10.003.

Zhao, L., Xiao, H., Liu, X., 2006. Variations of foliar carbon isotope discrimination and nutrient concentrations in Artemisia ordosica and Caragana korshinskii at the southeastern margin of China's Tengger Desert. Environ. Geol. 50, 285–294. https://doi.org/10.1007/s00254-006-0209-1.

Zhao X.N., Wu P.T., Gao X.D., Persaud N. (2015). Soil quality indicators in relation to land use and topography in a small catchment on the loess plateau of china. land degradation & development, 26, 54–61. doi: 10.1002/ldr.2199.

Zhou, X., Sherry, R.A., An, Y., Wallace, L.L., Luo, Y., 2006. Main and interactive effects of warming, clipping, and doubled precipitation on soil CO_2 efflux in a grassland ecosystem. Glob. Biogeochem. Cycles 20, B1003. https://doi.org/10.1029/2005GB002526.

Zimmermann, M., Leifeld, J., Conen, F., Bird, M.I., Meir, P., 2012. Can composition and physical protection of soil organic matter explain soil respiration temperature sensitivity? Biogeochemistry 107, 423–436. https://doi.org/10.1007/s10533-010-9562-y.