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Combining private and common property management: The impact of a hybrid ownership structure on grassland conservation

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ABSTRACT

This study finds that a hybrid property structure, where private ownership and communal ownership coexist, outperforms pure private or pure public ownership in terms of grassland conservation after a grassland tenure reform in China. The tenure reform of privatization replaced public ownership gradually and led to a significant 5.4% increase in grassland quality on average. The grassland quality increase is twice as large for private grassland with additional access to public grassland compared to those without such access. Interestingly, public grassland quality did not decline, indicating sustainable utilization by herders. These findings are consistent with the literature which suggests that a properly structured hybrid ownership arrangement could benefit from the positive effects of grassland privatization while mitigating the negative impacts of natural disasters. We further provide empirical support and show that the gains from public grassland access are substantially larger when there are adverse climatic shocks. Our study provides important policy implications for property rights and sustainable grassland management under more frequent climate events.

1. Introduction

Grasslands cover more than two-thirds of the global agricultural area and directly support the livelihoods of more than 800 million people (FAO, 2015). Grasslands degradation is widespread and accelerating in many parts of the world. Nearly half of grasslands experience various degrees of degradation, mostly due to overgrazing (Herrero and Thornton, 2013; Gibbs and Salmon, 2015). Sustainable use and management of grasslands have been of great concern to academics and policy-makers (Suttie et al., 2005; Bardgett et al., 2021). Privatization of grassland property or use rights has long been regarded as an effective approach to prevent overgrazing and avoid the “tragedy of the commons” (Hardin, 1968; Dietz et al., 2003; Hornbeck, 2010). While grasslands were mainly in communal use for nomadic herding in the past (Honeychurch and Makarewicz, 2016), grassland tenure reform and privatization have become the mainstream worldwide nowadays (Abdulai et al., 2011; Deininger and Byerlee, 2011; Bardgett et al., 2021).

It is still far from conclusive that ownership privatization could lead to the most effective grassland conservation. While Garrett Hardin used the grassland as an example to illustrate the “tragedy of the common” (Hardin, 1968), there are only a few empirical studies on the effects of ownership privatization on grassland conservation, and the findings are mixed (e.g., Hou et al., 2022;

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Liu et al., 2019; Sneath, 1998).[1] In addition, pastoral specialists have criticized the privatization of grassland, as it could harm grassland quality by causing fragmentation that limits the mobility and flexibility of grassland use (e.g., Behnke, 1994; Sneath, 1998; Hobbs et al., 2008; Wang et al., 2013). Mobility is essential for ensuring the sustainable use of grasslands by pastoralists, given the strong spatial and temporal heterogeneity in grasslands (Rota and Sperandini, 2009; Tessema et al., 2014), while flexibility can serve as an important risk management strategy for coping with the spatial variability of vegetation and the vulnerability of grasslands (McCarthy and Di Gregorio, 2007; Fernandez-Gimenez, 2002).

Existing studies imply that a hybrid property structure that incorporates the advantages of both privatization and nomadic herding could outperform pure public and pure private ownership in grassland conservation. Grassland privatization could have a positive effect on grassland quality through the conservation (Dutta and Sundaram, 1993) and investment effects (Jung et al., 2022). Grassland privatization could also have a negative effect on grassland quality by causing fragmentation that limits the mobility and flexibility of grassland use, which are critical for herders to offset the damage from natural disasters occurring differently across grassland parcels each year through nomadic herding (e.g., Behnke, 1994; Sneath, 1998; Hobbs et al., 2008; Wang et al., 2013). Therefore, an intuitive hypothesis is that a hybrid ownership structure that enables additional access to public grasslands for herders who also own private parcels could enjoy both the positive conservation and investment effects of grassland privatization and the risk-abating benefits of public grassland access.

We test this hypothesis based on unique data from China's grassland tenure reform. We obtained parcel-year grassland quality data for 5728 parcels from 1986 to 2020 in a study area of 22 thousand square kilometers in Inner Mongolia, China. The study area experienced a grassland tenure reform that was gradually rolled out from 1997 to 2011. The reform altered the original communal (village) use rights of grasslands to the private use rights of individual households while reserving a substantial area of public grasslands in some villages for nomadic herding by all herders from the village.[2] As a result, after the tenure reform, herders have access to only private grasslands in some villages and to both private and public grasslands in others.

To empirically investigate the impact of a hybrid property structure on grassland quality, we first estimate the effect of the tenure reform on grassland quality by employing a generalized difference-in-differences (DID) model that relies on the gradual rollout of the tenure reform for identification. We measure parcel-year-level grassland quality using the Normalized Difference Vegetation Index (NDVI), which is constructed based on remote sensing images and parcel-boundary maps drawn from field measurements. We address endogeneity concerns by demonstrating that preexisting grassland quality and its determinants have no impact on the timing of the tenure reform. An event study confirms that there were no divergent preexisting trends in grassland quality among villages with different tenure reform dates. The DID estimates suggest that the tenure reform increased the quality of the privatized grasslands by 5.4%. Furthermore, we demonstrate that the tenure reform had no adverse effect on the quality of grasslands that remained in public use after the reform.

We then proceed to examine the effect of additional access to public grasslands by comparing private parcels in villages with and without such access after the tenure reform. Specifically, we expand the DID model to incorporate the interaction between the tenure reform dummy and the public grassland access dummy. The estimated coefficient of the interaction term is significantly positive, suggesting that approximately one-third of the benefits from grassland privatization can be attributed to the additional access to public grasslands. To address the concern that the status of public grassland access might be endogenous, we also estimate a difference-in-discontinuity (DID-RD) model that compares parcels located near the borders of villages with and without public grassland access. The DID-RD estimates indicate that, depending on the chosen bandwidth, between one-third and one-half of the gains from grassland privatization can be attributed to the additional access to public grasslands. This finding corroborates the hypothesis that a hybrid property structure outperforms the pure public or pure private ownership in terms of grassland conservation.

Finally, we explore the mechanisms behind the effect of additional access to public grasslands. First, we demonstrate that the gains from additional public grassland access do not come at the expense of public grassland degradation. The gains cannot be explained by a mechanical decline in the grazing pressure on public grasslands. Specifically, we illustrate that the tenure reform did not diminish the quality of the remaining public grasslands and that access to public grasslands also increased the village's average grassland quality (i.e., the average quality across private and public grasslands). Subsequently, we explore the significance of the risk-abating function of public grassland access. We reveal that the gains from public grassland access are significantly larger in the presence of harmful climatic shocks and notably smaller in the presence of favorable climatic conditions. Additionally, we demonstrate that when the size of the private parcel is large enough to allow nomadic herding within the parcel, the gains from additional public grassland access disappear.

This study contributes to the literature on the impact of property rights on environmental outcomes. Scholars have long recognized the significance of property rights in mitigating environmental degradation (e.g., Coase, 1960; Hardin, 1968). However, empirical studies on this topic have generally centered on the forest and fishery sectors, rather than on grasslands (e.g., Costello et al., 2008; Liscow, 2013; BenYishay et al., 2017; Isaksen and Richter, 2019; Tseng et al., 2021; Jung et al., 2022), despite the critical role that grasslands play in global ecosystems and the substantial degradation risks they face. This paper is one of the few studies that identify the effect of property rights on grassland conservation (e.g., Hou et al., 2022; Liu et al., 2019; Sneath, 1998). We utilize the exogenous timing of the tenure reform and long-term parcel-level data to estimate the effect of grassland privatization.

[1] Although many studies have examined the environmental impacts of property rights in the forest and fishery sectors, they too have produced mixed results (e.g., Costello et al., 2008; Liscow, 2013; BenYishay et al., 2017; Isaksen and Richter, 2019; Jung et al., 2022). For a comprehensive review, see Tseng et al. (2021).

[2] In China, herders only have the use rights of grasslands, while the property rights belong to the village collective. Since the grassland use rights of Chinese herders are long-term, there is no need to distinguish between use rights and property rights for the purpose of this article.

Previous studies primarily concentrated on cross-sectional comparisons of grassland quality across administrative units and were less equipped to address concerns related to endogenous property rights (Ayres et al., 2021).

This study also provides a new perspective for reconciling the mixed findings regarding the impact of property rights on environmental outcomes (Dietz et al., 2003; Tseng et al., 2021). Scholars who advocate privately managed natural resources believe that well-defined property rights incentivize land users to protect their lands and maximize long-term benefits (Hardin, 1968; Farzin, 1984; Banks, 2003; Libecap, 2009). In contrast, other studies advocate collective action management, arguing that the privatization of property rights may fail when faced with high transaction costs (Calvo-Mendieta et al., 2017; Doss and Meinzen-Dick, 2015; Poteete and Ostrom, 2008; Libecap, 2014). The systematic review by Tseng et al. (2021) demonstrates that empirical findings on the impact of property rights on environmental outcomes are highly varied. Existing studies attempt to reconcile these mixed findings by highlighting the coexistence of positive conservation effects and negative investment effects resulting from improved property rights (e.g., Liscow, 2013; Jung et al., 2022).[3] Following the wisdom of pastoral scientists (e.g., Sneath, 1998; Wang et al., 2013) and the traditional practice of nomadic herding, this study suggests that privatization may lead to grassland fragmentation, thus limiting the risk-mitigating function of traditional nomadic herding.

