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Dong Wang[1,2]
Yu Liu[1,2]
Zhan-Huan Shang[1,3]
Fu-Ping Tian[4]
Gao-Lin Wu[1–3]
Xiao-Feng Chang[1,2]
David Warrington[1,2]

[1]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi, P. R. China
[2]Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi, P. R. China
[3]State Key Laboratory of Grassland Agro-Ecosystems, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou, Gansu, P. R. China
[4]Lanzhou Scientific Observation and Experiment Field Station of Ministry of Agriculture for Ecological System in the Loess Plateau Area, Lanzhou Institute of Animal and Veterinary Pharmaceutics Sciences, Chinese Academy of Agricultural Sciences, Lanzhou, Gansu, P. R. China

Research Article

Effects of Grassland Conversion From Cropland on Soil Respiration on the Semi-Arid Loess Plateau, China

Soil respiration is considered to be the second largest terrestrial carbon flux, and is influenced by land use changes. The impact of a cropland to grassland program on soil respiration was quantified. It tried to identify the dominant factors driving soil respiration along the restoration project of "Grain for Green Program" on the semiarid Loess Plateau, China. Soil respiration and different abiotic and biotic factors were measured for cropland and grasslands after five, 15, and 30 years of natural restoration. Soil respiration ($g\,C\,m^{-2}\,d^{-1}$) was significantly greater for grassland with litter left that had been restored for 15 years than for cropland and grassland (five years), but did not significantly change from 15 to 30 years. Soil temperature and litter were the main factors affecting soil respiration along the restoration chronosequence. The contribution of litter to soil respiration after 15 years restoration was about 12%. The temperature sensitivity of the soil respiration ranged from 1.30 in the wheat land to 2.44 in the 30 years restoration grassland with litter left, and it increased with litter removed in the grasslands. Our findings suggest that grasslands after 15-year natural restoration must be utilized properly to balance changes in soil respiration with the soil organic carbon accumulation during the cropland to grassland restoration process.

Keywords: Arid/semiarid climate; Carbon cycle; Grassland recovery; Land use change; Litter

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1 Introduction

Soil respiration is one of the largest fluxes in the global carbon (C) cycle and will act as an important determinant in the global ecosystem carbon budget in the future [1]. It was estimated that the soil respiration rate (R_S) would increase by 0.1 $Pg\,C\,y^{-1}$ from 1989 globally. Soil respiration accounted for 98 ± 12 Pg C of the carbon budget in 2008 [2], and soil respiration contribution was about ten times higher compared with fossil fuel burning and cement manufacturing combined [3]. Land use and management changes have been widely recognized as key drivers of global C cycling, and small changes in R_S over large areas could have an impact on annual increases in the conjunction of atmospheric carbon dioxide (CO_2) [4–6]. The magnitude of daily soil CO_2 flux under different land use types can be used to determine the potential of grasslands to sequester carbon [7]. Since the CO_2 flux is affected by diel cycles, it is important to measure it continuously throughout a 24-h period in order to get more accurate estimates. This emphasizes the importance of using automated R_S measurements to avoid bias since manual measurements are typically only made during daytime [1].

The Loess Plateau in China is characterized by an arid to semiarid climate and is subjected to severe soil erosion. Aimed to control erosion, the Chinese government implemented an integrated soil erosion control project in 1981 and the Grain for Green Program (GTGP) in 1999 by increasing vegetative cover and changing land use types [8]. The GTGP had converted almost 0.09 million km^2 of cropland into forest or grassland and had afforested 0.12 million km^2 of barren land by the end of 2006 [8]. Soil organic carbon in semi-arid areas, characterized as fragile ecological systems, can vary greatly with the land use change and increased at a rate of 0.712 $Tg\,C\,y^{-1}$ across the Loess Plateau under the GTGP project [9]. In recent years, many studies have investigated soil carbon stocks along a vegetation restoration chronosequence, and actually show that many biotic and abiotic factors control on soil organic carbon (SOC) stocks [10–13]. Understanding soil respiration dynamics is essential to clarify the contribution of vegetation restoration to the C budget.

