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Effects of grazing exclusion on carbon sequestration and plant diversity in grasslands of China—A meta-analysis

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A B S T R A C T

Widespread land degradation has strengthened the urgent need to restore overgrazing grasslands. China has implemented the program 'Returning Grazing Land to Grassland' (RGLG) through grazing exclusion by fence since 2003. Despite a lot of field experiments, there is still controversy on the effects of grazing exclusion on rangeland restoration, highlighting the need for synthetic analysis. We conducted a meta-analysis of 447 entries from 78 papers to analyze the spatiotemporal effects of grazing exclusion on plant diversity, productivity and soil carbon sequestration in the major RGLG-implemented provinces of China. Our results showed that, compared with the grazed sites, grazing exclusion significantly increased carbon stored in aboveground biomass, litter mass, belowground biomass and soils by 84.7%, 111.6%, 25.5% and 14.4%, respectively. Plant coverage, soil available nitrogen, soil available phosphorus and soil microbial biomass carbon increased by 52.0%, 21.7% 22.8% and 26.3%, respectively. However, grazing exclusion had little effects on recovering plant diversity in China's grasslands. Of the factors examined, climatic factors strongly modified the effects of grazing exclusion on ecosystem carbon stocks, for example, precipitation significantly amplified the positive effects. Grazing exclusion played a positive role in soil carbon sequestration in most grassland types except in temperate desert-steppe. But annual soil carbon sequestration rates decayed rapidly over time in both alpine meadow and temperate steppe. Short-term (≤5 years) grazing exclusion remarkably increased species richness, but not significantly in the long run. The threshold from neutral to negative effects of grazing exclusion on species evenness occurs after approximately ten years. Our findings provide evidence that grazing exclusion is an effective way to restore vegetation and sequestrate carbon in degraded grasslands, but not beneficial to plant diversity maintenance. The benefits of grazing exclusion are more effective in humid area than arid area. We suggest that grazing exclusion should be ceased after about six to ten years. Additionally, grazing exclusion should integrate with other appropriate management practices instead of operating on a stand-alone basis.

1. Introduction

Grasslands have an important feedback effect in global climate change (Scurlock and Hall, 1998; Lal, 2004), as they contain a large amount of carbon susceptible to anthropogenic disturbance (Anderson, 1991; Derner et al., 2006). Livestock grazing is a pivotal issue affecting plant growth, species diversity and soil carbon accumulation in grasslands (Olff and Ritchie, 1998; Watkinson and Ormerod, 2001; Piñeiro et al., 2010; McSherry and Ritchie, 2013). Globally, excessive grazing is identified as one of the key disturbances leading to grasslands degradation and soil carbon loss (Snyman and du Preez, 2005; Akiyama and Kawamura, 2007; Papanastasis 2009; Jeddi and Chaieb, 2010). Widespread land degradation has strengthened the urgent need to restore overgrazing degraded grasslands in order to alleviate its negative effect and improve ecosystem goods and services.

Grazing exclusion by fence has become a common practice worldwide for managing overgrazed grasslands. The aim of grazing exclusion is to reverse the negative effects of overgrazing and recover degraded grasslands through their self-healing capacities (Smith et al., 2000; Shrestha and Stahl, 2008; Wu et al., 2009; Golodets et al., 2010). However, there is controversy in the effects of grazing exclusion on grassland carbon stocks and plant diver-

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sity. For carbon sequestration, some studies found that grazing exclusion facilitated vegetation recovery, increased plant productivity and thus enhance soil carbon stocks in degraded grasslands (Biondini et al., 1998; McIntosh and Allen, 1998; Li et al., 2008; Mekuria et al., 2007; Mekuria and Veldkamp, 2012; Xiong et al., 2014). Others, however, reported no change (McNaughton et al., 1998; Pucheta et al., 2004) or even decline of carbon stocks in grasslands (Schuman et al., 1999; Leriche et al., 2001; Frank et al., 2002; Wienhold et al., 2001). Controversial results have also been found on a regional and global scale. For example, Derner and Schuman (2007) synthesized data from the North American Great Plains and found that soil carbon stocks were lower in un-grazed than in grazed sites in areas with mean annual precipitation (MAP) of 600 mm or less. In contrast, in central Asia or Africa, many studies found positive effects of grazing exclusion on soil organic carbon (SOC) at sites with MAP less than 600 mm (Su et al., 2005; Wu et al., 2008; Mekuria et al., 2007; Mekuria and Veldkamp, 2012). For plant diversity, the results are also conflicting. Several studies reported no effects of grazing exclusion on plant diversity (Milchunas and Lauenroth, 1993; Meissner and Facelli, 1999), while a number of studies reported increases (Shaltout et al.,1996; Eweg et al., 1998; Shang et al., 2008; Mayer et al., 2009; Jeddi and Chaieb, 2010; Zhao et al., 2011), and others reported decreases (Proulx and Mazumder, 1998; Dullinger et al., 2003; Altesor et al., 2005; Peco et al., 2005, 2006; Wu et al., 2009), in plant diversity in response to grazing exclusion. Generally, the effectiveness of grazing exclusion denpends on its duration (Milchunas and Lauenroth, 1993; Su et al., 2005; Wu et al., 2008; McSherry and Ritchie, 2013), environmental conditions (Conant and Paustian, 2002; Derner and Schuman, 2007; Piñeiro et al., 2010; J.S. Wu et al., 2012, 2014) and vegetation types (Proulx and Mazumder, 1998; Tanentzap and Coomes, 2012; McSherry and Ritchie, 2013) in specific sites.

