Ecological Engineering 74 (2015) 196–205

Contents lists available at ScienceDirect

Ecological Engineering

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

Responses of soil respiration to land use conversions in degraded ecosystem of the semi-arid Loess Plateau

Yanjun Zhang [a], Shengli Guo [a,b,c,*], Qingfang Liu [c], Jishao Jiang [b], Rui Wang [c], Nana Li [a]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China
[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resource, Yangling 712100, China
[c] College of Resources and Environment, Northwest A&F University, Yangling 712100, China

ARTICLE INFO

Article history:
Received 4 April 2014
Received in revised form 21 September 2014
Accepted 1 October 2014
Available online 29 October 2014

Keywords:
Soil respiration
Soil organic carbon
Fine root biomass
Revegetation
Temperature sensitivity

ABSTRACT

A better understanding of the response of soil respiration to land-use conversion has important practical implications for ecological restoration in degraded regions. In this study, *in situ* soil respiration was monitored in a typical land-use sequence on a ridge slope in Wangdonggou watershed of the Loess Plateau, China, during a three-year period from 2011 to 2013. The land-use conversion sequences included cropland (control), apple orchard, grassland, and woodland. The results clearly showed that soil respiration and temperature sensitivity (Q_{10}) varied significantly with land-use conversion. Soil respiration was decreased by 10% after conversion of cropland to orchard, and increased by 7–46% after conversion of cropland to grassland and woodland. Q_{10} was increased by 19% after conversion of cropland to woodland, and decreased by 9–26% after conversion of cropland to grassland and orchard. Soil respiration increased linearly with soil organic carbon (SOC) storage and fine root biomass (<2 mm). The results indicated that root biomass and SOC storage were the major factors influencing Q_{10} after conversion of cropland to non-natural ecosystem, and substrate quality or root system adaptability may be the real reason for the difference in Q_{10} after conversion of cropland to natural grassland ecosystem. Although soil temperature and moisture significantly influenced soil respiration among the four typical land-use types, their difference derived from land-use conversions could not well explain the difference in soil respiration among land-use conversions. In conclusion, the increases in SOC storage and fine root biomass were the major factors influencing soil respiration among land-use conversions. Thus, conversion of cropland to natural grassland seemed to be the most effective integrated small watershed management to increase soil carbon storage and decrease CO_2 concentration in the loess regions of China.

1. Introduction

Soil respiration is an important component of global carbon cycle, and a small variation of soil respiration can prominently influence atmospheric CO_2 concentration and soil organic carbon (SOC) storage. Land area globally affected by soil erosion is 1643 million ha, and erosion-induced CO_2 emission is 0.8–1.2 PgC year^{-1} (Lal, 2003). Land-use conversion plays an important role in soil erosion, SOC and soil respiration in the erosion-degraded areas (Lal, 2001; Rey et al., 2011; Shi et al., 2014). The vegetation changes resulting from land-use conversions could directly affect soil physicochemical and microbiological properties, and impact the ability of soil respiration (Frank et al., 2006; Iqbal et al., 2008, 2010; Raich and Tufekcioglu, 2000; Sheng et al., 2010; Zhang et al., 2013a) and SOC content (Chang et al., 2011; Deng et al., 2013). In recent years, considerable effort has been made to understand the influence of the conversion of native forest to cropland or grassland in tropical and subtropical regions (Adolfo Campos, 2006; Fernandes et al., 2002; Sheng et al., 2010) and in temperate regions (Arevalo et al., 2010). Some other studies have also investigated the influence of the conversion between woodland and grassland in temperate regions (Smith and Johnson, 2004; Wang et al., 2013). However, to our knowledge, few studies have focused on the conversion of cropland to woodland or grassland in degraded ecosystems (Rey et al., 2011; Shi et al., 2014).

The Loess Plateau is located in the northwest of China and covers a total area of 640,000 km^2. It is particularly susceptible to soil erosion due to the fractured and steep terrain and the continental monsoon climate, and this is further aggravated by intensive agriculture, such as hill slope cultivation. To address this problem, an integrated management of small watershed has been

* Corresponding author at: Institute of Soil and Water Conservation, Xinong Road 26, Yangling, Shaanxi 712100, China. Tel.: +86 29 87012411; fax: +86 29 87012210.
E-mail address: slguo@ms.iswc.ac.cn (S. Guo).

http://dx.doi.org/10.1016/j.ecoleng.2014.10.003
0925-8574/

practiced since 1980s in an attempt to convert cropland to woodland or grassland in the Loess Plateau, leading to a significant improvement in the ecological environment, soil productivity, and household income level (Chang et al., 2011; Deng et al., 2013; Ping et al., 2013; Zheng and Wang, 2013). Therefore, the typical land-use sequence, including cropland, apple orchard, grassland, and woodland with a clear land-use history in this region provides a unique opportunity to study the ecological restoration processes following land-use conversion. Soil respiration varies significantly with land-use conversion (Frank et al., 2006; Iqbal et al., 2008, 2010; Raich and Tufekcioglu, 2000; Sheng et al., 2010; Zhang et al., 2013a). It may decrease (Iqbal et al., 2008; Raich and Tufekcioglu, 2000; Zhang et al., 2013a) or increase with the conversion of cropland to woodland or grassland (Frank et al., 2006; Sheng et al., 2010). Land-use conversions inevitably influence the input of organic matter and soil carbon source (Lee et al., 2013; French et al., 1979). Both SOC content and belowground root production increase significantly during the conversion of degraded cropland to woodland or grassland (Chang et al., 2011; Deng et al., 2013; French et al., 1979; Ping et al., 2013; Zheng and Wang, 2013). It has been shown that the conversion of cropland to perennial vegetation can effectively increase soil carbon capacity in the loess regions (Chang et al., 2011; Deng et al., 2013). Soil respiration increases linearly with the increase of SOC content (Sheng et al., 2010) and belowground root system (Hertel et al., 2009). In addition, soil micro-environment such as soil temperature and moisture also varies with land-use types (Iqbal et al., 2008; Shi et al., 2014; Smith and Johnson, 2004), which is known to be important in controlling soil respiration (Iqbal et al., 2010; Xu and Qi, 2001; Tang et al., 2005). However, there have been no studies investigating the effects of land-use conversions from cropland to woodland or grassland on soil respiration, biotic (root biomass and SOC), and a-biotic factors (soil water and temperature).

In this study, we measured soil respiration, SOC content, fine root biomass and soil microclimate in degraded areas of the semi-arid Loess Plateau from 2011 to 2013, and addressed the following two questions: (1) the responses of soil respiration to land-use conversion; and (2) the correlation of soil respiration with SOC storage and fine root biomass among land-use conversions.

2. Material and methods

2.1. Site description

The study site is located on a typical ridge slope in Wangdonggou watershed (35°13′N, 107°40′E; 1095 m asl), Changwu Country, Shaanxi Province, China. It is situated in the tableland-gully region of the southern Loess Plateau in the middle reaches of the Yellow River in northern China. The tableland is often used for grain production, and the gully is highly prone to soil erosion due to steep terrain and human activities. The soil erosion there is so rampant (soil erosion modulus is higher than 50 t ha^{-1}) that has greatly reduced crop yield and surface water quality and altered regional hydrologic regimes. The study site is characterized by a continental monsoon climate. The annual mean precipitation is 560 mm, 60% of which occurs between July and September; annual mean air temperature is 9.4 °C, and ≥10 °C accumulated temperature is 3029 °C; annual sunshine duration is 2230 h, annual total radiation is 484 kJ cm^{-2}, and frost-free period is 171 days. The meteorological data (mean daily air temperature and daily total precipitation) were provided by the State Key Agro-Ecological Experimental Station established in 1984 in Changwu County.