Finally, our study explores a hybrid ownership structure as an alternative to current grassland management practices. Results suggest that a hybrid structure of grassland use rights has the potential to combine the advantages of both private ownership and communal ownership. Private ownership encourages sustainable grassland use by reducing the uncertainty associated with property rights (Farzin, 1984; Dutta and Sundaram, 1993), while public ownership ensures sustainable grassland use by mitigating risks associated with natural disasters through providing more mobility, flexibility, and reciprocity of grassland use Sneath (1998), Wang et al. (2013). We demonstrate that a hybrid structure, in which herders have additional access to public grasslands alongside their private grasslands, effectively improves the grassland quality.

The paper is organized as follows. Section 2 presents the conceptual framework, Section 3 provides the study background and summary statistics of key variables, Section 4 illustrates our empirical strategies, Section 5 presents the main empirical results, Section 5.3 explores potential mechanisms, and Section 6 concludes.

2. Conceptual framework

Existing studies suggest that grassland privatization could have a positive effect on grassland quality through the conservation and investment effects. Improved property rights could lead grassland owners to discount the future less and to obtain the long-term benefits (Farzin, 1984). Therefore, grassland privatization is more likely to protect grasslands (i.e., the conservation effect) (Dutta and Sundaram, 1993). At the same time, improved property rights could increase grassland quality by enhancing investment in grasslands and the returns on grassland intensification use (i.e., the investment effect) (Jung et al., 2022). Therefore, the privatization of grassland property or use rights has been regarded as an important approach to preventing overgrazing and avoiding the "tragedy of the commons" (Hardin, 1968; Dietz et al., 2003; Hornbeck, 2010).

However, many pastoral specialists believe that the privatization of grassland could also harm grassland quality by causing fragmentation, which limits the mobility and flexibility of grassland use (e.g., Behnke, 1994; Sneath, 1998; Hobbs et al., 2008; Wang et al., 2013). Mobility and flexibility serve as important risk management strategies for coping with the spatial variability of vegetation and the vulnerability of grasslands to natural disasters (McCarthy and Di Gregorio, 2007; Fernandez-Gimenez, 2002). Natural disasters such as drought, frost, wildfire, pests, and diseases are frequently observed in pastoral areas (Nandintsetseg and Shinoda, 2013; Fernandez-Gimenez et al., 2012, 2015). Given that the impact of natural disasters in different years could vary across grassland parcels with different slopes, elevations, water sources, soil conditions, and surrounding environments, herders are able to partly mitigate the damage from natural disasters by driving their livestock to unaffected grasslands. The traditional communal use of grasslands and the accompanying nomadic herding represent an important mechanism to prevent grassland degradation caused by the uncertainty of natural disasters.

Our data supports the idea that grassland privatization leads to grassland fragmentation and limit the risk-abating function of traditional nomadic herding. In our study area, the total grassland accessible for nomadic herding for each herder before the tenure reform was 27,600 hectares, but the private grassland accessible for each herder after the tenure reform was less than 200 hectares. The substantial reduction in accessible grassland after the tenure reform has clearly reduced the mobility and flexibility of grassland use. We also observed substantial variations in adverse climatic shocks across our sample parcels each year (Figures A.2 and A.3), suggesting the possibility of offsetting the damage from climatic shocks by nomadic herding if not for the tenure reform. After the tenure reform, herders with only private grasslands have to continue using the grasslands even when they are damaged by a natural disaster, which further reduces the grassland quality.

Given the coexistence of positive and negative effects of grassland privatization on grassland quality, an intuitive hypothesis is that a properly structured hybrid ownership that enjoys the positive effects of grassland privatization while avoiding its negative effects could be superior to pure public and pure private ownership in grassland conservation. The hybrid ownership structure in our study area, which enables additional access to public grasslands for herders who also own small private parcels, provides an ideal context to test this hypothesis. It is possible for these herders to benefit from the positive conservation and investment effects of their private grasslands and enjoy the positive risk-abating effect when a natural disaster does not simultaneously occur in their own grassland and the accessible public grassland.

[3] Specifically, these studies argue that improved property rights can lead landowners to discount the future less and obtain long-term benefits, making them more likely to protect their lands (i.e., conservation effects). On the other hand, improved property rights can also increase investment in land and the returns of land intensification use (i.e., investment effects), which could result in environmental degradation.

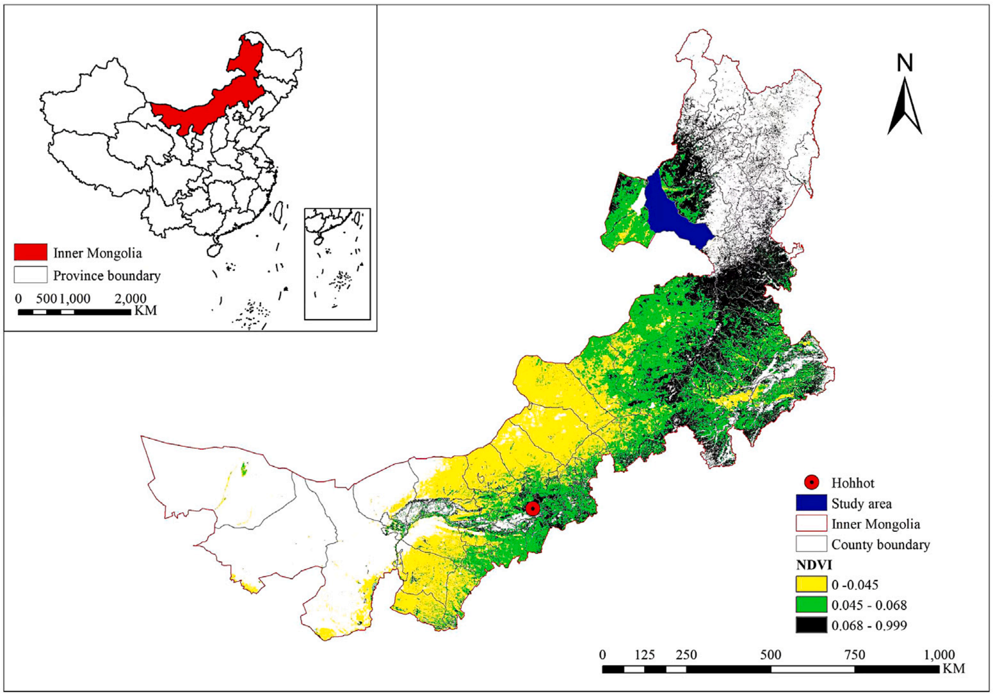

Fig. 1. The location of the study area. Note: The figure presents the location of the study area (marked in blue) within the Inner Mongolia province (marked in red) of China.

3. Background and data

3.1. Grassland tenure reform in China

Grasslands in China are primarily situated in the Inner Mongolia Plateau, the Loess Plateau, and the Qinghai–Tibetan Plateau, collectively accounting for 27.6% of China's territory. For thousands of years, grasslands in China were owned by princes, clans, landlords, or lamaseries, and were commonly used by tenant herders (Liu, 2017). During the collectivist period (1955–1980) of the People's Republic of China, grasslands were owned by the production team (or People's commune) and managed and used collectively by all local herders (Hua and Squires, 2015). China initiated grassland tenure reform after the abolishment of the People's Commune in the 1980s. The tenure reform assigned the use rights of grassland to individual households based on the size of each household (Banks et al., 2003).[4] However, the allocation of grassland use rights was not well-implemented initially, as communal use was a long-standing tradition, and taxes are based on the area of contracted grasslands. Although individual households received grassland property certificates indicating the areas and locations of grassland parcels, most of the grasslands were not privately used at the beginning of the tenure reform because animals grazed semi-randomly on the grasslands, and there were no physical barriers to stop them.

The construction of wire fences since the 1990s accelerated the grassland tenure reform. Traditional herders initially found it challenging to adopt private use of grasslands because building wire fences were not popular or affordable. The building of wire fences, which divided grasslands according to the boundaries of each individual household's grasslands, received subsidies from national and local governments starting in the 1990s (Liu et al., 2020). With legislative and financial support, the privatization of the grasslands gradually gained acceptance among herders in the traditional pastoral areas (Cai et al., 2020).[5] Private use increasingly replaced traditional open access to land with the introduction of fences (Hua and Squires, 2015). The finding that wire fences promoted the progress of privatization has also been found in previous studies based in China (Hou et al., 2022) and other countries (McCallum and McCallum, 1965; Hornbeck, 2010).

[4] The first Grassland Law of China, introduced in 1985, stipulated that the property rights over grasslands were owned either by the state or the collective, but the use rights to the grasslands could be contracted out to households. In 2002, the revised Grassland Law reaffirmed the shift from state- and collective-oriented land use rights to those of individual households (Liu et al., 2019).

[5] According to Liu et al. (2020), less than 30% of counties in the pastoral area of Inner Mongolia had completed assigning more than half of their grasslands to individual households by 1995. The privatization process accelerated after 1996, and almost all counties had implemented the privatization of grassland use rights by 2008.

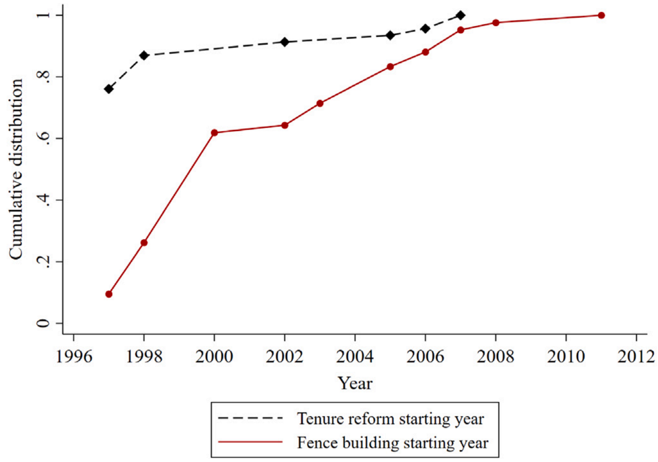

Fig. 2. Roll out of tenure reform and fence building. Note: This figure presents the cumulative distribution of the village-level tenure reform starting year (dashed black line) and grassland fence building starting year (solid red line) across the 48 sample villages. The data is obtained from our field survey.

