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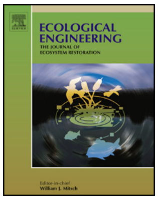

Research paper

Precipitation does not amplify the efficiency of fencing measures for temperate grassland restoration: A case study in northern China based on remote sensing

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ABSTRACT

Increasing anthropogenic interventions involving utilization and conservation of vegetated ecosystems has attracted considerable attention focused on large-scale assessments of the roles played by human-domination. The effects of specific anthropogenic measures have generally been ignored by large-scale assessments, which has probably resulted in irrational regulations and imprecise understanding of these specific measures. This paper aims to reveal the effect of a grassland restoration measure—fencing in northern China—as well as the spatial patterns of fencing efficiency. Spatially continuous Normalized Difference Vegetation Index (NDVI) data based on remote sensing was used to detect grassland vegetation changes during fencing periods. Using subsequent processes to smooth the impact of precipitation from the current year and by setting thresholds for identifying changed/unchanged NDVI, the spatial vegetation changes were converted into two groups of statistical data: the mean NDVI-increase value in each sample region and the pixel areas with different grassland change types in each sample region. The precipitation lag effect on NDVI increases was assessed by multiple comparison tests, and regions with a significant precipitation lag effect were removed from the fencing effect assessment. Finally, the areas with different grassland change types were related to changes in fenced area using regression analyses under different precipitation gradients. The results indicated that the precipitation lag effect caused by legacy moisture significantly affected the spatio-temporal vegetation changes. By excluding the regions with legacy moisture, the increase in fenced area facilitated an expansion of improved grassland and a reduction in degraded grassland. Fencing efficiency was maximized in the 250–300-mm precipitation zone, where the expansion rate of improved grassland area reached 0.70 ($R^2 = 0.54$, $p < 0.01$). The second-best and least effective zones lay in the mean annual precipitation (MAP) >300-mm and MAP <250 mm zones, respectively. We conclude that a wetter climate does not automatically result in a better fencing effect, and legacy moisture will lead to an overestimation of the fencing effect. A rational fencing implementation should consider the resilience and degradation degree of steppes.

1. Introduction

To improve the sustainability of terrestrial ecosystems for humankind, increasing numbers of anthropogenic utilization and conservation measures have intervened in vegetated ecosystems, altering both their biological material and energy flow. Human-dominated roles are increasing in terrestrial ecosystems (Haberl et al., 2014). Distinguishing and quantifying the large-scale effects of human-induced changes in vegetated ecosystem from those driven by natural factors is crucial for understanding human-dominated roles in ecosystems, and these tasks have received considerable attention from researchers (Haberl et al., 2007; Imhoff et al., 2004; Krausmann et al., 2013; Vitousek et al., 1997). These previous assessments of anthropogenic factors have generally included all human activities, whereas the impact and the efficiency of distinct human factors that are primary factors affecting

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regional ecosystems still lack attention. This neglect is prone to lead to blind expansions of human activities after a measure was deemed effective in one or more sites, the subsequent consequences tend to surpass managers' expectations. This is particularly true for temperate grasslands that have been partly restored by protected-status projects after experiencing serious degradation led by a large increase in livestock populations (Ministry of Agriculture of the People's Republic of China, 2013; Spieles, 2010). This paper aimed to assess the large-scale efficiency of a specific primary anthropogenic measure—fencing—which has been adopted by many countries to promote the restoration of temperate grassland vegetation (Hao et al., 2014; Spieles, 2010).

Fencing grasslands to promote grassland restoration is a controversial intervention because it deprives wild ungulates of mobility and hinders local herdsmen from using their grasslands in traditional nomadic ways. However, by eliminating livestock pressures on grasslands, fencing measures can achieve productivity increases (Barros et al., 2014), biodiversity rehabilitation (Gao et al., 2013; He et al., 2011) and other goals (Deng et al., 2014; Teague et al., 2011) as the fencing duration increases (Firincioglu et al., 2007; Liu et al., 2015).

Fencing was prolifically implemented as part of the 'Returning Grazing Lands to Grasslands' project–which was a part of 'Grain to Green' program of China (Armitage et al., 2012; Wu et al., 2014), and it was a recommendation of China's revised Grassland Law in 2003. According to statistics from the National Animal Husbandry Station of the Agricultural Ministry of China, fencing enclosed 69.8 Mha of grassland in China in 2010, and nearly half (46%) of this fencing was implemented in Inner Mongolia at a cost of approximately 270 million RMB. From 2000–2010, the fenced area increased by 1.7 Mha per year in the Inner Mongolian grasslands; nearly 1/3 of the open grazing grassland was converted to fenced grassland. The total area of other measures (including such measures as improving soil, planting grass and shrubs, and so forth) implemented for the 'Returning Grazing Lands to Grasslands' project amounted to less than 6% of the total grassland area from 2000 to 2010. Moreover, fenced grassland usually overlapped the implementation areas of these other measures.

In this context, Inner Mongolian grasslands were selected as the study area for assessing the large-scale efficiency of the fencing measure. To monitor grassland vegetation changes, the normalized difference vegetation index (NDVI) of remote sensing image was applied, NDVI is closely related to vegetation biomass (Barrachina et al., 2015) and coverage (Lehnert et al., 2015), and it has spatial continuity (Turner et al., 2005). However, two difficulties existed in assessing the large-scale effects of anthropogenic measures on vegetated ecosystems: (1) smoothing the impact of climate on vegetation changes and (2) quantifying the relationship between remote sensing-based vegetation changes and anthropogenic measures. We proposed a solution that combines remote sensing monitoring and ecological analysis approaches. The key to this solution lay in the statistical conversion of remote sensing image data, which includes regional averages of NDVI values and area statistics concerning grassland vegetation changes.