Soil respiration is governed directly or indirectly by biotic and abiotic factors including soil temperature (T_S), soil volumetric water content (SWC), SOC, vegetation type, aboveground and belowground biomass, photosynthesis, litter, etc. [5, 14, 15]. SWC and T_S are regarded as the dominant abiotic factors of R_S [16]. These two factors interact with each other to affect the productivity and the decomposition rate of soil organic matter [17]. Among the biotic

Correspondence: Dr. G.-L. Wu, State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, P. R. China
E-mail: gaolinwu@gmail.com

Abbreviations: BGB, belowground biomass; **GTGP**, Grain for Green Program; $\boldsymbol{R_S}$, soil respiration rate; **SOC**, soil organic carbon; **SWC**, soil volumetric water content factors, litter and belowground biomass are the main sources of soil organic carbon and provide the substrate for soil microbial activity resulting in heterotrophic respiration [18]. The quantity and quality of substrate have been shown to affect Q_{10}, a factor that indicates the sensitivity of soil respiration to a temperature change interval of 10°C, especially when the substrate supply is limited [19]. Furthermore, photosynthesis has a substantial effect on soil respiration and provides an important immediate C source for soil respiration [14, 18].

Land-use changes inevitably influence the structure and species composition of plant communities that alter the nature of the litter, induce variations in the soil physical properties and cause photosynthesis changes, all of which ultimately affect root respiration, soil respiration, and Q_{10} [18, 20]. Therefore, reassessments of controlling factors of soil respiration are necessary during land use changes occurring along a revegetation chronosequence, such as the cropland to grassland program on the Loess Plateau. In this study, we investigated the effects of environmental factors, root biomass, and litter mass on the R_S in cropland ecosystems (wheat and maize) and grassland ecosystems (five, 15, and 30 years of vegetation succession) on the Loess Plateau. The major objectives of this study were to (i) quantify the differences of R_S and identify the dominant variables driving R_S among the cropland and grassland ecosystems; (ii) calculate diurnal temperature effects on soil respiration and Q_{10} during the growing season; and (iii) conclude a best management practice to keep soil respiration during “cropland to natural grassland restoration project” on the Loess Plateau.

2 Materials and methods

2.1 Study site

The study area was located in the Wangdonggou watershed (107° 41′E, 35°14′N, 1120 m above sea level) at a field station of the National Ecosystem Research Network of China in Changwu County, Shaanxi Province, China. This gully watershed adopted small watershed comprehensive management practices to solve the problems of serious losses of water and soil erosion during rainfall events, frequent drought, and low crop yield in 1984. Afterwards, the crop land changed to natural restoration grassland in the gully. Based on the climate data from 1984 to 2005, the mean annual precipitation is 584 mm, nearly 52% occurs between July and September. The annual mean temperature is 9.1°C. The soil is a Heilu soil, which corresponds to a Calcarid Regosol according to the FAO/UNESCO classification system.

Monitoring of vegetation, soil, and soil respiration along a vegetative chronosequence under similar soil and climate conditions is a basic approach to study soil changes over the natural restoration time. The alternative chronological approach is considered as “retrospective” research, because existing conditions are compared with original conditions and treatments [21]. Since there is no historical record of changes in most soil properties due to grassland restoration during the past 30 years, “space-for-time” substitution has become the main method to study the evolution of ecosystem properties over time. Based on the process of plant succession in the study area, we studied three restoration treatments (R5, R15, R30) that had been enclosed for five, 15, and 30 years, respectively, which allowed natural vegetation restoration. Another site represented the initial conditions planted with crops (wheat and maize). The seeding period and harvest period of the maize were mid-April, and mid-September, respectively, while those of the wheat were mid-September and late June in the study region. Site details are given in Table 1.

We selected three blocks (50 × 50 m) for each treatment and three plots (10 × 10 m) were arranged in each block. Six quadrants (50 × 50 cm) were set to monitor soil respiration, litter, and belowground biomass. The litter (dead plant material) was estimated from harvesting squares (0.25 m^2) in each quadrant, located close to the plots. Three belowground core samples at the depth of 0–50 cm were collected from each quadrant using a cylinder auger of 80 mm in diameter. Belowground biomass (BGB) was separated from the soil by washing over a 0.2-mm mesh and was oven-dried at 80°C for 72 h to weigh dry matter.

