Reconsidering the efficiency of grazing exclusion using fences on the Tibetan Plateau

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ABSTRACT

Grazing exclusion using fences is a key policy being applied by the Chinese government to rehabilitate degraded grasslands on the Tibetan Plateau (TP) and elsewhere. However, there is a limited understanding of the effects of grazing exclusion on alpine ecosystem functions and services and its impacts on herders’ livelihoods. Our meta-analyses and questionnaire-based surveys revealed that grazing exclusion with fences was effective in promoting aboveground vegetation growth for up to four years in degraded alpine meadows and for up to eight years in the alpine steppes of the TP. Longer-term fencing did not bring any ecological and economic benefits. We also found that fencing hindered wildlife movement, increased grazing pressure in unfenced areas, lowered the satisfaction of herders, and rendered substantial financial costs to both regional and national governments. We recommend that traditional free grazing should be encouraged if applicable, short-term fencing (for 4–8 years) should be adopted in severely degraded grasslands, and fencing should be avoided in key wildlife habitat areas, especially the protected large mammal species.

1. Introduction

The Tibetan Plateau (TP) is, in general, a large and fragile alpine ecosystem [1] with an area of 2.5 million km² and an average elevation of approximately 4000 m. The TP is extremely sensitive to climate change [2] and human activities [3] due to its harsh environment and vulnerable biomes. Alpine grassland is the dominant biome across the TP, but it has been severely degraded over the past few decades mainly due to overgrazing [4]. Since 2003, grazing exclusion has been widely adopted by the local and central government, predominantly through the use of fences, to restore the degraded alpine grasslands (Fig. S1 online) [5].
The impact of fences on natural ecosystems where both domestic livestock and wildlife graze is of global concern [6]. Grazing exclusion aims to improve ecosystem functions including vegetation production [7], species diversity, soil physical and chemical properties, and soil fertility of degraded grasslands [7,8]. Fencing constructed for grazing exclusion often shows immediate effects in the first few years after its establishment. For instance, vegetation coverage, community height, and aboveground biomass are significantly improved under grazing exclusion within a few years [9]. However, long-term studies have shown that fencing has little sustainable benefit after six–eight years. Moreover, a recent review [10–12] argued that grazing exclusion could even exacerbate grassland degradation on the TP and negatively impact the wellbeing of the herders due to a poor financial support for the construction of fences. Given the large scale and high costs of the fencing project on the TP, a comprehensive study is needed to clarify the effectiveness of grazing exclusion on ecosystem functions and services for improving sustainable grassland policies in the TP and beyond [13].

Previous studies have explored the effects of border [14–16], highway [17], nature reserve [18], and railroad fences [19] on wildlife in North America, Europe, Africa, and China, respectively. These studies have shown that the building of fences can affect wildlife foraging, migration, and reproduction, and the connectivity of populations – primarily due to wildlife habitat isolation and fragmentation [15]. Fencing could also reduce gene flow [20] and recolonization rates, making smaller isolated populations more vulnerable and exposed to external threats [21]. The sixth plenary session of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) [22] reported that populations of large wild mammals have significantly declined across the Asia-Pacific region. In Africa, Percival [23] found that most wildlife deaths are caused by fence entanglements. On the TP, increased fencing has also led to more wildlife deaths including in the Przewalski’s gazelle, a critically endangered species on the International Union for Conservation of Nature (IUCN) Red List [24]. Many conservation experts [25] have proposed the cessation of fence building to allow free movement of wildlife. However, fence construction with barbed wire is still ongoing on the TP. In general, the effects of grazing exclusion on most wildlife are largely unknown, especially in the central and northern areas of the TP.

