Ecological Engineering 106 (2017) 1–9

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Soil nutrient changes induced by the presence and intensity of plateau pika (*Ochotona curzoniae*) disturbances in the Qinghai-Tibet Plateau, China

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ARTICLE INFO

Article history:
Received 13 January 2017
Received in revised form 18 May 2017
Accepted 18 May 2017
Available online 25 May 2017

Keywords:
Alpine meadow
Plateau pika
Presence
Intensity
Soil nutrients

ABSTRACT

The plateau pika (*Ochotona curzoniae*), one of the main bioturbators, creates extensive disturbances in the soil of the alpine meadow of the Qinghai-Tibet Plateau (QTP). This study investigated the effects of the presence and intensity of plateau pika disturbances on the main soil nutrients of the *Kobresia pygmaea* meadow across three study sites in the QTP by using the method of counting the active burrow entrance densities of plateau pika in the field as a representation of the disturbance intensity. Our results showed that the presence of plateau pika significantly increased the soil total nitrogen (TN), soil organic carbon (SOC) and total phosphorus (TP) concentrations and decreased the available phosphorus (AP) concentrations across the three study sites. The presence of plateau pika increased the NO_3^--N and NH_4^+-N concentrations in Luqu County and Maqu County, but had no significant effect on these concentrations in Gonghe County. The soil TN, SOC and TP concentrations showed a downward parabola and the NO_3^--N, NH_4^+-N and AP concentrations showed an upward parabola as the intensity of the disturbances increased in Luqu County and Maqu County. These soil nutrients had a threshold (inflection point) of 475 (475 ± 90) burrow entrances per ha. However, the soil TN, SOC and TP concentrations increased linearly while the NO_3^--N, NH_4^+-N and AP concentrations decreased linearly with the increasing intensity of disturbances in Gonghe County ($\leq$512 burrow entrances per ha). These results implied that the soil nutrient changes induced by plateau pika disturbances are not only related to their presence but are also related to the intensity of the disturbances, and that the most appropriate disturbance intensity (475 (475 ± 90) burrow entrances per ha) of plateau pika was beneficial to the storage of soil carbon and nitrogen in the alpine meadow in the QTP.

1. Introduction

Soil, an essential part of grasslands, physically supports primary producers and decomposers and maintains biotic communities in grassland ecosystems (Brady and Weil, 1996; Lavelle et al., 1997; Dominati et al., 2010; Eisenhauer et al., 2011; Bueno et al., 2013) by regulating nutrient cycling or material-energy flows (Brady and Well, 1996; Lavelle et al., 1997). However, the soil properties of grassland ecosystems are usually disturbed by various direct and indirect soil bioturbators (Jones et al., 1997; Gabet et al., 2003; Richards, 2009; Resner et al., 2015). These bioturbators often alter the soil nutrients concentration of grassland by redistributing soil nutrients within soil profiles (Villarreal et al., 2008), which occurs rapidly on the temporal and spatial scales when compared to other plant-driven and geologic processes (Fleming et al., 2014). Wild boar rooting increases the soil total nitrogen and NO_3^--N concentrations while it decreases the NH_4^+-N concentrations in the alpine grassland of the Spanish Central Pyrenees (Bueno et al., 2013). The burrowing and casting activities of earthworms (*Allolobophora hrabei*) induce an increase in the concentrations of soil dissolved organic carbon and archaea richness, which enriches the available nutrients in the steppe grasslands of southern Moravia in the Czech Republic (Jirout and Pižl, 2014). Tuco-tucos (*Ctenomys Mendocinus*) disturbances soften the topsoil and increase soil nitrogen, phosphorus and potassium while decreasing soil calcium in the South Brazilian coastal plain (Malizia et al., 2000; Galiano et al., 2014). These effective studies show that soil bioturbators alter the spatial and temporal heterogeneity of soil nutrients and become important agents for maintaining species diversity and soil nutrient cycling in grassland ecosystems.

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http://dx.doi.org/10.1016/j.ecoleng.2017.05.029
0925-8574/

The plateau pika (*Ochotona curzoniae*), an important bioturbator, is an endemic and dominant small animal of the alpine meadow ecosystem in the Qinghai-Tibet Plateau (QTP) (Smith and Foggin, 1999; Lai and Smith, 2003). For a long time it has been considered to be the main cause of the alpine meadow degradation in China by its foraging and digging behavior (Smith and Foggin, 1999; Guo et al., 2012; Liu et al., 2013). Plateau pikas alter the soil properties of the alpine meadow through its roles as a forager of vegetation, constructor of extensive burrow networks and producer of bare patches (Smith and Foggin, 1999; Sun et al., 2015a; Wu et al., 2015). For example, the burrowing behavior of plateau pikas usually creates a complex mosaic of disturbed patches of different sizes (Davidson and Lightfoot, 2008; Wu et al., 2015), redistributing soil among different horizons, and these alter the concentration and distribution of the soil nutrients and further affect the ecological functions of the alpine meadow (Zhou et al., 2010; Fleming et al., 2014; Qin et al., 2015). Published findings illustrate that the effectiveness of plateau pika disturbances on soil properties is dependent not only on the presence but also on the intensity of the disturbances (Zhou et al., 2010) because severe soil erosion and degradation often occur with the high intensity of plateau pika disturbance rather than low intensity (Wangdwei et al., 2013). Soil nutrients are remarkably sensitive in the alpine meadow due to cool temperatures and a relatively short growing season in the QTP (Körner, 2003; García-González, 2008), and the sensitivity of soil nutrients may be exacerbated by plateau pika disturbances. Studies indicate that the presence of plateau pika accelerates soil erosion and vegetation degradation, reduces the palatable forage proportion for domestic livestock (Wei et al., 2007; Dong et al., 2013), and increases CO_2 emitted into the atmosphere (Qin et al., 2015). Some other studies argue that the presence of plateau pika stimulates microbial activity, improves organic matter decomposition and soil nitrogen availability (Villarreal et al., 2008; Zhang et al., 2016) and increases soil organic matter in the topsoil layer (Li et al., 2006). Meanwhile, the presence of plateau pika often creates microhabitats in the alpine meadow, resulting in an increase in plant species richness and "hot spots" of biological activity over longer timescales (Smith and Foggin, 1999; Davidson and Lightfoot, 2008; Zhang et al., 2016). These results indicate that the responses of the soil properties to the presence of plateau pika are not consistent in a partial microenvironment. The population size of plateau pika is a direct indicator that can be used to evaluate whether these impacts are beneficial or detrimental to alpine meadow ecosystems (Guo et al., 2012; Sun et al., 2015b).