3.2. *The study area and tenure reform roll out*

Fig. 1 presents our study area (X county, marked in blue), located in the northeast of Inner Mongolia, spanning from 117°33′ to 120°12′E and 46°10′ to 49°47′N. The study area covers an area of 22 thousand square kilometers, roughly equivalent to the land area of Wales. The grasslands in this area belong to the meadow steppe. The area accommodated approximately 1.2 million animals in 2022, including 0.8 million sheep, 0.3 million cattle, and 0.1 million other livestock such as horses and camels. The area contains 55 administrative villages. After excluding villages and parcels dominated by urban land, cropland, and forests, there are a total of 48 villages and 5728 grassland parcels left for our empirical analysis. The left panel of Fig. 3 presents the location and size of each sample parcel.

The study area initiated the grassland tenure reform in 1997 when nearly all villages began assigning their grasslands to individual households. Individual households received grassland property certificates indicating the areas and locations of grassland parcels during the reform. As shown in Fig. 2 (dashed black line), 75% of the sample villages began the grassland tenure reform in 1997, which increased to 92% by 2002. By 2007, all villages had commenced the tenure reform. However, at the beginning of the reform, most of the grasslands were not privately used by herders because there were no physical barriers to prevent semi-random grazing. The construction of fences, necessary for the exclusive use of private grassland, progressed more slowly. As indicated in the same figure (red line), only 10% of the sample villages started building fences in privatized grasslands in 1997, which increased to 62% by 2000, 93% by 2007, and by 2011 all villages had begun fence construction.

3.3. *A hybrid property structure*

Not all grasslands were allocated to individual households and some villages retained public grasslands after the tenure reform. This allowance is in accordance with Chinese land law to permit possible land adjustments in the future due to potential population growth. The unassigned grasslands were developed for communal use and remained accessible to all herders from the village. As illustrated in the right panel of Fig. 3, herders in 40 out of the 48 sample villages have access to public parcels, in addition to the private parcels.[6] A hybrid property structure has emerged in the 40 villages where private ownership and communal ownership coexist. The remaining 8 villages have no public parcels, and all the grasslands were assigned to individual households. The 975 parcels from the 8 villages will form the base of the control group when we analyze the effect of additional public grassland access.

On average, the tenure reform assigned the use rights of 86% of the grasslands to individual households, while allocating the remaining 14% to village collectives for communal use. The average private grassland area per household is 179 hectares, while the average public grassland area per village is 2902 hectares. The significant expanse of public grasslands opened up opportunities for nomadic practices among local herders. Herders would move their livestock to the public grasslands for nomadic herding and live in mobile residences there for several months each year (see Appendix Figure A.1 for an illustration of herders' temporary mobile residences in the public grassland). After the tenure reform significantly reduced the amount of grassland accessible to each herder, traditional rotational grazing became feasible only when public grasslands were available.

[6] The public parcels in 35 villages are located inside the villages and are accessible only to their own villagers. The public parcels in the remaining 5 villages (marked by the red star) are interconnected and open to herders from all five villages. We will exclude these 5 villages in a robustness check.

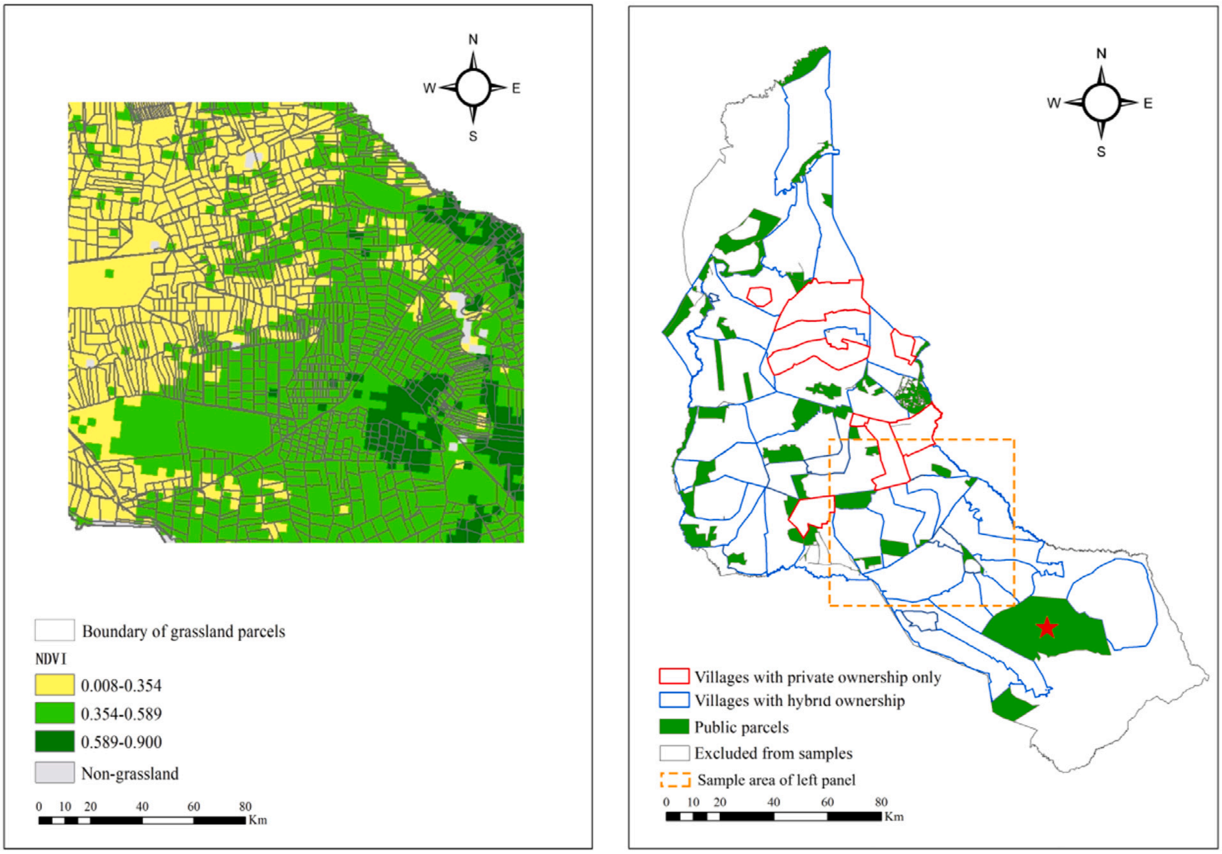

Fig. 3. Grassland quality and property ownership types. Note: This figure presents the distribution of grassland quality (left panel) and ownership types (right panel) across the sample parcels in 2020. Due to the data provider's restrictions on publishing grassland parcel boundary information, the left panel displays only a portion of the grassland parcel boundaries. The right panel highlights the specific location of the displayed area in the left panel.

3.4. Summary statistics of the key variables

Our primary analysis utilizes parcel-year data from 1986 to 2020 for the 5728 grassland parcels. The key variables employed in our analysis include the indicator of grassland quality, the timing of grassland tenure reform, and measures of climatic shocks.

3.4.1. Grassland quality

We measure grassland quality at the parcel-year level using the annual maximum of the Normalized Difference Vegetation Index (NDVI), a standard measure of vegetation coverage that effectively separates vegetation from the natural environment.[7] The NDVI data was derived from Landsat, launched by the U.S. National Aeronautics and Space Administration, which has a spatial resolution of 30×30 m and a 16-day retrieval period. We extracted the NDVI of each land parcel from 1986 through 2020 using remote sensing technology based on the Maximum Value Composite method (Holben, 1986) and the land-boundary map. The land-boundary map, demonstrating the geographical boundaries of each parcel, was drawn by the local government based on field measurements in 2016 and 2017.

Fig. 3 (left panel) presents the parcel-level NDVI in 2020, where the NDVI in the southern region is generally higher than that in the northern and middle regions.[8] The mean and standard deviation of the NDVI across the 5728 parcels over the sample period are 0.39 and 0.11, respectively. Fig. 4 presents the changes in the distribution of NDVI across the sample parcels before (1996) and after (2012) the grassland tenure reform. The distribution shifted rightward after the tenure reform, suggesting a potential positive impact of the tenure reform on grassland quality.

[7] The NDVI measurement is based on the differential absorption, transmittance, and reflectance of energy by vegetation in the red and near-infrared portions of the electromagnetic spectrum (Senay and Elliott, 2000). NDVI is strongly associated with the percentage of vegetation coverage, leaf area index, potential photosynthesis, above-ground net primary productivity, and biomass availability (Soriano and Paruelo, 1992; Weber et al., 2018).

[8] The figure also reveals that about 81% of the land is grassland, and the southeast area (labeled as "Non-grassland" in gray) is occupied by forest and cropland.