In the alpine grasslands of the TP, the long-established social-ecological systems that have developed over millennia are vulnerable to climate change and increasing human activities [26]. Herders have learnt how to survive in the harsh climate and to sustain their household livelihoods. Historically they have obtained their food, clothing, shelter, and medicines from the local ecosystems [27]. Today, herder households are under pressure to obtain more resources from the plateau as the available land has been reduced due to decreased mobility, increased settlements, increasing human populations, and the creation of national parks. Herders are engaged more in the market economy and seek better education and healthcare as well as modern lifestyles, such as motor vehicle and cell phone ownership. Nevertheless, many of the grassland residents are still struggling with poverty [28]. Degradation of the alpine grassland has limited their capacity to support more animals. Meanwhile, many herders do not want to abandon their traditional lifestyles [29–31].

Given these issues, a comprehensive assessment of the effects of grazing exclusion on vegetation dynamics, soil properties, wildlife, and the perceptions of herders is urgently needed to evaluate the effectiveness of current grassland management policies in protecting the vulnerable ecosystems of the TP. In this study, we conducted a comprehensive analysis of available data across the TP. Specifically, the effects of grazing exclusion on grassland vegetation (aboveground and belowground biomass (AGB and BGB, respectively), plant cover, and species diversity) and soil properties (chemical and physical) were analysed using a meta-analysis of 52 sites (Fig. S2, Table S1 online). The effects of fences on wildlife were analysed using data on fences (Fig. S3 online) and wildlife (Fig. S4, Table S2 online) from the published literature. The perceptions of local herders on the grazing exclusion policy was investigated via a questionnaire-based survey in 42 counties within the TP (Fig. S5 online). From our results, we propose a policy framework to improve the grassland management and thus the herder’s livelihoods on the TP.

2. Materials and methods

2.1. Study area and sites

The TP (26°00′–39°47′N, 73°19′–104°47′E) is located in southwestern China (Fig. S2 online) and is characterised by a harsh environment and fragile ecosystems with minimum temperatures of −31.12 °C in January and annual precipitation of less than 1000 mm in many parts of the plateau. Alpine grasslands, such as alpine meadows, alpine steppes, and alpine desert steppes, are the dominant biomes on the TP. The plateau also has a fair amount of shrubland and alpine tundra. Forest coverage is low and present in scattered, small patches at lower elevations. Although vegetation productivity is low, the TP is one of the most important grazing lands in China. The alpine rangelands and pastures have supported the Tibetan people and their civilization for thousands of years [32,33].

2.2. Meta-analysis of fenced grassland management across the Tibetan Plateau

Web of Science and the China National Knowledge Infrastructure were used to identify papers published between 1980 and 2017 on grazing exclusion on the TP (Table S1 online). The keywords used were “Tibetan Plateau” in combination with each of the following: “steppe”, “grassland”, “enclosure”, and “grazing exclusion”, resulting in a list of 355 unique articles. Thirty-nine of the 355 articles were used in the current study. The specific rules for paper selection were: (1) comparative field studies included (free grazing vs. grazing exclusion); (2) duration of grazing exclusion was no less than one year; (3) no other treatments (e.g., warming or burning) were conducted in the grazing exclusion sites. From each selected study, several data were collected from control and grazing exclusion treatments, including: vegetation characteristics (vegetation production, coverage, AGB, BGB, and species diversity), soil properties (physical and chemical) and site information (longitude, latitude, and altitude). The responses of these variables to grazing exclusion were assessed by a meta-analysis. The effect size of each variable was calculated using the following equation:

$$InRR = ln(X_T/X_C),$$

where $InRR$ represents the natural logarithm of the response ratio and $X_T$ and $X_C$ are the means of the treatment and control groups, respectively. MetaWin [34] software was used to calculate the mean response ratios and the 95% confidence intervals (CIs) with the bootstrap technique. If the 95% bootstrap CI did not overlap 0, then the effect caused by fencing was considered statistically significant, either positively or negatively. Meanwhile, the Shannon index ($H$) was calculated by the following equation:

$$H = - \sum_{i=1}^{S} p_i \ln p_i,$$
where $S$ is the total number of species, and $p_i$ is the proportion of species $i$ in $S$.

