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Effects of rodent-induced land degradation on ecosytem carbon fluxes in alpine meadow in the Qinghai–Tibet Plateau, China

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Abstract

Land degradation induced by rodent activities is extensively occurred in alpine meadow ecosystem in the Qinghai–Tibet Plateau that would affect the ecosystem carbon (C) balance. We conducted a field experiment with six levels of land degradation (D1–D6, degradation aggravates from D1 to D6) to investigate the effects of land degradation on ecosystem C fluxes. Soil respiration (Rs), net ecosystem exchange (NEE), ecosystem respiration (ER) and gross ecosystem production (GEP) were measured from June to September 2012. Soil respiration, ER, GEP and above-ground biomass (AGB) was significantly higher in slightly degraded (D3 and D6) than in severely degraded land (D1, D2, D4 and D5). Positive averages of NEE in the growing season indicate that alpine meadow ecosystem is a weak C sink during the growing season. Net ecosystem exchange had no significant difference among different degraded levels, but the average NEE in slightly degraded group was 33.6 % higher than in severely degraded group. Soil respiration, ER and NEE were positively correlated with AGB whereas soil organic C, labile soil C, total nitrogen (N) and inorganic nitrogen were associated with root biomass (RB). Our results highlight the decline of vegetation C storage of alpine meadow ecosystem with increasing number of rodent holes and suggest the control of AGB on ecosystem C fluxes, and the control of RB on soil C and N with development of land degradation.

1 Introduction

Soil contains the largest ecosystem organic carbon (C) pool (1462 Pg C in the top 1.0 m, 1 Pg = 10^{15} g) (Batjes, 1996). Desertification, degradation of soil and vegetation in drylands worldwide have resulted in 19–29 Pg C loss (Lal, 2001). Restoration of the degraded ecosystems, therefore, had a great potential to sequestrate atmosphere C (Lal, 2004). Total potential of C sequestration in drylands is estimated to be 0.9–1.9 Pg C y^{-1} for a 25 to 50 year period (Lal, 2001).

SED
6, 3003–3023, 2014

Carbon storage in grasslands accounts for 15.2 % of the terrestrial C pool, and 89.4 % of the C in grassland is sequestrated in the soil (Ajtay, 1979). The total vegetation and soil C pool in alpine ecosystem in the Qinghai–Tibet Plateau (QTP) is estimated to be 24.03 Pg C, 54.5 % of grassland C storage in China (Ni, 2002). Above-ground C in the alpine grassland in the QTP is estimated to be 1.87 Pg C, accounting for 65.4 % of that in grassland ecosystem in China (Fan et al., 2007). Below-ground C storage in the top 1 m in the alpine grasslands is much higher that the vegetation C pool, which is estimated to be 7.4 Pg (Yang et al., 2008). Due to climate change and human activities (grazing and road constructing), alpine grassland has been severely degraded in the QTP, for example, over one-thirds of the grassland in the QTP has degraded (Ma et al., 1999), and the area of degraded land has increased by 27.3 % from 1980s to 2000 in a county (Xue et al., 2009). The degradation of vegetation in the alpine ecosystem in QTP has led to 1.8 Gg C loss from 1986 to 2000 due to land cover change resulted from warming and grazing (Wang et al., 2008a). In addition to the vegetation C loss, land degradation could also result in reduction in soil C and nitrogen (N) concentration, (Wang et al., 2008b) and soil organic C pool (Wen et al., 2013), and consequently might convert the alpine meadow ecosystem from C sink to C source (Li et al., 2012).

The "black soil type" degradation„ the secondary bare soil in alpine meadow in cold area with elevation higher than 3700 m and mainly resulted from rodent grazing and burrowing is widely distributed over the QTP (Ma et al., 1999). Rodent grazing activity declines quantity of biomass, and their burrowing activity changes below-ground biomass distribution, soil structure, microclimate, soil erosion, nutrient loss and imbalance of nutrient cycling (Li et al., 2011). Those changing processes finally could affect the C balance.