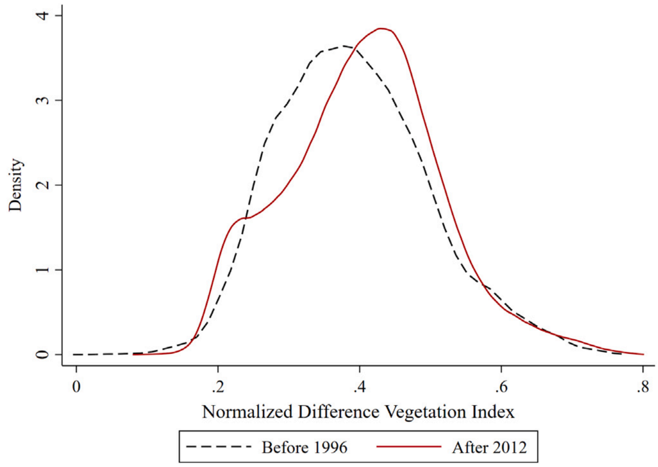

Fig. 4. Distribution of NDVI before and after the grassland tenure reform. Note: This figure presents the distribution of NDVI across the 5728 sample parcels before 1996 and after 2012.

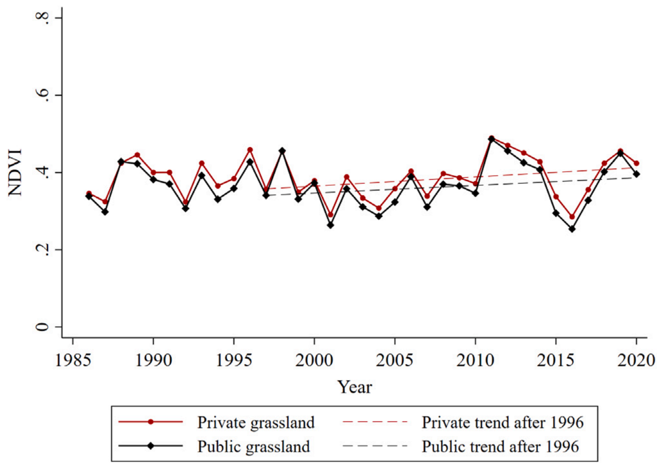

Fig. 5. Time trends of grassland quality from 1986 to 2020. Note: This figure presents the time evolution of the average quality of private and public grasslands, respectively, from 1986 to 2020. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5 displays the time evolution of private (red line) and public (black line) grasslands separately, from 1986 to 2020. Our sample consists of 5679 private parcels and 49 public parcels.[9] As mentioned earlier, public parcels account for 14% of the total grassland area because they are considerably larger than private parcels. The figure illustrates that the quality of public parcels is slightly lower than that of private parcels for most of the sample years. Additionally, the figure shows slightly increasing trends in the quality of both private and public parcels after the tenure reform.[10]

3.4.2. *Tenure reform and fence building*

We gathered information on the grassland tenure reform and fence construction through a field survey that involved interviews with village heads responsible for implementing local grassland tenure reform. The survey included questions about when the land tenure reform commenced in the village and when the construction of fences to enclose private grassland parcels began in the village.[11] The starting years of tenure reform and fence construction are presented in Fig. 2.

[9] A parcel is categorized as private or public based on its status after the tenure reform.

[10] The figure shows a sharp decline in grassland quality around 2015. When discussing this issue with local herders in the study area, we learned that a severe locust plague occurred in the region during 2014–2015. Therefore, the sharp decline in grassland quality might have been caused by the locust infestation.

[11] Our empirical analysis does not utilize the completion year of tenure reform or fence construction as they are more likely to be influenced by local conditions.

3.4.3. Climatic shocks

We constructed climatic shock measures based on daily temperature and precipitation data at a spatial resolution of 0.5 × 0.5 degrees. The data were derived from the latest global meteorological reanalysis database provided by the European Centre for Medium-Range Weather Forecasts. We used the data from the climate grid covering each parcel as an approximation of the parcel's climate. Using the parcel-level data, we constructed four measures of climatic shocks: negative precipitation shock, negative precipitation shock, negative precipitation shock, and negative precipitation shock. Specifically, we follow the literature (e.g., Miller et al., 2021; Ashraf and Michalopoulos, 2015) to calculate the positive (negative) temperature shock as the count of months in each year with a mean temperature of at least one standard deviation above (below) the long-run average temperature of the same month.[12] Similarly, we calculated the positive (negative) precipitation shock as the number of months with precipitation at least one standard deviation above (below) the long-run average. In addition to the climatic shock measures, we also constructed various climatic control variables from the data, including the annual mean and variance of temperature and precipitation, and the total degree-days.[13] Appendix Figures A.2 and A.3 reveal substantial variations in climatic shock measures over the 35 sample years and across the 5728 grassland parcels, respectively. This finding confirms that natural disasters frequently occur in our study area.

To examine the risk-abating function of public grasslands, we also need to know if there is significant within-village climatic variation, as herders can only get access to public grasslands within their own village. Recall that our study sample covers an area of 22 thousand square kilometers with 48 administrative villages and 7 very small urbanized areas. The average size of each sample village is about 450 square kilometers. Such a large geographic area of each village allows for significant within-village climatic variation, especially when considering the differences in landscapes across parcels and the irregular shape of the villages.

Our data also show significant within-village climatic variation. To measure within-village climatic variation, we first calculate the standard deviation of temperature and precipitation shocks within each village for each year, using the climatic shock measures constructed above. We then plot the standard deviation over years for each village, after sorting. As presented in Appendix Figures A.4–A.7, we find significant differences in climate shocks within each village. Specifically, we find significant within-village differences in climatic shocks in about one-third of the sample years. The years with no within-village variation in climatic shocks are mainly because no climatic shocks occurred in those years.

4. Empirical strategy

4.1. Effect of grassland privatization

We employ the gradual rollout of fence building following the grassland tenure reform to identify the effect of grassland privatization on grassland quality. In the absence of physical barriers to deter semi-random grazing, property certificates indicating the areas and locations of grassland parcels cannot ensure the private use of grasslands. Therefore, our main analysis uses the year of grassland fence construction, rather than the year of tenure reform commencement, as the year of grassland privatization. We will also examine the effect of the tenure reform year in a robustness check. For simplicity, we refer to the fence-building starting year as the tenure reform year when there is no confusion.

4.1.1. Baseline model

Formally, we estimate the effect of grassland privatization on grassland quality using the following generalized difference-in-differences (DID) model:

$$Y_{ivt} = \beta_0 + \beta_1 Post_{vt} + X_{ivt}\gamma + \eta_i + \eta_t + \epsilon_{ivt}, \tag{1}$$

In this model, Y_{ivt} represents the NDVI for land parcel i in village v and year t. The key explanatory variable $Post_{vt}$ is a dummy variable that equals 1 if the year of observation is after the fence building starting year in village v, and 0 otherwise. The vector X_{ivt} includes a set of five time-varying control variables: the annual mean and variance of temperature, annual total and variance of precipitation, and total growth degree days. The model incorporates parcel-fixed effects (η_i) to account for time-invariant confounding factors at the parcel level and year-fixed effects (η_t) to account for time-varying confounding factors that are common across parcels in the same year. Our main analysis clusters the error term (ϵ_{ivt}) at the village-year level. We estimate model (1) using data from 1986 to 2020 for all private grassland parcels.[14]

[12] For a given parcel in a given year, if there was a month with a temperature higher than one standard deviation above the average temperature for that month over the past 30 years, the shock indicator took a value of 1; otherwise, it was set to 0. The temperature shock measure was then calculated as the number of months in each year subject to the temperature shocks defined in this way.

[13] We follow the literature (e.g., Schlenker et al., 2006) to construct the temperature measure of total degree-days as the sum of truncated degrees between two bounds. Specifically, we use bounds of 8 °C and 32 °C, and the degree-days in each day is calculated as:

$$d(T_d) = \begin{cases} 0 & \text{if} \quad T_d \leq 8 \\ T_d - 8 & \text{if} \quad 8 < T_d < 32 \\ 24 & \text{if} \quad T_d \geq 32 \end{cases},$$

where T_{dt} is the mean temperature on day d. The annual total degree-days is then calculated as the sum of degree-days across all days in the year $g\left(T_d\right) = \sum_{d=1}^{365} d(T_d)$.

[14] The 49 parcels reserved for public use are excluded in the main analysis but will be included in robustness checks.

The coefficient of interest, β_1, would capture the effect of grassland privatization on grassland quality if the fence building starting year is not affected by omitted village-specific time-varying determinants of grassland quality.[15] Climate variables are the most important time-varying determinants of grassland quality. We control for a set of five climatic variables. Parcel features such as parcel size, perimeter, and slope could also significantly affect both grassland quality and fence building, but these features are generally time-invariant and should have been controlled for by the parcel-fixed effects. To further address the concern that time-invariant parcel features may have time-varying effects on grassland quality, we will also control for the interaction between these features and a full set of year dummies in robustness checks.

As a robustness check, we estimate the additional effect of the tenure reform starting year based on:

$$Y_{ivt} = \beta_0 + \delta Interim_{vt} + \beta_1 Post_{vt} + X_{ivt}\gamma + \eta_i + \eta_t + \epsilon_{ivt}, \tag{2}$$

In this model, $Interim_{vt}$ is a dummy variable that equals 1 if the year of observation is after the tenure reform starting year but before the fence building starting year in village v, and 0 otherwise (Richardson et al., 2022). All other variables are the same as defined in model (1). The coefficient δ captures the additional effect of the tenure reform starting year besides the effect of the fence building starting year, which is again captured by β_1. Since tenure reform alone cannot ensure the exclusive use of private grassland, we expect to see an insignificant estimate of δ.

4.1.2. Addressing endogeneity concerns

The above efforts may not completely eliminate the endogeneity concern related to the fence building starting year. There might still be omitted time-varying factors that simultaneously influence both grassland quality and fence building. For instance, certain villages may experience positive income shocks that facilitate fence building by easing budget constraints and, simultaneously, improve grassland quality by reducing grazing intensity. To further address this concern, we take the following two steps.

