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Tradeoffs between forage quality and soil fertility: Lessons from Himalayan rangelands

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ABSTRACT

Pastoralists on Eurasian rangeland often believe that traditional management practices involving moderate rotational grazing ensure sustainable yield, increase plant digestibility and promote biodiversity. To assess the generality of these suppositions we compared biomass production, community leaf C, N and P stoichiometry, leaf trait diversity and carbon and nutrient pools in root and soil for moderately grazed vs. ungrazed plots in Tibetan alpine meadows. We used five leaf traits (leaf C, leaf N and leaf P concentrations; SLA: specific leaf area, and LDMC: leaf dry matter content) as indicators of plant digestibility and rangeland quality. We measured these foliar traits and the ramet numbers for component species in moderately grazed plots as well as in exclosures (3–11 years) at five sites across the Qinghai-Tibetan plateau. Community weighted mean (CWM) trait values and functional dispersion (FDis) were used to quantify the mean and the variance in the distribution of trait values, respectively. Both the leaf P_{CWM} and leaf P_{FDis} generally increased under grazing and the $LDMC_{CWM}$ decreased, leading to improved plant digestibility and rangeland quality (e.g. high, community-wide leaf nutrients). The leaf C_{CWM}, leaf N_{CWM} and SLA_{CWM} increased under grazing but the FDis of these traits tended to decrease. Grazing generally increased species diversity but decreased aboveground biomass, organic carbon, and nutrient concentrations in soil and root, especially decreasing root nitrogen and soil available phosphorus. Both root biomass and the leaf C:N $_{CWM}$ decreased in grazed plots at wet sites, but increased at dry sites. The community-wide increase and greater interspecific diversity in leaf nutrient concentrations coupled with decreasing $LDMC_{CWM}$ show that grazing induced an increase in plant digestibility, nutrient concentrations, and nutrient diversity in these alpine meadows. However, this increase in forage quality comes at the cost of losses in both carbon stock and nutrient availability that depress biomass production. Our findings and a review of related literature suggest that traditional grazing practices involve a trade-off between short-term yield and sustainability, a management challenge that must be addressed on rangelands with low soil fertility.

1. Introduction

From the beginning of agriculture during the Mesolithic–Neolithic transition, Eurasian grasslands have been subject to grazing by livestock (Hejcman et al., 2013; Miehe et al., 2014). Traditional management practices in these rangelands often try to ensure sustainable yield via a regime involving rotational grazing (Briske et al., 2011; Fernández-Giménez and Estaque, 2012; Reid et al., 2014). For instance, in Tibetan and European alpine regions, pastoralists live at low-altitude pasture during winter but move their livestock and even their homes to high-altitude pasture in summer (Hernández-Morcillo et al., 2014; Miehe et al., 2014; Molnár, 2014). Similarly, in Mongolian and Kazakhstan steppe a nomadic rangeland management regime characterized by moving livestock to track the shifting availability of water and forage prevails (Cerny, 2010; Liao et al., 2014). Additionally, excessive livestock often are slaughtered in autumn to ensure moderate grazing intensity during the winter when rangeland productivity is low (Galvin, 2009). These traditional management regimes are intended not only to ensure sustainable yield but also to keep forage digestibility high and promote diversity in the rangeland

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plant community (Glindemann et al., 2009; Teague et al., 2013; Török et al., 2016).

In principle, moderate grazing should increase community species diversity by reducing competitive exclusion (Olff and Ritchie, 1998; Hille Ris Lambers et al., 2012; Niu et al., 2015b), creating spatial heterogeneity favouring establishment, and increasing seed dispersal and colonization (Parson and Dumont, 2003). Forage digestibility potentially can be ensured through regrowth of perennial herbs under continuous removal of aboveground biomass by grazing (Huber et al., 1995; Glindemann et al., 2009). Hence, it is possible that productivity can be sustained under traditional rotational grazing regimes if the loss of soil nutrients through removal of biomass can be compensated by increases in mineralization rate, compositional turnover and soil microbial activity (Bagchi and Ritchie, 2010a, 2011; Ziter and MacDougall, 2013). In fact, both pastoralists and researchers have found increasing evidence for declining productivity and biodiversity in Chinese grasslands during recent decades (Nan, 2005; Kang et al., 2007; Harris, 2010; Ho and Azadi, 2010) as well as reduction in soil nutrient stocks (Hong et al., 2014; Yang et al., 2014b). Studies on the cause of these declines often focus on the consequence of rapidly changing climate factors, but overlook land use change and shifts in grazing management (but see Addison et al., 2012; Eldridge et al., 2015). Hence there is a need to further examine the sustainability of the traditional rotational grazing regime in Tibetan rangelands.