Current studies concerning ecosystem C balance in alpine meadow ecosystem focus on net carbon exchange (NEE) (Kato et al., 2004), inter-annual variation in NEE (Kato et al., 2006), soil respiration (Rs) and ecosystem respiration (ER) responses to experimental warming (Luo et al., 2010; Lin et al., 2011). Effects of land degradation

SED
6, 3003–3023, 2014

resulted from rodents on ecosystem C fluxes are rarely investigated. To our knowledge, there were two studies examining the responses of Rs to land degradation (Wang et al., 2007b; Zhang et al., 2010). However, Rs only cannot provide solid evidence to determine the ecosystem C balance. Till present, no field experiment has been conducted in the permafrost region of the QTP to investigate the effect of land degradation NEE, which provides a direct measure of the ecosystem C balance, and of its components: ER and gross ecosystem production (GEP). We conducted a field study to investigate (1) how the NEE and its components respond to rodent-induced land degradation, and (2) the controlling factors for change in those C fluxes with degradation in *Kobresia* dominated alpine meadow in a permafrost area of the QTP.

2 Materials and methods

2.1 Site description

The study site is situated in the region of the Yangtze River source, inland of the QTP near the Beilu River research station (34°49′ N, 92°56′ E,) at an altitude of 4635 m. This area has a typical alpine climate: mean annual temperature is −3.8 °C and monthly air temperature ranges from −27.9 °C in January to 19.2 °C in July. Mean annual precipitation is 290.9 mm, of which over 95 % falls during the warm growing season (May–October). Mean annual potential evaporation is 1316.9 mm, mean annual relative humidity is 57 %, and mean annual wind velocity is 4.1 m s^{-1} (Lu et al., 2006). The study site is a winter-grazed range, dominated by alpine meadow vegetation: *Kobresia capillifolia*, *K. pygmaea*, and *Carex moorcroftii*, with a mean plant height of 5 cm. Plant roots occur mainly within the 0–20 cm soil layer, and average soil organic C is 1.5 %. The soil development is weak, and the soil belongs to alpine meadow soil (Chinese soil taxonomy), or is classified as a Cryosol according to World Reference Base, with a Mattic Epipedon at a depth of approximately 0–10 cm, and an organic-rich layer at a depth of 20–30 cm (Wang et al., 2007a). The parent soil material is of fluvio-glacial origin and is

SED
6, 3003–3023, 2014

composed of 99 % sand. The Mattic Epipedon lowers the saturated soil water content, but increases soil water storage, and plant roots are dense and compressed within this layer. Permafrost thickness observed near the experimental site is 60–200 m and the depth of the active layer is 2.0–3.2 m (Lu et al., 2006; Pang et al., 2009). However, because of climatic warming, the thickness of the active layer has been increasing at a rate of 3.1 cm y^{-1} since 1995 (Wu and Liu, 2004).

2.2 Experimental design and measurement protocol

2.2.1 Experimental design

Twelve plots (4 m × 4 m) covering six levels of rodent-induced land degradation (D1–D6) according the number of rodents holes (NRHs), coverage, plan height and major species (Table 1) were set up in 2012. There were two plots in each degradation level and each plot was divided into two 4 m × 2 m subplots for measurements of Rs, NEE and ER.

2.2.2 Measurement protocol

Soil temperature: soil temperature at the depth of 5 cm was monitored by a thermo-probe attached to Li-cor 6400 (Li-Cor, Inc., Lincoln, NE, USA.) when measurements of Rs, NEE and ER were conducted.

C fluxes: soil respiration was measured using 5 cm tall PVC collars, which were permanently inserted 2–3 cm into the soil in the center of each plot. Small living plants were cut at the soil surface at least one day before measurements to eliminate the effect of respiration from aboveground biomass (Zhou et al., 2007). Ecosystem respiration and NEE were measured with a transparent chamber (0.5 m × 0.5 m × 0.5 m) attached to an infrared gas analyzer (IRGA, Li-6400, Lincoln, NE, USA). During measurements, a foam gasket was placed the chamber and the soil surface to minimize leaks. One small fan ran continuously to mix the air inside the chamber during measurements. Nine

SED
6, 3003–3023, 2014

consecutive recordings of CO_2 concentration were taken in each plot at 10 s intervals during a 90 s period. Following the measurement of NEE, the chamber was vented for several minutes and covered with an opaque cloth for measuring ER, as the opaque cloth eliminated light (and hence photosynthesis). CO_2 flux rates were determined from the time-course of the CO_2 concentrations used to calculate NEE and ER. The method used was similar to that reported by (Steduto et al., 2002) and (Niu et al., 2008). GEP was the calculated as the difference between NEE and ER. Rs, NEE and ER were measured in each subplot form June to September once a month.