First, we investigate the impact of preexisting grassland quality and its determinants on the timing of fence building. The timing of fence building is considered endogenous if it correlates with preexisting grassland quality or its determinants. As shown in Appendix Table A.2, we observe that the connection between preexisting (1990–1995 average) grassland quality and the timing of fence building is very weak and statistically insignificant (column 1). Similarly, we find that none of the eight preexisting determinants of grassland quality significantly affect the timing of fence building (columns 2–9). In addition, we follow the literature (e.g., Jenkins, 1995; Galiani et al., 2005) to adopt a discrete-time hazard model to estimate the effect of nine time-invariant and time-varying factors on the probability of fence building in a village and year, while controlling for duration dependence by a fifth order polynomial in time. As presented in Appendix Table A.3, we still find no significant effects of these factors on the timing of fence building. These findings alleviate concerns that the timing of fence building might be influenced by omitted determinants of grassland quality.

Second, we employ an event study to explore whether there were different preexisting trends in grassland quality between villages that commenced fence building earlier and those that started later. Specifically, we estimate the following event-study model:

$$Y_{ivt} = \beta_0 + \sum_{j=1}^{J-1} \beta_j Lag_{vt}^j + \sum_{k=0}^{K} \lambda_k Lead_{vt}^k + X_{ivt}\gamma + \eta_i + \eta_t + \epsilon_{ivt}, \tag{3}$$

where Lag_{vt}^j is a dummy variable indicating that the observation year t was j periods before the fence building starting year of village v, and $Lead_{vt}^k$ is a dummy variable indicating that the observation year t was k periods after the fence building starting year. All other variables are defined as in model (1). We omit the first lag indicator due to perfect collinearity. We would invalidate the identification assumption of model (1) if we discover that the estimates of β_j significantly differ from zero.

Fig. 6 illustrates the event-study estimates. We divided the 35-year sample period into seven five-year intervals and subsequently estimated the effects of three lags and three leads (with the first lag omitted). Our findings reveal that all β_j estimates are close to zero and statistically insignificant. This outcome offers compelling evidence that the estimated impact of fence building is not a result of preexisting disparities among villages. Furthermore, our analysis indicates that fence building had a substantial and positive impact on grassland quality. According to our estimates, fence building increased NDVI by 0.009 during the initial five-year period and subsequently raised this effect to 0.02 in the following two periods. These findings are consistent with the DID estimates presented in Table 1.

4.2. The impact of additional access to public grassland

4.2.1. DID estimates

To investigate the effect of additional access to public grasslands, we estimate a modified version of model (1) that incorporates the interaction between the fence-building dummy and the public grassland access dummy:

$$Y_{ivt} = \beta_0 + \tau_1 Post_{vt} + \tau_2 Post_{vt} \times Public_v + X_{ivt}\gamma + \eta_i + \eta_t + \epsilon_{ivt}, \tag{4}$$

In this equation, the dummy variable $Public_v$ equals 1 if village v has public grassland access for herders, in addition to their private grasslands after the tenure reform, and 0 otherwise. All other variables follow previous definitions. A significantly positive (negative)

[15] The time-invariant confounding factors have been accounted for by the parcel-fixed effects, and the time-varying confounding factors that are common for all parcels have been accounted for by the year-fixed effects. Therefore, the remaining endogeneity concern of the fence building starting year comes from omitted village-specific time-varying determinants of grassland quality.

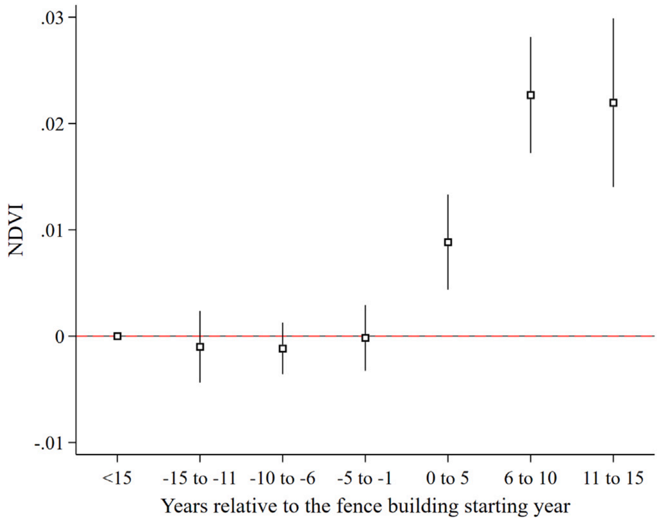

Fig. 6. Dynamic effects of fence building on grassland quality. Note: This figure presents the estimated effects of lags and leads in the starting year of fence building on grassland quality based on model (3).

Table 1
Impact of grassland privatization on grassland quality.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Interim period	Interim period	Baseline	Excluding controls	Including more controls	Cluster at plot level	Shorter periods	Impact on public grasslands
Interim period	−0.008	−0.007						
	[0.011]	[0.010]						
Post fence building	0.021***	0.020***	0.021***	0.022***	0.020***	0.021***	0.023***	0.013*
	[0.006]	[0.005]	[0.006]	[0.006]	[0.005]	[0.001]	[0.001]	[0.007]
Time-varying controls	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Time-invariant controls	No	Yes	No	No	Yes	No	No	No
Year-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plot-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	192,434	192,434	192,434	192,434	192,434	192,434	65,094	1666
R-squared	0.680	0.689	0.680	0.677	0.689	0.680	0.709	0.710

Notes: Columns 1 and 2 presents the estimates of model (2). Column 3 presents the baseline estimates based on model [eq:base]. Columns 4–8 provide robustness checks of the baseline estimates (details are explained in the main text). Standard errors, reported in square brackets, are clustered at the parcel level (column 6) or village-year level (all other columns). Significance levels are denoted as *** for $p < 0.01$, ** for $p < 0.05$, and * for $p < 0.1$.

estimate of τ_2 would suggest that public grassland access increases (reduces) the effect of fence building. In a robustness check, we will also employ a continuous measure of public grassland access.

The primary concern regarding model (4) is the comparability of villages with and without public grassland access, especially when villages without public grassland access are concentrated in the middle region of the study area (see Fig. 3). Therefore, the estimate of τ_2 may inadvertently capture the effect of preexisting differences between villages with and without public grassland access. To address this concern, Appendix Table A.4 demonstrates that the share of public grassland in each village is not significantly correlated with pre-reform grassland quality, land endowment, population pressure, geographic, and climatic factors.[16]

This findings alleviates the concern that public grassland access could be influenced by preexisting determinants of grassland quality. Moreover, we estimate various versions of model (4) that limit the sample to parcels within different "buffers" of the public grassland access boundary, as defined by the boundary between villages with and without public grassland access. This approach helps ensure a more comparable treatment and control group in the estimation.

[16] Specifically, we examine the correlation between village-level share of public grassland and 9 potential preexisting confounding factors. Column 1 of shows that the share of public grassland is uncorrelated with pre-reform (1990–1995 average) grassland quality. Columns 2–4 show that the share of public grassland is uncorrelated with total grassland area of the village, grassland area per herder, and average slope of grassland parcels. Grassland area per herder measures the population pressure of the village, and average slope of grassland parcels measures the quality of the land. The grassland area per herder is calculated as the ratio between total grassland area of the village (including both the private and public grasslands) and the number of households in the village. Columns 5–9 show that the share of public grassland is uncorrelated with various climatic measures, which are key determinants of grassland quality and thus herders' income.

4.2.2. Difference-in-discontinuity estimates

We further address the concern of endogenous public grassland access by estimating a difference-in-discontinuity (DID-RD) model. Our setting is suitable for a spatial regression discontinuity analysis. However, when applying a regression discontinuity approach based solely on the post-tenure reform data, we also need the village boundary to be exogenous. The DID-RD model relaxes this assumption and only necessitates that factors affecting the endogeneity of the boundary remain constant over time (Butts, 2021; Keele and Titiunik, 2015).

Formally, we follow the literature (e.g., Lee and Lemieux, 2010; Briant et al., 2015; Shenoy, 2018; Lu et al., 2019) to estimate the following DID-RD model:

$$Y_{ivt} = \beta_0 + \tau_1 Post_{vt} + \tau_2 Post_{vt} \times Public_v + \sum_{k=1987}^{2020} \theta_k d_{iv} \times D(t = k) + X_{ivt}\gamma + \eta_i + \eta_t + \epsilon_{ivt}, \tag{5}$$

where d_{iv} is the running variable used to capture the effect of the distance to the public grassland access boundary. Specifically, we set

$$d_{iv} = \omega_1 Distance_{iv} + \omega_2 Distance_{iv} \times Public_v \ , \tag{6}$$

where $Distance_{iv}$ is the distance from parcel i's centroid to the nearest border of the village without public grassland access, and $Public_v$ again is the dummy of public grassland access. The distance is set to be positive (negative) for parcels in villages with (without) public grassland access. The specification of d_{iv} allows the effect of the distance to be different inside ($\omega_1 + \omega_2$) and outside (ω_1) the border. We interact the running variable with a full set of year dummies ($D(t = k)$) to allow its effect (i.e., θ_k) to change over time. All other variables are the same as defined in model (4).

