Multi-household grazing management pattern maintains better soil fertility

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Abstract

In addition to changes in land use and cover, changes in land management pattern can also have a significant effect on soil fertility. However, to date, changes in grassland grazing management pattern caused by policies have received less attention in terms of their impact on soil fertility. In this paper, we investigated the influence of two different grazing management patterns: the multi-household grazing management pattern (consisting of pastures managed by two or more households with no fences separating them) and the single-household grazing pattern (with fences between adjacent pastures managed by different households), which were implemented after the enactment of grassland contract policy, on soil fertility in the Qinghai-Tibetan Plateau. Our hypothesis was that soil fertility differed between the two grazing management patterns. We selected five study sites with both grazing management patterns in Maqu County on the eastern Qinghai-Tibetan Plateau and sampled 30 winter grasslands from each grazing management pattern to explore differences in soil organic carbon, soil total nitrogen, and soil total phosphorus. We showed that these indicators of fertility status were significantly greater under the multi-household grazing management pattern (47 g C kg⁻¹, 4.6 g N kg⁻¹, and 0.77 g P kg⁻¹) compared to the single-household grazing management pattern (43 g C kg⁻¹, 4.3 g N kg⁻¹, and 0.73 g P kg⁻¹). This is the first study of the effects of grazing management pattern on soil fertility in this environment, and it indicated that the multi-household grazing management pattern could maintain better soil fertility and help to support sustainable use of these grasslands.

Keywords Pastoral lifestyles · Grassland contract policy · Multi-household grazing management pattern · Single-household grazing management pattern · Trampling · Maqu county

1 Introduction

The Qinghai-Tibetan Plateau (QTP) has a grassland area of approximately 15×10^7 ha (of which approximately 60% is alpine grassland) and plays an important role in climate regulation in Asia, global carbon recycling, and the protection of unique species. Consequently, a lot of research has been conducted in this region on environmental and social developmental issues, highlighting the functions and services provided to people (Dong and Sherman 2015; Zhang et al. 2016). Historically, the people living on the QTP implemented conservation and sustainable utilization measures for these grassland resources through collective nomadism. However, driven by socioeconomic developments, as in many other countries (Török et al. 2016), a grassland contract policy was eventually introduced to the QTP in the 1990s.

The policy stipulated that all winter grasslands were required to be contracted to individual households, but many herders were unwilling to participate in such an isolative

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practice because of their historic nomadism and dependence on a collective lifestyle (Cao et al. 2011b). As a result, two distinct grazing management patterns emerged: (i) the multi-household grazing management pattern (MMP), in which the grasslands are collectively managed by two or more households without fences between them, and (ii) the single-household grazing management pattern (SMP), in which the grasslands are managed by individual households with fences (Cao et al. 2011b, 2013) (Fig. 1). Some researchers have studied the impacts of land use changes (including changes in cover) on the soil fertility of the alpine grasslands and their ecosystem services (Dong et al. 2012; Wang et al. 2014), but few researchers to date have documented the influence of change in grassland grazing management practices (excluding changes in cover) despite the importance of this region as an agricultural and socioeconomic hub for its people and the nation.

Soil fertility, which governs the ability of soils to supply appropriate nutrients to plants, and which is particularly important for agronomic utilization, has an important role in the productivity of all terrestrial ecosystems (Fernández-Lugo et al. 2013). It often responds more slowly than vegetation to disturbance and thus can be used as a reliable indicator of the extent of land degradation and the effects of grazing pressures (Wang and Wesche 2016; Hazarika et al. 2014). Soil fertility and sustainability, which have a profound impact on the sustainability and health of an agricultural region, depend on the behavior of individuals, political decisions, and economic development (Keesstra et al. 2016).

The aim of this work was to explore whether a grazing management pattern has an influence on the maintenance of soil fertility in this ecologically important area. The

hypothesis was that soil fertility was potentially greater under the MMP than under the SMP because vegetation conditions, including aboveground biomass (dry matter), the number of species, and cover, have been found to be better under the MMP (42 g and 18 per 0.25 m² and 92%, respectively, in 2011) than under the SMP (35 g and 15 per 0.25 m² and 87%, respectively, in 2011) (Cao et al. 2013), and vegetation degradation can reduce soil fertility (Wang et al. 2014).

