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Effects of warming and nitrogen deposition on the coupling mechanism between soil nitrogen and phosphorus in Songnen Meadow Steppe, northeastern China

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ABSTRACT

Songnen Meadow Steppe, which is in northeast China, is increasingly affected by global warming and incremental increases in atmospheric nitrogen deposition. However, the responses of nitrogen (N) and phosphorus (P) in steppe soil, and of the coupling mechanism between them, to the dual effects of global warming and N deposition are still unknown. In this study, the effects of simulated atmospheric warming and N deposition on N and P in Songnen steppe soil, as well as on the coupling between N and P, were examined under in situ conditions. Infrared heaters were used to elevate soil temperature by approximately 1.7 °C since 2006. N additions were treated once a year with aqueous ammonium nitrate at a rate of 10 g m^{-2} a^{-1}. During the four-year study, addition of N increased the amount of total N, and available N, as well as the rate of N mineralization in the soil. Moreover, the amounts of total P and available P in the soil were considerably reduced. Thus, the N:P ratio increased, and the coupling between N and P decreased. Similar values for the N:P ratio were obtained for the addition of N by itself and for the combination of warming and addition of N, which indicates that a small amount of soil warming in Songnen Meadow Steppe would not have a substantial effect on the ratio. With the growth of China's industrialization, N deposition continues to increase. The study area of Songnen Meadow Steppe, and northeast China in general, are characterized by widespread distribution of saline alkali soil. Therefore, the finding of increased P limitation in the soil of Songnen Meadow Steppe has major implications for ecosystems in northeast China. Reasonable regulation and management of meadow soil nutrients will be of great importance in increasing soil productivity and promoting sustainable use of grassland ecosystems.

1. Introduction

Global change, including warming, N deposition, increasing concentration of CO_2, and changes in atmospheric composition are associated with ecological problems that have become important topics of current study (Zhang et al., 2007). According to the Fourth Evaluation Report of the IPCC, the trend in global warming over the past fifty years indicates an increase in temperature by an average of 0.13 °C per decade, almost the twice the rate of increase over the past 100 years; in the next 20 years, the temperature is predicted to increase by an average of 0.2 °C per decade (IPCC, 2007). Meanwhile, the amount of atmospheric N deposition is also increasing steadily (Aber, 1992; Kaiser, 2001). Currently, North America, Europe, and East Asia (especially China) are the regions experiencing the greatest amount of N deposition worldwide (Liu et al., 2013; Vitousek et al., 1997; Galloway et al., 2008). Estimates of the active N generated by human activity have increased from 15 Tg N a^{-1} in 1860 to 165 Tg N a^{-1} in 1995 (Galloway and Cowling, 2002), an increase of a factor of 11; the 1995 estimate represents about 1.6 times the critical load of global N of 100 Tg N a^{-1} (Kaiser, 2001). The continual increase of N deposition will seriously affect the circulation of soil nutrients and the relationships among nutrients, and will affect ecosystem stability (Galloway et al., 1994; Melillo and Cowling, 2002). Therefore, it is essential to explore the

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effects of global warming and N deposition on soil nutrient stoichiometry of grassland ecosystems, these data will contribute to the understanding of soil nutrient status and may have potential significant implications for the management of grassland restoration.

Temperature is the most important non-biological factor affecting N mineralization. An increase in soil temperature affects N mineralization, decomposition of organic material, amount of soil nutrients present, and migration of soil nutrients, thus altering ecosystem structure and function (Agren et al., 1991; Coughenour and Chen, 1997). Some research indicates that the increase in temperature will influence microbial processes in the soil, increasing the activity of soil enzymes and the bioavailability of N (Zhang et al., 2005; Rustad et al., 2001). The increase of the amount of available nutrients will increase the primary productivity of vegetation and reduce species richness, leading to the redistribution of soil nutrients. However, the specific mechanisms for this process are still unknown, and further exploration and research is required (Freeman et al., 1993; Zak et al., 1999; Maestre et al., 2005). Other research indicates that warming has no noticeable influence on the rate of net mineralization of N and P, or on net primary productivity, and therefore will not facilitate vegetation growth (Rinnan et al., 2007; Menge and Field, 2007). However, there is a lack of information on the response of the coupling mechanism between N and P in soil as temperature increases.

A great deal of research on land plants indicates that the available N:P ratio is sensitive to occurrences of nutrient limitation during vegetation growth and is closely related to the N:P ratio in plant foliage. Therefore, the available N:P ratio can be regarded as an effective index for evaluating ecosystem health (Schipper et al., 2004). Previous study observed that an ecosystem is controlled by N when the N:P ratio is low (<10), by P when the N:P ratio is high (>20), and by both N and P when the N:P ratio is between 10 and 20 (Güsewell, 2004). However, results vary in some ecosystem studies. For example, research conducted in Dutch wetlands indicated that the ecosystem is controlled by N when the N:P ratio is low (<14), by P when the ratio is high (>16), and by both N and P when the ratio is between 14 and 16 (Koerselman and Meuleman, 1996). The critical values of the N:P ratio for barren grassland are considered to be 10 and 14 (Braakhekke and Hooftman, 1999). Different threshold values of the N:P ratio have been suggested for perennial grassland: the system is considered to be controlled by N when the ratio is less than 21, and by P when the ratio is more than 23 (Zhang et al., 2004).