The DID-RD approach enables us to address the endogeneity concern that grassland parcels with and without public grassland access are different not only in their access to public grassland. If this is true, the estimate of τ_2 from model (4) could capture the effect of these additional differences, not only the effect of additional public grassland access. The DID-RD approach addresses this concern by focusing on grassland parcels close to the border of villages with and without public grassland access. The underlying assumption is that parcels close to the border are comparable to each other after removing the time-invariant differences using the parcel-fixed effects (see Fig. 7 for evidence supporting this assumption). Given that the estimate of τ_2 captures only the effect of additional access to public grassland, a significantly positive τ_2 would suggest that the risk-sharing function of public grassland increased grassland quality.

Our baseline DID-RD estimation uses a linear running variable (Gelman and Imbens, 2019), and we will demonstrate that the results are similar when employing a non-linear running variable (Dell, 2010). We use a triangular kernel function to fit the distance of each parcel to the village border and apply the robust, bias-corrected methods for confidence interval inference (Calonico et al., 2014). We also apply different bandwidths to examine the robustness of the estimates.

The identification assumption of the DID-RD model is that factors affecting the endogeneity of the boundary are constant over time (Butts, 2021; Keele and Titiunik, 2015). If this assumption holds, the coefficient τ_2 from the DID-RD model would capture the effect of additional access to public grassland. Following the literature (e.g., Keele and Titiunik, 2015; Butts, 2021), we test this assumption by plotting the first difference of the dependent variable around the boundary. A continuous first difference at the boundary before the tenure reform would suggest that factors affecting the endogeneity of the boundary are constant over time. Consequently, the discontinuity of the first difference after the reform can be explained as the causal effect. Fig. 7 shows that the first difference of NDVI is continuous at the boundary before the tenure reform (Panels A and B) but becomes discontinuous afterward (Panels C and D).

5. Results

5.1. Effect of grassland privatization on grassland quality

5.1.1. Baseline estimates

We estimate the effect of grassland privatization on grassland quality using models (1) and (2). Recall that the only difference between these two models is that the former treats fence building as the de facto timing of the tenure reform, while the latter separately identifies the effect of tenure reform and fence building. Columns 1 and 2 of Table 1 reports the estimates of model (2), while all other columns report the estimates of model (1). Column 1 confirms that while the tenure reform itself has no significant effect on grassland quality, fence building following it significantly increased grassland quality. This finding is consistent with the fact that fence building is necessary for exclusive grassland access. Column 2 shows that the finding in Column 1 is robust to controlling for a set of time-invariant variables (i.e., parcel area, perimeter, and slope, interacted with a full set of year dummies). Column 3 presents our baseline estimates based on models (1). The estimated effect of the indicator of fence building is identical to that in Column 1. The estimates suggest that grassland privatization increased NDVI by 0.021, which is 5.4% of the mean NDVI over the sample period (i.e., 0.39).

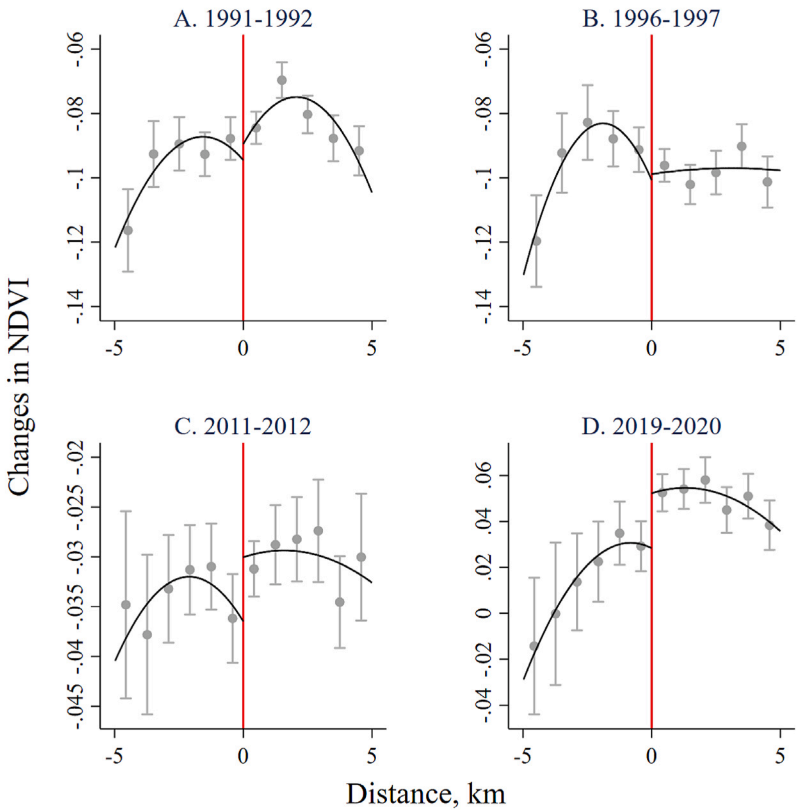

Fig. 7. Local discontinuity before and after the tenure reform. Note: This figure depicts the first difference of NDVI for representative years before (Panels A and B) and after (Panels C and D) the tenure reform for parcels within 5 km of the border of villages without public grassland access.

5.1.2. Robustness checks

Columns 4–7 present robustness checks of the baseline estimate. Column 4 excludes the five time-varying control variables and finds a very similar result, suggesting that the estimates are not sensitive to omitted variables. Column 5 additionally controls for the interaction between three key time-invariant determinants of fence building (i.e., parcel area, perimeter, and slope) and a full set of year dummies. The resulting estimate is very close, confirming that the estimated effect is not primarily driven by the omitted time-varying effects of time-invariant variables. Column 6 clusters the error term at the parcel level and finds a smaller standard error, confirming that clustering the error term at the village-year level has indeed adjusted the downward bias of the error term. Column 7 limits the study sample to between the five years before and five years after the fence-building starting year and finds a slightly larger estimated effect, suggesting the temporal stability of our finding.

5.1.3. Effect on public grassland quality

Column 8 employs model (1) to estimate the effect of grassland privatization on the quality of the public grassland remaining in the villages after the tenure reform. Note that all estimations in columns 1–6 are based on data from parcels that are privately used after the tenure reform. If the remaining public grasslands are more intensively used after grassland privatization, one might expect to see a significantly negative estimated effect of the fence-building indicator. This is a possibility because grassland privatization results in smaller private parcels, potentially increasing the use of public grasslands. However, the estimates suggest that grassland privatization also significantly increased the quality of the remaining public grasslands, even though the effect size and significance level are lower than that for private grasslands. Appendix Table A.5 shows that we still find no negative effects of fence building on the quality of public grassland when including more control variables, excluding all control variables, excluding sample villages with public land outside the village, and adopting a shorter sample period. This finding suggests that once herders owned private grasslands, they tended to reduce their use of public grasslands, potentially due to the relatively high cost of accessing more distant public grasslands.

5.2. The impact of public grassland accessibility

5.2.1. Baseline estimates

Table 2 presents the estimated effect of additional public grassland access on the quality of private grasslands based on model (4). Column 1 presents the estimates based on the full sample, while the remaining columns limit the sample to parcels within

Table 2
Impact of public grassland access, DID estimates.

	(1) Full sample	(2) <6 km	(3) <5 km	(4) <4 km	(5) <3 km
Post fence	0.018***	0.016***	0.016***	0.015***	0.014***
	[0.001]	[0.001]	[0.002]	[0.002]	[0.002]
Post fence × public	0.003***	0.006***	0.006***	0.007***	0.007***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]
Time-varying controls	Yes	Yes	Yes	Yes	Yes
Year-fixed effects	Yes	Yes	Yes	Yes	Yes
Plot-fixed effects	Yes	Yes	Yes	Yes	Yes
Observations	190,983	89,167	78,376	67,497	55,530
R-squared	0.679	0.648	0.646	0.650	0.654

Notes: This table presents the estimates of model (4). Column 1 uses data from all private grassland parcels, while columns 2–5 limit the sample to parcels within 6 km to 3 km buffers, respectively, of the border of villages without public grassland access after the tenure reform. Standard errors, reported in square brackets, are clustered at the village-year level. Significance levels are denoted as follows: *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

Table 3
Robustness checks of the DID estimates (<6 km).

	(1) Excluding controls	(2) Including more controls	(3) Excluding villages with public land outside the village	(4) Excluding large private parcels	(5) Excluding tiny private parcels	(6) Public grassland share
Post fence	0.018***	0.014***	0.011***	0.015***	0.018***	0.013***
	[0.001]	[0.001]	[0.001]	[0.002]	[0.002]	[0.001]
Post fence × public	0.004***	0.007***	0.005***	0.007***	0.004***	0.017***
	[0.001]	[0.001]	[0.001]	[0.001]	[0.001]	[0.006]
Time-varying controls	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Plot-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	91,803	89,167	83,431	80,504	79,938	62,811
R-squared	0.646	0.660	0.645	0.649	0.652	0.634

Notes: This table presents robustness checks for the estimates presented in column 2 of Table 2. Column 1 excludes all control variables. Column 2 additionally controls for the interaction between the three time-invariant control variables and a full set of year dummies. Column 3 excludes the five villages with public grassland located outside the village. Columns 4 and 5, respectively, exclude private parcels with sizes ranked above the top decile and below the bottom decile. Column 6 replaces the dummy of public grassland access in the interaction term with the village-level share of public grassland in total grassland and uses data only from villages with public grassland access. Standard errors reported in square brackets are clustered at the village-year level. Significance levels are *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

6 km to 3 km buffers around the border of villages without public grassland access.[17] The estimates of the interaction term suggest that public grassland access significantly increased grassland quality, and the estimated effect is larger when we reduce the buffer. Specifically, when limiting the sample to 6 km to 3 km buffers, the estimates suggest that additional public grassland access increases the NDVI by 0.006–0.007, which is about 1.5–1.8% of the mean NDVI. It is also worth noting that the estimated coefficient of the fence-building indicator declines by approximately the magnitude of the effect of the interaction term. Therefore, the estimates suggest that 1.5–1.8 percentage points of the 5.4% gains from grassland privatization can be attributed to the additional public grassland access.