The soils of interest are derived from wind-deposited loess and belong to loessal soil group according to the soil classification system of FAO-UNESCO. They originate from parent material of calcareous loess, which are relatively uniform and dominated by loam. For soils collected in 2011 at a depth of 0–20 cm, the pH is 8.3, clay content (<0.002 mm) is 24%, field capacity is 22.4%, and permanent wilting point is 9.0%, respectively.

2.2. Experimental design and routine management

The slope tillage was converted to level terrace for more grain production several hundred years ago under the pressure of population growth in this region. However, the land-use patterns there have undergone dramatic changes with the implementation of the integrated management of small watershed since 1980s, and then cropland in level terrace was revegetated. In this study, a typical land-use sequence in level terrace on a typical ridge slope with a slope angle <5° and an elevation of 1039–1043 m was chosen, including maize cropland (control treatment), naturally recovered grassland, apple orchard, and artificially recovered woodland, which were similar in topography, climate and soil type.

Winter wheat was once widely cultivated in this region, but replaced by higher yielding annual spring maize (*Zea mays*) since 1980 due to adequate rainfall and sunshine in its growing season, and the planting area reached 19,000 km^2 with an annual production of 690 million tons. In the cropland of 0.51 ha, maize was planted 0.3 m apart within the row and 0.6 m between rows, and the average annual yield was about 5000 kg ha^{-1}; Apple tree (*Malus pumila* Mill.) was the most widely cultivated cash crop and had great economic and ecological value, and the planting area was increased 20 times in the past 30 years and now was estimated to be over 15 million ha. In the apple orchard of 0.56 ha, perennial apple trees were planted in 1986 spaced 2 m apart within the row and 4 m between rows, now they were 6.8 ± 1.6 m in height (H) and 6.4 ± 2.6 cm in DBH, and the average annual yield was about 4000 kg ha^{-1}; *Bothriochloa ischaemum* (L.) Keng was the dominant indigenous wild grass species in the grassland communities in the Loess Plateau and had high drought-resistance. The grassland with a total area of 0.45 ha was naturally revegetated about 28 years ago, and now was dominated by *B. ischaemum* (L.) Keng and *Artemisia argyi* with an average height (H) of 60 ± 5 cm and canopy area of 90%; Black locust (*Robinia pseudoacacia* L.) had high drought- and barren-resistance, and thus was widely planted in this region to control soil and water loss. The woodland with a total area of 0.68 ha was dominated by black locust (*R. pseudoacacia* L.) planted about 28 years ago and some *Rubus parvifolius* L. and *B. ischaemum* (L.) Keng. The trees were 6.8 ± 1.6 m in height on average, the DBH was 6.4 ± 2.6 cm, the canopy area was 55%, and the density was 1213 stems ha^{-1}, respectively.

Only apple orchard and cropland were regularly managed and fertilized primarily by chemical fertilizers. The amount of N, P and K applied per year was 600, 375 and 200 kg ha^{-1} for apple orchard, and 200, 117, and 37.5 kg ha^{-1} for cropland, respectively. Fertilizers were usually applied twice a year in November and July for apple orchard (trenching fertilization), and in middle April and early June for cropland (broadcasting fertilization), respectively. Both were weeded and hand-hoed twice a year, but no irrigation was performed during the experiment. In cropland, tillage was done twice a year and straw was removed in March of the following year. However, no tillage was done in apple orchard, but branches and blossom were pruned and fruit was thinned during the early growing season.

Three 1.5 m × 1.5 m permanent plots were established for each land use in December, 2010. One day before the first measurement, a polyvinyl chloride collar, 20 cm in diameter by 12 cm in height, was inserted 2 cm into each plot. Most collars were left in place throughout the study period from March 2011 to December 2013; while those in cropland were renewed twice a year after tillage and sowing.

2.3. Measurement of root biomass and SOC

To minimize the disturbance of human activities, fine root (<2 mm in diameter) biomass for each land-use was collected and measured only once a year in July, as the fine root biomass at this time was shown to be able to represent the maximum root biomass (Sheng et al., 2010). Six cores (9 cm in diameter by 20 cm in depth) were collected at a depth of 0–20 cm from each plot and then mixed into a composite sample. Roots were washed and oven-dried at 60 °C for 48 h to a constant weight, and then root biomass C and N were measured using a Carlo Erba CHN analyzer (Carlo-Erba Strumentazione, Milan, Italy).

Soil samples were collected only in 2011 for analysis of SOC and soil total nitrogen (TN). Five cores (3 cm in diameter) were collected at a depth of 0–20 cm from each plot, and subsoils were air-dried and then ground to a size of less than 0.15 mm. SOC was determined using the $K_2Cr_2O_7{\cdot}H_2SO_4$ oxidation method, and TN was determined using the Kjeldahl acid-digestion method with an Alpkem autoanalyzer (Kjektec System 1026 Distilling Unit, Sweden).

2.4. Measurement of soil respiration, temperature and moisture

Soil respiration was measured twice for each plot using an automated closed soil CO_2 flux system equipped with a portable chamber (20 cm in diameter, Li-8100, Lincoln, NE, USA). All visible living organisms were removed before the measurement. If necessary, one or more additional measurements would be taken until the variations between two consecutive measurements were less than 15%. The final instantaneous soil respiration for a given collar was the average of the two measurements with a 90 s enclosure period and 30 s delay between them. The measurements were performed from 09:00 am to 11:00 am from March 2010 to November 2012, but not in December–February due to cold weather. Soil respiration was measured for 16, 18 and 13 times for each land-use in 2011–2013, respectively. Soil bulk density at a depth of 0–20 cm was measured using the cutting ring (5 cm in depth and diameter) method (Li et al., 2006).

Soil temperature (three measurements per collar) and moisture (four measurements per collar) 10 cm away from the collar were measured at the same time as the soil respiration measurement. Soil temperature and moisture at a depth of 5 cm were measured using Li-Cor thermocouple probe and Theta Probe ML2X with an HH2 moisture meter (Delta-T Devices, Cambridge, England), respectively. Soil water-filled pore space (WFPS) was calculated by the following equation: WFPS (%) = [volumetric water content/100 × (2.65 − soil bulk density)/2.65].

2.5. Data analysis

Soil respiration, soil temperature, and soil moisture were calculated by averaging the three replicates on each sampling day. A repeated measures analysis of variance was performed using the GLM procedure of SAS (version 8; SAS Institute, Cary, NC) to determine the difference of soil respiration, temperature and moisture among different land-use sequences. An exponential (or "Q_{10}") function was used to simulate the relationship between soil respiration and soil temperature (Xu and Qi, 2001):

$$F = \beta_0 e^{\beta_1 T} \tag{1}$$

$$Q_{10} = e^{10\beta_1} \tag{2}$$

where F (μmol m^2 s^{-1}) is the soil respiration, T (°C) is the soil temperature at a depth of 5 cm, and β_0 and β_1 are the fitted parameters, respectively.

The mechanism of the response of soil respiration to soil moisture is extremely complex and poorly understood (Iqbal et al., 2010). After comparing different functional forms and residual plots, a quadratic polynomial function was adopted in this study to describe the effect of soil moisture on soil respiration (Tang et al., 2005).

$$F = \beta_3\theta^2 + \beta_2\theta + \beta_4 \tag{3}$$

where θ is the soil moisture at a depth of 0–5 cm, and β_2,β_3, and β_4 are the fitted parameters, respectively.

Regression analysis was conducted between soil respiration and potential substrate availability using the REG procedure. The mean daily soil respiration for each plot was interpolated between measurement dates, and then the annual cumulative soil respiration was calculated.

