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

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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

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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.