The temporal variability of precipitation had a more significant effect on temperate grassland than did temperature over relatively short timespans and was the dominant climatic factor impacting temperate grassland of north China (Piao et al., 2006). The impact of the temporal variability of precipitation on temperate grassland stems primarily from two factors: the precipitation impact of the current year (Mowll et al., 2015) and the precipitation lag effect (Reichmann et al., 2013). Therefore, we first smoothed the precipitation impact from the current year and then assessed the precipitation lag effect on NDVI using multiple comparison tests. The regions with a significant precipitation lag effect were removed from the subsequent fencing effect assessment. Three types of grassland changes were identified spatially according to NDVI unchanged thresholds. The total area of each type of grassland change was determined statistically for each sample region and, finally, related to fenced area changes by regression analysis. To reach the ultimate goal of determining the spatial patterns from the fencing effect, the relationship between the areas with grassland changes and the fenced area changes were evaluated under different precipitation gradients.

2. Materials and methods

2.1. Study area

The Inner Mongolian Autonomous Region (IMAR) in northern China covers an area of 118 Mha, including 78.8 Mha of natural grasslands and 22.7 Mha of desert area, which account for 66% and 19% of the total area, respectively (Fig. 1). Inner Mongolian grassland is representative of typical Eurasian steppe. The grassland area usable for human activities is approximately 63.59 Mha. The IMAR ranges from 37°24′N to 53°23′N in latitude and from 97°12′E to 126°04′E in longitude. As shown in Fig. 1, this transect exhibits significant spatial variability, and mean annual precipitation (MAP) varies from 50 mm in the northwest to 450 mm in the southeast. Moving from east to west, the steppe type shifts with the decreasing annual precipitation, from meadow steppe (300–450 mm), to typical steppe (250–400 mm), to desert steppe (150–250 mm). According to official statistics (Ministry of Agriculture of the People's Republic of China, 1996), these grassland types respectively constitute 10.95%, 35.12% and 10.68% of the total grassland. Most of the annual rainfall is concentrated between May and September. The primary productivity of the steppe peaks in July and August (Potter et al., 1993; Zhou et al., 2001). The average annual temperature varies from 0 °C to 8 °C. The topography of the study area consists of gently rolling hills and tablelands, with elevation ranging from 700 m in the east to 1500 m in the west.

2.2. Datasets

In 2000, Inner Mongolia covered 87 banners (counties). Grassland fencing data were collected from both early (2000–2002) and later (2009–2011) fencing periods, using individual banners (counties) as units. The official fenced grassland area data from 2010 were provided by the Department of Livestock Production of the Ministry of Agriculture, China. The fenced area of most banners remained the same from 2009 to 2011. The data for a few banners with different fenced areas were acquired from the Inner Mongolian Yearbooks of 2010 and 2012. Due to the lack of official statistics, the early fenced area data for the 2000–2002 period were acquired by compiling published Chinese literature, including the Inner Mongolian Yearbooks of 1999–2003, the local chronicles of 46 banners, 7 articles from the Chinese Academic Journal Network Publishing Database (identified through searches using keywords relating to banner names and pasture or grassland management) and 7 reports from an official website. However; two problems were encountered during data compilation for ten banners. (1) While some published sources reported increases in fenced areas for several successive years they lacked data for the initial fenced area for the corresponding years. Therefore; we adopted the available fenced area from the most recent report (usually in the 1990s) as the initial fenced area and calculated the total fenced area during the early period by summing the initial fenced area and the increased fenced area acquired from the published literature. (2) In the 1990s; other sources reported only the initial fenced area and provided no information regarding increases or decreases in fenced area over subsequent periods. In this case; we assumed that

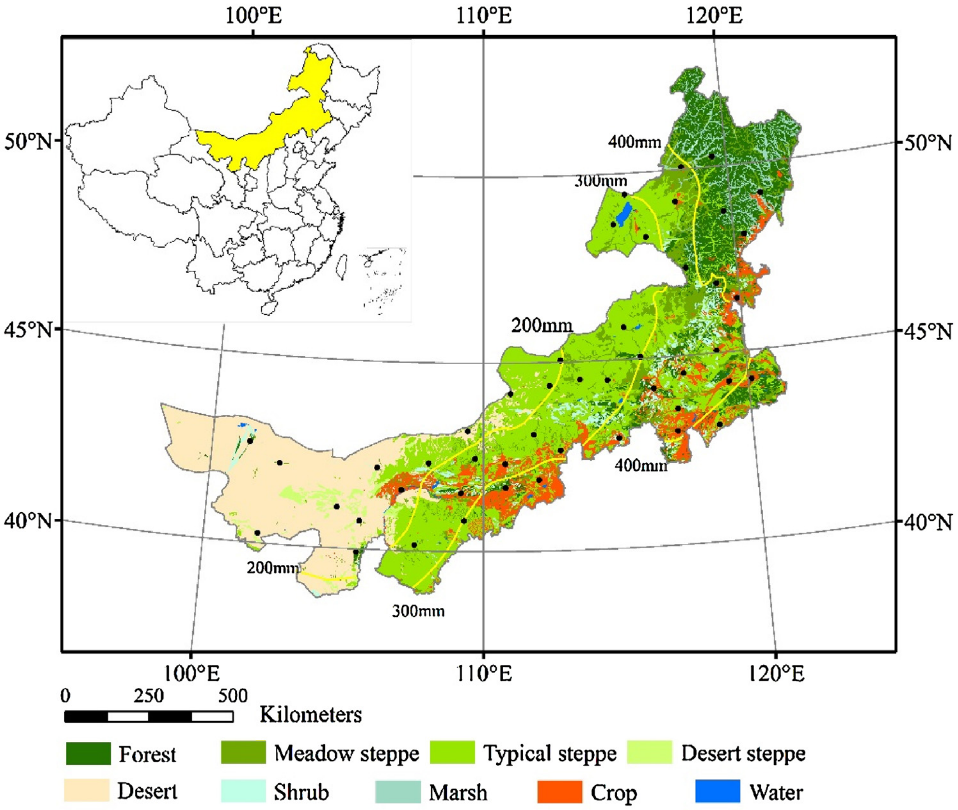

Fig. 1. Study area and land cover types based on a 1:1,000.000 vegetation type map. The black dots correspond to the locations of the meteorological stations involved in this study. The inset map indicates the location of the study area in China. The yellow lines represent rainfall isoclines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