3. Results

3.1. Effect of land-use conversions on biotic and a-biotic factors

Both SOC and fine root biomass varied significantly with land use conversions ($P < 0.05$) (Table 1). SOC increased from 5.39 ± 0.19 to 5.85 ± 0.35 and 6.80 ± 0.45 with the conversion of cropland to grassland and woodland, and decreased to 5.20 ± 0.26 with the conversion of cropland to apple orchard, respectively (Table 2). Fine root biomass increased from 71 ± 9 to 99 ± 5 and 172 ± 46 with the conversion of cropland to grassland and woodland, and decreased to 53 ± 4 with the conversion of cropland to apple orchard, respectively (Table 2).

The changes in soil temperature coincided with that in air temperature during the study period from 2011 to 2013, with the maximum soil temperature occurring in summer and the minimum soil temperature occurring in winter (Fig. 1a and b). Soil temperature varied significantly with land use ($P < 0.05$), and the mean soil temperature (2011–2013) was 16.18 ± 0.57 °C for grassland, 15.30 ± 0.35 °C for cropland, 15.00 ± 0.87 °C for apple orchard, and 13.03 ± 0.26 °C for woodland, respectively. The results implied that soil temperature was greater in low stalk vegetation (grassland) than in tall stalk vegetation (cropland, orchard and woodland) due to the lack of canopy shading.

Soil moisture at the depth of 0–5 cm fluctuated tempestuously in response to irregular rainfall, with the minimum soil moisture occurring in spring due to less rainfall, and the maximum soil moisture occurring in autumn or winter due to abundant rainfall (Fig. 1c). Soil moisture varied significantly with land-use ($P < 0.05$),

Table 1
Site characteristics and topsoil (0–20 cm) properties of the four land-uses in Wangdonggou watershed (n = 18).

Land-uses	Bulk density (cm cm^{-3})	SOC (g kg^{-1})	C:N ratio	Fine root biomass (g m^{-2})	Root C:N ratio
Woodland	1.23 ± 0.12a	6.80 ± 0.45a	10.3 ± 0.23a	172 ± 46a	25 ± 3a
Grassland	1.28 ± 0.23ab	5.85 ± 0.35b	9.2 ± 0.12a	99 ± 5b	61 ± 1b
Orchard	1.32 ± 0.21b	5.20 ± 0.26b	7.3 ± 0.19b	53 ± 4c	52 ± 2bc
Cropland	1.25 ± 0.13b	5.39 ± 0.19b	8.4 ± 0.28a	71 ± 9bc	38 ± 1ac

Table 2
Cumulative soil respiration (F) (gC m^{-2} $year^{-1}$) and mean soil respiration rate (SR) ($\mu mol\ m^{-2}\ s^{-1}$) for woodland, grassland, apple orchard, and cropland from 2011 to 2013.

Land-uses	2011		2012		2013		Mean values	
	SR	F	SR	F	SR	F	SR	F
Woodland	1.82 ± 1.21a	635 ± 40a	2.69 ±1.57a	745 ± 73a	3.15 ± 1.57a	961 ± 179a	2.55 ± 0.68a	780 ± 166a
Grassland	1.48 ± 0.71b	542 ± 98ab	2.03 ± 1.17b	602 ± 104ab	2.09 ± 1.12b	605 ± 72b	1.87 ± 0.34b	583 ± 36b
Orchard	1.40 ± 0.58b	539 ± 36ab	1.68 ± 0.5b	541 ± 27b	1.63 ± 0.66b	554 ± 53b	1.57 ± 0.15b	545 ± 8b
Cropland	1.20 ± 0.78b	469 ± 17b	1.89 ± 1.17b	577 ± 77b	2.14 ± 1.17b	651 ± 68b	1.75 ± 0.49b	566 ± 92b

Note: for cumulative soil respiration (F) $n = 3$, for soil respiration (SR) $n = 16$ in 2011, $n = 18$ in 2012, and $n = 13$ in 2013.

and the mean soil moisture (2011–2013) was 39.2% ± 3.41 WFPS for apple orchard, 36.8% ± 3.09 WFPS for cropland, 36.3% ± 2.62 WFPS for woodland, and 33.8 ± 1.98 WFPS for grassland, respectively.

3.2. Response of soil respiration to land-use conversions

Soil respiration showed similar significant seasonal variations among the four land-use patterns ($P < 0.05$) (Fig. 2). The dynamics of soil respiration coincided with that of the air and soil temperature, with the maximum soil respiration occurring in summer and the minimum soil respiration occurring in autumn or spring (Figs. 1a,b and 2). Mean soil respiration (2011–2013) increased from $1.75 \pm 0.49\ \mu mol\ m^{-2}\ s^{-1}$ to 1.87 ± 0.34 and $2.55 \pm 0.68\ \mu mol\ m^{-2}\ s^{-1}$ with the conversion of cropland to grassland and woodland, and decreased to $1.57 \pm 0.15\ \mu mol\ m^{-2}\ s^{-1}$ with the conversion of cropland to apple orchard, respectively (Table 2). The similar trends were found in mean cumulative soil respiration, which followed the order of woodland (780 gC m^{-2} $year^{-1}$) > grassland (583 gC m^{-2} $year^{-1}$) > cropland (566 gC m^{-2} $year^{-1}$) > apple orchard (545 gC m^{-2} $year^{-1}$), respectively (Table 2).

The mean apparent Q_{10} varied significantly with land use conversion ($P < 0.01$), and followed the order of woodland (2.76 ± 0.05) > cropland (2.31 ± 0.12) > grassland (2.11 ± 0.11) > apple orchard (1.70 ± 0.09) in this study.

3.3. Relationship between soil respiration and biotic and a-biotic factors under land-use conversions

Soil respiration increased exponentially with soil temperature among the four typical land-use types ($P < 0.01$) (Fig. 3), and had a nearly negative quadratic relationship with soil moisture