2.2 Soil respiration

R_S was measured using a multiplexer (LI-8150, LI-COR, USA) equipped with six portable chambers (Model 8100-104). Measurements were performed in a time period as short as possible in order to keep the conditions inside the chamber as similar to the outside environmental conditions. A soil temperature probe Type E (LI-8150, LI-COR) was used to estimate T_S at 5 cm depth. SWC at 5 cm depth was estimated by a soil water content probe (model EC-5, ECH_2O, Decagon Devices, Pullman, WA, USA). The temperature probe and soil water content probe were installed in soil close to the chambers. Soil temperature, soil water content, and soil respiration were measured at the same times.

R_S at each block was measured on a clear day, 12 times per day at 2-h intervals in June 2012. At each plot, six collars (20.3 cm in diameter and 10 cm in height) were randomly inserted into the soil surface to a depth of 2 cm about two days before the first measurement in order to stabilize soil conditions. Growing plants inside the soil respiration collar were manually removed by cutting their stems close to the soil surface to ensure that measurements represented the real belowground soil CO_2 flux. Litter was removed

Table 1. Description of experimental sites properties

Restoration grassland (year)	Dominant species	Total biomass (g m^{-2})	Litter mass (g m^{-2})	Belowground biomass (g m^{-2})	Soil carbon content (g kg^{-1})
0	Wheat/maize	–	–	1257 ± 32^a	5.6 ± 0.6^b
5	*Agropyron cristatum Artemisia sacrorum*	161 ± 24^b	74 ± 6^b	1697 ± 95^a	5.9 ± 0.2^b
15	*Helictotrichon dahuricum Poa subfastigiata*	379 ± 62^a	103 ± 12^b	1409 ± 252^a	7.4 ± 0.3^a
30	*Poa subfastigiata Vicia amoena f. albiflora*	731 ± 147^a	342 ± 41^a	1763 ± 157^a	7.3 ± 0.5^a

Values of biomass and litter are mean ± SE. Within a column, values followed by different letters denote significant differences between the means at $p < 0.05$ (ANOVA, Tukey HSD post hoc test).

from three of the collars (treatments designated as $R5_R$ or $R15_R$ or $R30_R$ according to the site) but was left in three other collars (corresponding to treatments designated as $R5_L$ or $R15_L$ or $R30_L$). At the cropland plots, three collars were inserted in soil under maize and three under wheat, with the two crops growing in plots adjacent to each other. The wheat was at the end of the growing season and the maize was at the beginning of the growing season in June.

2.3 Statistical analysis

All statistical analyses were performed using SPSS software (version 12.0, SPSS, Chicago, IL). One-way analysis of variance with a post hoc Tukey's HSD test was used to test the significance of differences in R_S, T_S, SWC, and Q_{10} values among the cropland and grassland with different restoration ages. Statistical significance was established at the 5% level, apart from certain exceptions where another level is specifically reported. All results were presented as the mean value ± SE. Stepwise regression analysis was used to determine diel variations in soil respiration and the significant impact of included factors (T_S, SWC, litter mass, BGB) was set at $p < 0.05$.

To evaluate the relationship between daily R_S and T_S, nonlinear regression model analyses were performed using [15]:

$$R_S = \alpha\, e^{\beta Ts} \quad (1)$$

where R_S is mean soil respiration rate (μmol CO_2 m^{-2} s^{-1}), T_S is the soil temperature (°C) and α and β are constants fitted by the least-square technique.

Q_{10} is the temperature sensitivity of respiration and is calculated by the following function [15]:

$$Q_{10} = e^{10\beta} \quad (2)$$

where Q_{10} is the temperature sensitivity of soil respiration, e is the natural function base and β is a constant fitted by the least-square technique in the R_S function.

