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Tillage and haymaking practices speed up belowground net productivity restoration in the degraded Songnen grassland

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ABSTRACT

The improvement of productivity and soil organic matter is a central issue for the restoration of degraded land. Belowground net primary productivity (BNPP) is a major source of soil organic matter. Therefore, understanding BNPP dynamics is crucial to improving our knowledge of belowground C allocation and storage in grasslands. However, how tillage and haymaking practices affect BNPP and belowground C allocation remains poorly understood. To investigate effects of tillage and haymaking practices on BNPP and root fraction (f_{BNPP}), a field experiment set within three fenced areas, one each for maize cultivation, artificial grassland, and natural grassland, was carried out during 2012–2014. The treatments were: maize tillage; maize no-tillage, keeping residues; maize no-tillage, removing residues; artificial grassland, no haymaking; artificial grassland, haymaking; natural grassland, no haymaking; and natural grassland, haymaking. The ingrowth donuts method was used to determine BNPP. Across the years, BNPP varied from 220 to 1331 $g\,m^{-2}$. Tillage and haymaking practices significantly increased BNPP and f_{BNPP} in maize cultivation and grassland managements, respectively, suggesting that more C is allocated to soil with BNPP in those land-use practices. On average, f_{BNPP} ranged from 0.25 to 0.54 and was significantly higher in 2014 than in 2012 and 2013, irrespective of the practices, indicating that precipitation is the controlling factor for determining C allocation between belowground and aboveground. Our findings highlight that tillage and haymaking practices can enhance BNPP and belowground C allocation. Therefore, from the perspective of the whole plant, they should be considered as feasible management practices for restoration of degraded grassland.

1. Introduction

Net primary productivity (NPP) is composed of aboveground net primary productivity (ANPP) and belowground net primary productivity (BNPP). It is an important component of the global carbon budget and is used as an indicator of ecosystem function (Scurlock et al., 1999). In semi-arid grassland ecosystems, BNPP is greater than ANPP (Milchunas et al., 2005; Gao et al., 2008). Since approximately 60% of annual C originates from plants, BNPP constitutes a major source of organic matter in soil (Milchunas and Lauenroth, 2001; Chen et al., 2006; Li et al., 2011). Therefore, understanding BNPP dynamics is crucial to improving our knowledge of belowground C allocation and storage in grasslands.

There is a lack of information on the responses of BNPP and root fraction to different land-use practices due to methodology and difficulty of root research. Previous results from various studies across the world demonstrated that root biomass varied among grasslands. For example, in Central and Northern American grasslands, root biomass increased with increasing water input (Li et al., 2011; Fahnestock and Delting, 1999), whereas the results from an alpine meadow of India showed a decline of root biomass after a two-year application of N (Ram et al., 1991). In Inner Mongolian grasslands, clipping and removing aboveground biomass and leaves through grazing dramatically changed species composition and significantly decreased ANPP (Zhou et al., 2006) and BNPP (Gao et al., 2008) Unfortunately, knowledge of BNPP and root fraction is still quite limited compared to ANPP, despite the tremendous importance of belowground ecological processes (Milchunas and Lauenroth, 2001; Wu et al., 2011; Xu et al., 2012).

In China, grasslands occupy more than 400 million ha in comparison to 120 million ha of arable land, and they play an important role

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for millions of people (Chen and Wang, 2000). The Songnen grassland, located in northeastern China, has been facing serious degradation due to anthropogenic activities and natural phenomena (Kang et al., 2007; Yi et al., 2012). Research has shown that over the past three decades, more than 30% of Songnen grassland has been changed into farmland, which may have consequences for ecosystem C processes and the cycle of nutrients (Liu et al., 2009; Yu et al., 2014; Diabate et al., 2015). Tillage and haymaking practices are important types of land-use management in grassland ecosystems. A suitable selection of tillage can improve the availability of water for yield performance by enhancing the storage capacity in soil water, reducing evaporation from the soil and allowing better development of root systems (Lampurlanés et al., 2001). Merrill et al. (1996) observed that spring wheat roots penetrate deeper into soil under no-tillage than under spring disking, with a higher density of root length due to cooler soil and higher water conservation in the near-surface area. Nevertheless, the practice of no-tillage can progressively increase mechanical resistance of the ground surface, limiting the distribution of roots within different soil profiles (Mosaddeghi et al., 2009). Roots are thinner and longer under tilled compared to no-tilled soil, and they are generally more profuse in tilled than in no-tilled soils at all depths (Karunatilake et al., 2000). The effects of haymaking on belowground productivity are different from tillage. Haymaking can accelerate the increase in carbon allocation to shoots, promote change in light regime and nutrient input, and create gaps and soil disturbance (Schaffers et al., 1998; Bakkar, 1989). As the constant supply of nutrients through atmospheric deposition can increase nutrient concentration, haymaking has become a significant tool in counteracting or reversing the changes in plant species decomposition of the vegetation (Schaffers et al., 1998).