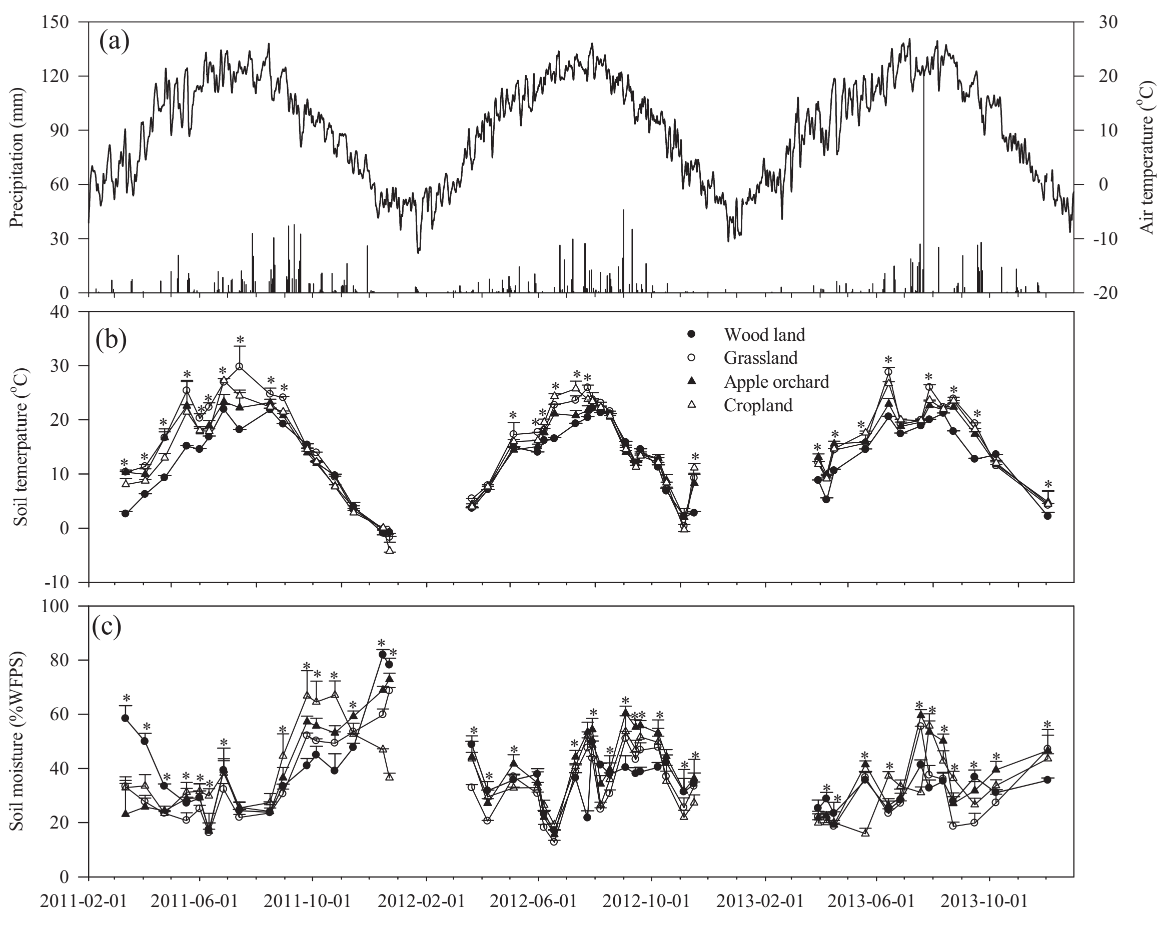

Fig. 1. Variation of (a) precipitation (mm), air temperature (°C), (b) soil temperature (°C), and (c) soil moisture (%WFPS) over a three-year period from 2011 to 2013. The asterisk indicates a significant difference at $P < 0.05$.

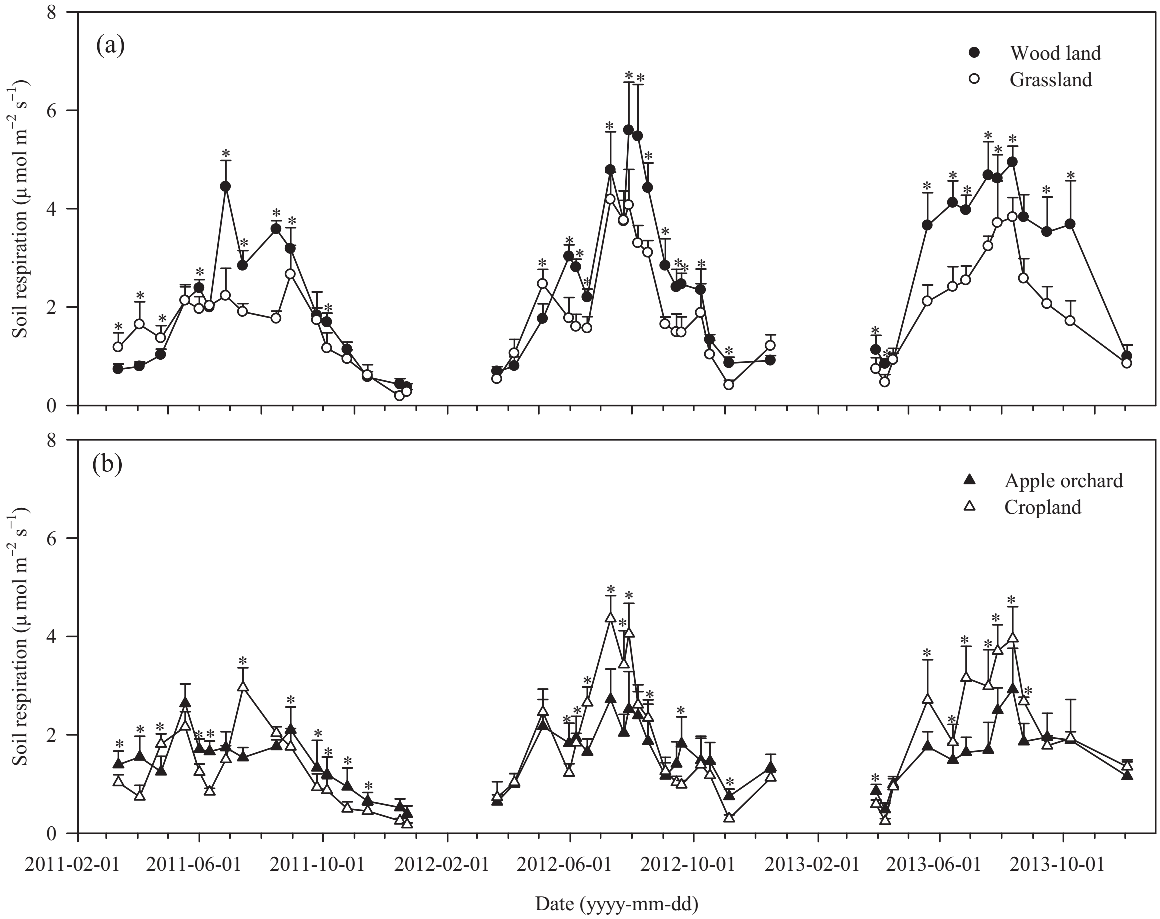

Fig. 2. Dynamics of soil respiration (μmol m^{-2} s^{-1}) from 2011 to 2013 in (a) woodland and grassland, and (b) apple orchard and cropland in semi-arid Loess region. The asterisk indicates a significant difference at $P < 0.05$.

($P < 0.05$) except for woodland and cropland at relatively low temperatures (Fig. 4). Although the relationships between soil respiration and soil temperature/moisture are similar among the four typical land-use types, the coefficient of determination (R^2) was greater in woodland and grassland than in cropland and orchard from 2011 to 2013 (R^2: 80% vs. 64% for the relationship between soil respiration and soil temperature, and 54% vs. 39% for the relationship between soil respiration and soil moisture at relatively high temperature) (Figs. 3 and 4). These results suggested that land-use conversions influenced the relationship between soil respiration and a-biotic factors. However, no significant relationships between soil respiration and a-biotic factors were found over the experimental period. More importantly, soil respiration increased linearly with both SOC content and fine root biomass ($P < 0.05$) (Fig. 5) under land-use conversions. The results clearly showed that biotic (substrate availability) factors could have a considerable influence on soil respiration under land-use conversions in our sites.

4. Discussion

4.1. Soil respiration in degraded ecosystem

In this study, we found that the mean cumulative soil respiration ranged from 0.55 to 0.78 kgC m^{-2} year^{-1} among different land-use conversions, which fell right into the range reported in a meta-analysis (ranging from 0.52 to 0.99 kgC m^{-2} year^{-1}) (Chen et al., 2010). Soil respiration in the black locust woodland (2.55 μmol m^{-2} s^{-1}) was significantly lower that of the deciduous forest in the northern hemisphere temperate regions (3.5 μmol m^{-2} s^{-1}) (Hibbard et al., 2005). Again, soil respiration in grassland (1.87 μmol m^{-2} s^{-1} or 0.58 kgC m^{-2} year^{-1}) was slightly lower than that in the northern hemisphere temperate (2.1 μmol m^{-2} s^{-1}) or global grassland system (0.84 kgC m^{-2} year^{-1}) (Chen et al., 2010; Hibbard et al., 2005). It was only 1.75 μmol m^{-2} s^{-1} in degraded cropland in this study, significantly lower than that in the non-degraded agricultural ecosystem in temperate regions (3.95 μmol m^{-2} s^{-1}) (Han et al., 2007; Zhang et al., 2013b). The cumulative soil respiration in apple orchard was 545 gC m^{-2} year^{-1}, also significantly lower than that in citrus orchard in subtropical China (698 gC m^{-2} year^{-1}). The lower soil respiration observed in our degraded ecosystems as compared with that in temperate regions (Chen et al., 2010; Hibbard et al., 2005; Sheng et al., 2010) is possibly due to poor soil properties, such as low SOC content (6.52 vs. 1.67 for cropland, 5.30 vs.1.50 for grassland, 6.52 vs. 1.67 kg m^{-2} for woodland, and 27.44 vs. 13.7 Mg ha^{-1} for orchard) and ecosystem productivity, especially belowground productivity (158 vs. 99 for grassland, 342 vs. 172 g m^{-2} for woodland, 27.44 vs. 13.7 Mg ha^{-1} for orchard), in degraded ecosystems caused by long-term soil erosion (Ping et al., 2013).