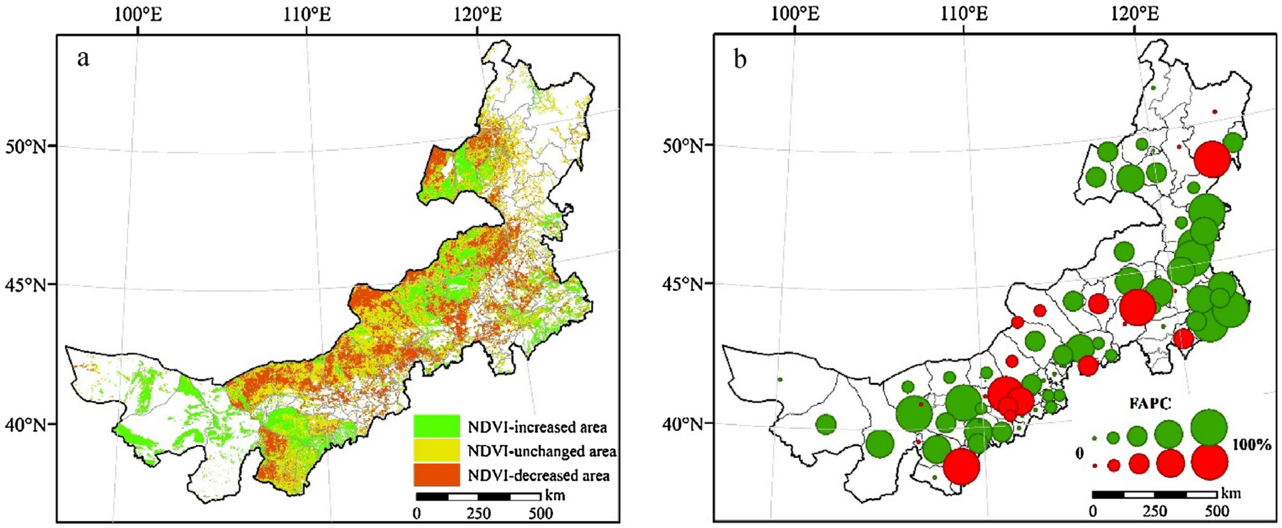

Fig. 2. (a) A mosaic NDVI change map of Inner Mongolian grassland; (b) fenced area proportion change (FAPC) of each banner, where grey regions have no fencing implementation and the green and red circles represent fenced area proportion increases and decreases, respectively. Larger circles indicated relatively greater increases or decreases in the fenced area proportion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the grassland fenced area remained unchanged until 2000; then; we acquired the fenced areas for 2000–2002.

Grassland distribution information was extracted from a 1:1,000.000 vegetation map (Editorial Board of Vegetation Map of China, 2001) and then revised based on a 1:100,000 land use map of Inner Mongolia (Liu and Deng, 2010) (acquired from the website http://westdc.westgis.ac.cn/). The revised grassland shapefile was used to extract the grassland NDVI distribution of Inner Mongolia, as well as the NDVI distribution of meadow steppe, typical steppe, desert steppe and desert from remote sensing data.

The 16-day NDVI image data extracted from the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD13Q1 products (acquired from the website at http://www.ntsg.umt.edu) for July and August of 2000–2002 and 2009–2011 were used to detect grassland vegetation changes. At a spatial resolution of 250 × 250 m, the NDVI data allow more detailed vegetation information to be captured than do data at a coarser spatial resolution, especially for smaller and more fragmented areas of fenced grassland. The NDVI data were first corrected to minimize the effects of noise (e.g., sensor degradation, solar zenith angle, and atmospheric and aerosol scattering) (Tucker et al., 2005). Then, they were re-projected using the Albers Conic Equal Area technique and converted into signed 8-bit NDVI. We then delineated the NDVI data using the Inner Mongolian grassland shapefile and computed the average NDVI of the Inner Mongolian grasslands for July and August. The average maximum NDVI is more than 0.60 for meadow steppe, and it is approximately 0.40 for typical steppe, but it varies between 0.10 and 0.20 for desert steppe (Lunetta et al., 2006).

The precipitation data were obtained from 89 meteorological stations in Inner Mongolia and neighbouring provinces. Based on the idea that the biomass of Inner Mongolian temperate steppe is highly affected by the amount of precipitation that falls during the growing season of the current year (Bai et al., 2008; Guo et al., 2013), the growing season precipitation (from May to September) was estimated annually for each banner for 2000–2002 and 2009–2011.

2.3. Smoothing and removing the precipitation effect

2.3.1. Precipitation smoothing

To smooth the impact of precipitation from the current year, paired years with minimum precipitation differences were respectively selected from the early fencing period (2000 –2002) and the later fencing period (2009–2010) for each banner, to monitor changes in the NDVI and fenced area. Fifty-four banners had minimal precipitation differences between 2002 and 2010. 15, 1, 3, 3, 10 and 1 banners exhibited minimum precipitation differences in 2010 vs. 2000, 2010 vs. 2001, 2009 vs. 2000, 2009 vs. 2001, 2009 vs. 2002 and 2011 vs. 2002, respectively. The NDVI and fenced area changes were calculated by subtracting the previous years' values from the values of later years. Although this precipitation smoothing method is more efficient and simpler than traditional precipitation smoothing processes (Begue et al., 2011; Wessels et al., 2007), it is not suitable for time-series vegetation change detection.

