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Soil respiration and its autotrophic and heterotrophic components in response to nitrogen addition among different degraded temperate grasslands

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ABSTRACT

Atmospheric nitrogen (N) deposition greatly affects grassland soil respiration (Rs) and its components. However, whether there exists a similar pattern in the response of Rs and its components to N deposition among the grasslands with varying degradation status remains unclear. We established a 3-year field experiment with six N addition levels on three grassland sites (non-degraded, moderately degraded and severely degraded) and measured autotrophic respiration (Ra), heterotrophic respiration (Rh), Rs and their influencing factors, including abiotic and biotic variables. Our results showed that Ra had an increasing tendency, whereas Rh and Rs had decreasing tendencies, in response to increasing N addition in the non-degraded and moderately degraded grasslands. In the severely degraded grassland, Ra, Rh and Rs exhibited increasing tendencies under lower N addition levels and decreasing tendencies under higher N addition levels. In the non-degraded grassland, N addition mainly affected Rs by directly increasing Ra and decreasing Rh. Conversely, in the moderately degraded grassland, N addition tended to indirectly affect Ra through increased aboveground biomass. In the severely degraded grassland, Rh was influenced indirectly by an increase in aboveground biomass. The findings of this research highlight the importance of considering the degradation level of grasslands when assessing grassland soil carbon emissions under N deposition scenarios.

1. Introduction

As the second largest flux of carbon (C) between terrestrial ecosystems and the atmosphere, soil respiration (Rs) is an important component of the global C cycle (Shao et al., 2014). The C emissions from Rs account for approximately 10% of the global atmospheric carbon dioxide (CO_2) each year, more than 10 times that from fossil fuel burning (Bond-Lamberty and Thomson, 2010; Silver, 2014). Because of the magnitude of the soil-atmosphere C flux, a minor variation of Rs rate in response to environmental changes has the potential to greatly alter atmospheric CO_2 concentrations (Riley et al., 2005) and induces an important feedback to global climate change (Knops and Reinhart, 2000). Rs mainly consists of microbial heterotrophic respiration (Rh) and autotrophic respiration (Ra) associated with root biomass and root activity. Rh reflects the dynamics of soil organic C decomposition and mineralization, whereas Ra is primarily influenced by the supply of the photosynthetic product to roots (Zhou et al., 2007). The two components of Rs may therefore respond to environmental changes in different ways.

Grassland is one of the most widespread vegetation types, occupying approximately 40% of the Earth's land area (excluding areas of permanent ice cover) (White et al., 2000; Wang and Fang, 2009), and plays an important role in the global C cycle. In China, nearly 78% of grasslands are located in northern temperate and semiarid areas (Chen and Wang, 2000). Grassland degradation has become a serious problem in these areas because of the dry climate conditions and disturbances from human activities. Previous studies have reported that 61.49% of northern grasslands in China have experienced degradation to various extents (Zhou et al., 2014), as a result of desertification and a prolonged nitrogen (N)-deficient status (Christensen et al., 2004; Yuan et al., 2006). Grassland degradation involves both a reduction of vegetation growth (Cheng et al., 2007) and a decline of soil quality such as soil C and N (Liu et al., 2008), and thus significantly affects Rs (including Ra and Rh). However, limited information is available on Rs and its

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components, in degraded grasslands. Because the C pool in grasslands is large and variable, assessment of the potential changes in Rs and its components in degraded grasslands is needed (de Figueiredo et al., 2017).

The availability of N in grassland ecosystems has increased in recent decades owing to atmospheric N deposition (Galloway et al., 2008) and anthropogenic N fertilization (Law, 2013; Field et al., 2014). Lower level N addition (≤ 5 g N m^{-2} $year^{-1}$) has been shown to relieve soil N limitation on microbes (Esch et al., 2013), thereby increasing Rh by increasing the microbial biomass (Huang et al., 2018), and causing a reduction in the photosynthetic product allocation to belowground (Adair et al., 2009), thus decreasing Ra. However, at higher N addition levels, soil acidification caused by excess N addition can inhibit microbial growth and activity, and result in a negative effect on Rh (Janssens et al., 2010; Yao et al., 2014). Moreover, due to N saturation at higher N availability, a gradient of N addition shows a nonlinear Rs response, increasing at lower N availability but decreasing at higher N availability (Du et al., 2014). However, previous studies have generally been conducted in forests or non-degraded grassland ecosystems. In degraded grasslands, available soil C and N are decreased (Liu et al., 2017), plant growth and biomass are reduced (Braz et al., 2013; Li et al., 2015) and microbial activities decline (He et al., 2013; Liu et al., 2013). In degraded grasslands there is less aboveground biomass and root biomass compared with non-degraded grasslands, resulting in lower Ra (Cheng et al., 2007), and a reduced substrate supply for microbial decomposition that in turn results in lower Rh (Adair et al., 2009). Empirical studies on degraded grasslands have shown that artificial N addition could be an effective management technique to restore aboveground grassland productivity (Torok et al., 2014; Chen et al., 2017). It has been shown that small rates of N addition are able to greatly promote plant biomass production (Gargano et al., 2001) and improve soil nutrient conditions (Zhang et al., 2014). Increasing plant biomass increases Ra and the better soil nutrient supply stimulates the growth of microbes thus increasing Rh in degraded grasslands. Consequently, when equivalent rates of N are added, the magnitude of the Ra and Rh increases in response to N addition in degraded grasslands may be larger than in non-degraded grasslands. In addition, because of the more serious N scarcity in degraded grasslands, the nonlinear response of Rs with increasing N availability is likely to disappear and a linear Rs response probably occurs (Christensen et al., 2004). Therefore, an increase of N availability in degraded grasslands may enhance the release of CO_2 from the soil, thus reducing soil C storage, and have a negative effect on grassland restoration. Hence, a better understanding of Rs and its components in response to increasing N availability in the grasslands with varying degradation status will assist in conserving natural grasslands and enable appropriate management strategies to be used in degraded grasslands.