4.2. Biotic factors influencing soil respiration among land-use conversions

Land use conversion could change root type and biomass, as well as the substrate carbon input and availability, thus indirectly influencing soil respiration (Sheng et al., 2010; Uchida et al., 2012). Fine root biomass was increased by 39% in grassland and

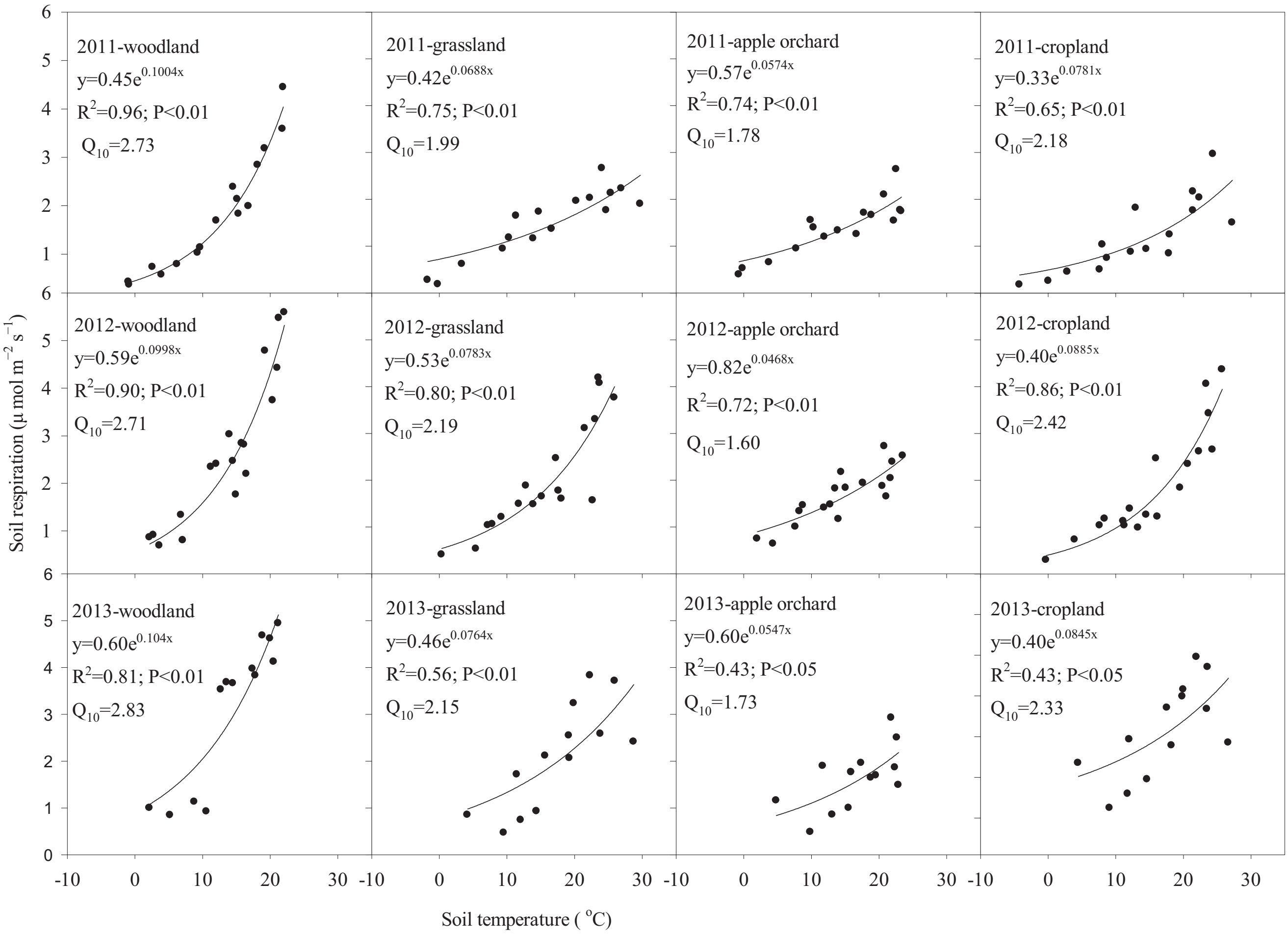

Fig. 3. Relationship between soil respiration (μmol m^{-2} s^{-1}) and soil temperature (°C) at 5-cm depth among the four land-use types from 2011 to 2013.

142% in woodland as compared with that of cropland, which was similar to what has been reported in previous studies (French et al., 1979). The SOC content was also increased by 26% in woodland and 9% in grassland as compared with that of cropland (Table 1), which was in agreement with the meta-analytic results (Chang et al., 2011; Deng et al., 2013). The lower root biomass and SOC content in cropland than in woodland and grassland can be explained as follows: firstly, frequent soil tillage in cropland promotes mineralization and decomposition of soil organic matters, thus indirectly decreasing the SOC content (Pandey et al., 2013). Secondly, reduced input of aboveground litter (removed from the land) in cropland inevitably reduces the SOC content. Finally, the single species in cropland ecosystems forms a single community that can decrease species richness and the ability of cropland ecosystem to resist the environmental impacts, thus indirectly contributing to the decrease in system productivity and SOC content (Zheng and Wang, 2013; Zhang and Dong, 2010).

The results showed that soil respiration varied significantly with land-use conversion (Fig. 2) and increased by 7–46% following the conversion of cropland to woodland and grassland, which was in line with previous studies (Frank et al., 2006; Jenkins and Adams, 2010; Wang et al., 2013). This may likely be related to the increase in SOC content and fine root biomass. In this study, annual mean soil respiration increased linearly with fine root biomass (<2 mm) and SOC content (Fig. 5a and b), which was in line with previous studies (Hertel et al., 2009; Sheng et al., 2010). Root respiration mainly reflects the root activity and biomass (Kuzyakov, 2006); and SOC is probably the major factor restricting the supply of substrates for microbial respiration (Uchida et al., 2012).

Soil respiration was decreased by 10% after conversion of cropland to apple orchard, and this appeared to be related to root and carbon substrate supply. In this study, fine root biomass and SOC content were decreased by 25% and 4%, respectively, which agreed well with previous results (Iqbal et al., 2010; Sheng et al., 2010), in which soil respiration was decreased by 25% after conversion of cropland to citrus orchard (Sheng et al., 2010) due to larger fine root biomass and SOC content in cropland than in orchard. All these results suggested that root biomass and SOC content had important influence on soil respiration.