Soil sampling: one soil sample was collected in each subpolot at the soil depth of 0–30 cm in June 2012.

Above-ground biomass calculation and root biomass: above-ground biomass (AGB) was obtained from a step-wise linear regression with AGB as the dependent variable, and coverage and plant height as independent variables. 100 small plots (30 cm × 30 cm) were included in the regression analysis (AGB = 22.76 · plant height + 308.26 · coverage – 121.80, $R^2 = 0.74$, $p < 0.01$). Coverage of each plot was measured using a 10 cm × 10 cm frame in four diagonally divided subplots replicated eight times in each degraded level in June 2012. Plant height was measured 40 times by a ruler and averaged for each plot. Root biomass (RB) was obtained from soil samples that were air-dried for one week and passed through a 2 mm diameter sieve to remove large particles. Roots were separated from the soil by washing, and a 0.25 mm diameter sieve was used to retrieve fine roots. Living roots were separated from dead roots by their color and consistency (Yang et al., 2007). Separated roots were dried at 75 °C for 48 h.

Chemical analysis: soil organic C was analyzed using the Walkley–Black method (Walkley, 1947). Total nitrogen was measured via the Kjeldahl method. NO_3^--N and NH_4^+-N was measured colorimetrically through a spectrometer. Labile soil carbon (LC) measurement was carried out by the procedure advocated by (Blair et al., 1995).

SED
6, 3003–3023, 2014

2.3 Data analysis

One way-ANOVA was used to examine effects of land degradation Rs, NEE, ER and GEP. Monthly data measured in each subplots from June to September were used in the analysis. Carbon fluxes data in D3 and D6 were ranked as group I and data in D1, D2, D4 and D5 were group II. In the one way-ANOVA analysis, C fluxes were the dependent variable and the group was the fixed variable. The monthly differences in C fluxes were analyzed by repeated ANOVA. Linear regression analyses were used to examine the relationships of Rs, NEE and ER with soil temperature, above-ground and root biomass, and soil nitrogen content. Pearson correlation analyses were used to investigate the relationships of NRHs with soil chemical properties and biomass. The linear regression and Pearson correlation were considered significant with $P < 0.05$. Soil respiration, NEE and ER data were the averages of four months in each degrade level when conducting the correlation analyses. All the analyses were conducted in SPSS 16.0 for windows. The differences of soil properties and biomass among different degradation levels were analyzed by one-way ANOVA with Tukey post-hoc.

3 Results

3.1 Soil temperature

Soil temperature at the depth of 5 cm maximized in July and monthly average soil temperature had no significant change ($P > 0.05$) among different degradation levels (Fig. 1). The average soil temperature was 10.02±1.70, 9.64±2.81, 12.33±4.02, 11.0± 2.78, 12.40 ± 3.95 °C from D1 to D6. Soil temperature also had no significant difference between group I (D3 and D6) and II (D1, D2, D4, D5).

SED
6, 3003–3023, 2014

3.2 Soil chemical properties and biomass

Soil organic carbon, LC, TN, $NH4^+$-nitrogen and RB were highest in D2 than in other degradation levels (Table 2). Above-ground biomass was higher in D3 and D6 than in others. Soil organic carbon, LC, TN, and inorganic nitrogen ($NH4^+$-N and $NO3^-$-N) had no obvious trend with the increasing NRHs, whereas AGB ($r = -0.89$, $P < 0.05$) and root biomass ($r = -0.36$, $P > 0.05$) negatively correlated with the NRHs.

3.3 Soil respiration, net ecosystem exchange and gross ecosystem production

Repeated ANOVA showed the significant seasonal change in Rs ($P < 0.01$), ER ($P < 0.05$), NEE ($P < 0.01$) and GEP ($P < 0.01$). The maximum Rs and ER were in July (Fig. 2a and b), whereas the maximum NEE and GEP were in June in all degraded levels (Fig. 2c and d). The average Rs and NEE in the growing season had no significant difference among different degradation levels, ER and GEP were marginally higher in D3 and D6 than in other degradation levels (Table 3). When the six degradation levels were divided into two groups (D3 and D6 as group I, and others as group II), Rs, ER and GEP were higher in group I than in group II ($P < 0.05$). Net ecosystem exchange had no significant difference between the two groups (Table 3), but average NEE was higher in group I (2.13 $\mu mol\, m^{-2}\, s^{-1}$) than in group II (1.09 $\mu mol\, m^{-2}\, s^{-1}$).