2.3.2. Assessing the precipitation lag effect

To remove precipitation lag effects, two precipitation tendencies comprising three scenarios were extracted from the natural precipitation trends of each sample banner. The tendencies involved the two years previous to the study years. The wet tendency criterion was that the precipitation of the two previous years must have been higher than that of the following study year. The dry tendency criterion was that the precipitation of the two previous years must have been lower than that of the following study year. The wet/dry (WD) scenario involved a wet tendency in the early fencing period and a dry tendency in the later fencing period, and it was associated with eight of the sample banners. The dry/wet (DW) scenario involved an early dry tendency and a later wet tendency, and it was associated with six of the sample banners. As a control, a scenario with identical trends of precipitation (ITP) was added. This scenario has identical precipitation trends for both the earlier and the later fencing periods, and it was associated with nine of the sample banners. In this paper, the precipitation lag effects were evaluated only for the improved grassland areas. The significance of the differences in fenced areas proportions, increased NDVI values and the proportion of improved grassland were tested under different precipitation scenarios using multiple comparison tests (Fisher's Least Significant Difference (LSD)). Note that the multiple comparison tests of increased NDVI and improved grassland areas proportions must be based on the precondition that the new fenced areas proportions showed no significant differences between the ITP, DW and WD scenarios. Finally, the regions that exhibited a precipitation lag effect were removed during the fencing effect evaluation.

2.4. Vegetation change detection

The grassland vegetation changes were assessed for two purposes: to identify areas with a precipitation lag effect and to conduct the fencing effect assessment. Three grassland change types were identified: improved grassland (areas with increased NDVI), unchanged grassland (unchanged NDVI) and degraded grassland (decreased NDVI). The key to identifying these areas lay in the threshold settings. Because desert steppe, typical steppe and meadow steppe had different peak NDVI values, their changed/unchanged thresholds were set differently, but all referred to the NDVI variation range of desert in Inner Mongolia between the early and later fencing periods; desert NDVI is generally considered to be constant because much bare earth surface is exposed. The NDVI variation range of desert was defined as the unchanged NDVI range of desert steppe. However, because variability exists between the NDVI values in different comparable years, we used a standardized processing method for the unchanged thresholds of desert steppe as shown in Formula (1). The result ranged from approximately −0.01 to 0.01. The NDVI values below −0.01 were classified as having decreased, while those exceeding 0.01 were classified as having increased. The unchanged thresholds of typical steppe and meadow steppe were set according to the fold differences of their annual NDVI max with desert steppe (Lunetta et al., 2006), which were −0.04–0.04 and −0.06–0.06, respectively. Finally, the grassland change types were identified as shown in Fig. 2a. Both the mean increases in NDVI values and the pixel areas of different grassland change types for each banner were computed to assess the precipitation lag effect and fencing effect. These processes were completed using ArcMap 10.0 software. Formula (1) is as follows:

$$\delta = \frac{w_{i,j \times \delta(NDVI_j - \mathrm{NDVI}_i)}}{n}, \qquad (1)$$

where δ is the standardized threshold value, $\delta_{(NDVI_j - \mathrm{NDVI}_i)}$ represents the upper or lower limit value of the unchanged NDVI range of different pairwise years, w_{ij} is the number of banners with the minimum precipitation difference between year j and year i, and n is the number of banners (87) in Inner Mongolia, China.

2.5. Assessing fencing effects and efficiency

An area proportion measure was adopted to describe the grassland change types in each banner: the areas of improved, unchanged and degraded grassland in each banner were divided by the total grassland area of that banner. A similar procedure was applied to describe the fenced area changes in each banner (fenced area change/grassland area). Adopting these measures facilitated the assessment of fencing effects and efficiency because no precise location information was available for the fenced regions. Regression analyses were performed to relate the area proportions of grassland change types (the independent variables) to the fenced grassland (the dependent variable). Based on repeated trials, banners with increased fenced area were classified into three precipitation gradient zones: MAP < 250-mm, 250-mm ≤ MAP ≤ 300-mm (250–300-mm) and MAP > 300-mm. A regression model was generated for each gradient. The statistical significance of the slope was evaluated using *t*-tests. The slope represents the fencing efficiency—that is, the average change rate of the proportion of improved or degraded grassland area caused by the increase in the proportion of the fenced area. The significance levels (*p*) and the slopes under the different gradients were compared to identify the most suitable zones for effective fencing.

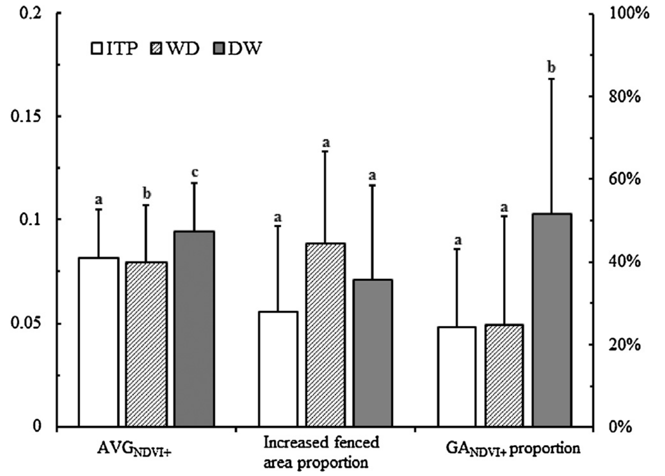

Fig. 3. Significance of difference of increased NDVI and area proportion of improved grassland under different precipitation scenarios. AVG$_{NDVI+}$ indicates the mean value of increased NDVI, GA$_{NDVI+}$ indicates grassland areas with increased NDVI. The man Y-axis represents the NDVI value; the secondary Y-axis represents the area proportion of the grassland area; and a, b, and c represent the statistical significance of differences.

3. Results

3.1. Distributions of grassland fencing and NDVI variations

The NDVI variations of Inner Mongolian grasslands and the fenced area changes are shown in Fig. 2a and b, respectively. The areas of improved grassland, unchanged grassland and degraded grassland correspond to 24.4% (14.9 Mha), 41.3% (25.3 Mha) and 34.3% (21 Mha) of the Inner Mongolian grassland area, respectively (Table 1). Simultaneously, the net increase in fenced areas amounted to 26.5% (16.5 Mha) of the total Inner Mongolian grassland (Table 1); 59 banners had fenced area increases of 18.3 Mha and 20 banners had fenced area decreases of 1.7 Mha (Table 1). Eight banners with no fencing implementations were located mainly in the southern agricultural area and the northern meadow steppe area (Table 1).