2.3. Data collection on fence distribution, livestock quantity, and fence investment

Information of the distribution of fences was collected from the published literature on fencing in northern Tibet [35]. We used the statistical yearbook to get the information of livestock in 16 counties in Tibet. Data documenting the investment in fences by the government, grassland area, and hay yield were obtained from the Agricultural and Pastoral Office of Tibet.

2.4. Index of grazing intensity

The index of grazing intensity (GI, standard sheep units per km$^2$ of grassland) before and after grazing exclusion in the alpine grassland of Tibet was calculated using the following equation:

$$GI = \frac{S}{A},$$

where $S$ is the number of livestock in each county and $A$ is the actual grassland area used by animals before and after grazing exclusion.

Theoretical and actual livestock capacity was calculated with reference to the standard for the calculation of the livestock capacity and the balance of grass and livestock (DB51/T1480-2012).

2.5. Wildlife data collection

Wildlife data were collected from the published literature and included the population size and geographic distribution of each species (Table S2 online). We used the software GetData Graph Digitizer 2.24 (www.getdata-graph-digitizer.com) to obtain the geographic coordinates of wildlife distributions from the published literature. Further spatial analysis of species distribution was conducted in ArcGIS 10.2 (ESRI, Inc., Redlands, CA, USA). Ultimately, we obtained and identified 11 wildlife species, namely, Panthera uncia, Bos mutus, Procapra picticaudata, Equus kiang, Pr. przewalskii, Cervus albirostris, Ovis ammon, Pantholops hodgsonii, Pr. gutturosa, Camelus ferus, and Pseudois nayaur, most of which are nationally protected species on the TP (Fig. S4, Table S2 online).

2.6. Connectivity index

The impact of fencing on the wildlife can be approximated by the connectivity of fences. We used Conefor Sensinode 2.6 to calculate the connectivity indices [36,37]. If a fence ran across the habitat of a wild species, we considered that the fence would have an impact on that species. We used the occurrence data and the home range of each species to determine its spatial occupancy. In the current study we chose three mammal species to investigate the impact of fencing on wildlife. The home range of three species, namely goa ($P$. picticaudata), wild yak ($B.$ mutus), and Tibetan wild donkey ($E$. kiang), was empirically determined as 15, 30, and 50 km, respectively, based on literature searches, field surveys, and interviews with local herdsmen. In addition, we used the probability of connectivity (PC) index to estimate the importance of each fence in a network. The effective distances among the patches and the number of links per patch were used to measure the dispersal probability [38]. The PC index was calculated as

$$PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} p_{ij}^2}{A_i},$$

where $a_i$ and $a_j$ represent the attributes (distance) of fences $i$ and $j$, respectively; $A_i$ is the area of each patch; and $p_{ij}$ is the maximum PC of all the possible paths between $i$ and $j$. The node importance was computed as delta-PC ($dPC$) and calculated as follows:

$$dPC(\%) = \frac{PC - PC^*}{PC} \times 100,$$

where $PC$ is the probability of connectivity if the fences were removed.

2.7. Herder survey questionnaire

To determine the attitudes of local herdsmen to the fencing project and relevant policies, 15 interviewers (in five groups) spent 20 days conducting household surveys in the Sanjiangyuan region in August 2016, and 13 interviewers (in four groups) spent 50 days conducting household surveys in the other regions of the TP in August, September, and October 2018. In total, randomly sampled interviews were performed in 42 counties, with 622 representative herdsmen, and the primary data collected included: basic family information, local grassland and livestock management practices, and herder’s opinions of the effectiveness of grazing exclusion on various grasslands.

3. Results and discussion

3.1. Has grazing exclusion improved grassland growth and soil fertility?

By dividing the duration of fencing into short (1–4 years), medium (5–8 years), and long term (8–30 years), short-term grazing exclusion significantly increased the AGB, plant community diversity (as indicated by the $H$ value, Fig. 1a), and the total soil phosphorus content (STP), but had little effect on BGB, canopy coverage, soil organic carbon (SOC), and soil total nitrogen (STN) (Fig. 1b) in the alpine meadows on the TP. The benefits of grazing exclusion diminished or even disappeared with longer duration of fencing; namely, medium- and long-term grazing exclusions in the alpine meadows (Fig. 1a, b).