3 Results

3.1 Diel variation of soil environmental conditions

The diel variation of T_S, measured at 2-h intervals at a depth of 5 cm, changed significantly over time ($F_{11,\ 276} = 55.735$, $p < 0.001$) (Fig. 1). The highest values occurred between 11:00 and 15:00 BST (Beijing standard time), and the lowest values occurred between 03:00 and 05:00 BST. The maximum T_S occurred under maize, while the minimum was measured under grassland restored for 30 years with the litter removed ($R30_R$) (Table 2). SWC measured at 2-h intervals at a depth of 5 cm, exhibited very weak diel variation patterns ($F_{11,\ 276} = 1.424$, $p = 0.162$) (Fig. 2). The highest SWC was under grassland restored for 30 years with the litter removed ($R30_R$), while the lowest SWC was under wheat land (Table 2).

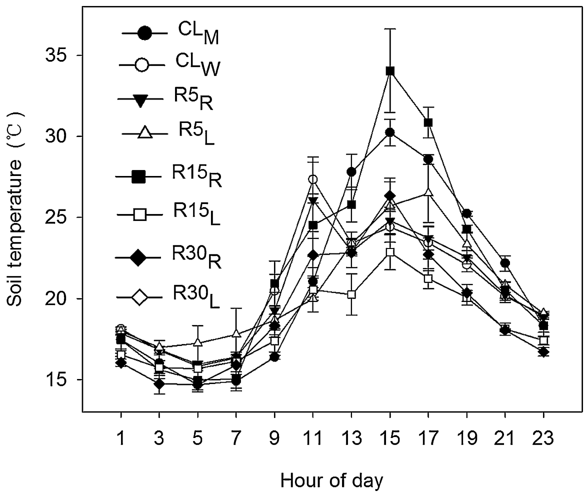

Figure 1. Diel changes in soil temperature at a depth of 5 cm under different treatments: designation for natural grassland restoration sites (R) refers to the number of years of restoration (R5, R15, R30) and litter either removed ($R5_R$, $R15_R$, $R30_R$) or left ($R5_L$, $R15_L$, $R30_L$). Vertical bars indicate the standard error of the measurement mean ($n = 3$) for each time.

3.2 Diel variation and temperature sensitivity of soil respiration

We measured the diel changes of R_S at four sites (under eight treatments) on clear days (Fig. 3). The diel patterns of R_S under the eight treatments were similar to the diel patterns of the soil surface temperature. The peak R_S occurred between 13:00 and 15:00 BST and the lowest occurred between 03:00 and 05:00 BST. There were significant differences in R_S ($F_{7,\ 280} = 24.784$, $p < 0.001$) among the eight treatments. The lowest daily CO_2 flux was measured under maize (1.26 ± 0.06 g CO_2-C m^{-2} day^{-1}), while the highest daily CO_2 flux occurred under $R15_L$ (2.69 ± 0.07 g CO_2-C m^{-2} day^{-1}) (Table 2). Compared with the cropland site, R_S under the grassland sites increased along the natural succession, but no significant difference

Table 2. Mean (SE) values of daily soil respiration rate, soil temperature, and soil water content across sites

Treatment	Soil respiration (g C m^{-2} day^{-1})	Soil temperature (°C)	Soil water content (%)
CL_M	1.26 (0.06)^d	24.41 (1.2)^a	12.64 (0.11)^b
CL_W	1.9 (0.09)^c	21.07 (0.92)^{ab}	10.44 (0.35)^d
$R5_R$	1.98 (0.12)^{bc}	20.61 (0.61)^b	12.74 (0.17)^b
$R5_L$	1.78 (0.09)^c	20.46 (0.6)^b	11.92 (0.13)^{bc}
$R15_R$	2.36 (0.09)^{ab}	20.63 (0.59)^b	11.28 (0.1)^{cd}
$R15_L$	2.69 (0.07)^a	21.87 (1.05)^{ab}	11.34 (0.11)^c
$R30_R$	2.34 (0.12)^{ab}	18.5 (0.42)^b	14.49 (0.21)^a
$R30_L$	2.67 (0.11)^a	19.12 (0.64)^b	13.72 (0.26)^a

CL_M, maize land; CL_W, wheat land; designation for natural grassland restoration sites (R) refers to the number of years of restoration (R5, R15, R30) and litter either removed ($R5_R$, $R15_R$, $R30_R$) or left ($R5_L$, $R15_L$, $R30_L$). Different letters behind the values mean the significant difference between the treatments at $p < 0.05$ (ANOVA, Tukey HSD post hoc test).