3.2. Precipitation lag effect on vegetation changes

The significance of the difference of increased NDVI, new fenced area proportions and improved grassland area proportions under different precipitation scenarios is shown in Fig. 3. The new fenced areas proportions under the ITP, DW and WD scenarios showed no significant differences. Compared with the control scenario of ITP, the WD scenario showed a significantly lower value for increased NDVI and no significant differences for improved grassland area proportions, while the DW scenario showed significantly higher values both for mean increased NDVI and for mean improved grassland areas (Fig. 3). The comparisons showed that WD did not constrain the fencing effect and that the DW scenario may induce overestimations of the fencing effect. Among the 6 banners in the DW scenario, 5 are located in the MAP > 300-mm precipitation zone and 1 in the MAP < 250-mm precipitation zone.

3.3. The contribution of fencing to variations in grassland vegetation

The contribution of fenced area increases to grassland restoration was assessed after removing the 6 banners in the DW scenario. Both the improved (Fig. 4a) and degraded (Fig. 4c) grassland areas were significantly linearly ($p < 0.01$) associated with an increase in fenced areas. Approximately 30% (Fig. 4a) and 15% (Fig. 4c) of the variability could be explained by the increased fenced areas. When the fenced area proportion doubled, the improved grassland area proportion increased by 42% (Fig. 4a) and the degraded grassland area proportion decreased by 35% (Fig. 4c). The fenced area increase did not affect areas of unchanged grassland (Fig. 4b) These data suggest a positive fencing effect in expanding improved grassland areas and in reducing degraded grassland areas (Fig. 4a and c). However, decreases in the fenced area showed no obvious effects on grassland vegetation variation (Fig. 4d–f). This result might be due to low variability in the decrease of fenced area—the largest decrease was less than 20%. Moreover, the sampling of these areas was inadequate (20 banners). Consequently, the following assessment of the spatial patterns of fencing efficiency focused primarily on the impact of increased fenced area.

3.4. Spatial patterns of fencing efficiency

Different grassland change type exhibited different responses to fenced area increases under the three precipitation gradients (MAP < 250-mm zone, 250–300-mm zone and MAP > 300 mm zone). Fig. 5a–c depict grassland responses to fenced area increases in the MAP < 250-mm zone. The improved grassland (Fig. 5a) and degraded grassland (Fig. 5c) exhibited no obvious relationship ($p > 0.1$) with fenced area increases. However, fenced area increases explained 41% of the variability in the grassland areas with unchanged NDVI (Fig. 5b), indicating that grassland improvements in the MAP < 250-mm zone were insensitive to fenced area increases during the 2001–2010 period. In the 250–300-mm zone, the expansion rate of improved grassland was 0.70 (Fig. 5d) and the reduction rate of degraded grassland was 0.60 (Fig. 5f). In this zone, 54% of the expansion and 38% of the reduction were attributable to fenced area increases. Fencing measures were less effective in the MAP > 300-mm zone, a relatively gentle expansion rate (0.26) of improved grassland was found while fenced area doubled (Fig. 5g), to which the increase in fenced area contributed 21%. However, the correlation between fenced area increases and degraded grassland area was insignificant ($p = 0.15$, Fig. 5i). It is obvious that the highest fencing efficiency was achieved in the 250–300-mm MAP zone. The MAP > 300-mm zone was the second most effective zone, and fencing measures were the least efficient in the MAP < 250 mm zone. Additionally, a general trend was found in that the expansion rates of improved grassland were higher than the reduction rate of degraded grassland in both the MAP 250–300-mm zone and in the entire study region.

4. Discussion

4.1. Evaluation of the precipitation lag effect on the fencing measure

A widely applied viewpoint is that the biomass of the Eurasian temperate steppe is significantly affected by precipitation periods that occur during the growing season of the current year (Guo et al., 2012). The precipitation lag effect is a controversial issue concerning the relationship between precipitation periods and the grassland biomass of Inner Mongolia (Guo et al., 2013; Guo et al., 2006). The precipitation lag effect—at minimum—involves the previous two years on arid and semiarid grassland (Reichmann et al., 2013; Sala et al., 2012). According to the mechanism of the precipitation lag effect, under the supposition that, given two identical arid/semi-arid grassland communities with the same rainfall amount in the current year–the grassland that previously experienced a continuously wet climate will produce more biomass than the grassland that previously experienced a continuous drought. Therefore, it is supposed that the role of the fencing measure in

Table 1
Grassland NDVI Variation Statistics for Different Changes in Fencing in Regions of Inner Mongolia.

(Area unit: Mha)

Fence change regions	No.	GA	FCA	Increased NDVI		Unchanged NDVI		Decreased NDVI	
				Area	Proportion	Area	Proportion	Area	Proportion
Increase	59	48.1	18.3	13.2	27.5%	19.7	40.9%	15.2	31.6%
No fencing	8	0.6	0.0	0.2	29.6%	0.3	47.2%	0.1	23.2%
Decreased	20	12.6	−1.7	1.5	12.2%	5.3	42.4%	5.7	45.3%
Sum	87	61.3	16.5	14.9	24.4%	25.3	41.3%	21.0	34.3%

Note: The abbreviations No., GA and FCA represent number, grassland area and fencing change area, respectively. The proportion of grassland change area was achieved by dividing the sum of grassland areas with increased NDVI, unchanged NDVI and decreased NDVI by the total grassland area.