4.3. A-biotic factor influencing soil respiration among land-use conversions

Soil microclimate such as soil temperature and soil moisture varied significantly with land-use conversion in each observation day ($P < 0.05$) (Fig. 1b and c). Soil temperature was 1.75 °C greater in low stalk vegetation than in tall stalk vegetation due to canopy shading. Similar results have also been reported in the northeastern Kansas, USA (Smith and Johnson, 2004). Soil respiration in our sites increased exponentially with soil temperature (Fig. 3), which was in line with other studies (Bond-Lamberty and Thomson, 2010; Davidson et al., 2006; Raich and Schlesinger, 1992; Xu and Qi, 2001). Changes in soil temperature due to land-use conversion could not explain the differences in cumulative soil respiration,

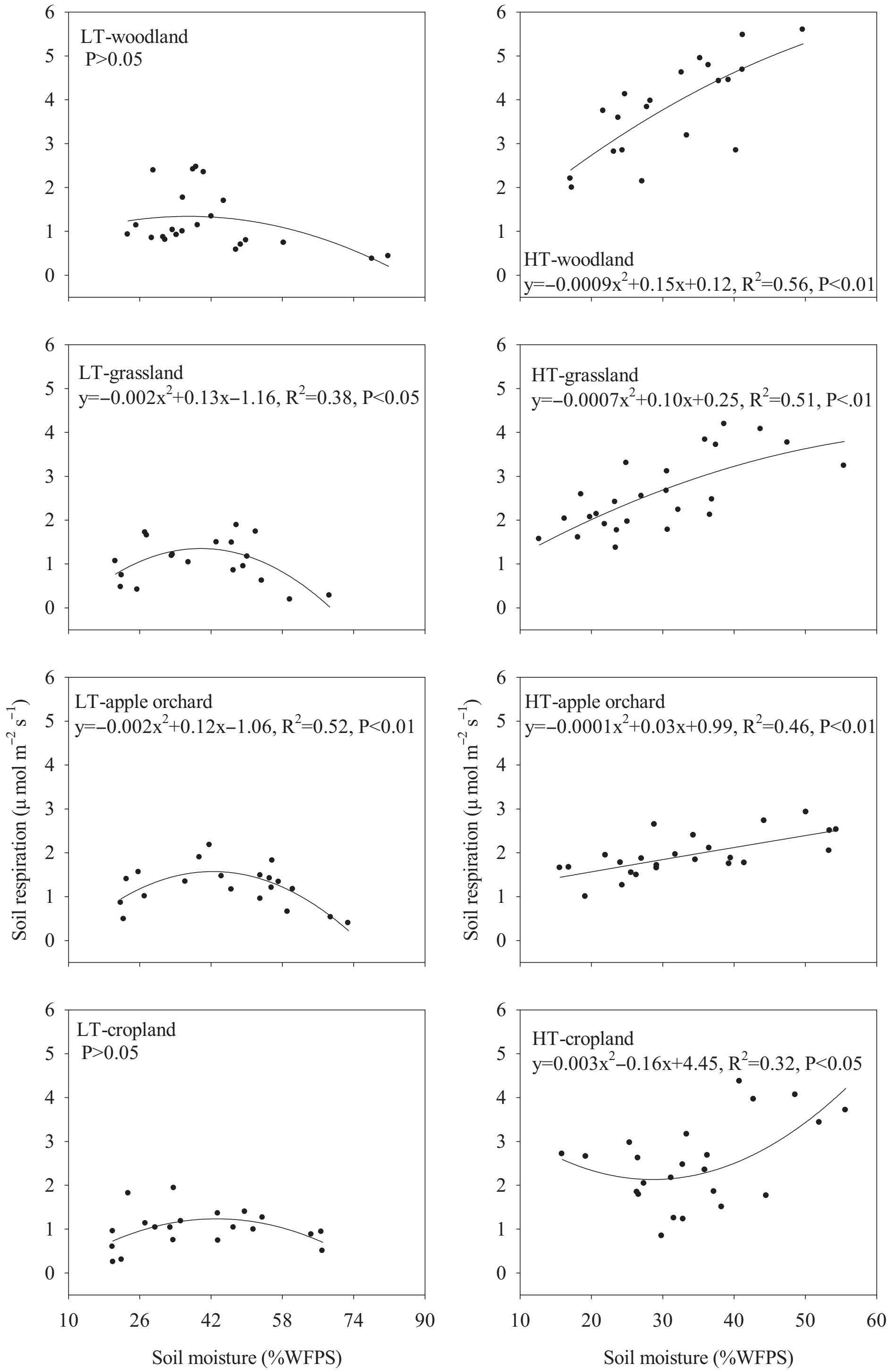

Fig. 4. Relationship between soil respiration (μmol m^{-2} s^{-1}) and soil moisture (%WFPS) at 0–5 cm depth with soil temperature of 15 °C as the critical point from 2011 to 2013 (LT means data with soil temperature lower than 15 °C, and HT means data with soil temperature higher than 15 °C).

thus contributing little to the difference in soil respiration among the land-use conversions. For instance, mean annual soil temperature was 2.27 °C greater in cropland than in woodland, whereas cumulative soil respiration was 214 gC m^{-2} $year^{-1}$ lower in cropland than in woodland.

Soil moisture is the major factor limiting the ecological recovery in semi-arid regions (Fehmi and Kong, 2012; Zhang and Dong, 2010), and the response mechanisms of soil respiration to soil moisture is extremely complex (Iqbal et al., 2010) and may be confounded with the effect of soil temperature (Hibbard et al., 2005; Rey et al., 2011; Sheng et al., 2010). Soil respiration in our sites was significantly influenced by soil moisture ($P < 0.05$) except for in woodland and cropland ($P > 0.05$) at relatively low temperature after partitioning the measurement data into two subsets using the soil temperature of 15 °C as the critical point (Fig. 4). Similarly, soil moisture was found to be the main driver of soil respiration for most of the year when temperatures were above 20 °C in semi-arid steppe ecosystems of Spain (Rey et al., 2011). Differences in soil moisture contributed little to the difference in soil respiration among the land-use conversions

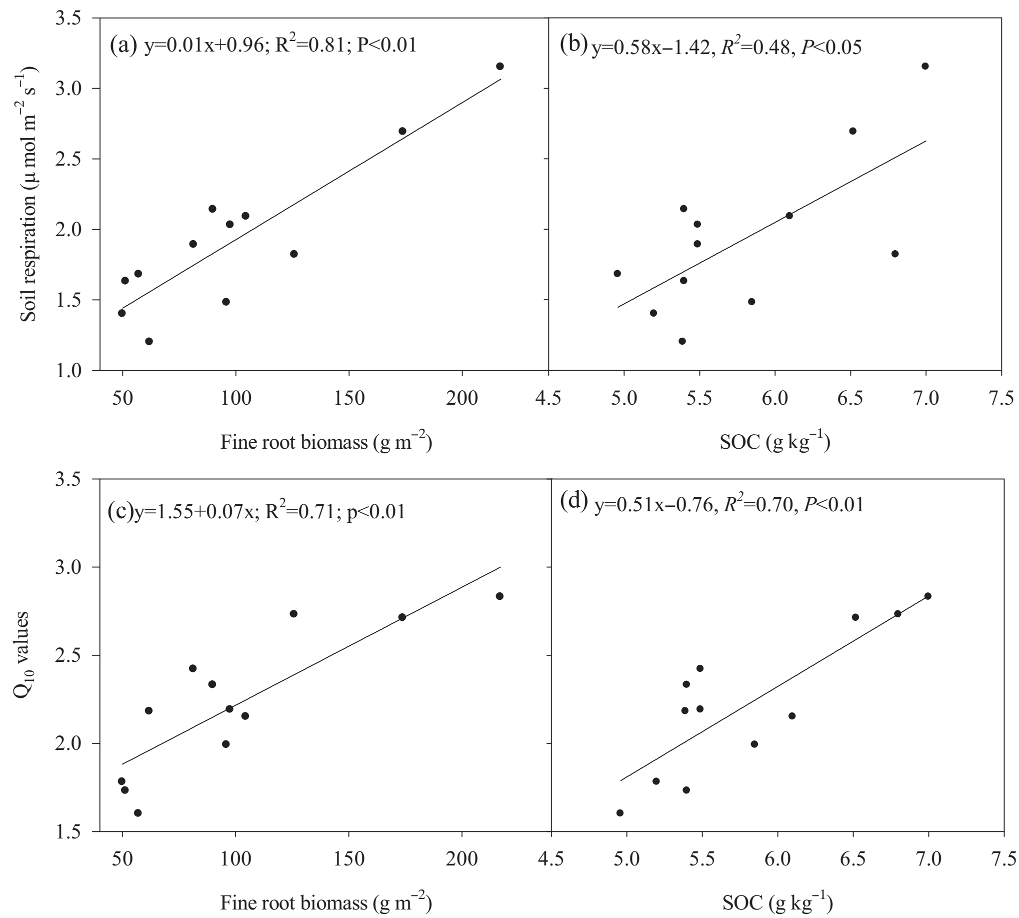

Fig. 5. Relationships between soil respiration (μmol m^{-2} s^{-1}) and (a) fine root biomass (g m^{-2}), (b) soil organic carbon (g kg^{-1}), and between mean Q_{10} values and (c) fine root biomass (g m^{-2}), (d) soil organic carbon (g kg^{-1}).

