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Beyond property rights: all roads lead to sustainable grassland management

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ABSTRACT

The impacts of property rights on the sustainable management of natural resources have long been debated, yet a consensus remains elusive. Empirical observations reveal puzzling inconsistency: as similar property regimes produce varying outcomes, whereas different property regimes can lead to similar results. A key reason for this inconsistency is that previous studies have often overlooked the complex causal relationships between property rights and other social, economic and natural factors affecting natural resource uses. This study focuses on pastoral areas in China and explores how grassland property rights, together with adaptive grassland management strategies, and wider socio-economic factors, jointly shape grassland ecosystems. Using data from 129 villages across four major pastoral provinces, we employed fuzzy set qualitative comparative analysis (fsQCA) to explore the diverse pathways leading to grassland sustainability or degradation and to investigate the complex causal relationships among the factors. This study offers the first empirical, village-level evidence on how property rights affect grassland quality, drawing on data from a nationwide village survey. The results reveal that the relationship between property rights and grassland quality is shaped by the complex interaction between property rights and the broader socioecological context. Beyond the property rights solution, adaptive management strategies emerges as crucial alternatives for enhancing sustainability of grassland, particularly in the face of climate disaster or in communities with limited grassland resources.

1. Introduction

The impacts of property rights on natural resource management have been debated for decades, with a focus on whether privatization can effectively foster the sustainable utilization of natural resources, thereby addressing the tragedy of the commons—the idea that common ownership inevitablely leads to over-use of the resource (Hardin, 1968; Ostrom, 1990). Research on natural resource management grounded in self-organization and collective action, which was notably pioneered by Ostrom, has gained considerable attention (Agrawal & Yadama, 1997; Dietz et al., 2003; Ostrom, 1990; Ostrom et al., 2007), offering alternative solutions beyond the privatization of resources.

Grasslands, which cover half of the global land area, are critical to livestock production and form the basis of the livelihoods of pastoral communities. Yet, these landscapes are increasingly threatened by degradation worldwide (Bardgett et al., 2021). In response, identifying effective property rights has become a key concern in global grassland governance (Goldman & Riosmena, 2013; Humphrey & Sneath, 1999), with the mainstream approach, influenced by the concept of the tragedy of the commons, encouraging privatization (Bański, 2017; Hardin, 1968). However, a growing body of empirical studies indicates that grassland privatization has led to a series of ecological problems, including land fragmentation, weakened biodiversity and economic problems, such as increased grazing costs and reduced household income (Behnke & Mortimore, 2016; Fernández-Giménez, 2002; Hobbs et al., 2008).

Conversely, increasing empirical evidence suggest that, with appropriate management strategies, common property rights can foster positive ecological outcome (Banks, 2003; Goldman & Riosmena, 2013; Humphrey & Sneath, 1999; Li & Huntsinger, 2011). Nevertheless, empirical observations across different contexts reveal puzzling inconsistencies, as similar property regimes may produce varying outcomes, whereas different property regimes can lead to similar results. These inconsistencies imply that the influences of property rights are not deterministic but contingent upon their complex interaction with broader ecological and social-economic conditions. Adaptive management strategies can be essential factors in shaping how property rights impact local grassland use and, consequently, grassland ecological

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outcomes.

Adaptive management strategies refer to flexible approaches designed to cope with high levels of complexity, respond to uncertainty, adapt to and prepare for the rapid changes of the system by adjusting their production methods, resource utilization strategies and other social-economic activities (Akther & Evans, 2024; Chaffin et al., 2014; Folke et al., 2005). In this context, they emphasize flexible responsiveness to local conditions through diverse governance structures, network building, the integration of evidence-based science with localized practical knowledge, and modification of institutions in grassland governance (Bardgett et al., 2021; Wang et al., 2022). In recent years, adaptive grassland management strategies, such as community-based grassland governance in Central Asian pastoral areas and grassland leasing in African pastoral areas, have emerged worldwide (Catley et al., 2013; Scoones, 2021). In China, adaptive strategies, such as grassland leasing, pastoral cooperatives, and joint management, have been developed in pastoral areas (Ao et al., 2015; Li & Tan, 2018). These adaptive strategies, when combined with property rights systems, can enhance grassland resource efficiency (Cao & Du, 2011; Tang & Gavin, 2015), and facilitate the adaptation of local communities to climate variability (Wang et al., 2013). The effectiveness of these management strategies depends on the synergistic effects of several factors, including the scale of cooperation, grazing patterns and pasture size (Li et al., 2018).