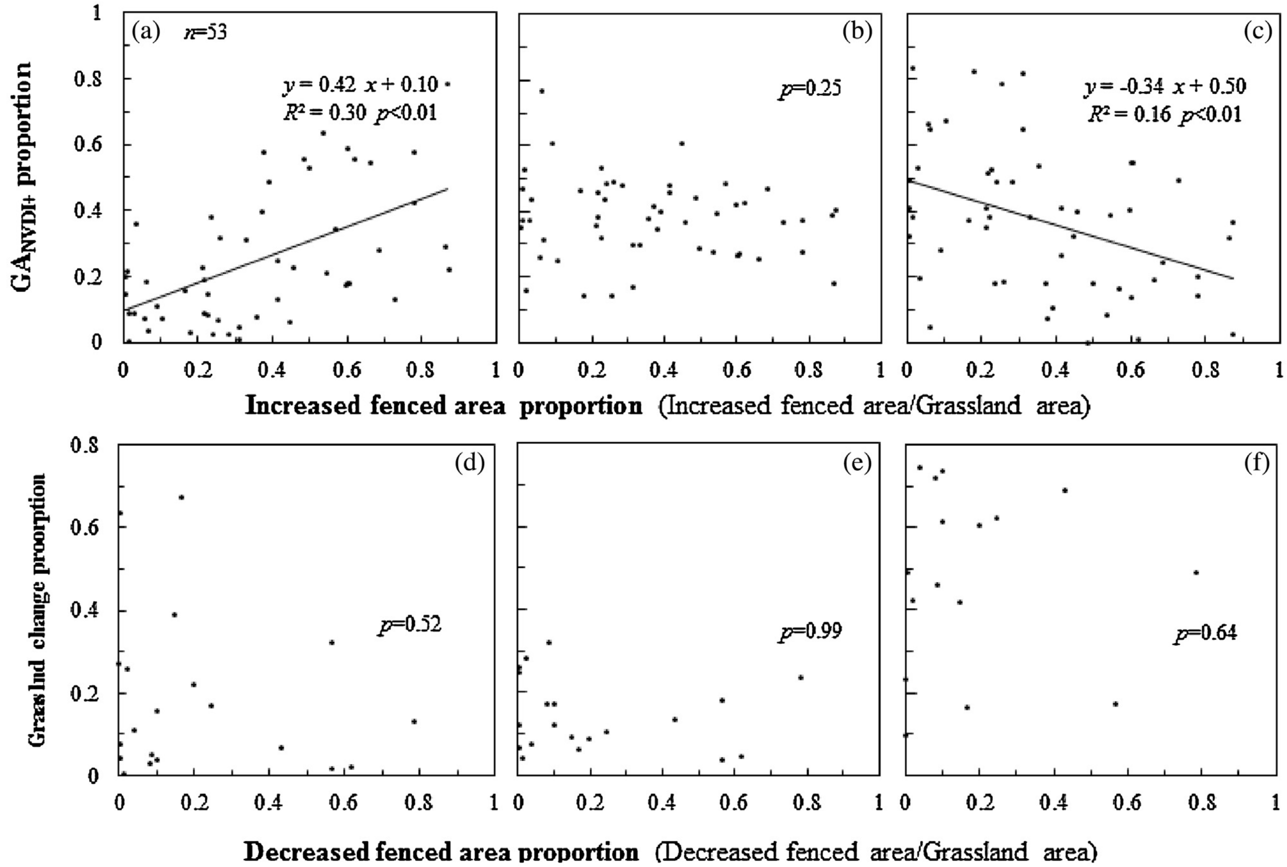

Fig. 4. Grassland change responses to fenced area increases and decreases. The relationships between the proportion of improved (increased NDVI) grassland area and the proportion of increased fenced area (a), the proportion of unchanged (unchanged NDVI) grassland area and the proportion of increased fenced area (b), and the proportion of degraded (decreased NDVI) grassland area and the proportion of increased fenced area (c). (d)–(f) represent the relationships of the above area proportions with decreased fenced area. The *X*-axes in (a)–(c) and in (d)–(f) represent the proportions of increased and decreased fenced areas, respectively. The *Y*-axes represent the proportions of grassland areas with increased NDVI (a and d), unchanged NDVI (b and e) and decreased NDVI (c and f), respectively.

grassland restoration was probably supressed in the WD scenario and overestimated in the DW scenario. Although the suppression effect of the WD scenario was found to have a slight impact on the NDVI increases, the WD scenario did not inhibit the expansion of improved grassland. This phenomenon may be explained by the highest rainfall use efficiency (RUE) (Huxman et al., 2004; Zhang et al., 2014) which generally occurs in the dry tendency defined by this paper. In contrast, the DW scenario had an evident impact on the overestimation of the fencing effect (Fig. 6). In the banners under the DW scenario, the expansion rates of improved grassland were increased to 0.45 for the entire study area and to 0.35 for the MAP >300-mm zone—both accompanied by a decline in R^2. However, no similar case was found when removing regions in the WD scenario. Generally, the temporal precipitation pattern of temperate grassland showed a prevalent high between-year variability. We ignored any precipitation lag effect that occurred only in the previous one year, which may have induced minor uncertainties in our work (Guo et al., 2006).

4.2. Patterns of grassland fencing efficiency

The distinct high-to-low order of the effective fencing zones was 250–300-mm zone, MAP >300-mm zone and MAP <250-mm. A previous study based on field observations in the Xilin Gol steppe indicated that a wet climate amplifies fencing effects, resulting in increased biomass as precipitation increases (Hao et al., 2014). Here, we propose that although precipitation did not magnify the overall efficiency of fencing, it did magnify it in specific precipitation ranges (<300-mm). Indeed, different precipitation ranges are a major reason for the inconsistent conclusions of these two