For the alpine steppe, the duration effect of grazing exclusion was slightly different from that of the alpine meadows. Short- and medium-term grazing exclusion significantly increased the AGB and canopy coverage (Fig. 1c). Short-term grazing exclusion had little effect on SOC and STN contents, but medium-term grazing exclusion significantly enhanced both of these variables in the alpine steppes (Fig. 1d). Similar to the findings in the alpine meadows, grazing exclusion had little effect on the BGB regardless of the duration of grazing exclusion. The same was true for plant diversity and STP content in the alpine steppes (Fig. 1c, d).

Our results show that grazing exclusion has improved vegetation growth, especially the AGB, in the alpine meadows and steppes on the TP, but this exclusion effect was only seen in the first few years (the first four years in the alpine meadows and the first eight years in the alpine steppes). This confirms that grazing limited aboveground plant growth but not the belowground growth. Previous studies have reported that overgrazing was commonly seen on the TP [41]. Therefore, grazing exclusion can quickly reverse vegetation degradation and restore aboveground vegetation growth effectively in the first few years of fence use. Surprisingly, longer-term grazing exclusion had little effect on vegetation growth, suggesting that short-term fencing is more beneficial than long-term fencing. Our results suggest that the fencing policies implemented in recent years on the TP could be adjusted by focusing on the construction of short-term fences or reusable fences.
After a few years of vegetation recovery, the fences can be removed and reused in other areas. Our results also provide field evidence to support the currently attempted de-fencing projects on the TP because the old long-term fences had little ecological benefits and limited the migration of wildlife on the alpine landscape.

The decline of vegetation growth with long-term fencing requires more attention and explanation. Driving processes for the alpine meadows and steppes may be different. Climate effects on our observed grazing exclusion results can be excluded because each exclusion experiment was run as pair-wised and conducted within a small area with similar growing conditions. Additionally, there were no significant spatial differences in perennial mean temperature (1982–2013, Fig. S2a, c online) and perennial mean precipitation (1982–2013, Fig. S2b, d online) among the grazing exclusion durations (one–four years, five–eight years and eight or more years, Fig. S2 online). The alpine meadows of the TP usually have deep soils with good levels of water and nutrient supply. Thus, biotic factors are more likely to explain the vegetation decline observed associated with long-term fencing. Indeed, we found that plant diversity, just like AGB, significantly increased with short-term grazing exclusion and decreased with longer duration of grazing exclusion in the alpine meadows (Fig. 1a). Many studies have shown that biodiversity regulates community and ecosystem productivity [42,43]. Therefore, we suggest that the decline in plant diversity resulting from the continued grazing exclusion was at least one of the key drivers of the decline of vegetation growth in the medium- and long-term grazing exclusion experiments. On the alpine steppes, biological interactions at community level are relatively weak because the vegetation coverage is normally low and sparse in some areas. This is confirmed by our result that the vegetation coverage significantly increased with grazing exclusion regardless of the duration of exclusion (Fig. 1c). Therefore, we speculate that soil processes might have led to the decline of vegetation growth with the long-term grazing exclusion in the alpine steppes. In fact, the SOC and STN contents significantly increased with the medium-term grazing exclusion as the AGB was significantly promoted with short- and medium-term grazing exclusion (Fig. 1c, d). Therefore, we think that the decline in vegetation growth with the long-term grazing exclusion was mainly caused by soil fertility, which became more limited with the long-term grazing exclusion (Fig. 1d).