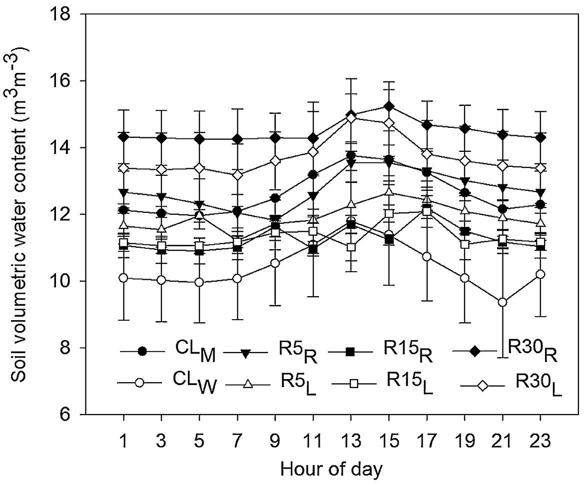

Figure 2. Diel changes in the volumetric soil water content (at a depth of 5 cm) under different treatments: designation for natural grassland restoration sites (R) refers to the number of years of restoration (R5, R15, R30) and litter either removed ($R5_R$, $R15_R$, $R30_R$) or left ($R5_L$, $R15_L$, $R30_L$). Vertical bars indicate the standard error of the measurement mean ($n = 3$) for each time.

could be observed between the 15 and 30 year sites. There were no significant differences in R_S between the litter treatments at any of the grassland sites. However, R_S values under $R15_L$ and $R30_L$ were larger than under $R15_R$ and $R30_R$, respectively. The contribution of the litter to soil respiration at the 15 and 30 years sites would then be considered to be about 12%.

R_S was significantly correlated with T_S (Table 3, Fig. 4). Q_{10} was higher under grassland than under cropland, except for $R15_L$ (Table 3). The diel Q_{10} values of sites with litter were lower than sites without litter for five, 15, or 30 years of revegetation.

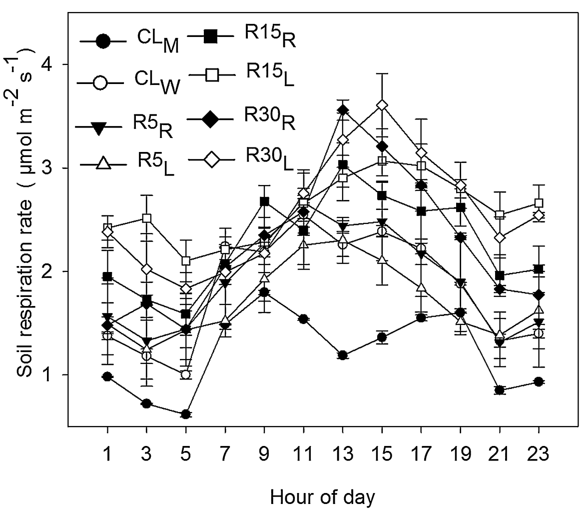

Figure 3. The diel changes in soil respiration rate under different treatments: designation for natural grassland restoration sites (R) refers to the number of years of restoration (R5, R15, R30) and litter either removed ($R5_R$, $R15_R$, $R30_R$) or left ($R5_L$, $R15_L$, $R30_L$). Vertical bars indicate the standard error of the measurement mean ($n = 3$) for each time.