because changes in soil moisture derived from land-use conversions could not explain the difference in cumulative soil respiration. For instance, mean annual soil moisture was 5.4% WFPS greater in orchard than in grassland, whereas cumulative soil respiration was 38 gC m^{-2} $year^{-1}$ lower in orchard than in grassland. Thus, soil microclimate may not be the major factors to drive soil respiration among land-use conversions.

4.4. Land-use conversions influenced temperature sensitivity of soil respiration

In this study, Q_{10} ranged from 1.60 to 2.83 among different land-use types and years, which fell right into the range of the mean Q_{10} of different ecosystems (mean: 2.4; range: 1.3–3.3) at global scale (Raich and Schlesinger, 1992). Despite the significant influence of land-use conversions on Q_{10}, the apparent Q_{10} did not show a consistent increasing or decreasing trend with the conversion of cropland to grassland, woodland or orchard. Q_{10} could be affected by a variety of factors, including root activity (Davidson et al., 2006), soil water and temperature (Peng et al., 2009), substrate quality and quantity, and microbial population composition and size (Davidson et al., 2006 Zheng et al., 2009). In line with previous studies (Peng et al., 2009; Sheng et al., 2010; Zhang et al., 2013a Zheng et al., 2009), Q_{10} was increased by 19% following the conversion of cropland to woodland, and decreased by 9–26% following the conversion of cropland to grassland and orchard in this study.

In this study, the observed difference in Q_{10} may probably result from the root properties and SOC storage in degraded ecosystems of the Loess Plateau, because the apparent Q_{10} increased with increasing substrate availability (Fierer et al., 2005; Knorr et al., 2005). This can be substantiated by the regression analysis results that there was a positive linear relationship between the apparent Q_{10} and both SOC and fine root biomass (Fig. 5c and d). In addition, the results showed that both of them were greater in woodland than in cropland than in apple orchard ($P < 0.05$) (Table 1).

Although SOC and fine root biomass were lower in cropland than in grassland, Q_{10} was 9% larger in cropland than in grassland, which was in line with previous meta-analysis (Peng et al., 2009). The quality of potential substrate availability appeared to be one reason for this difference, as it was lower in grassland than in cropland (Table 1). The ratio of soil carbon to nitrogen was 5.39 in cropland and 5.85 in grassland, and the ratio of root carbon to nitrogen was 38 in cropland and 61 in grassland, respectively. There were more fungi in grassland than in cropland (Lauer et al., 2011), and the biochemically recalcitrant substrates would be more depleted in this case (Djukic et al., 2010). Q_{10} was larger in relatively labile substrates than in biochemically recalcitrant substrates (Guntinas et al., 2013). In addition, root respiration might be another important reason for the observed difference in Q_{10}, as some root systems can adapt to warming while the others can not (Loveys et al., 2003). Thus, natural grassland may have adapted to climatic warming, whereas the cropland may be sensitive to climate warming (Hyvönen, 2008; Tungate et al., 2007).

The results of this study clearly implied that root biomass and SOC storage were the major factors influencing Q_{10} following conversion of cropland to non-natural ecosystem, and substrate quality or root system adaptability may be the real reason for the difference in Q_{10} following conversion of cropland to natural ecosystem (grassland in our study). SOC content was significantly increased in both woodland and grassland, whereas the increase of CO_2 concentrations in the atmosphere was greater in woodland than in cropland than in grassland. This was because that Q_{10} was 31% greater in woodland than in grassland, and 9% greater in cropland than in grassland, respectively. Therefore, the conversion of cropland to natural grassland might be the most effective measure for small watershed management in the loess regions.

5. Conclusions

A better understanding of the response of soil respiration to land-use conversion has important practical implications for ecological restoration in degraded regions. The results of this study showed that both soil respiration and Q_{10} varied significantly with land-use conversion. The difference in soil respiration among different land-use types may result from the changes in substrate availability such as SOC and soil carbon input such as fine root turnover. Although soil temperature and moisture significantly influenced soil respiration, the difference derived from land-use conversions could not well explain the difference in soil respiration among land-use conversions. Potential substrate availability (SOC and root) may be the major factor influencing Q_{10} following land-use conversion, and the substrate quality or adaptability of root system may be the real reason for the difference in Q_{10} between cropland and natural grassland. The conversion of cropland to grassland in degraded loess regions could greatly increase SOC storage and ecosystem production on one hand, and decrease the CO_2 concentrations in the atmosphere on the other hand. Thus, it is an effective integrated management of small watershed in the loess regions to increase soil carbon storage and decrease the CO_2 concentrations in the atmosphere.

Acknowledgment

This study was funded by National Natural Science Foundation of China, No. 41371279. Two anonymous reviewers were greatly appreciated for their constructive comments on the manuscript.