2 Materials and methods

2.1 Study area

Maqu County is located on the eastern QTP, traversing the boundaries of Qinghai and Sichuan provinces. The altitude ranges from 2900 to 4000 m and the annual rainfall from 450 to 780 mm. The average annual temperature in this region is approximately 1.8 °C, with a minimum of −10.7 °C in January and a maximum of 11.7 °C in July. The maximum air temperature during the growing season can be as high as 29 °C, and there are, on average, 270 frost days annually. The grassland area of Maqu covers approximately 87×10^4 ha, and approximately 59% is classified as alpine meadow, dominated by Poaceae spp. (e.g., *Festuca ovina* and *Poa poophagorum*) and Cyperaceae spp. (e.g., *Kobresia capillifolia* and *K. pygmaea*). Generally, the alpine meadow soil contains substantial gravel.

Historically, herders in Maqu County grazed their livestock on the grassland and frequently shifted among four distinct seasonal pastures (Cao et al. 2011b). However, in 1996, a new policy requiring grassland enclosures and awarding

Fig. 1 Single-household management pattern (SMP) (left) and multi-household management pattern (MMP) (right). Note: This photo does not depict a sampled winter grassland used because it was not possible to take such a clear image depicting the two grazing management patterns at any of the sites when visited for sampling

grassland contracts to individual households was enacted. Due to the unwillingness of some herders to separate from the wider community, the grasslands were eventually managed by both multiple and single households. With the implementation of these grassland contracts, the scope and area of the available rangeland were reduced. Currently, most of the MMP households have only one summer pasture and one winter pasture and some of the SMP households only have a single pasture for year-round use (Cao et al. 2013). In light of these changes in the kinds of pastoral practices that emerged post-implementation of the grassland contract policy, the study area presents a unique opportunity to investigate the influence of two different grazing management patterns on soil fertility in the Qinghai-Tibetan Plateau.

2.2 Experimental design

In the first half of 2016, we designed a set of field measurements based primarily on our previous vegetation sampling sites (Cao et al. 2013) (Fig. 2). Sites were sampled to capture known differences in vegetation properties (aboveground biomass, the number of species, and cover) that reflected grazing management patterns across Maqu County. To ensure comparable sample sets in terms of other environmental factors for each management pattern, sampling sites were chosen with the same elevation, aspect, and soil texture and with at least two MMP and two SMP winter grasslands at each of the five sites. However, the number of sampled grasslands of the MMP was not equal to that of the SMP at each site due to their uneven distribution. In addition, the sampling strategy also had the following stipulations: (1) they had been continuously grazed since the implementation of the grassland

contracts in 1996 to ensure that the initial vegetation and soil conditions under the MMP and the SMP were similar and (2) they were predominantly used to graze yak to exclude the effect of type of grazing animal on the soil properties. In Maqu, although some areas are suitable for feeding yaks and others are generally used to feed sheep and horses (because different areas have different topographic and geomorphic conditions and unique combinations of water and forage), it is common to feed yaks across the county; (3) all grazing livestock on MMP and SMP depended only on foraging from the grassland resources and did not receive any supplementary feed to exclude the effect of nutrient import via excretion on the soil surface, and (4) they had the same stocking rate, which in this area is expressed in equivalent number of sheep per ha; two sheep per ha is mandated, monitored, and enforced by the Pastoral Supervisor Stations, as detailed in a previous study (Cao et al. 2013). In all, we sampled 30 MMP and 30 SMP winter grasslands over the five sites.

At each of the 60 sampled winter grasslands, one sample was composited from three plots (10×10 m) that were 10 m apart. In each plot, three soil samples (50×50 cm) were collected at the ends and midpoint of the diagonal to a depth of 30 cm using soil control sections (0–15 cm; 15–30 cm). This procedure permits the best comparison of soil properties at multiple depths compared with other methods (Qin et al. 2016). Although the sampled grasslands were identical to those used in a previous study, a few households within the MMP had separated from others between the two sampling events. However, based on our survey, we found that most of them had begun separation in 2014, and little change in the soil fertility properties was likely to have occurred.