3.4 Relationship of Rs, ER, NEE and GEP with abiotic and biotic factors

Soil temperature only positively correlated with Rs (Fig. 3a). Inorganic nitrogen had no significant relationship with C fluxes (Fig. 3b). Above-ground biomass positively correlated with all the C fluxes (Rs, ER and NEE) with steepest regression slope in Rs, followed by ER and NEE (Fig, 3c). Root biomass only positively correlated with ER (Fig. 3d).

SED
6, 3003–3023, 2014

4 Discussion

4.1 Effect of land degradation on soil properties

Desertification would cause the decline in SOC and total nitrogen (TN) density, and decline in the C and N storages in either temperate grassland (Li et al., 2014) or in alpine meadow ecosystem (Zhang et al., 2013). Lower SOC, LC and TN in D1, D4, D5, and D6 (Table 1) support the above findings. However, SOC, LC, TN and inorganic N was higher in D2 than in other degraded levels (Table 2), although there were more number of rodents holes in D2. Soil loses C and N during the desertification process by (1) reducing vegetative growth and exposing the soil surface to wind and water erosion, and (2) reducing the return of litter to soil (Huang et al., 2007). The AGB was lower in D2 than in D3 and D6, but the highest root biomass was in D2 (Table 2) would contribute to the highest SOC, LC, TN in D2, which indicates that root biomass is the major origin of soil C and N in the alpine meadow ecosystem. Higher AGB in D3 and D6 could have resulted in more C and N input into soil, but higher Rs and ER in D3 and D6 also could have led to more C output because Rs and ER was positively correlated with AGB (Fig. 3c) therefore results in a lower SOC, LC and TN.

4.2 Effect of land degradation on C fluxes

Soil respiration is found to decrease with intensification of desertification in an alpine meadow ecosystem, and the significant reduction in Rs is only observed in severely degraded level (Zhang et al., 2010). The significant lower Rs in group II than in group I supports the above finding because coverage in D1, D2, D4 and D5 (Table 1) complies to the standard of the severely degraded land for alpine meadow ecosystem (Xue et al., 2009). Soil temperature explains most of the variation in Rs although Rs estimates can be improved by including both soil temperature and soil moisture (Euskirchen et al., 2003). The positive relationship between Rs and soil temperate (Fig. 3a) could not be the reason for higher Rs in D3 and D6 (Fig. 2) because soil temperature had no

SED
6, 3003–3023, 2014

significant difference among different land degradation levels (Fig. 1). Soil respiration is composed of two sources: autotrophic respiration from plant roots and their symbionts, and heterotrophic respiration from litter and SOC decomposition (Hanson et al., 2000). Above- and below-ground biomass of alpine meadow all decreased with development of degradation (Sun and Wang, 2008), and SOC was also lower in degraded alpine meadow comparing with the intact meadow ecosystem due to the declined litter input from less above-ground biomass into soil and lower plant detritus in soil (Wang et al., 2009; Wen et al., 2013). Root biomass, SOC and LC was even smaller in D3 and D6 than in D1 and D2 (Table 2), therefore the higher Rs could have been resulted from the higher above-ground biomass in D3 and D6 (Table 2) because of the positive correlation relationship of Rs with above-ground biomass (Fig. 3c). This indicates that decomposition of C allocated in root zone from above-ground biomass is the major source of Rs in alpine meadow ecosystem. This is similar to the result in a tall-grass prairie (Wan and Luo, 2003).

Ecosystem respiration was higher in group I than in group II. Ecosystem respiration is composed of above-ground biomass respiration and Rs (Zhang et al., 2009). The higher Rs could be one reason for the higher ER in D3 and D6. Relative difference of Rs (38.2 %) between the two groups was lower than that in ER (44.5 %), which suggests above-ground biomass could also contribute to the ER difference among different groups. The positive correlation relationship between ER and above-ground biomass (Fig. 3c) support our finding.

