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Responses of soil C stock and soil C loss to land restoration in Ili River Valley, China

Meifang Yan[a,b,*], Wenjing Zhang[a], Zeyu Zhang[c], Lu Wang[a], Hongrui Ren[d], Yuan Jiang[b], Xinshi Zhang[b]

[a] College of Environmental Science and Engineering, Taiyuan University of Technology, 79 Yingzexi Street, Taiyuan 030024, China
[b] State Key Laboratory of Earth Surface Process and Resource Ecology, Beijing Normal University, 19 Xinjiekouwai Street, Beijing 100875, China
[c] College of Science, Beijing University of Chemical Technology, 15 Beisanhuan East Road, Beijing 100029, China
[d] College of Mining Engineering, Taiyuan University of Technology, 79 Yingzexi Street, Taiyuan 030024, China

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ABSTRACT

In the past decades, massive destroying of natural vegetation and extension of agricultural lands strongly affected soil carbon (C) cycling. Returning cropland to forestry or grass land is one of restoration measures sponsored by the Chinese government. Land use change exerts a great influence on soil microclimate and litter quality, and is therefore an important determinant of soil C dynamics. However, knowledge on the effects of land restoration on soil C in northwest China was limited. To address this problem, a study was undertaken in the arid Ili River Valley to estimate soil C dynamics for representative land uses: grassland and forest plantations (transformed from croplands), and cropland. The results showed that there were significant differences in soil C stock among the vegetation types. Soil C stock increased in poplar plantation eight years after conversion from cropland, whereas it significantly declined after conversion to spruce plantation. The 15-year-old poplar plantation had the highest soil C stock (59.60 Mg C ha^{-1}), including C sequestration in forest floor and in mineral soil (0–30 cm). High litter mass in the old poplar forest facilitated the accumulation of soil C. There were significant differences in soil respiration rate and cumulative soil C loss among the land use types, with the highest in clover grassland. Furthermore, the grassland had a higher Q_{10} value, which implies that an increase in soil temperature would lead to more soil C loss under global warming. Our results suggested that conversion of croplands to fast-growing woody crops might be beneficial to soil C sequestration, which was helpful for land management and mitigation of climate change.

1. Introduction

Soil is the largest carbon (C) reservoir in the terrestrial biosphere, and even a minor change in soil C storage may result in a significant alteration in atmospheric CO_2 concentration (Lal, 2004). Previous studies have underpinned the role of soil as a C sink, the importance of soil organic C (SOC) in the global C cycle and the potential feedback to climate change (Drewnik et al., 2016; Guo and Gifford, 2002; Wang et al., 2014). Soil respiration (Rs) is the second largest C flux in the terrestrial ecosystem, estimated to reach 50–75 Pg C $year^{-1}$ globally, 10 times greater than C emission from fossil fuel combustion (Raich and Schlesinger, 1992). The huge discharge of C by Rs directly affects the SOC concentration, which controls the soil fertility and productivity (Sarzhanov et al., 2017). Understanding C dynamics helps to determine the role of soil as a bridge for the terrestrial C storage and potential global warming.

SOC stock is controlled by a balance between C input from litter-fall and output by soil C loss (Bashkin and Binkley, 1998). The input of C to soil is affected by litter production and the rate of biomass allocation, while the output is controlled by organic matter content, litter C/N ratio, soil temperature and soil moisture (Laganière et al., 2010; Yan et al., 2017). Particularly, soil C stock is strongly affected by land cover and land use patterns which is changing rapidly due to human activities (Murty et al., 2002; Paul et al., 2003; Wasak and Drewnik, 2015). In the past decades, massive destroying of natural vegetation and extension of agricultural lands leaded to enormous soil C release. It was reported that net C efflux derived from land use change accounted for up to 12.5% of anthropogenic C emissions from 1990 to 2010 (Houghton et al., 2012). Wu et al. (2003) estimated that about 7.1 Pg SOC had been lost as a result of land use change in China, and most of the loss

* Corresponding author at: College of Environmental Science and Engineering, Taiyuan University of Technology, 79 Yingzexi Street, Taiyuan 030024, China.
E-mail address: mfyan2010@aliyun.com (M. Yan).

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occurred in cultivated soils. Furthermore, previous studies have demonstrated that land use type is an important determinant of Rs by influencing soil microclimate, root growth, and quality of detritus (Jenkins and Adams, 2011; Wang et al., 2013). Thus, different ecosystems may exhibit different temperature sensitivities of Rs, commonly referred to as Q_{10} values (the factor by which Rs increases with a 10 °C rise in temperature) (Jenkins and Adams, 2011).

Returning farmlands to forestry or grass lands was one of restoration measures put into practice by the Chinese Government, which was so called as 'Grain-for-Green Program' (Deng et al., 2014). Afforestation of croplands may potentially reverse the process of soil C loss and increase ecosystem C storage (Arevalo et al., 2011; Yan et al., 2017). For example, several studies have found that afforestation increased SOC (Laganière et al., 2010; Murty et al., 2002). Nevertheless, the change in SOC may vary significantly according to forest type and cultivation stage (Wang et al., 2013). Conversion of cropland to grassland is one of the most effective strategies for C sequestration (Guo and Gifford, 2002; Machmuller et al., 2015). Therefore, quantifying the effects of land restoration on soil C dynamics is important to curb C loss from soils.

Due to low productivity of arid and semi-arid lands, soil C dynamics in these environments have received considerably less attention than other ecosystems (Conant et al., 2004; Maestre et al., 2013). However, arid lands cover a large portion of the Earth's land surface and store more than 25% of the global terrestrial C (Maestre et al., 2013). The predicted increases in temperature and changes in rainfall patterns in the dry-lands make ecosystem functions such as C cycling particularly sensitive to global change. In arid northwest China, excessive cultivation and grazing had resulted in severe land degradation, which was required to restore to grass land or forest plantation by the local government (Ait et al., 2009; Deng et al., 2014; Ren et al., 2018). However, little was known about the effect of land use conversion on soil C dynamics, detailed information was needed.