5.2.2. Robustness checks

Table 3 presents six robustness checks of the estimates from column 2 of Table 2. In Column 1, all control variables are excluded, and results show a significant increase in grassland quality due to the interaction term. In Column 2, additional control for the interaction between the three time-invariant control variables and a full set of year dummies results in a slightly larger estimated effect. Column 3 excludes the five villages with public grasslands located outside the villages (see Footnote 6), and it finds a similar estimated effect. In Columns 4 and 5, private parcels with sizes ranked above the top decile and below the bottom decile are excluded, respectively. The estimates show larger effects in Column 4 and smaller effects in Column 5, suggesting that the gains from public grassland access decline with parcel size. Column 6 replaces the dummy of public grassland access with the village-level share of public grassland in total grassland. The estimate indicates that villages with a larger share of public grassland benefit more from public grassland access.

[17] We do not use buffers larger than 6 km because it would encompass the diameter of most sample villages, and we do not use buffers smaller than 3 km because it would result in too few parcels in the sample.

Table 4
Impact of public grassland access, DID-RD estimates.

	(1) <6 km	(2) <5 km	(3) <4 km	(4) <3 km
Post fence	0.013***	0.013***	0.012***	0.009***
	[0.002]	[0.002]	[0.002]	[0.003]
Post fence × public	0.008***	0.007***	0.008***	0.010***
	[0.002]	[0.002]	[0.002]	[0.003]
Time-varying controls	Yes	Yes	Yes	Yes
Year-fixed effects	Yes	Yes	Yes	Yes
Plot-fixed effects	Yes	Yes	Yes	Yes
Observations	89,167	78,376	67,497	55,530
R-squared	0.654	0.652	0.656	0.662

Notes: This table presents the estimates of the DID-RD model (5) with the bandwidths denoted in each column header. Significance levels are *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

5.2.3. DID-RD estimates

Table 4 presents the DID-RD estimates based on model (5). We use a triangular kernel function to fit the distance of each parcel to the boundary and employ the robust bias-corrected method of Calonico et al. (2014) for standard error inference. To assess the robustness of the estimates to the bandwidth, we apply different bandwidths ranging from 6 km to 3 km. All estimations adopt the local linear running variable to mitigate concerns about bias associated with high-order running variables (Gelman and Imbens, 2019). Comparable results are found when using a quadratic running variable (Appendix Table A.1).

Consistent with the DID estimates, the DID-RD estimates also suggest that public grassland access significantly increased the quality of private grasslands. The estimated interaction effect of public grassland access remains stable, ranging from 0.007 to 0.010, when different bandwidths are applied. The DID-RD estimates are generally larger than the corresponding DID estimates presented in Table 2. The DID-RD estimates suggest that 35% to 53% of the estimated effect of grassland privatization can be attributed to the benefits from additional public grassland access. When applying the methods of Calonico et al. (2014), we find that the optimal bandwidth is around 3 km. Therefore, the most credible DID-RD estimate suggests that public grassland access can explain about half of the gains from grassland privatization.

5.3. Why additional access to public grassland matters?

This section examines why additional access to public grasslands after grassland privatization increased the quality of private grasslands. We first demonstrate that this phenomenon is not merely due to the increased accessibility of grasslands or at the detriment of public grassland degradation. Then, we will discuss how the risk-reduction function of additional public grassland access can account for the estimated benefits.

5.3.1. More accessible grasslands

A potential explanation for the positive effect of additional access to public grasslands is that such accessibility reduced grazing pressure on private grasslands. If this were the primary reason, we would estimate a much smaller effect on the average quality of both public and private grasslands. However, empirical evidence does not support this explanation. We conducted a village-level version of model (4), using village-average grassland quality as the dependent variable.[18] As presented in column 1 of Table 5, the estimated effect of additional access to public grasslands remains significantly positive and is even larger than that obtained from the parcel-level estimation. Furthermore, as shown in column 7 of Table 1, we found that the tenure reform also increased, rather than reduced, the quality of public grasslands. Therefore, the gains from additional access to public grasslands are not primarily due to the increased availability of grasslands or at the expense of public grassland degradation.

5.3.2. Risk abating

We proceed to test the mechanism proposed in our conceptual framework, which suggests that additional access to public grasslands reduces the damage of natural disasters on grassland quality. Grassland privatization leads to grassland fragmentation, limiting the risk-abating function of traditional nomadic herding, which can be partially restored by additional access to public grasslands. We test this mechanism by examining the effect of climatic shocks.

Formally, we extend the DID-RD model (5) to include the interaction between fence building, public grassland access, and climatic shock measures:

$$\begin{aligned} Y_{ivt} = \beta_0 + \tau_1 Post_{vt} + \tau_2 Post_{vt} \times Public_v + \tau_3 Post_{vt} \times Public_v \times Shock_{ivt} + \tau_4 Post_{vt} \times Shock_{ivt} \\ + \tau_5 Shock_{ivt} + \sum_{k=1987}^{2020} \theta_k d_{iv} \times D(t=k) + X_{ivt}\gamma + \eta_i + \eta_t + \epsilon_{ivt} \ , \end{aligned} \tag{7}$$

[18] Village-average grassland quality is calculated as the area-weighted average across all private and public parcels accessible to herders from the village.

Table 5
Sources of gains from additional access to public grasslands.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Village level estimates	Baseline (DID-RD, <3 km)	Negative temperature shock	Positive temperature shock	Negative rainfall shock	Positive rainfall shock	Farm size
Post fence (τ_1)	0.010	0.009***	0.008***	0.002	0.004	0.013***	0.010***
	[0.006]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.001]
Post fence × public (τ_2)	0.023**	0.010***	0.000	0.027***	0.011***	0.007***	0.009***
	[0.009]	[0.003]	[0.003]	[0.003]	[0.003]	[0.003]	[0.001]
Post fence × public × shock (τ_3)			0.005***	−0.010***	0.006***	0.004	
			[0.001]	[0.001]	[0.002]	[0.003]	
Post fence × Shock (τ_4)			0.000	0.006***	0.014***	−0.006***	
			[0.001]	[0.001]	[0.002]	[0.001]	
Shock (τ_5)			−0.006***	0.005***	−0.010***	0.000	
			[0.001]	[0.001]	[0.001]	[0.001]	
Post fence × public × size (τ_3)							−0.003***
							[0.001]
Post fence × size (τ_4)							0.001
							[0.001]
Time-varying controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plot-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1380	55,530	55,530	55,530	55,530	55,530	55,530
R-squared	0.722	0.662	0.662	0.663	0.663	0.662	0.662

Notes: Column 1 estimates a village-level version of model (4) that employs village-average grassland quality as the dependent variable. Column 2 replicates the DID-RD estimates presented in column 4 of Table 4. Columns 3–7 estimate different versions of model (7). The only distinction between columns 3–7 is that the term shock represents a negative precipitation shock in column 3, a negative precipitation shock in column 4, a negative rainfall shock in column 5, a positive rainfall shock in column 6, and the log size of the private parcel in column 7. Significance levels are *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

where $Shock_{ivt}$ is a measure of climatic shock, and all other variables are the same as defined in model (5). The coefficient τ_3 captures the effect of public grassland access under a given climate shock.

Columns 3–6 of Table 5 report the estimates of model (7). For comparison, column 2 presents the baseline DID-RD estimates without the interaction term $Post_{vt} \times Public_v \times Shock_{ivt}$ (i.e., the estimates reported in column 4 of Table 4). Columns 3 and 5 report the estimated effect of negative precipitation shock and negative rainfall shock, respectively. We define negative temperature (rainfall) shock as the months in each year with temperature (rainfall) 1-SD lower than the long-run average. Since our study area belongs to a semi-arid temperate meadow steppe, negative temperature and rainfall shocks are detrimental to grassland quality. This is confirmed by the significantly negative estimates of τ_5 in columns 3 and 5. More importantly, we find that the estimates of τ_3 are significantly positive in columns 3 and 5, suggesting that the gain from public grassland access is larger when there are harmful climatic shocks. This finding confirms the importance of the risk-abating mechanism. To further support this finding, columns 4 and 6 present the effect of positive temperature and rainfall shocks, which tend to increase grassland quality in the semi-arid temperate area. The estimates confirm that the gains from public grassland access are indeed lower under favorable temperature, although the estimated effect of positive rainfall shock is statistically insignificant.

We further support the risk-abating mechanism by examining the difference in the effect of public grassland access for large and small private parcels. If the risk-abating mechanism is at work, we expect to see that a large parcel should gain less from public grassland access than a small parcel because a large parcel should be more able to abate the damage of natural disasters by rotational grazing within the parcel. To do so, we estimate a version of model (7) that replaces the variable $Shock_{ivt}$ by the log of parcel size. As reported in column 7 of the table, the estimate of τ_3 is significantly negative, confirming that the gain from public grassland access declines with the size of the private parcel.