Recent studies have reported climate change as the main driver of vegetation degradation on the TP in recent decades [44]. However, our results suggest that the short-term grassland degradation on the TP has been mainly driven by overgrazing rather than climate change. Both above and belowground growth would be expected to be affected by climate change, while grazing should only affect aboveground parts, as evidenced in the current study. Long-term degradation might still be driven predominantly by climate change because long-term grazing exclusion had little impact on both AGB and BGB, suggesting that long-term grazing does not dramatically affect vegetation growth in the alpine grazelands.

3.2. Fencing increases grazing pressure in unfenced areas

Grazing exclusion redistributed the grazing pressure in space, with increasing pressures in the unfenced areas. The presence of enclosures could increase the pressure on non-enclosed areas
due to the decrease in grazeable land areas (Fig. 2) if the livestock population and periods of grazing remained constant. Taking northern Tibet as an example [35], the total fenced area accounts for 33% of the total grazeland area in the region. We found that fencing exacerbated the overgrazing issue in this region, increasing the average overgrazing rate from 27.41% before the installation of fences to 83.02% after (Table 1). It should be noted that the overgrazing rate we calculated might be different from that used in the ecological compensation programs because we did not consider the imported and exported fodder of each county. Fencing-induced overgrazing is more severe in the south and southeast part of northern Tibet where more fences have been established (Fig. 2). Overgrazing was already a problem in these areas before the installation of fences, which subsequently exacerbated the issue. Fencing contributed little to overgrazing in the western and northern parts of northern Tibet because the grassland was understocked, and the fence density was relatively low in these areas (Fig. 2). When fencing is necessary to protect degraded grazelands from further damage, consideration of fence density is important because fencing may accelerate overgrazing outside of the fenced areas and thus do more harm than good to the overall landscape.

3.3. Fencing limits wildlife activity

Fencing restricts not only the movement of domestic livestock but also activities such as migration and mating in some wild animals [16]. The TP is inhabited by many wild species including those under national protection, such as the Tibetan antelope [45]. Fencing particularly impacts large mammals by restricting their movements. In northern Tibet, approximately 20% of the sightings of three protected species (wild yak, goa, and Tibetan wild donkey) occurred in fenced areas, indicating that fencing has a direct impact on individuals and populations of these species because their home ranges are much larger than most of the fenced areas (Fig. 3). Animals outside the fenced areas could also be affected by being forced to walk longer distances for browsing, drinking, mating, and migrating. In addition, fencing can harm or even kill animals when they try to jump over the fences, particu-

![Fig. 2. The spatial distribution of grazing-excluded pastures with fences that were constructed on the northern Tibetan Plateau during 2004–2012, the distribution of fences is represented by green patches in the 16 counties.](image)

| County | TGI | BGE | AGE | ORBE | ORAE |
|--------|-----|-----|-----|------|------|
| Nyima C | 0.25 | 0.21 | 0.50 | -15.60 | 102.11 |
| Zhasha C | 0.27 | 0.14 | 0.18 | -47.61 | -32.66 |
| Ga’er C | 0.27 | 0.20 | 0.21 | -25.52 | -22.05 |
| Pulan C | 0.40 | 0.25 | 0.29 | -35.14 | -26.91 |
| Geji C | 0.26 | 0.21 | 0.15 | -44.65 | -26.21 |
| Ritu C | 0.20 | 0.11 | 0.11 | -56.89 | -45.30 |
| Gaize C | 0.21 | 0.09 | 0.11 | -27.28 | 70.38 |
| Shenzha C | 0.44 | 0.43 | 0.76 | -78.37 | 93.63 |
| Bange C | 0.44 | 0.57 | 0.21 | 28.37 | 67.88 |
| Jiali C | 0.61 | 0.70 | 1.03 | 13.27 | 51.23 |
| Anduo C | 0.36 | 0.39 | 0.55 | 8.30 | 51.23 |
| Nierong C | 0.93 | 0.87 | 1.51 | -6.61 | 62.33 |
| Baqing C | 0.87 | 1.19 | 2.00 | 35.79 | 129.20 |
| Naqu C | 0.90 | 1.39 | 1.89 | 54.73 | 111.00 |
| Biru C | 0.73 | 0.72 | 1.00 | -1.41 | 37.52 |
| Suo C | 1.00 | 1.23 | 2.56 | 23.97 | 157.44 |