Fig. 2 The sample sites in Maqu County. At each site, at least two multi-household management pattern (MMP) and two single-household management pattern (SMP) winter grasslands were sampled, with a total of 60 winter grasslands (30 from the MMP and 30 from the SMP) from the five sites

2.3 Soil analysis

Soil pH was determined using a standard pH meter with a 2.5:1 water to air-dried soil ratio, while soil organic carbon (SOC) was determined using wet dichromate oxidation with an air-dried homogenized subsample of 0.2 g soil and titration with FeSO_4 (Qin et al. 2016). Soil total nitrogen (STN) and soil total phosphorus (STP) were both quantified using a Smartchem 140 automatic chemistry analyzer (AMS/Westco, Italy) due to its high accuracy and efficiency (Chen et al. 2016).

2.4 Statistical analysis

Data were analyzed using the Statistical Package for Social Sciences (SPSS) version 18.0 (IBM, New York, USA). Due to the sampling strategy and the non-normal data distribution, non-parametric tests were used (Wigley and Santer 1990). The approach of Efron and Tibshirani (1993) was adopted using a non-parametric bootstrap-based statistical test, which has been widely applied (e.g., McAlpine et al. 2007; Deo et al. 2009). We examined the underlying differences in soil properties, both as an overall mean and as a function of the different soil depths (0–15 and 15–30 cm), between the MMP and the SMP using the bootstrapping test. Kendall's tau coefficients were employed to generate the overall mean of the bootstrap-based correlation coefficients between soil properties, to address the issues of non-linearity in the dataset (McAlpine et al. 2007).

3 Results and discussion

3.1 Changes in soil properties

SOC, STN, and STP decreased as soil depth increased, similar to results obtained in previous research (Francaviglia et al. 2014; Qin et al. 2016); soil pH, however, showed an increasing trend with soil depth (Table 1). Although pH values declining with increasing soil depth have been reported in some studies outside the QTP region (Sonmez et al. 2014), soil pH has also been shown to increase with soil depth in studies conducted elsewhere; for example, in the southeastern USA (Sigua and Coleman 2010) and in the central Qilian Mountains in the upper Heihe River Basin in China (Qin et al. 2016). This indicates that the relationship between pH and soil depth is region-dependent, due to the different interactions among the specific regional climate, soil texture, and human activities.

Table 1 pH, soil organic carbon (SOC), soil total nitrogen (STN), and soil total phosphorus (STP) under the multi-household grazing management pattern (MMP) and the single-household grazing management pattern (SMP). The letters indicate differences at $p < 0.05$. Capital letters denote differences in the overall average between the MMP and the SMP, while lowercase letters denote differences in a particular soil layer between them

Property	MMP	SMP
pH		
0–15 cm	6.76 a	7.02 b
15–30 cm	6.96 b	7.12 a
Average	6.86 A	7.06 B
SOC (g kg^{-1})		
0–15 cm	56.17 a	49.01 b
15–30 cm	38.38 b	34.83 a
Average	47.27 A	42.96 B
STN (g kg^{-1})		
0–15 cm	5.57 a	5.08 b
15–30 cm	3.62 c	3.47 c
Average	4.60 A	4.28 B
STP (g kg^{-1})		
0–15 cm	0.82 a	0.76 b
15–30 cm	0.71 c	0.70 c
Average	0.77 A	0.73 B