Table 3. Parameters of the exponential relationship between soil respiration rate ($\mu mol\, m^{-2} s^{-1}$) (R_S) and soil temperature (°C) (T_S) (Eq. (1)), $N = 36$

Treatment	α	β	R^2	F	p	Q_{10}
CL_M	0.95	0.0124	0.05	1.84	0.1839	–
CL_W	1.05	0.026	0.26	11.92	0.0015	1.30
$R5_R$	0.66	0.0527	0.27	12.59	0.0012	1.69
$R5_L$	0.7	0.0436	0.30	14.36	0.0006	1.55
$R15_R$	1.15	0.0329	0.29	13.79	0.0007	1.39
$R15_L$	1.86	0.015	0.39	21.57	< 0.0001	1.16
$R30_R$	0.45	0.0894	0.39	21.63	< 0.0001	2.44
$R30_L$	1	0.0492	0.58	45.79	< 0.0001	1.64

CL_M, maize land; CL_W, wheat land; designation for natural grassland restoration sites (R) refers to the number of years of restoration (R5, R15, R30) and litter either removed ($R5_R$, $R15_R$, $R30_R$) or left ($R5_L$, $R15_L$, $R30_L$).

3.3 Biotic and abiotic factors controlling the CO_2 flux

Stepwise regression retained T_S and litter mass in the models that accounted for the R_S variation. T_S was the first factor chosen in the model, which explained 21.5% of the soil respiration variation ($p < 0.001$). R_S was better predicted by T_S and litter mass, which

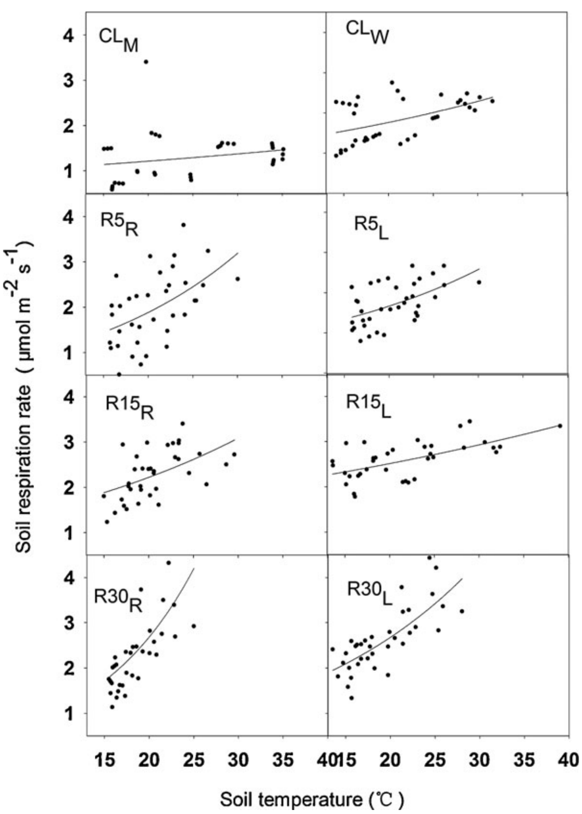

Figure 4. Measured diel soil respiration rate as a function of soil temperature (symbols), with the solid line representing the fitted model from which Q_{10} was calculated, under different treatments: designation for natural grassland restoration sites (R) refers to the number of years of restoration (R5, R15, R30) and litter either removed ($R5_R$, $R15_R$, $R30_R$) or left ($R5_L$, $R15_L$, $R30_L$).

explained 42.4% of the variation ($p < 0.001$). Therefore, T_S and the litter mass were the main factors determining R_S along the restoration succession.

4 Discussion

4.1 Soil respiration changes with the restoration years

R_S under cropland was significantly lower than under grassland after a restoration period of 15 or 30 years, but was not significantly different under grassland restoration after only five years (Table 2). Frank et al. [22] found that soil CO_2 efflux averaged 2.8 g CO_2-C m^{-2} day^{-1} under grassland compared to 1.6 g CO_2-C m^{-2} day^{-1} under continuous wheat treatments, because the grassland had a significantly greater root biomass and return of plant biomass. R_S in a wheat field was markedly lower than in a steppe plot, which was due to notable lower soil carbon storage, mineralization rate of SOC root systems and microbial population that released restricted CO_2 through decomposition [23, 24]. The topsoil organic carbon content ranged from 5.6 g kg^{-1} in cropland to 7.3 g kg^{-1} in R30 in the study region (Table 1). Thus, the conversion of crop fields to grassland would significantly increase CO_2 fluxes from the soil to the atmosphere due to the increments of root biomass and SOC.