Recent research has moved beyond the simple "private vs. public" property debate. For example, Cox (2024) shows how property rights and environmental sustainability interact in different social-economic settings. However, we still lack a deep understanding of how property rights work with other social, economic, and environmental factors. This is especially true in changing systems like grasslands. Our study fills this gap by examining how grassland property rights, together with adaptive grassland management strategies and other biophysical factors, jointly shape grassland ecology. To do this, we use a causal complexity approach to study grassland governance. The case of Chinese pastoral communities offers a unique opportunity to explore these dynamics. First, grasslands in China constitute the largest terrestrial ecosystem, but they are facing severe land degradation and a salient combination of ecological protection and economic development challenges, which is likely to intensify with increasing natural disasters due to climate change (Ma & Qiao, 2018). Second, the Grassland Household Responsibility System was implemented in the 1980 s with the use right of 88.2 % usable grassland had been contracted to households in China by 2018. Yet the grassland property in practice remains diverse with the use right of some grassland remain collectively owned and managed due to historical production practices, ethnic customs, and specific resource endowments (Yu & Farrell, 2013; Liu et al., 2024; Li & Kerven, 2024). Third, in recent decades, different adaptive management strategies have been developed in local communities, and the geographical and social conditions of pastoral communities are largely different.

The coexistence of multiple grassland property rights, diverse adaptive management strategies, and the significant differences in social and natural conditions across different pasture areas in China provide valuable insights into how property rights interact with other social and ecological factors to influence grassland sustainability. To explore these complex causal relationships, we adopted the concepts of conjunctural causation and equifinality and apply the fuzzy set qualitative comparative analysis (fsQCA) method to study sustainable grassland governance (Ragin, 1987; Ragin & Fiss, 2008; Eisenack & Roggero, 2022). This study uses data from 129 randomly selected villages across four major pastoral provinces to analyze the complex causal pathways that lead to either the sustainability or degradation of grassland. Additionally, we examined the different impacts of property rights on households with different per capita grassland areas.

This study contributes to the ongoing discourse concerning the impacts of property rights on grassland ecosystems in two ways. First, it provides the first empirical, village-level evidence on how property rights affect grassland quality, drawing on data from a nationwide village survey. Second, it demonstrates that the relationship between property rights and grassland quality is shaped by its interactions with other socioecological conditions. Beyond the property rights solution, adaptive grassland management strategies have emerged as crucial alternatives for enhancing resilience and promoting sustainable grassland use, particularly in the face of climate disasters or in communities with limited grassland.

2. Literature review and analytical frameworks

2.1. Impacts of the property rights regime on grassland quality

Property rights have long been viewed as critical factors influencing grassland sustainability. Since the publication of the concept of the tragedy of the commons, grassland privatization and tenure reform have been widely implemented in pastoral communities (Abdulai et al., 2011; Li & Huntsinger, 2011; Wang et al., 2013). However, evidence on the impacts of grassland privatization on grassland quality remains inconsistent. A recent study quantified the impacts of privatization on grassland quality and reported a 3 % improvement in grassland quality under the privatization with security tenure in China (Hou et al., 2022). This study provides the first empirical evidence based on a comprehensive, long-term dataset in pastoral China. Further analysis by Liu et al. (2024), which incorporated detailed grassland plot information, revealed a 5.4 % increase in grassland quality through grassland privatization from 1991 to 2020 in Inner Mongolia, China. Their findings also suggested that hybrid ownership structures (e.g., privatized grasslands with additional access to public grasslands) derive more benefits than other property rights regimes do.

Despite these positive findings, a growing body of empirical evidence suggests that privatization may trigger adverse effects, such as the erosion of reciprocal relationships, reduced adaptive capacity to climate variabilities and increasing social inequality (Fernandez-Gimenez & Le Febre, 2006; Huntsinger et al., 2010; Li & Huntsinger, 2011). Additionally, privatization often entails the division of grasslands into smaller, fenced parcels, each allocated to individual households or small groups of households. This fragmentation restricts the movement of livestock across the land, a practice that is central to traditional pastoralism. Historically, pastoralists have relied on the ability to move their herds across expansive areas to access diverse grazing resources, particularly during seasonal transitions or in response to natural disasters. However, with the introduction of privatization and fencing, these traditional movement patterns are disrupted, significantly reducing the flexibility needed to implement sustainable grazing practices and adapt to changing ecological conditions (Conte & Tilt, 2014; Hobbs et al., 2008; Li et al., 2007; Qi & Li, 2021). The breakdown of traditional communal systems may limit the effectiveness of adaptive management practices that are vital for sustainable use of grassland.

Conversely, some empirical cases show that local communities can manage common grasslands effectively through self-organizing activities. For example, in Qinghai-Tibetan pastoral communities, where grasslands are shared, local pastoralists have developed a grazing quota system to regulate communal grazing while maintaining grassland sustainability (Gongbuzeren et al., 2016; Qi & Li, 2021). Similarly, in agro-pastoral communities, locals have implemented self-organized rotation systems and joint herding and trading mechanisms to maintain the sustainability of grasslands under common property regimes (Yu, 2016; Yu & Farrell, 2013). Additionally, overgrazing has been found to be more prevalent in small, privatized, family-managed grasslands than in common grasslands (Wei & Qi, 2017), suggesting that joint management may be more effective in preventing overuse.