In contrast to the abandonment of many pastures in European grasslands in recent decades, Tibetan rangelands have been subjected to a changing pattern of differential grazing pressures associated with development of settlements around which grazing is concentrated (Yan et al., 2005; Li and Huntsinger, 2011; Fan et al., 2015). Combined with increased demand for livestock production, this has led to overgrazing and accelerated rangeland degradation near these new towns and villages (Li et al., 2007; Harris, 2010; Fan et al., 2015). Increased livestock production has reduced the return of soil available phosphorus (e.g. losses with output of meat, bone and milk) but increased the demand for soil available phosphorus due to enhanced plant growth in response to removal of aboveground biomass by grazing. Nitrogen deposition and climate warming may be further increasing plant growth (Du et al., 2004; Shen et al., 2015). Consequent deficiencies in soil available phosphorus can significantly impact rangeland sustainability via: i) promoting rangeland degradation and depressing productivity through limits on plant growth and regrowth; ii) changing forage quality by shifting community functional structure and C: N: P stoichiometry in plants (Sterner and Elser, 2002; Stiefs et al., 2010); and iii) increasing community biodiversity by favoring infrequent species (Wassen et al., 2005). Despite these possibilities, to our knowledge, few studies have examined the relationships among soil fertility, forage quality, community C: N: P stoichiometry and biodiversity in response to shifts in the traditional grazing regime.

We assess these relationships in Tibetan alpine meadows, which provide an especially useful natural laboratory for this purpose. First, traditional rotational grazing has persisted in Tibetan rangeland despite rapid changes in land use and a marked increase in livestock production in recent decades (Miehe et al., 2009; Harris, 2010). Second, recent general studies in Chinese rangelands document an enrichment of soil nitrogen and increasing productivity (Peng et al., 2011; Shen et al., 2015) and an associated decline in soil available phosphorus (Hong et al., 2014; Yang et al., 2014b). Third, grazing has been shown to depress productivity and favor infrequent species through niche differentiation (Niu et al., 2015a, 2015b). Fourth, the Chinese rangelands have high root biomass and plant phosphorus content in common species (He et al., 2008), increasingly so in recent decades (Mi et al., 2015). Last but not least, addition of P fertilizer significantly increases productivity (Yang et al., 2014a; Zhou et al., 2015). Hence we hypothesize that the traditional rotational grazing in the Qinghai-Tibetan Plateau induces depletion of soil available phosphorus and depresses productivity, but ensures forage quality and promotes species diversity.

To test these expectations, we adopted a trait-based approach to assessing the effect of grazing on rangeland quality and soil nutrient availability gauged through changes in plant community functional structure (Diaz et al., 2007a; Garnier and Navas, 2012; Wood et al., 2015), which was quantified by the mean (*i.e.* community weighted mean, CWM) and variance (*i.e.* functional diversity, FDis) of trait distributions (Pakeman et al., 2011; Ricotta and Moretti, 2011). The CWM is calculated for a trait as the mean of trait values of each species weighted by the respective relative abundance of the species in the community, thus linking to delivery of ecosystem services through a mass effect (Garnier et al., 2004; Diaz et al., 2007a). The FDis assesses trait diversity weighted by species relative abundances in the community, and is related to ecosystem function via a diversity effect that can strengthen resilience (Diaz et al., 2007a; Lavorel et al., 2011). Using these metrics, we quantified community functional response to grazing by tracking changes for several key traits involved in community assembly and delivery of ecosystem services, e.g. aspects of forage quality (see below). To test our expectations that grazing mediated tradeoffs in rangeland digestibility and soil fertility, we examine the effect of grazing on these measures of community functional structure, linking them with soil nutrient availability.

We measured above- and below-ground biomass as well as C:N:P stoichiometry for all the species in grazed as well as ungrazed communities at each of five sites distributed from east to north and west on the Qinghai-Tibetan Plateau (Fig. 1). We also measured five key leaf traits (leaf C, leaf N and leaf P concentration, SLA: specific leaf area, LDMC: leaf dry matter content) to assess digestibility and rangeland quality. Plant digestibility is generally positively correlated with leaf N and SLA, but negatively correlated with LDMC and leaf C (Al Haj Khaled et al., 2006; Pontes et al., 2007; Duru et al., 2008; Gardarin et al., 2014) due to the high digestible biomass fraction in plant tissues associated with low structural carbohydrate content in cell walls together with a low degree of lignification (Choong et al., 1992; Bruinenberg et al., 2002). Additionally, forage quality depends not only on digestibility but also N and P concentration in aboveground biomass (Van Soest, 1994; Owensby et al., 1996; Grant et al., 2000; Danger et al., 2013) as well as forage C:N:P stoichiometry and nutritional diversity (Sterner and Elser, 2002). For ruminants, high forage quality often tends to be related to high digestibility and nutrient concentration in biomass and high plant biochemical diversity (Whitehead, 2000; Provenza et al., 2003; Reynolds and Kristensen, 2008). In short, in the present study we examine the effect of grazing in Tibetan alpine meadows on biomass production, the CWM and FDis of key functional traits, the C:N:P stoichiometry of plants and soil, and species diversity in the plant community. We use these data to test whether traditional grazing regimes promote forage quality and species diversity at a cost in depletion of soil available phosphorus and reduced productivity.

2. Material and methods

2.1. Study sites

We conducted a field experiment in alpine meadows distributed from east to north and west on the Qinghai-Tibetan Plateau (Fig. 1a): AZ and WLK sites in Maqu county of Gansu province (WLK: *cf.* Niu et al., 2014; AZ: *cf.* Zhang et al., 2014), HY site in Hongyuan County of Sichuan province (*cf.* Zhao et al., 2013), QH