To date, neither information about BNPP based on the ingrowth donut method nor information about effects of tillage and haymaking practices on BNPP and root fraction (f_{BNPP}) has been available for the Songnen grassland. Therefore, the present study was performed to investigate effects of tillage and haymaking practices on BNPP and root fraction (f_{BNPP}) at a site with three main management practices, i.e., cultivation, artificial grassland, and natural grassland. Specifically, two questions should be answered: (1) Can different management practices of tillage and haymaking speed up BNPP restoration, increase belowground C allocation, and further enhance soil organic matter? (2) Which land-use management is the best feasible approach for grassland restoration from the point of view of the whole plant? Understanding the effects of tillage and haymaking practices on BNPP and f_{BNPP} could improve our knowledge of the terrestrial C cycle, build a more complete theory framework, and provide suggestions for land-use practices and sustainable grassland ecosystems restoration.

2. Material and methods

2.1. Study site

2.1.1. Site description

This field experiment was carried out at Grassland Farming Research Station of Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences at the Songnen grassland, Changling County, Jilin Province, Northeast China. The Songnen grassland has an area of 300 ha and extends from 44° 34′ to 44° 38′ N and from 123° 30′ to 123° 35′ E. The study site is relatively flat, with an elevation about 145 m above sea level and characterized by a temperate, semi-arid continental monsoon climate. The climate is hot and wet in summer but very dry and cold in winter, with a mean temperature of 23 °C in July and −20 °C in January. The annual average air temperature is between 4.9 °C and 6.4 °C, and the frost-free period is about 140–160 days. The mean annual precipitation is around 450 mm, with 70% falling from June to September. The three experimental years were distinct in terms of precipitation (Supplemental Fig. S1). 2012 was a wet year with 481 mm of rainfall between June and September and an annual precipitation of 525 mm, while rainfall in 2013 was relatively low in terms of amount (355 mm) but with a clear seasonal distribution and most of the rain events occurring in July and August. The year 2014 had the driest season, with an annual precipitation of 248 mm. Mean annual temperature in 2012–2014 was between 5.15 °C and 6.96 °C (Supplemental Fig. S1). The soil type is meadow saline-alkali, with high basic salt content. The pH of the soil varied from 7.5 to 10. The dominant native species were *Leymus chinensis* (Trin.) Tzvel., *Chloris virgata* Sw., and *Puccinellia* spp (Yu et al., 2014). Community coverage was 60%-90%, with 100–200 g m^{-2} standing biomass.

2.1.2. Experimental design

The experiment includes three main types of management, i.e., maize cultivation; artificial grassland; and natural grassland. Maize cultivation management was divided into: maize tillage (MT); maize no-tillage, keeping residues (MNTKR); and maize no-tillage, removing residues (MNTMR). Artificial and natural grassland management was divided into no-haymaking (NHM) and haymaking (HM) treatments. Therefore, in each block (45 m in length, 11 m in width), there were seven treatments: MT; MNTKR; MNTMR; artificial grassland, no haymaking (AGNHM); artificial grassland, haymaking (AGHM); natural grassland, no haymaking (NGNHM); and natural grassland, haymaking (NGHM). A total of four blocks were established, with four replications for each treatment. Artificial grassland was composed totally (100%) of the perennial rhizome species *L. chinensis*, and the natural grassland was about 30% constituted of weeds species (*Carex duriuscula* and *Phragmites australis*) and about 40% of *C. virgata*. At the end of each growing season, all plants in maize cultivation management were harvested and cut down, with residues left until the early beginning of next growing season. During the same period, plants in haymaking plots of both artificial and natural grasslands were cut down to 5 cm height and taken away for hay, while in the no-haymaking plots, plants were kept intact throughout the entire study period. At the early beginning of following growing season, the first plot of maize cultivation management was completely tillage, while the second and third plots were not tillage. In the second plot, all maize and plant residues were kept, whereas in the third plot, residues were removed. In the haymaking plots, all plants residues were removed.

2.2. Plant samples collection and measurements

2.2.1. Aboveground net primary productivity (ANPP), belowground net primary productivity (BNPP), net primary productivity (NPP), and root fraction (f_{BNPP})

During the three years, plants were harvested when aboveground biomass attained its peak value between August and September. For each treatment, all the plants within an area of 1 m × 1 m with three replicates were collected by cutting at ground level and the aboveground biomass was considered approximately equal to the aboveground net primary productivity (ANPP). For maize cultivation management, only one replicate was considered. All samples were dried at 75 °C for 48 h.

The ingrowth donut method (Milchunas et al., 2005) was performed to determine BNPP (g m^{-2}). In autumn 2011, three PVC tubes were installed in every treatment for root collection throughout the entire experiment period. Roots were collected at the end of each growing season. Briefly, during root collection, PVC tubes were extracted from the holes. Soils and nylon mesh in the holes were collected, bagged, labeled, and taken to the laboratory for separation. All roots, residual impurities contained in soils, and nylon mesh were separated manually. Clean soil and nylon mesh were then returned to the original holes for the next sampling. Collected roots were handwashed and dried at 75° C for 48 h, and then weighed. BNPP was calculated as:

$$BNPP = \Delta x/\pi(R_1^2 - R_2^2)$$