The influence of N deposition on soil nutrients is an issue of great interest among researchers (Adams et al., 2004; Robinson et al., 2004; Xia et al., 2009; Liu et al., 2011). Much of the research indicates that N deposition promotes net N mineralization in soil, increases the bioavailability of N in soil, and increases the net productivity of plants and the output of litter (Aerts et al., 2006; Vourlitis et al., 2007; Sirulnik et al., 2007). Long-term deposition of N will reduce the richness of the plant community and change its composition (Nkana et al., 1999; Prieto et al., 2009). Global change factors such as N, CO_2 and warming frequently limit plant growth, can increase or decrease primary production (Field et al., 1992). The increase in the availability of N will increase primary production, plants need to maintain a stable N:P ratio which encourages the absorption and utilization of soil P (Menge and Field, 2007). Thereby it increasing P demand or limitation and changing N limitation in soil to P limitation.

The influence of the increase of N on soil enzyme activity may be the major reason leading to the change of the limiting factor (Wedin and Tilman, 1993; Rinnan et al., 2007). An increase in N deposition can increase the output of litter, which is an important source of available soil nutrients because it adds available N and P to soil and increases the net P mineralization rate (Bradley et al., 2006). In studies of the influence of N deposition on availability of P, some researchers have noted that the addition of N increases the amount of inorganic N but reduces the amount of P in soil, thereby increasing the N:P ratio (Limpens et al., 2004).

In summary, research on the influence of global change on important soil nutrient factors is mostly centered on a single factor. However, the interaction between warming and N deposition will cause changes in the absolute amount of N and P in soil as well as in their relative proportions. These changes will profoundly influence vegetation growth, species competition, community composition, and ecosystem function. Unfortunately, the current lack of studies on how warming and nitrogen deposition influence the N:P ratio leaves a major gap in our understanding of the effects of alterations in this ratio.

Because about one-third of Earth's land surface is covered by grassland, the effects of global change on grasslands have major implications for the planet (Gao et al., 2006). *Leymus chinensis* Meadow, located in Songnen Meadow Steppe in northeast China, is the most typical and the largest grassland type in China (Zhu, 2004). This is an important area to study the effects of climate change and to determine possible ways to mitigate them. In nearly twenty years, the average temperature of Songnen Meadow Steppe has increased by 2 °C (Wang et al., 2006). The average atmospheric N deposition is approximately 10.5 g m^{-2} a^{-1} (Bai et al., 2010), and it is increasing year by year. Soil N and P are not only important nutrients but also are limiting factors on vegetation growth (Güsewell, 2004). This limiting function is more pronounced in the Songnen Meadow Steppe because of the widespread distribution of saline alkali soil (Su, 1995). Songnen Meadow Steppe was chosen as the research site for this study, which explores the influence of simulated warming and N deposition on soil N, soil P, and the coupling mechanism linking them under in situ conditions. The hypothesis under investigation is that there is coupling mechanism between soil N and P, and that N addition by itself, or a combination of N addition and warming, will increase the rate of net mineralization of N in soil, thus increasing the amount of available N and facilitating vegetation growth. Increased absorption of P by vegetation will lead to a reduction in the amount of soil P. These processes will ultimately reduce the coupling mechanism between soil N and P. This research provides a theoretical basis for understanding the influence of ongoing trends related to global changes on soil nutrients in Songnen Meadow Steppe, and it is relevant to determining methods to facilitate the recovery of grassland ecosystems and protect the environment as global changes occur.

2. Materials and methods

2.1. Study site

The study was conducted at the Songnen Grassland Ecosystem Research Station (44°45′ N, 123°45′ E, 160 m a.s.l.), Jilin Province, northeastern China. This region has a temperate semi-arid monsoon climate. The annual average air temperature is 4.9 °C. Mean annual precipitation (1980–2006) is approximately 410 mm, with more than 70% received from June to September. The total precipitation received during 2007–2010 was 275.9 mm, 384.2 mm, 390 mm, and 352.5 mm, respectively. The type of grassland is meadow steppe, and most of the grassland has a sodic saline meadow soil with a pH value of 8.2. The vegetation at the site is dominated by the perennial grass *Leymus chinensis* (Trin.) Tzvel.; *Phragmites communis*, *Kalimeris integrifolia* Turcz. Ex DC. and *Carex duriuscula* C. A. Mey. are also present at lower density.