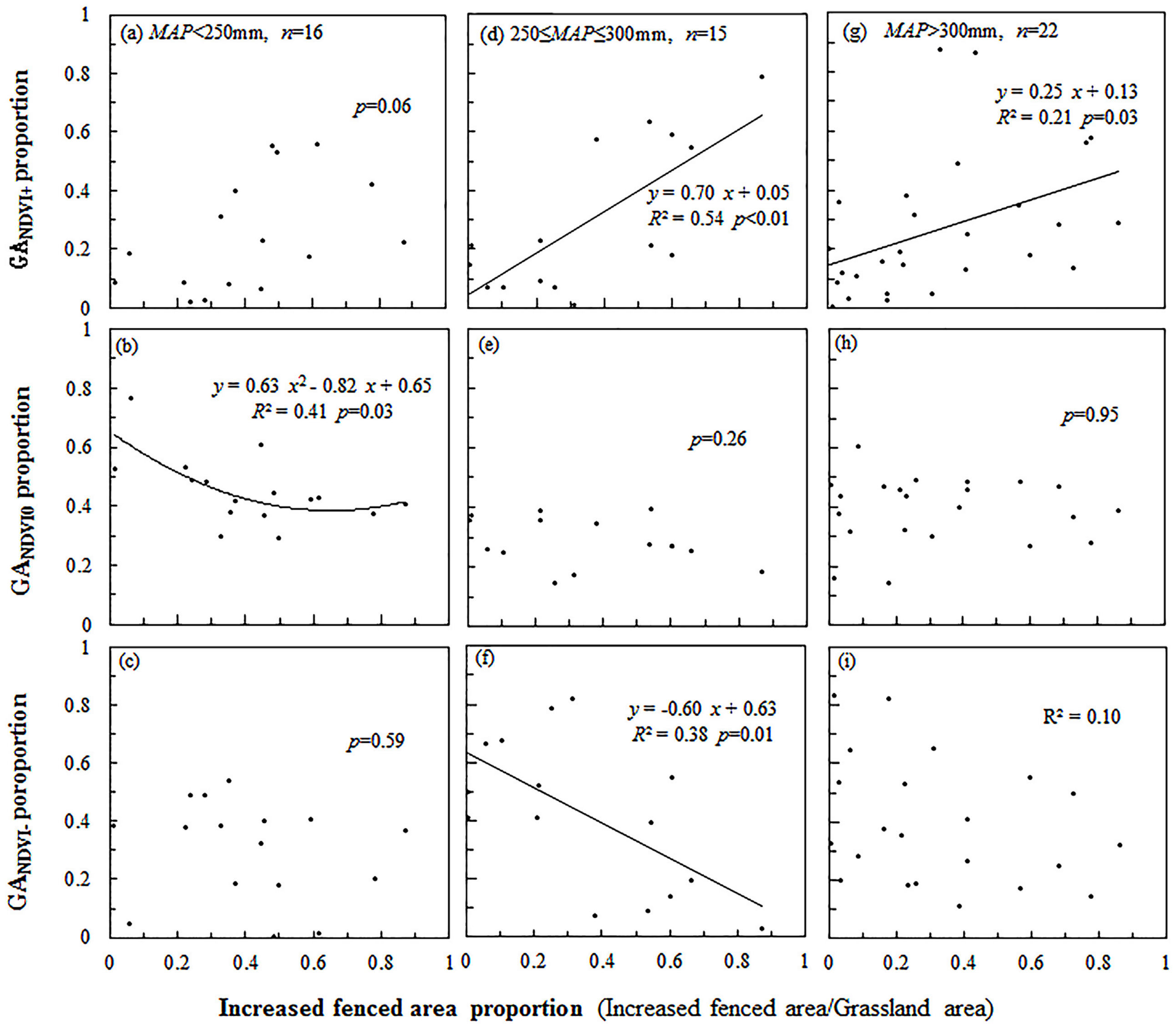

Fig. 5. The grassland response to increased fenced area at different precipitation gradients. The series (a)–(c), (d)–(f) and (g)–(i) depict the relationships of the proportions of improved, unchanged and degraded grassland vegetation areas, respectively, with increased fenced area in the *MAP* < 250-mm, 250–300-mm and >300-mm zones. *n* represents the number of banners in each precipitation gradient. GA$_{NDVI+}$, GA$_{NDVI0}$, and GA$_{NDVI-}$ indicate grassland areas with increased NDVI, unchanged NDVI and decreased NDVI, respectively.

studies. The spatial patterns of fencing efficiency may be related to both the ability to resist disturbances and to the degree of damage of different grassland types. Because the most rapid self-recovery capability of meadow steppe occurred in the MAP >300 zone, only 5% of meadow steppe were severely damaged. Also, previous site-based observations have suggested that fencing measures only positively affect seriously degraded meadow steppe (Zheng et al., 2005) and that lightly or only moderately damaged meadow steppe could be restored simply by controlling grazing (Briske et al., 2008; Luo et al., 2012; Turner et al., 1993). The typical steppe has weaker self-recovery capability and the desert steppe, which has the weakest self-recovery capability, both experienced moderate or severe degradation (Han et al., 2008). Compared with typical steppe distributed in 250–300-mm zone, the extreme arid climate of the MAP <250-mm zone is a major limiting factor for aboveground vegetation growth (Paruelo et al., 1999; Webb et al., 1978); only the unchanged grassland area of the MAP <250-mm zone was related to fenced area increases during the 2000–2010 period (Fig. 5b). Site-based experiments suggested that longer fencing durations are required for desert steppe restoration (Liu et al., 2013) and that planting shrubs is a more effective measure than fencing (Miao et al., 2015; Zhao et al., 2007). Note that the main limitations of this research were the lack of data concerning fencing duration and location compared to field observations. Therefore, the mechanism behind the spatial pattern of fencing efficiency is still focused on qualitative analysis.