Finally, we verify the risk-abating mechanism by examining how the distance between private and public parcels moderates the effects of climate shocks. Longer distances have two opposing effects. While it is harder to move herds from private to public parcels, it is also more likely that the public and private parcels experience different weather shocks, making risk abate more feasible. If the risk-abating mechanism exists, we expect a U-shaped moderating effect of the distance between private and public parcels under negative weather shocks, which can be tested by estimating the following model:

$$\begin{aligned} Y_{ivt} =\; & \tau_0 + \tau_1 Post_{vt} + \tau_2 Post_{vt} \times d_{iv} + \tau_3 Post_{vt} \times d_{iv}^2 + \tau_4 Post_{vt} \times d_{iv} \times Shock_{ivt} \\ & + \tau_5 Post_{vt} \times d_{iv}^2 \times Shock_{ivt} + \tau_6 Post_{vt} \times Shock_{ivt} + \tau_7 Shock_{ivt} + X_{ivt}\gamma + \eta_i + \eta_t + \epsilon_{ivt} \,, \end{aligned} \tag{8}$$

where d_{iv} is the distance between private parcel i and the public parcel in the village, d_{iv}^2 is the square of d_{iv}, and all other variables are the same as defined before.[19] As presented in Appendix Table A.6, we find that the estimates of τ_4 and τ_5 from model (8) are significantly negative and significantly positive, respectively, suggesting a U-shaped moderating effect of distance, when there are

[19] Here we no longer adopt the RD setting that controls for the effect of distance because the target here is to capture the nonlinear effect of distance.

Table 6
Effects of using public grasslands on private grassland quality and livestock production.

	(a1)	(a2)	(a3)	(a4)	(b1)	(b2)	(b3)	(b4)
	Effect on NDVI				Effect on livestock numbers			
If using public grasslands	0.061*** [0.016]	0.062*** [0.015]			−0.091 [0.181]	−0.150 [0.188]		
Days using public grasslands			0.014*** [0.005]	0.014*** [0.004]			−0.034 [0.040]	−0.045 [0.039]
Time-varying control variables	Yes	No	Yes	No	Yes	No	Yes	No
Household- and year-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	948	948	948	948	948	948	948	948
R-squared	0.207	0.207	0.207	0.207	0.199	0.211	0.201	0.214

Notes: This table reports the effects of public grasslands use on private grassland quality (columns a1–a4) and the number of livestock (columns b1–b4), estimated based on model (9). Standard errors clustered at the village level are reported in square brackets. Significance levels are denoted as *** for $p < 0.01$, ** for $p < 0.05$, and * for $p < 0.1$.

bad weather shocks (columns 1 and 3). Recall that low temperature and low precipitation are harmful in the study area. In contrast, column 2 shows that distance has no significant moderating effect when there is a positive temperature shock, which is beneficial in our study area.[20]

5.4. Additional micro evidence

This subsection provides additional evidence on the effect of public grasslands access based on field-survey data. As detailed in Appendix A.2, we conducted a field survey to collect data on public grasslands use and livestock production from 294 households during 2018–2022 in our study area (i.e., Xin Barag Zuo county). For each household, we gathered various household characteristics, livestock production, grassland use, and the location of herders' grassland parcels. Appendix Table A.8 summarizes the 18 variables constructed based on data from the survey.

We find that 12.5% of observations have experiences of using public grasslands, and the average number of days of using public grasslands is 13 days per year. Appendix Table A.9 examines the differences between households using and not using public grasslands based on t-tests. The tests confirm that the grassland quality of households using public grasslands is significantly higher than that of households not using public grasslands, confirming the positive effect of public grasslands access on the quality of private grasslands identified in the main analysis. In addition, the tests also find that all of the household characteristics that are uncorrelated with public grasslands access have no significant difference between households using and not using public grasslands, supporting the exogeneity of public grassland access.[21]

More importantly, the microdata enables us to directly examine the effect of public grassland use on private grassland quality and livestock production. Since we do not have household-level data before the reform, we no longer adopt the DID model setting used in the main analysis. Instead, we estimate the following panel model with household-fixed effects:

$$Y_{it} = \alpha_1 P_{it} + X_{it}\beta + \mu_i + \mu_t + \varepsilon_{it} \ , \tag{9}$$

where Y_{it} is the grassland quality (measured by NDVI) or the number of livestock of household i in year t, P_{it} is a measure of public grassland use, X_{it} is a vector of time-varying control variables including private grassland area and household income, and ε_{it} is the error term. We adopt two measures of public grassland use, one is the dummy of using public grasslands (1 = use; 0 = not use) and the other is the number of days using public grasslands. The model also includes household-fixed effects (μ_i) to account for time-invariant confounding factors and includes year-fixed effects to account for common shocks.

As presented in Table 6, we find that access to public grasslands significantly increases the quality of private grasslands but has no effect on the number of livestock. Specifically, column a1 shows that compared with households not using public grasslands, the NDVI of the private grasslands of herders using public grasslands is 0.061 units higher. Column a2 shows that this finding is robust to excluding the time-varying control variables. Similarly, columns a3 and a4 show that an increase in the number of days using public grasslands significantly increases the quality of private grasslands. In the same model setting, columns b1–b4 estimate the effect of using public grassland on the number of livestock of the herder. The estimates suggest that the use of public grasslands is not significantly correlated with the number of livestock. This finding suggests that herders do not increase their livestock number with the use of public grasslands, providing an explanation of why public grassland access does not reduce the quality of public grasslands.

Finally, the survey data also provide suggestive evidence supporting that risk abatement is a key mechanism for public grassland access to affect private grassland quality. The survey data do not allow for a direct test of the mechanism of risk abatement because

[20] Column 4 of Table A.6 shows that the distance also has an U-shaped moderating effect when there is a positive precipitation shock. As the estimate of τ_7 suggests no significant effect of a positive precipitation shock, the U-shaped relationship may reflect the effect of damaging factors correlated with positive precipitation shocks, such as low temperature.

[21] We do find significant differences for two factors correlated with public grasslands access—the distance to public grasslands and the number of family labor; the distance determines the costs of using public grasslands, and public grassland use could be labor-intensive.

we do not have data before the tenure reform and the climatic variations are too small within the survey sample.[22] Nevertheless, we still find suggestive evidence supporting the channel of risk abatement when examining the effect of distance to public grasslands on public grassland use based on:

$$P_{it} = \gamma_1 D_i + \gamma_2 D_i^2 + Z_{it}\theta + \mu_v + \mu_t + \varepsilon_{it} \ , \tag{10}$$

where P_{it} measures the use of public grasslands, D_i is the log distance of herder i's grassland to the public grassland, and D_i^2 is the square of D_i. As the distance is time invariant, the model includes village-fixed effects (μ_v) instead of household-fixed effects. To address the concern of omitted variables, we control for a vector of 15 household-level characteristics (Z_{it}) listed in Appendix Table A.8. As presented in Table A.10, the estimates suggest a U-shaped relationship between the distance and public grassland use. The first decline of public grassland use with the distance is natural as the costs of using public grasslands increase with distance. The later increases of public grassland use with distance are not surprising when realizing that the risk-abating function is more important when the shocks to public and private grasslands are different, which is more likely when the public grassland is more distant from the private grassland. As such, the U-shaped relationship can be taken as suggestive evidence supporting the risk-abating function of public grassland access.

6. Conclusions

Grasslands play a crucial role in global ecosystems and economic systems and face significant degradation risks due to overgrazing. Existing empirical studies on common-pool resource management focus on the forest and fishery sectors rather than grasslands. Scholars have long recognized the importance of property rights in mitigating environmental degradation, but existing evidence on the impact of property rights on environmental outcomes is mixed. Therefore, it is challenging to infer the extent to which grassland privatization could facilitate grassland conservation. Many pastoral scientists have criticized the privatization of grasslands for potentially damaging grassland quality by leading to fragmentation though these concerns have not deterred the global trend of grassland privatization. This study provides robust evidence that grassland privatization significantly increases grassland quality. While pure private ownership is better than pure public ownership in terms of grassland conservation, a properly structured hybrid ownership could be more effective in grassland conservation. This finding is consistent with pastoral literature that nomadic herding presents a key mechanism for herders to offset the uncertainty from natural disasters.

We conclude this study by highlighting two limitations. First, due to data limitations, we have not examined the effect of grassland privatization or hybrid ownership on the economic outcomes of herders. Therefore, we cannot draw conclusions about the welfare effect of the tenure reform. The observed grassland conservation may come at the cost of a substantial decline in herders' income. If the income decline results from grassland fragmentation and the associated higher grazing costs, rather than from herders' utility maximization decisions, taking future incomes into account, the income decline would represent a welfare loss from the tenure reform. If the welfare loss outweighs the welfare gains from observed grassland conservation, we cannot definitively conclude that hybrid or private ownership is better than communal ownership when grassland conservation is not the sole objective. Future studies examining the economic outcomes of hybrid grassland ownership would make a significant contribution to the literature.

Second, as we do not have herd size data before the tenure reform, we cannot directly examine the effect of tenure reform on herd size. Therefore, this study is unable to directly examine if the grassland quality increase after the tenure reform is caused by better management or reduced herd size. As a remedy, we explored household-level field survey data from recent years to examine the impact of additional access to public grasslands after the tenure reform, which is the focus of this study, on herd size. We find that the use of public grasslands does not have a significant effect on herd size, providing suggestive evidence that the tenure reform in China affects grassland quality mainly through better management but not adjusting the herd size. Future studies could contribute to verifying the mechanism of the gains from tenure reform if the herd size data are available both before and after the tenure reform.

CRediT authorship contribution statement

Min Liu: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Pengfei Liu:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Kaixing Huang:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[22] Recall that the survey data come from only 15 villages in 5 years. As the chances of climatic shocks are low, we do not have enough climatic shocks from such a small sample to examine the effect of climatic shocks.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jeem.2024.103069.

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