In this study, we established an N fertilization experiment on temperate steppes with varying degradation status (non-degraded, moderately and severely degraded) at the southeastern edge of the Inner Mongolian Plateau, China. A gradient of six N fertilization levels was established at each site. We measured Rs and its components and the associated abiotic and biotic factors. The measured abiotic factors were soil pH, soil total C concentration, soil total N concentration, soil inorganic N and soil dissolved organic C. The measured biotic factors were microbial biomass C, microbial biomass N, root total C concentration, root total N concentration, aboveground biomass, and belowground biomass. We aimed to determine (i) the patterns of Rs and its components in response to N addition in grasslands of varying degradation status, and (ii) whether Rh and Ra were affected by different pathways in grasslands with different degradation status.

2. Materials and methods

2.1. Site description

The study area was located on the Ulan Buton, Inner Mongolian Plateau, China (42°33′–42°38′N, 117°5′–117°8′E), with a mean annual temperature of about −1.4 °C and mean annual precipitation of around 400 mm. The altitude is 1503 m above sea level. The original soil type is a Chernozem according to the Food and Agriculture Organization classification, with sand and silt dominating its surface layer. The original vegetation in the study area was meadow steppe dominated by *Leymus chinensis, Stipa baicalensis* and *S. grandis* (Liu et al., 2008). Since the beginning of last century, agricultural and pastoral areas have expanded due to the increase in the human population in this area. With the intensification of farming and grazing, the amounts of the dominant species in the non-degraded grassland have gradually decreased and the amounts of degradation indicator species such as *Potentilla acaulis, Artemisia frigida* and *A. capillaries* have gradually increased. These agricultural activities have also caused a reduction of vegetation cover and many of the fine particles in the soil surface layer have been blown off by the wind. Consequently, the soil texture becomes coarser and the soil nutrient content becomes poorer (Liu et al., 2008; Xu et al., 2015). Most grasslands in this area have experienced degradation. Since the 1970s, a series of ecological restoration projects have been conducted in China, resulting in extensive conversion of cropland or abandoned fields for grassland restoration (Liu et al., 2008). As a result, the grasslands in this area now vary in terms of their degradation status. Three sites in this area, with different degradation status, were chosen on flat land where the slope was < 5° and the elevation differences were no more than 23 m. The distances between sites were less than 10 km in order to maintain similar climatic conditions (such as temperature and precipitation) and the original soil and vegetation types before degradation (Chen et al., 2017). Details of the plant communities and soil properties at the three study sites were shown in Table S1.

2.2. Grassland degradation definition and evaluation

Grassland degradation is defined as the main form of land desertification, which is caused by climate change (such as less frequent but more intense rainfall events and higher winter temperatures) and human activities (such as overexploitation, overgrazing and cultivation) in arid and semi-arid areas (United Nations Convention to Combat Desertification, 2012). It results in lower production, decreases in vegetation biodiversity and soil fertility, and soil texture changes (Food and Agriculture Organization, 2010). We established an evaluation system combining plant and soil properties to quantify the degree of grassland degradation. The plant properties included the relative cover of herb species categorized into three groups: annuals (mainly appearing in the severely degraded steppe), moderate grazing degradation indicators, and climax species in non-degraded steppe (Liu et al., 2008). The soil properties included soil total C concentration, soil total N concentration and soil sand content. We calculated the grassland degradation index (GDI) for each site using Equation (1) as follows:

$$GDI = (P_1 \times 1/3 + P_2 \times 2/3 + P_3) \times 1/3 + (STC \times 1/2 + STN \times 1/2) \times 1/3 + (1/SAND) \times 1/3 \quad (1)$$

where P_1, P_2 and P_3 indicate the relative cover of annual pioneer species, degradation indicator species and climax species, respectively; STC and STN indicate the soil total C concentration and soil total N concentration, respectively; and SAND indicates the soil sand content. The details of the properties involved in Equation (1) were listed in Table S1.

According to the GDIs, we classified the chosen grassland sites as having three different degradation degrees: non-degraded (GDI 0.91), moderately degraded (GDI 0.64) and severely degraded (GDI 0.38). The