China's grasslands cover approximately 6–8% of the world's total area and contain 9–16% of the world's total grassland C stocks (Ni, 2002), hence playing an important role in regional climate change and global C cycling (Ni, 2002; Piao et al., 2009). The stocking rates usually exceed the safe carrying capacity (Chen et al., 2003). Over 90% of rangelands have been widely degraded (Liu and Diamond, 2005; Han et al., 2008), owing to long-term overgrazing (Akiyama and Kawamura, 2007; X. Wu et al., 2014). In the last 20 years, fence has been widely used in China to restore degraded rangelands. Especially, the area of grazing exclusion has reached 26.2 million hectares, accounting for 10.8% of China's natural grasslands since national conservation program RGLG implemented in 2003 (MAO, 2007, 2014). Despite numerous site-level studies have analyzed the effects of grazing exclusion on diversity and carbon sequestration, controversial results still exist (Ren et al., 2008; Wu et al., 2010; Cheng et al., 2011; Hafner et al., 2012). These inconsistent results constrain our ability to make management decisions based on the literature. Therefore, it is necessary to make a synthetic assessment on the effects of grazing exclusion for grassland restoration. The synthesis would be highly relevant for knowledge sharing and providing recommendation for rangeland management. However, to our knowledge, there has been little synthetic analysis assessing the overall effects of grazing exclusion at the regional or country level in China.

Meta-analysis provides a robust, quantitative synthetic method for a collection of studies (Hedges et al., 1985), and can identify generalities of impacts over the large variability (Gurevitch and Hedges, 1999). The use of meta-analysis is important to summarize the generalities and identify influencing factors. In order to ascertain how grazing exclusion influences carbon sequestration and plant diversity in China's degraded grasslands, we collected published data of pair-wise comparison with grazed vs. un-grazed studies for meta-analysis. Specifically, we aimed to: (1) quantify the magnitude and direction of the overall effects of grazing exclusion on ecosystem carbon stocks, including aboveground biomass, belowground biomass and soils; (2) examine the overall effects of grazing exclusion on different diversity indices, species richness, species evenness, the Shannon index and the Simpson index; (3) identify factors influencing the effects of grazing exclusion on carbon sequestration and plant diversity, and provide recommendations for sustainable grassland management practices.

2. Materials and methods

2.1. Data compilation

This study focuses on the major implemention region of the RGLG project in China, mainly the temperate grasslands in the northern region and alpine grasslands on the Qinghai-Tibetan Plateau. To collect data that quantifies the effects of grazing exclusion, we searched peer-reviewed journal articles published both in English and in Chinese using the ISI Web of Science and China National Knowledge Infrastructure (CNKI) (1999–2014). We used the following search term combinations: "Grazing" OR "grazing exclusion" OR "enclosure" OR "fencing" OR "fence" OR "grazing removal" OR "exclosure" OR "no grazing", and then refined with the keyword "China". We also considered further studies cited in these references; and studies published as dissertations. From more than 2000 articles containing these search terms; we selected those which met the following criteria:

1. Comparative field studies either observational (free grazing vs. grazing exclusion) or experimental (simulated grazing vs. grazing exclusion) conducted in natural grazed grasslands. Those studies carried out in virgin grasslands or artificial grasslands were excluded.
2. Studies that measured any of the following variables: aboveground biomass (AGB), belowground biomass (BGB), SOC stock, coverage, aboveground litter mass, plant diversity, soil available nitrogen (SAN) content, soil available phosphorus (SAP) content, and soil microbial biomass carbon (SMBC) content. For belowground C stock, sampling depth information was essential.
3. Duration of grazing exclusion should be at least one year. When more than one articles published data from the same site, the latest publication with the most recent data was given priority.
4. There were no other practices (e.g. fertilization or seeding) conducted in the fenced sites.
5. The means, standard deviations or standard errors, and sample sizes of treatment and control were directly reported, or could otherwise be determined from the chosen articles.

We also collected potentially useful information from each publication, including coordinates, elevation, mean annual temperature (MAT), mean annual precipitation (MAP), duration of grazing exclusion, sampling soil depth and grassland type. If climatic information was not available in the original article, we used data from the nearest meteorological station instead. Data of biomass or C stock were extracted directly from tables or text in the original papers, or indirectly from figures using the DATATHIEF III software (B. Tummers, DataThief III. 2006 http://datathief.org/).

For plant diversity, researchers have used the values given by various diversity indices to quantify species diversity. Indices most frequently employed were species richness, species evenness, the Shannon-Wiener diversity index and the Simpson dominance index. Because different indices represent different aspects of species diversity, we compiled data for the above four diversity indices separately from individual studies.

For SOC, sampling depths ranged from 10 cm to 100 cm, which meant we were unable to establish a common maximum depth