There are also several ongoing debates concerning the effects of the intensity of plateau pika disturbances on the soil nutrients of the alpine meadow. Sun et al. (2015b) and Liu et al. (2013) reported that soil organic carbon, total nitrogen, total phosphorus and NH_4^+-N decrease but that soil temperature and NO_3^--N increase with the increased intensity of plateau pika disturbances. Guo et al. (2012) indicated that moderate disturbances by plateau pika increase the soil organic matter, total nitrogen and total phosphorus contents. However, Peng et al. (2015) argued that soil organic carbon, total nitrogen and inorganic nitrogen (NO_3^--N and NH_4^+-N) had no obvious trend with the increasing intensity of plateau pika disturbances. These findings provide useful information for understanding the role of plateau pika in the alpine meadow ecosystem, but these studies ignored the changes of dominant plant species in regard to different disturbance intensity areas across different grassland types. This creates a dilemma of whether the changes in the soil nutrients result from the intensity of plateau pikas disturbances or from the difference in the grassland types. Therefore, it is necessary to indentify the changes in the soil nutrients in same alpine meadow type, which will clarify the actual response of the soil nutrients to the intensity of plateau pika disturbances.

The *Kobresia pygmaea* meadow is the main alpine meadow type and its area is larger than areas of other alpine meadow types in the QTP. Its dominant plant is *K. pygmaea*, with low height and high nutritional value (Li et al., 2013), belonging to the *Cyperaceae*. Thus, the *K. pygmaea* meadow not only plays an irreplaceable role in sustaining native livestock production and biodiversity, conserving water and preventing soil erosion in the QTP (Wang et al., 2008; Wu et al., 2015), but it is also a good habitat with very easy access for plateau pikas due to its relatively low height of vegetation, which provides an open window for plateau pikas to detect and avoid predators (Wangdwei et al., 2013). Thus, the *K. pygmaea* meadow is a representative example of how the plateau pika dramatically affects soil properties. This study aimed to assess whether the presence and intensity of plateau pika disturbances affected the soil nutrients across three study sites where they share the common *K. pygmaea* meadow. Specifically, we hypothesized that: (1) the response of soil nutrients to the presence and intensity of plateau pika disturbances is inconsistent; (2) different intensities of plateau pika disturbances have different influences on the soil nutrients; (3) the response of the three study sites to the presence and intensity disturbances of plateau pika is consistent; (4) an appropriate intensity of plateau pika disturbance is beneficial to soil nutrients in the QTP. This study will be beneficial for understanding the influence of the presence of the plateau pika and its disturbance intensity on soil properties.

2. Materials and methods

2.1. Study area description

The study area was located in Luqu County (102°18′37″ E, 34°20′36″ N), Maqu County (101°53′15″ E, 33°40′41″ N) and Gonghe County (99°35′46″ E, 36°44′34″ N) in the QTP of China. The altitudes of the three study sites are 3550 m, 3530 m and 3750 m above sea level, respectively. The climate of the three study sites is the typical plateau continental climate that is windy, cold, and humid. The average annual temperature is 1–3 °C, with a minimum mean monthly temperature that falls below −10 °C in January and a maximum mean that rises above 12 °C in July. The mean annual precipitation is 60–80 cm in Luqu County and Maqu County and 25–50 cm in Gonghe County, 80% of which falls in the short summer growing season during the period of June–September. The mean annual potential evaporation is 110–130 cm in Luqu County and Maqu County and 80–100 cm in Gonghe County. The alpine meadow is widely distributed in the study area and is the major type of natural grassland in the QTP, which plays an irreplaceable role in water conservation as well as in maintaining the food safety, air quality, and ecological barrier of the Yellow River Basin (Qi et al., 2008; Feng et al., 2010).

The *K. pygmaea* meadow is the main alpine meadow type in the three study sites where plateau pikas are present. For the purposes of this study, our sampling was restricted to *K. pygmaea* meadow at the three study sites. The dominant plant of *K. pygmaea* is perennial forbs and endemic species, and its height is approximately 1–3 cm. The main associated plant species are *Elymus nutans* and *Poa pratensis* of the *Poaceae, Anemone obtusiloba* and *A. rivularis* of the *Ranunculaceae*, *Potentilla anserine* and *P. fragarioides* of the *Rosaceae*, and *Saussurea hieracioides* of the *Asteraceae*. The soil type is subalpine meadow soil, according to the Chinese soil classification system (Gong, 2001). The soil is characterized by the presence of a mattic epipedon at approximately 7 cm in the topsoil, which is an organic matter-rich soil horizon. This alpine meadow sustains yaks and Tibetan sheep production via warm and cold season pasture rotational grazing.