The maximum GEP in June (Fig. 2d) in the current is supported by the results that net photosynthesis is the highest in June for the alpine meadow ecosystem (Yi et al., 2000). Effect of land degradation on GEP was similar to that on ER. Although, sedge percentage in the species composition will decrease and forbs percentage will increase with the development of land degradation (Liu et al., 2008), and the net photosynthetic rate of forbs species (*Polygonum viviparum Linn.*) is almost two times of sedge species (*Carex atrofusca Schkuhr*, our unpublished data). The higher above-ground biomass might compensate for the effect of species composition change on GEP be-

SED
6, 3003–3023, 2014

cause above-ground biomass was positively correlated with GEP (Fig. 3c) in the current study.

The maximum NEE in June is resulted from (1) highest GEP in June and (2) lower ER due to lower soil temperature at this time (Fig. 1). Positive average NEE indicates alpine meadow is weak C sink in the growing season, and lower NEE in group II suggests the decline the C capacity of alpine meadow ecosystem due to land degradation. The non-significant difference of NEE in the two groups is resulted from the parallel change of ER (44.5 % higher in group I than in group II) and GEP (46.5 % higher in group I than in group II).

4.3 Implication of the soil C dynamics to land degradation

The non-significant difference in NEE among different degradation levels suggest that the soil organic C loss (in D1, D4 and D5) with development of desertification is not directly resulted from the changes in net C uptake and emission. The higher SOC, LC, TN in D2 with more NRHs and the positive correlation relationship between root biomass and soil C suggests that other dynamics associated with land degradation, like species composition and above- and below-ground biomass allocation change might involve in the soil C dynamic in degraded land in alpine meadow ecosystem.

5 Conclusions

With the development of land degradation with different number of rodent holes in the alpine meadow, Rs, ER and GEP is higher in slightly degraded than in severely degraded land. The higher above-ground biomass is the reason for the higher ecosystem C fluxes in slightly degraded land Alpine meadow ecosystem is a weak C sink in the growing season. No significant effect of land degradation on the net ecosystem C balance is resulted from the parallel responses of ER and GEP to degradation. Soil C change in degraded land is not directly resulted from changes in net ecosystem C bal-

SED
6, 3003–3023, 2014

ance but from other processes like species composition and above- and belowground biomass allocation.

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SED
6, 3003–3023, 2014

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SED
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SED
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SED
6, 3003–3023, 2014

Table 1. Features of different degradation levels. DD is the degradation levels which is represented by different number of rodents holes (NRHs, deep and shallow), coverage, plant hight (H) and major plant species.

DD	NRHs (deep)	NRHs (shallow)	Coverage	H (cm)	Major species
D1	19	7	0.18	9.5	*Carex Moorcroftii*
D2	5	13	0.35	7	*Kobresia Humilis, Kobresia Pygmaea*
D3	0	3	0.8	6.5	*Kobresia Pygmaea*
D4	12	15	0.42	8	*Carex Moorcroftii, Kobresia Pygmaea*
D5	17	13	0.3	7.5	*Carex Moorcroftii, Kobresia Pygmaea*
D6	2	0	0.6	12	*Carex Moorcroftii*

SED
6, 3003–3023, 2014

Table 2. Land degradation level (DD), Soil organic carbon (SOC), labile soil carbon (LC), total nitrogen (TN), inorganic nitrogen ($NH4^+$-N and $NO3^-$-N), above-ground biomass (AGB) and root biomass (RB) in different levels of land degradation (D1–D6).

DD	SOC ($g\,kg^{-1}$)	LC ($g\,kg^{-1}$)	TN ($mg\,kg^{-1}$)	$NH4^+_N$ ($mg\,kg^{-1}$)	$NO3^-_N$ ($mg\,kg^{-1}$)	AGB ($g\,m^{-2}$)	RB ($kg\,m^{-2}$)
D1	4.91 ± 0.13 b	1.21 ± 0.13 b	0.44 ± 0.02 b	8.21 ± 0.32 b	4.16 ± 0.62 a	149	3.8 ± 0.06 c
D2	8.70 ± 1.19 a	2.12 ± 0.31 a	0.75 ± 0.10 a	13.11 ± 1.23 a	3.81 ± 0.51 ab	145	13.8 ± 3.5 a
D3	5.02 ± 1.01 b	1.23 ± 0.29 b	0.46 ± 0.11 ab	8.54 ± 1.00 b	2.31 ± 0.38 bc	272	11.3 ± 1.3 a
D4	3.95 ± 0.62 b	1.28 ± 0.34 b	0.36 ± 0.05 ab	7.56 ± 1.39 b	2.62 ± 0.24 bc	189	6.0 ± 1.5 b
D5	3.77 ± 0.32 b	0.9 ± 0.09 b	0.38 ± 0.03 b	9.38 ± 1.33 b	1.98 ± 0.21 c	141	6.1 ± 0.9 b
D6	3.41 ± 0.35 b	0.83 ± 0.04 b	0.34 ± 0.02 b	8.08 ± 0.76 b	2.64 ± 0.10 bc	336	5.7 ± 0.3 b