3.2 Relationships among the measured properties

SOC was significantly correlated with STN (Table 2) and reflected a strong coupling between the soil C and N cycles, in which a change in one element directly influenced the other, in concurrence with other research (Luan et al. 2014). SOC was negatively correlated with pH, as has been observed in other studies (e.g., Zhang et al. 2012; Hobara et al. 2016), because acidic soil has a greater capacity for organic C adsorption. STP was positively related to SOC as well as STN. Although the exact cause of this is not clear yet, a plausible explanation is that STP can be fixed relatively slowly by the clay minerals, carbonates, and soil organic matter as part of biochemical cycling (Andriuzzi et al. 2016) and in turn, a higher value of soil P could allow for further N fixation and production of organic matter (Abril and Bucher 1999). STP was negatively correlated with pH, as observed by Zhang et al. (2012) and Hobara et al. (2016). A plausible explanation for this was that the CaCO_3 within the soils was likely to form mono-, bi-, and tricalcium phosphates as pH increased, which could reduce the concentration of P (Waqas 2008). However, this trend was not found by other researchers (e.g., Qin et al. 2016). The relationship between STP and pH exhibited no regular pattern, similar to the results of Shang et al. (2014). STN was not related to pH as found by Qin et al. (2016), but this finding was in contrast to other studies (e.g., Li et al. 2014; Zhang et al. 2012), suggesting that further studies are needed.

Table 2 Correlations between soil fertility properties (soil organic carbon (SOC), soil total nitrogen (STN), soil total phosphorus (STP), and pH) calculated using a non-parametric boot-strapping (bs) procedure with respective *p* values obtained for Kendall's tau coefficients. Correlation coefficients marked *** with *p* values significant at the 99% confidence interval (resampled 100,000 times) are shown

Correlation	Kendall's tau coefficient (bs value)	<i>p</i> value (99% interval, bs)
SOC vs. STN	0.8062***	0.000
SOC vs. STP	0.2023***	0.000
SOC vs. pH	−0.1635***	0.000
STN vs. STP	0.1971***	0.000
STN vs. pH	−0.0752	0.476
STP vs. pH	−0.3051***	0.000

3.3 Effects of grazing management patterns on soil

As shown in Table 1, all measured soil properties under the MMP at the 0–15-cm depth significantly differed from their corresponding counterparts under the SMP. SOC and pH also significantly differed between soils under MMP and SMP at the 15–30-cm depth, while STN and STP exhibited no significant differences at this depth. The average SOC, STN, and STP were significantly greater under the MMP compared to the SMP, with approximately 47, 4.6, and 0.77 g kg^{−1}, respectively, for the MMP, and 43, 4.3, and 0.73 g kg^{−1} respectively, for the SMP. These results indicated that soil under the SMP had lower soil fertility than under the MMP, which supported our initial hypothesis for this study.

To identify a set of plausible explanations in terms of underlying mechanisms, the following factors should be considered:

1. Although the vegetation properties of the MMP and the SMP were not measured in this study, previous results reported in Cao et al. (2013) showed that the aboveground biomass, the number of species, the and plant cover were lower under the SMP compared to the MMP. Less aboveground biomass and plant cover would mean fewer carbon and nutrient inputs into the soils, which in turn would limit soil fertility (Dong et al. 2012; Hirsch et al. 2016). The lower pH values of soil under the MMP relative to the SMP support this explanation since the contributions of decaying organic materials and consequent release of organic acids act to acidify the soil profile (Brady 1984).
2. It is possible that the SMP, with its limited grazing area imposed by fencing, resulted in a reduction in the flexibility and mobility of the livestock compared to the MMP (Yeh and Gaerrang 2011) and promoted increased trampling effects (Dlamini et al. 2014). Combined with other

degradation indicators, such as increased soil bulk density and surface wind erosion (Cao et al. 2013), this could have reduced the storage capacity and supply of soil nutrients (Christensen et al. 2004) and caused an increase in losses of C, N and P, mainly through the removal of nutrient-rich clay particles in the topsoil layer (Lu et al. 2014). On the QTP, Luan et al. (2014) found that the effect of trampling on soil C losses could primarily be attributed to a reduced heavy fraction organic carbon, and on soil N, losses were due to increased N₂O flux and enhanced soil N transformation rates. As topsoil fertility decreases, the soil surface is likely to become more alkaline, resulting in an increase in pH (Evans et al. 2012). This can affect the nutrient availability for plants because in this study area, soil available N and STN as well as soil available P and STP were often significantly and positively correlated (e.g., Zhang et al. 2012), suggesting that the maintenance of a stable soil pH was necessary for sustainable pasture management (Silveira et al. 2014). Among the physical properties of soil, soil bulk density is one of the most important properties and can be an indicator of soil quality (Askari and Holden 2014). Although we did not measure this property due to the restrictions imposed by digging to evaluate the soil profile, previous studies in this area and other areas on the QTP (Wang et al. 2014; Zou et al. 2009; Li et al. 2014) found that soil bulk density increased along gradients of grassland degradation and thus could influence other chemical properties of the soil.