References

Adolfo Campos, C., 2006. Response of soil surface CO_2 flux to land use changes in a tropical cloud forest (Mexico). Forest Ecol. Manage. 234, 305–312.
Arevalo, C., Bhatti, J.S., Chang, S.X., Jassal, R.S., Sidders, D., 2010. Soil respiration in four different land use systems in north central Alberta, Canada. J. Geophys. Res.: Biogeosci. 2005–2012, 115.
Bond-Lamberty, B., Thomson, A., 2010. Temperature-associated increases in the global soil respiration record. Nature 464, 579–582.
Chang, R., Fu, B., Liu, G., Liu, S., 2011. Soil carbon sequestration potential for Grain for green project in Loess Plateau, China. Environ. Manage. 48, 1158–1172.
Chen, S., Huang, Y., Zou, J., Shen, Q., Hu, Z., Qin, Y., Chen, H., Pan, G., 2010. Modeling interannual variability of global soil respiration from climate and soil properties. Agric. Forest Meteorol. 150, 590–605.
Davidson, E.A., Janssens, I.A., Luo, Y., 2006. On the variability of respiration in terrestrial ecosystems: moving beyond Q_{10}. Global Change Biol. 12, 154–164.
Deng, L., Liu, G.b., Shangguan, Z.P., 2013. Land use conversion and changing soil carbon stocks in China's 'grain-for-green' program: a synthesis. Global Change Biol doi:http://dx.doi.org/10.1111/gcb.12508.
Djukic, I., Zehetner, F., Mentler, A., Gerzabek, M.H., 2010. Microbial community composition and activity in different alpine vegetation zones. Soil Biol. Biochem. 42, 155–161.
Fehmi, J.S., Kong, T.M., 2012. Effects of soil type, rainfall, straw mulch, and fertilizer on semi-arid vegetation establishment, growth and diversity. Ecol. Eng. 44, 70–77.
Fernandes, S.A.P., Bernoux, M., Cerri, C.C., Feigl, B.J., Piccolo, M.C., 2002. Seasonal variation of soil chemical properties and CO_2 and CH_4 fluxes in unfertilized and P-fertilized pastures in an ultisol of the Brazilian Amazon. Geoderma 107, 227–241.
Fierer, N., Craine, J.M., McLauchlan, K., Schimel, J.P., 2005. Litter quality and the temperature sensitivity of decomposition. Ecology 86, 320–326.
Frank, A., Liebig, M., Tanaka, D., 2006. Management effects on soil CO_2 efflux in northern semiarid grassland and cropland. Soil Tillage Res. 89, 78–85.
French, N.R., Steinhorst, R.K., Swift, D.M., 1979. Grassland biomass trophic pyramids. Perspectives in Grassland Ecology. Springer, pp. 59–87.
Guntinas, M.E., Gil-Sotres, F., Leiros, M.C., Trasar-Cepeda, C., 2013. Sensitivity of soil respiration to moisture and temperature. J. Soil Sci. Plant Nutr. 13, 445–461.
Han, G., Zhou, G., Xu, Z., Yang, Y., Liu, J., Shi, K., 2007. Soil temperature and biotic factors drive the seasonal variation of soil respiration in a maize (*Zea mays* L.) agricultural ecosystem. Plant Soil 291, 15–26.
Hertel, D., Harteveld, M.A., Leuschner, C., 2009. Conversion of a tropical forest into agroforest alters the fine root-related carbon flux to the soil. Soil Biol. Biochem. 41, 481–490.
Hibbard, K., Law, B., Reichstein, M., Sulzman, J., 2005. An analysis of soil respiration across northern hemisphere temperate ecosystems. Biogeochemistry 73, 29–70.
Hyvönen, T., 2008. Impact of temperature and germination time on the success of a C_4 weed in a C_3 crop: *Amaranthus retroflexus* and spring barley. Agric. Food Sci. 20, 183–189.
Iqbal, J., Hu, R., Du, L., Lan, L., Shan, L., Tao, C., Ruan, L., 2008. Differences in soil CO_2 flux between different land use types in mid-subtropical China. Soil Biol. Biochem. 40, 2324–2333.
Iqbal, J., Hu, R., Feng, M., Lin, S., Malghani, S., Ali, I.M., 2010. Microbial biomass, and dissolved organic carbon and nitrogen strongly affect soil respiration in different land uses: a case study at three Gorges Reservoir area, South China. Agric. Ecosyst. Environ. 137, 294–307.
Jenkins, M., Adams, M.A., 2010. Vegetation type determines heterotrophic respiration in subalpine Australian ecosystems. Global Change Biol. 16, 209–219.
Knorr, W., Prentice, I., House, J., Holland, E., 2005. Long-term sensitivity of soil carbon turnover to warming. Nature 433, 298–301.
Kuzyakov, Y., 2006. Sources of CO_2 efflux from soil and review of partitioning methods. Soil Biol. Biochem. 38, 425–448.
Lal, R., 2001. Potential of desertification control to sequester carbon and mitigate the greenhouse effect. Clim. Change 51, 35–72.
Lal, R., 2003. Soil erosion and the global carbon budget. Environ. Int. 29, 437–450.
Lauer, F., Kösters, R., Du Preez, C.C., Amelung, W., 2011. Microbial residues as indicators of soil restoration in South African secondary pastures. Soil Biol. Biochem. 43, 787–794.
Lee, D.K., Park, C., Tomlin, D., 2013. Effects of land-use-change scenarios on terrestrial carbon stocks in South Korea. Landsc. Ecol. Eng. 1–13.
Li, X., Xiao, H.L., He, M.Z., Zhang, J.G., 2006. Sand barriers of straw checkerboards for habitat restoration in extremely arid desert regions. Ecol. Eng. 28, 149–157.
Loveys, B., Atkinson, L., Sherlock, D., Roberts, R., Fitter, A., Atkin, O., 2003. Thermal acclimation of leaf and root respiration: an investigation comparing inherently fast- and slow-growing plant species. Global Change Biol. 9, 895–910.
Pandey, D., Agrawal, M., Bohra, J.S., 2013. Impact of four tillage permutations in rice–wheat system on GHG performance of wheat cultivation through carbon foot printing. Ecol. Eng. 60, 261–270.
Peng, S., Piao, S., Wang, T., Sun, J., Shen, Z., 2009. Temperature sensitivity of soil respiration in different ecosystems in China. Soil Biol. Biochem. 41, 1008–1014.
Ping, Z., Anbang, W., Xinbao, Z., Xiubin, H., 2013. Soil conservation and sustainable eco-environment in the Loess Plateau of China. Environ. Earth Sci. 68, 633–639.
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.
Raich, J.W., Tufekcioglu, A., 2000. Vegetation and soil respiration: correlations and controls. Biogeochemistry 48, 71–90.
Rey, A., Pegoraro, E., Oyonarte, C., Were, A., Escribano, P., Raimundo, J., 2011. Impact of land degradation on soil respiration in a steppe (*Stipa tenacissima* L.) semi-arid ecosystem in the SE of Spain. Soil Biol. Biochem. 43, 393–403.
Sheng, H., Yang, Y., Yang, Z., Chen, G., Xie, J., Guo, J., Zou, S., 2010. The dynamic response of soil respiration to land-use changes in subtropical China. Global Change Biol. 16, 1107–1121.
Shi, W.-Y., Yan, M.-J., Zhang, J.-G., Guan, J.-H., Du, S., 2014. Soil CO_2 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.
Smith, D.L., Johnson, L., 2004. Vegetation-mediated changes in microclimate reduce soil respiration as woodlands expand into grasslands. Ecology 85, 3348–3361.
Tang, J.W., Qi, Y., Xu, M., Misson, L., Goldstein, A.H., 2005. Forest thinning and soil respiration in a ponderosa pine plantation in the Sierra Nevada. Tree Physiol. 25, 57–66.
Tungate, K.D., Israel, D.W., Watson, D.M., Rufty, T.W., 2007. Potential changes in weed competitiveness in an agroecological system with elevated temperatures. Environ. Exp. Bot. 60, 42–49.
Uchida, Y., Nishimura, S., Akiyama, H., 2012. The relationship of water-soluble carbon and hot-water-soluble carbon with soil respiration in agricultural fields. Agric. Ecosyst. Environ. 156, 116–122.
Wang, W., Zeng, W.J., Chen, W.L., Zeng, H., Fang, J.Y., 2013. Soil respiration and organic carbon dynamics with grassland conversions to woodlands in temperate China. PLoS One 8, 1–10.
Xu, M., Qi, Y., 2001. Spatial and seasonal variations of Q_{10} determined by soil respiration measurements at a Sierra Nevadan forest. Global Biogeochem. Cycles 15, 687–696.
Zhang, J.T., Dong, Y., 2010. Factors affecting species diversity of plant communities and the restoration process in the loess area of China. Ecol. Eng. 36, 345–350.

Zhang, T., Li, Y.F., Chang, S.X., Jiang, P.K., Zhou, G.M., Zhang, J.J., Liu, J., 2013a. Responses of seasonal and diurnal soil CO_2 effluxes to land-use change from paddy fields to Lei bamboo (*Phyllostachys praecox*) stands. Atmos. Environ. 77, 856–864.
Zhang, Q., Lei, H.M., Yang, D.W., 2013b. Seasonal variations in soil respiration, heterotrophic respiration and autotrophic respiration of a wheat and maize rotation cropland in the North China Plain. Agric. For. Meteorol. 180, 34–43.
Zheng, F., Wang, B., 2013. Soil erosion in the Loess Plateau region of China. Restoration and development of the degraded Loess Plateau, China. Ecohydrology 5, 77–92.
Zheng, Z.-M., Yu, G.-R., Fu, Y.-L., Wang, Y.-S., Sun, X.-M., Wang, Y.-H., 2009. Temperature sensitivity of soil respiration is affected by prevailing climatic conditions and soil organic carbon content: a trans-China based case study. Soil Biol. Biochem. 41, 1531–1540.