Different letters in each column stands for significant difference of at $P < 0.05$ level.

SED
6, 3003–3023, 2014

Table 3. Results (F values) of ANOVA on the effect of land degradation on soil respiration (Rs), ER (ecosystem respiration), NEE (net ecosystem exchange) and GEP (gross ecosystem respiration).

	D1–D6				Group I and group II			
	Rs	ER	NEE	GEP	Rs	ER	NEE	GEP
F	1.69	2.64	1.35	2.27	7.41	8.21	1.59	6.01
P	0.12	**0.04**	0.26	0.06	**0.01**	0.06	0.21	0.02

Group I includes D3 and D6 while group II includes D1, D2, D4, and D5.
Numbers in bold stands for the statistical significance at $P < 0.05$ level.

SED
6, 3003–3023, 2014

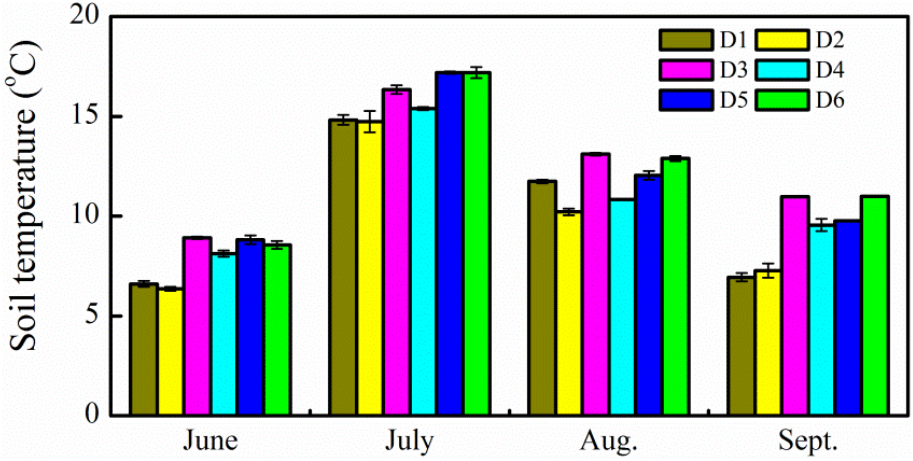


Figure 1. Soil temperature among different degradation levels (D1–D6) from June to September.