\(^{a1}\) TGI represents the theoretical maximum grazing intensity (GI) (average number of sheep units/hm² of grassland), BGE and AGE represent the GI before and after the implementation of grazing exclusion, respectively. ORBE and ORAE represent the overgrazing rate before and after the implementation of grazing exclusion, respectively. The bold fonts indicate that the actual grazing pressure is higher than the theoretical grazing pressure.
larly those with barbed wire. Fencing also restricts the movements of animals and thus increases their chances of being killed by their predators or human hunters. In areas with high fence density, such as northern Tibet, we found that many fenced pastures were connected to form a much larger barrier to animal movements, and the fences with the highest connectivity (18%) were found in Shenza and Nyima County (Fig. S3a online). Additionally, there were many wild animal (wild yak, goa, and Tibetan wild donkey) nodes that interacted with fenced patches (Fig. S3b–d online). These large-scale fencing networks have prevented wildlife movement, and thus the gene flow, and increased habitat fragmentation, creating challenges to biodiversity conservation on the TP. There is much

Fig. 3. The spatial distribution of wildlife and fences in northern Tibet. (a), (b), and (c) represent wild yak (*Bos mutus*), goa (*Procapra picticaudata*), and Tibetan wild donkeys (*Equus kiang*), respectively.
evidence that isolated wildlife populations have difficulty in completing their whole life cycle (e.g., reproduction, migration, and foraging) on the TP (Fig. S4b, c online). Many field studies have also confirmed that fencing threatens wild animals. Numerous cases have been reported of Tibetan wild donkeys being killed by fencing in Nyima County (Fig. S6 online) as well as Tibetan antelope in the Chang Tang National Natural Reserve [45].

3.4. Fencing reduces herders’ satisfaction with the current grassland management policy

Based on the field surveys in 42 counties on the TP, 57% of the interviewees argued that fencing increased the mortality of wildlife and 63% said that grazing exclusion increased the proportion of unpalatable species in the grazelands (Figs. 4 and S5 online). Although 41% of the interviewees attributed the main cause of grassland degeneration to climate change, such as extreme droughts, snowstorms, and flooding, 39% thought that human activities, such as overgrazing, were responsible for the grassland degradation. Among all the interviewees, 50% thought that the grassland had degenerated in recent years due to various factors while only 27% believed that the local grasslands were significantly improved as a result of the ecological restoration projects. Therefore, only 33% of the interviewees agreed to incorporate grazing exclusion into the grassland compensation program. Moreover, 50% of the herders preferred their traditional practice (free grazing) and only 17% disagreed in this regard. The greater support for free grazing indicates that many herders are not convinced by the benefits of fencing. An earlier study in Maqu County on the TP [46] provided a successful case of free grazing, where the local communities maintained the traditional grazeland management practices and social networks. We therefore suggest that policy makers need to reconsider the fencing policies on the TP and elsewhere in China for the sake of sustainable management of the grazelands and improving the livelihood of herder communities.

3.5. Fencing increases government financial burden and conservation expenses

Fences noticeably decrease habitat areas for wildlife, intensifying conflicts between humans and wildlife [47], which has led the government to provide more compensation to mitigate human-wildlife conflict (HWC). In Shuanghu County alone, 61.9% of the herder families in the county reported livestock loss from wildlife attacks from 2011 to 2015, resulting in a compensation of 1.75 million CNY (Fig. S7 online). Wildlife attacks on people are also reported occasionally. Previous reported that more than 20,000 herder households were compensated for wildlife-induced livestock loss and human injuries in 2008 and 2009 in Chang Tang National Nature Reserve [48]. However, these compensations are small in comparison with the high costs of constructing the fences. It is estimated that the total cost of constructing all kinds of fences in Tibet between 2004 and 2013 reached 1.37 billion CNY, most of which was paid by the central and local governments (Table S3 online). Given the problems associated with fencing as discussed earlier, the ecological, economic, and social benefits from the government investments have, so far, been limited.