Daily soil CO_2-C effluxes (1.78–2.70 g m^{-2} day^{-1}) under different grasslands in our study were in the range of equivalent annual R_S reported for several global studies [2]. The daily R_S for $R15_L$ was significantly higher than for $R5_L$, but without a significant difference with $R30_L$ (Table 2). R_S increased in the old-field grassland by providing more C substrate for respiratory processes of plant roots and soil microbes [16, 18]. However, Burke et al. [25] suggested that a sufficient time period is needed in order for full recovery of the active soil organic matter and nutrient availability, after that R_S increment would be restricted. R_S could not increase continuously with time since restoration started, but rather attains a higher rate which is in balance with the restrictions of the newly created ecosystem. Our study revealed that the best grassland management practice is to utilize natural grasslands after 15 years to balance soil respiration with carbon accumulation on the Loess Plateau.

4.2 Litter mass and soil temperature control the soil respiration

Decomposition of aboveground litter was the main factor influencing total respiration. Removed litter could reduce the mean rate of CO_2 evolution by approximately 12% at the sites R15 and R30 (Table 2). The litter contribution of R_S in the results was $< 37\%$ in the Peruvian Andes, where the mean annual temperature was about 3°C compared to this site [26]. T_S also plays a predominant role for R_S in time and space. A higher temperature can directly stimulate the activity and respiration of roots and microbes, and indirectly impact R_S via changes in plant growth, photosynthesis, belowground C allocation, and substrate availability [5, 14, 27]. Different components of R_S respond differently to these factors, while heterotrophic respiration is driven mainly by T_S and SWC. Root respiration may be more closely linked to carbon flow within plant-soil interactions, plant productivity, diversity of the soil [10, 28, 29]. The soil nutrient concentration in the produced biomass decreased with diversity, which could counteract the production-induced increase in soil respiration [29]. Decomposition is primarily driven by microbial activity, which can be best predicted by environmental factors such as temperature and litter quality. R_S was linearly correlated not only with mean temperature but also with litter mass under the restored grassland of three different ages [30]. However, the partition of the relative contributions of other factors, such as photosynthesis, bulk density, soil C content to R_S need to be studied in future.

4.3 Litter enhances temperature sensitivity of soil respiration

The temperature sensitivity of R_S changed with land use, micro-environment and ecosystem type [31, 32]. Q_{10} values of grassland ranged from 1.16 to 2.44 in the study, which were similar to that measured by Peng et al. [32] in other grassland ecosystems in China. Fierer et al. [33] suggested that substrate C quality has significant and predictable effects on the temperature sensitivity of microbial decomposition, and here the SOCs were higher in R15 and R30 grasslands than in the R5 grassland. Xiao et al. [19] found that Q_{10} was positive correlated with SWC and negative correlated with T_S in the temperate grassland ecosystems of northern China. Litter removal may cause changes in the local T_S and SWC, which consequently increased Q_{10} in the study (Tables 2 and 3). In future research, we should further examine the effects of quantity and quality of litter on Q_{10}.

5 Conclusions

We studied diel variations in soil respiration along a natural grassland restoration program that began with maize and wheat crops and progressed through restoration grassland at five, 15, and 30 years. Soil respiration varied significantly between cropland and grassland, with different R_S for the three ages. R_S increment would be restricted when the soil organic carbon stood stable after 15 years of natural restoration. The surface soil temperature and litter mass were the main influencing factors that control the diel variation of R_S. We suggest that grasslands after about 15-year natural restoration should be utilized properly to balance soil respiration with carbon accumulation on the Loess Plateau. Distinguishing the factors, such as photosynthesis, bulk density, soil C content that contributed to variations of soil respiration and the temperature sensitivity of soil respiration should be considered in future research.

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