SED
6, 3003–3023, 2014

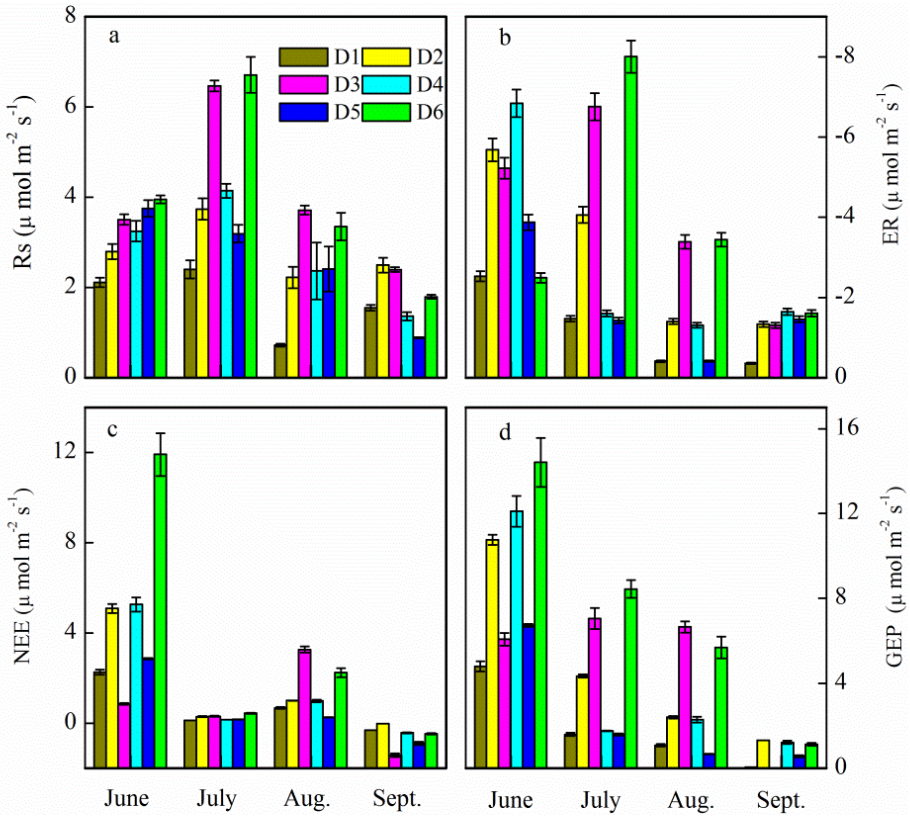
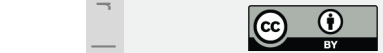


Figure 2. Monthly soil respiration (Rs), ecosystem respiration (ER), net ecosystem exchange (NEE) and gross ecosystem production (GEP) among different degradation levels from June to September. Values in the bars were the average of four replicates (two replicates in two subplots).

SED
6, 3003–3023, 2014



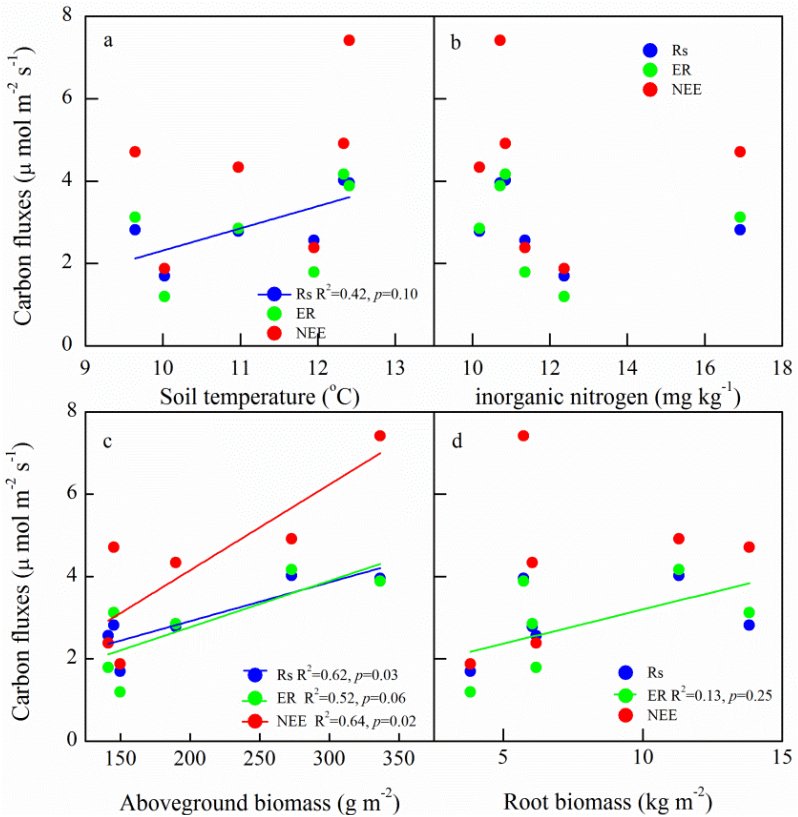


Figure 3. Linear regressions of carbon fluxes (soil respiration [Rs], ecosystem respiration [ER], net ecosystem exchange [NEE]) with soil temperature **(a)**, inorganic nitrogen **(b)**, aboveground biomass **(c)** and root biomass **(d)**. Rs, ER and NEE data were the average of four measurements from June to September within two subplots; SOC, inorganic nitrogen and root biomass (0–30 cm) was derived from soil samples at the 0–30 cm depth in June.

SED
6, 3003–3023, 2014