4. Conclusions and policy implications

By synthesizing the results of published studies on fencing experiments in the past few decades on the TP, we found that fencing promoted vegetation growth, but only in the aboveground parts and only in the first few years after the installation of fences. However, the effects of fencing on ecosystem processes and functions were slightly different in the alpine meadows and steppes. Short-term fencing enhanced plant diversity but not BGB and soil fertility metrics (SOC, STN, and STP) in the alpine meadows. Short- and medium-term fencing in the alpine steppes increase not only the AGB, but vegetation coverage as well. Interestingly, we also found that long-term fencing (present for more than eight years)
years) had little effect on vegetation growth and soil fertility. Our results confirmed that fencing hindered wildlife movement and increased grazing pressure in unfenced areas, exacerbating the overgrazing issue in the north of Tibet.

The headwaters of many of Asia’s major rivers that sustain the livelihoods of hundreds of millions of people in China and beyond are found on the TP. To deliver clean water in these rivers, the alpine grasslands need to be better managed for grazing and other ecosystem services. Grazing is an important management tool for many grasslands, which could stimulate tillering and overall vegetation growth. Maintaining a high level of aboveground plant biomass is essential to support livestock, and thus herders’ livelihoods, on the plateau. However, the alpine grazelands have been degraded for decades due to various factors, such as overgrazing and climate change. To restore the degraded grazelands, grazing exclusion with fences has been proposed and practiced in many areas on the TP. However, local herder communities do not appear to appreciate the costly fencing projects for various reasons.

Most importantly, although the Chinese government has implemented many policies over the past 20 years to protect grasslands (Table S4 online, [49]), there is a need to modify the core structure for policy making and ongoing management (Fig. 5). The grassland management policy for the TP was devised at national and local levels but lacked third-party evaluation. Reviews of the policy have been carried out, as in the current study, but without inbuilt mechanisms to implement findings. Reviews and policy adjustments need to be better aligned. Coordinating committees for policy review and management should include independent evaluators and herders as well as government officials, all charged with delivering clear environmental and livelihood benefits.

Given the complexity of the effects of fencing on ecosystem processes, livestock carrying capacity, wildlife habitat, and herders’ livelihoods and culture, we do not consider the existing studies on the topic to be conclusive and suggest that further studies, especially long-term field research, are urgently needed. Nevertheless, according to our results, we propose the following methods for improving current grassland management policies on the TP: (1) traditional free grazing is encouraged to maintain or resume the traditional grazing practices and culture if the grasslands have not been degraded; (2) in case fencing is necessary, such as in a severely overgrazed area, short-term fencing of four–eight years is preferable, with removable fences that can be reused elsewhere afterwards; (3) high fence density and connectivity should be avoided, and the existing long-term fences should be removed for the benefits of wildlife; and (4) regular and comprehensive assessments are needed to ensure the policy is being effectively managed to deliver benefits in a timely fashion.

**Conflict of interest**

The authors declare that they have no conflict of interest.

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Author contributions

Jian Sun and Guohua Liu conceived the study. Jian Sun, Miao Liu, Tiancai Zhou, Tianyu Zhan and Ge Hou collected and analysed the data, and drew the graphs. Jian Sun, Miao Liu, Bojie Fu, Ming Xu, and David Kemp wrote the manuscript. Wenwu Zhao, Guodong Han, Andreas Wilkes, Xuyang Lu, Youchao Chen, Genwei Cheng, Fei Peng, Hua Shang, Peili Shi, Yongtao He, Meng Li, Jinlin Wang, Atsushi Tsunekawa, Huakan Zhou, Yu Liu, Yurui Li, Shiliang Liu reviewed and revised the manuscript.

Appendix A. Supplementary materials

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