4.3. *Low efficiency of fencing implementation*

The conclusion that fencing implementation has low efficiency was the result of two issues: unreasonable fencing implementation and grassland outside of the fenced area continued to degrade. Unreasonable fencing implementation during 2000–2010 was showed by the facts that only 19% (3.4 Mha) of the new fencing implementations occurred in the most effective 250–300-mm zone (Table 2), while 63% (11.5 Mha) of new fencing implementations occurred in the least effective zone (MAP < 250-mm), which does not favour grassland restoration over the short term, particularly in the arid MAP < 200-mm zone (Table 2); Moreover, the fencing implementation area (3.3 Mha) in the MAP > 300-mm zone may

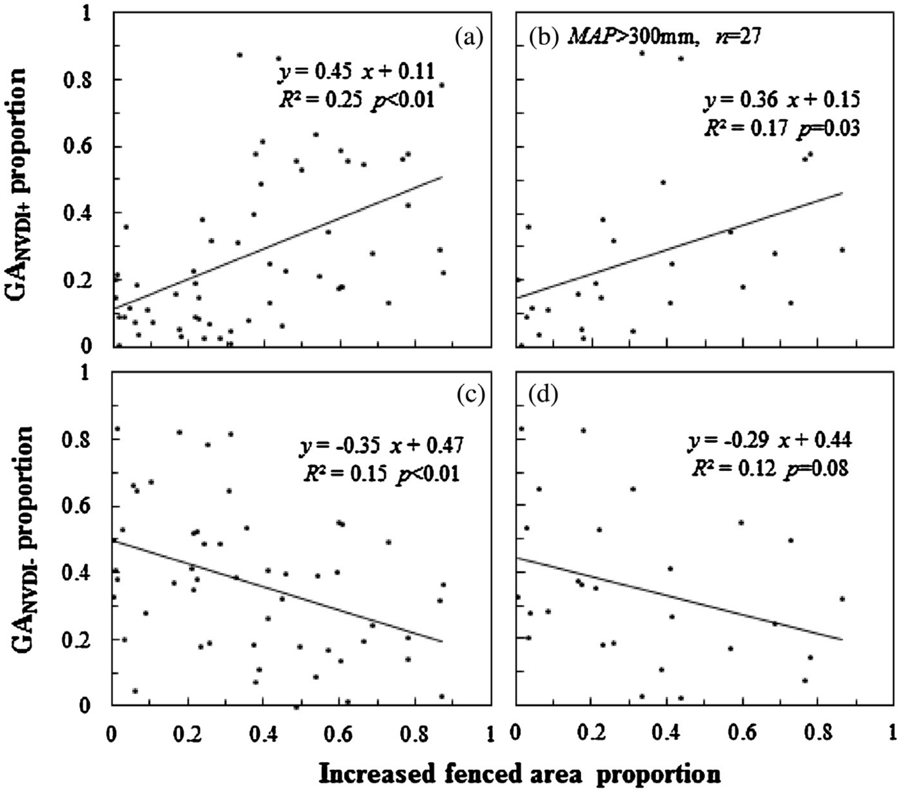

Fig. 6. Overestimation of the fencing effect on the entire Inner Mongolian grassland (a), (c) and on the MAP >300-mm zone (b) (d) from the influence of the DW scenario.

Table 2
Grassland Changes in Regions with Increased Fencing and Different Precipitation Gradients.

Area unit: Mha

MAP gradient (Unit: mm)	GA	Fence increase		Increased NDVI		Unchanged NDVI		Decreased NDVI	
		Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion
<200	14.6	5.5	38%	4.2	29%	7.0	48%	3.5	24%
200–250	15.3	6.0	39%	3.8	25%	6.3	41%	5.2	34%
250–300	8.7	3.4	39%	2.6	30%	2.6	30%	3.4	39%
300–350	6.6	2.5	38%	2.1	32%	2.6	40%	1.8	28%
>350	2.9	0.8	28%	0.5	18%	1.1	38%	1.3	45%
Sum.	48.2	18.2	38%	13.2	27%	19.7	41%	15.2	32%

Note: No. and *MAP* abbreviate number and multiple average annual precipitation, respectively. The fencing increase or grassland change area was divided by the grassland area, which is the sum of grassland areas with increased NDVI, unchanged NDVI and decreased NDVI regions at the same precipitation gradient.

represent an ineffective use of resources because most lightly and moderately damaged steppe can be restored through self-recovery. Another remarkable issue was that the grassland outside of the fenced area continued to degrade. This was inferred from the comparison that revealed that the reduction rate of degraded grassland area was smaller than the increased rate of improved grassland area caused by fencing area increases (Fig. 3): both rates would be expected to be the same in the absence of expanded degradation. Coupled with the issue of continuing grassland degradation is the fact that the actual number of livestock is far higher than the total estimated livestock-supporting capacity of 45.51 million sheep reported by Li and Ji (2004); the number of livestock was 162.29 million sheep in 2001, and it increased by 7.89 million sheep units per year until 2010 (statistic from the Inner Mongolian Statistics Yearbooks).

According to the expansion rate of improved grassland, we can estimate the potential benefit that resulted from advancing fencing implementation in 250–300-mm zone. While typical steppe and meadow steppe can achieve identical levels of peak aboveground biomass (AGB) (Ni, 2004), doubling the fenced area in the 250–300-mm zone could facilitate an approximately triple increase of AGB than doubling the fenced area in the MAP > 300 zone. Mowing in fenced grassland is a widespread activity that relieves the urgent need for forage to increase livestock yield, although how mowing impacts the fencing effect is still an unsettled issue. However, it is definitive that future fencing implementation should be implemented in the most suitable zone. Additionally, the interactions between the fencing measure and other anthropogenic factors such as overgrazing, mowing and even land use changes all need to be assessed to investigate the efficiency of each specific human activity.

5. Conclusions

For the first time, a specific anthropogenic factor—the fencing measure—was assessed to determine its efficiency and the most suitable area (250–300-mm MAP zone) for its large-scale implementations in the grassland areas of northern China. We propose the concept that wetter climate does not automatically result in a better fencing effect and that precipitation legacy is a factor that inevitably impacts the fencing effect assessment; the DW scenario could result in overestimations of the fencing effect. Furthermore, the concerns about blindly expanding a distinct anthropogenic measure were validated in our research. For effective grassland-restoration, the efficiency of the fencing measure—which is probably affected by the grassland ecosystem resilience and the degree of degradation—should be considered. This work has provided valuable suggestions for rational practices in temperate grassland restoration efforts. We believe that range managers, conservation biologists and restoration/rehabilitation ecologists could all benefit from fencing effect assessments. Moreover, while the approach used in this study—combining remote sensing monitoring methods with an ecological analysis approach—was not the first time such a combination has been used, this technique requires more attention and further studies for its broader development.

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