3. In addition to the interactions between overlying vegetation and soil, which caused lower fertility under the SMP than under the MMP, other factors could also explain this effect. For example, increased grazing intensity within the limited areas under the SMP could induce an increase in plant digestibility, nutrient concentrations, and nutrient diversity. This could increase the quality of forage at the expense of losses in both soil carbon and nutrient availability (Niu et al. 2016). In addition, as nutrient levels decline, the population of poisonous plants is likely to increase because such plants can tolerate nutrient-limited soil conditions, leading to further grassland degradation (Li et al. 2014), as confirmed in our previous studies (Cao et al. 2011a, 2013). These studies found that *Ligularia virgaurea* (a poisonous plant) became more common and the biomass of the C4 plant functional group, especially that of *Cyperaceae* spp., was significantly lower on the grasslands of the SMP compared to the grasslands of the MMP. Soil fertility under the MMP could therefore be higher because C4 grasses can potentially improve the aboveground biomass (Wu et al. 2009). The biomass of N₂-fixing legumes was also significantly lower under the SMP than under the MMP (Cao et al. 2013), and this may be another reason for the differences in soil fertility (Peoples et al. 1995).

With a limited grazing area, the SMP may not only lead to poor soil fertility but also result in a less uniform distribution of nutrients compared to the MMP because grazing intervals induced by transhumance under the MMP could improve the distribution and availability of nutrients in grazed pastures (Silveira et al. 2014). While our study provided plausible explanations for the degradation of vegetation and soils under the SMP, further studies using well-coordinated multidisciplinary approaches are warranted to identify the effects of the MMP and the SMP on soil fertility.

There are currently no nomadic management patterns to compare with the results of the MMP but based on the results of this study, it appears that the grassland contract policy should be reconsidered and that a set of fair tradeoffs between modernization, marketization, and environmental protection issues should also be carefully established. With the advancement of industrialization and urbanization, a larger proportion of herders are living in Maqu County to take advantage of better education for their children and improve the quality of their own lives, and they can conveniently lease their grasslands, thus causing the MMP arrangement to easily disintegrate into a SMP arrangement. If all grasslands on the QTP are managed by the SMP, it is likely that the losses of soil C, N, and P will become substantial. Considering the importance of the QTP, especially in terms of biogeochemical cycles and their roles in stabilizing the underlying environments, the losses of soil nutrients, especially P caused by the SMP, may lead to regional scarcity in plant productivity (Niu et al. 2016). Therefore, appropriate institutional arrangements must be considered as an important measure to promote sustainable grassland management and to mitigate the negative effects of global warming on rangeland quality on the QTP (Dong et al. 2011).

4 Conclusion

In this paper, the soil fertility indicators of SOC, STN, STP, and soil pH were quantified through extensive field measurements to ascertain the potential influences of different grazing management patterns on soil fertility within the most important agronomic region of the QTP. The results showed that the measured properties under the SMP were significantly different from those under the MMP. Based on these data and vegetation data from previous research (Cao et al. 2013), we concluded that the SMP has caused significant ecosystem degradation, which includes the plants and soils. Therefore, the grassland-use policy with its current objective of contracting the grassland to individual households should be implemented with caution in this important region. This study was conducted over a relatively small scale and to gain more extensive results and insights, further research is warranted at larger temporal and spatial scales not only on the QTP, but also in

other locations around the world where similar pasture and land management practices exist.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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