In this study, we conducted a field investigation for representative land use types in Ili River Valley, including cropland and grassland, poplar plantation and spruce plantation (converted from croplands). We hypothesized that land use change greatly affected soil C dynamics. The objectives of this study were: (1) to quantify and compare soil C stock in different land use types; and (2) to quantify the main factors impacting soil C stock and Rs.

2. Material and methods

2.1. Study site

Ili River Valley (80°09′–84°56′E, 42°14′–44°50′N) is located in the western part of the Tianshan Mountains in Xinjiang, northwest China. It is an inland continental river valley which surrounded on three sides by mountains. The region has a temperate continental climate with a mean annual precipitation ranging from 200 mm to 800 mm. The average annual temperature and evaporation range from 2.9 to 9.1 °C and 1260 to 1900 mm, respectively. The frost-free period lasts approximately 130–180 days, and the annual sunshine duration reaches 2700–3000 h (Ait et al., 2009). The soil type is Calciustoll (USDA Soil Taxonomy) originating from parent material of Loess sediments.

In Ili River Valley, massive grazing of natural pastures and extensive cultivation of farmlands had leaded to soil degradation (Ait et al., 2009). As an example, the grassland area decreased by 13.5% during 1985–2005, whereas the area of cropland increased by 10.1%. Major land uses include croplands (0.87 million ha), forest lands (0.62 million ha) and grasslands (3.2 million ha) in the Ili River Valley (Ait et al., 2009). Due to China's 'Grain-for-Green Program', croplands required to be returned to the green were mostly located in western region of Ili Valley where land cover had been strongly influenced by human activities.

The study site was located in the central region of western Ili Valley (Fig. 1). Soil texture is sandy loam with an organic carbon concentration of 7.3–14.6 g kg^{-1}, total nitrogen of 1.1–2.3 g kg^{-1} and a pH of 8–8.5 in the A horizon (Institute of Botany, Chinese Academy of Sciences, 1978). The study site was relatively flat with slopes < 10° and the mean elevation reached 600 m. Groundwater was typically 2.0–2.3 m below the soil surface. Because natural precipitation hardly meets the water demand of plant development, irrigation was necessary. Water resources in this area originated from the Ili River, which gave an advantage to vegetation development. Poplar (*Populus* ssp.) and spruce (*Picea obovata*) plantations were established on farmlands in 1990s, formerly growing wheat (*Triticum aestivum*) or maize (*Zea mays*). Forest plantations had undergone intensive managements, such as irrigation, fertilization and weed control. Because of weed control management, herbaceous vegetation of the plantations such as steppe sedge, Japanese bromrgrass, and lovelyachnatherum were very sparse. As a typical species of legume forage, clover (*Trifolium repens*) was frequently used in the conversion of croplands to pastures, and harvested for silage 2–3 times a year.

2.2. Soil and litter sampling

We selected 15 sampling plots in central region of western Ili Valley, with three replications for each land use type including 8-year-old poplar plantation (YP), 15-year-old poplar plantation (OP), 15-year-old spruce plantation (SP), white clover grassland (WG), and cropland growing wheat (CL). The grassland and forest plantations were transformed from croplands. Characteristics of the land use types are given in Table 1. The plots were 25 m × 30 m for forests and 3 m × 3 m for grass and crop. During the growth season (from May to September) in 2007, plots in poplar plantations were irrigated once a month, with a rough water amount of 40–45 mm, whereas other plots were irrigated three times, with a rough water amount of 20–30 mm.

Soil samples were taken to a 30 cm-depth (for assessing C stocks according to the IPCC guidelines) (IPCC, 2003) using a soil auger, and separated into increments of 0–10, 10–20 and 20–30 cm depths. In July and August 2007, soil cores were collected randomly from 6 points in an "S" shape at each plot and were mixed to a composite sample by depth. A total of 45 soil samples were collected. In October 2007, forest floor litter samples were collected from three random subplots of 20 cm × 20 cm in each plot using a wooden frame. Litter samples were sorted into foliar (leaves and needles) and non-foliar materials (twigs and small branches), and then oven-dried at 80 °C to constant weights. All litter samples within each plot were pooled to one sample for chemical analysis.

Total C content was analyzed using Walkley-Black wet oxidation method (Allison, 1975), and total N was measured by Kjeldahl method (Bremner, 1996). A soil water mixture (1:2.5 for soil to water ratio) and a glass electrode were used to determine soil pH. Soil bulk density of the three depths was estimated using a steel core (100 cm^3 in volume), with soil fraction (> 2 mm) neglected.

2.3. Measurements of Rs and environmental factors

To quantify soil C loss in the land use types converted from croplands, 3–6 subsamples (soil collars) were distributed randomly in each plot of poplar plantation, spruce plantation, and clover grassland. In May 2007, PVC collars were inserted 2–3 cm from ground surface into the soil after removing litter and cutting off herbaceous layers (Conant et al., 2004). Collar heights were checked monthly to avoid possible changes in collar volume. Rs rate was measured with a Li-6400 portable CO_2 infrared gas analyzer (IRGA) equipped with a Li-6400-09 chamber (Li-Cor Inc., Lincoln, USA). During the growing season in 2007 (from May to September), Rs was measured 3 times in each plot between 10:00–14:00 per month (Conant et al., 2004).

Soil temperature was monitored simultaneously with Rs measurement using a constantan thermocouple penetration probe (Li6000–09 TC, Li-Cor Inc), inserted to a depth of 5 cm in the vicinity of collars. Soil