Given these mixed findings, the impact of privatization on grassland ecosystems therefore remains a topic of debate. One reason for these inconsistency may be that the impacts of property rights on grassland quality are result from complex causal interactions between property rights and other institutional, ecological, and economic factors. These interactions are often overlooked, leading to an incomplete understanding of the effects of property right on grassland quality.

2.2. Impacts of adaptive grassland management strategies on grassland quality

In recent years, researchers have shifted their focus from examining property rights in isolation to investigating the impact of adaptive grassland management strategies on grassland ecology under existing property rights. Empirical results show that adaptive grassland management strategies in pastoral regions may foster a balance between grassland protection and livestock production with the flexibility to adapt as needed to disasters and the climatic variability, promoting sustainable pastoral ecosystems (Cai & Li, 2016; Cao et al., 2009). These strategies also serve as a foundation for herders to engage in collective action and risk-sharing mechanisms (Banks, 2003; Li & Huntsinger, 2011; Yu, 2016).

Collective actions, including pastoral cooperatives and joint management have received increasing attention in both academic discourse and practice. Pastoral cooperatives are formal organizations in which herders collectively manage grassland and coordinate livestock production and access to the market. By pooling resources, cooperatives help members achieve economy of scale, improve resource use efficiency and strengthen their ability to cope with climate and economic shocks (Ma & Qiao, 2018; Tang & Gavin, 2015; Wossen et al., 2017; Yu, 2016). They also provide opportunities for members to access new technologies and diversify production, and enhance individual's bargaining power in the market (Mojo et al., 2017). Importantly, many cooperatives develop shared grazing rules—such as rotational grazing—that alleviate ecological pressure on grasslands (Ao et al., 2015), and foster greater environmental awareness among members, thus promoting ecological sustainability (Lise et al., 2006). However, the development of the pastoral cooperatives often faces challenges such as a high dependency on policy subsidies and inadequate responsiveness to market dynamics (Ao et al., 2015; Li et al., 2018).

Joint management here refers to an informal arrangement in which multiple pastoralist households collaboratively manage shared grassland. This strategy has been shown to effectively reduce production costs, enhance labor allocation efficiency, and facilitate collective grazing strategies that achieve scale advantages (Li et al., 2007). Compared with single household operations, joint management, particularly when carried out at an intermedium scale, can significantly reduce the risk of overgrazing (Wei & Qi, 2017). By expanding access to grazing land through shared use, joint management help mitigate the negative ecological consequences of grassland fragmentation and promotes a more sustainable grassland use and livestock grazing. However, the success of joint management remains sensitive to external institutional interventions, such as grassland property rights reform or rigid land-use regulations, which can undermine the sustainable use of grassland (Yu, 2016; Yu & Farrell, 2013).

Furthermore, market-oriented grassland management strategies have emerged, driven by rapid urbanization and the integration of marketization in previously remote pastoral communities. An increasing number of pastoralists have migrated from pastoral areas to urban areas for employment, creating conditions to consolidate fragmented and privatized pastures, thereby enabling more efficient, large-scale operations. Grassland leasing, in this context, has become a key mechanism for reallocating land resources (Li & Tan, 2020) and serves as an indicators of market integration at the community level. It also emerged as a potential adaptive strategy for locals to address climate variability and weather disasters, and thus enhancing the resilience and flexibility of pastoral systems (Wang et al., 2013). However, in some cases, grassland leasing has contributed to ecological degradation due to a lack of economic incentives for households leased in grassland to invest in protecting grassland, and inadequate monitoring mechanism for leased grassland, and the absence of collective action to enforce sustainable grazing practices (Li et al., 2018).

2.3. Natural factors influencing grassland quality

Pastoral ecosystems are vulnerable to natural disturbances, which pose serious threats to their ecological stability. The frequent occurrence of large-scale persistent drought, sandstorms, snowstorms and other disasters disrupts grazing patterns, reduces forage availability and increases ecological fragility in pastoral areas. Pastoral ecosystems are characterized by significant spatial and temporal heterogeneity in terms of resource distribution and climatic conditions, which highlights the importance of adaptive responses to achieve ecological sustainability (Yan et al., 2015; Zhang et al., 2017). In light of these challenges, scholars have been devoted to understanding how natural disturbances affect pastoral systems and how herders develop strategies to adapt to these environmental shocks (Feng et al., 2021; Goldman & Riosmena, 2013). Historically, migration has been the primary adaptive strategy used by pastoralists worldwide to cope with weather disasters (Galvin, 2009). In addition, cooperative management based on mutual benefits in nomadic pastoral systems has enabled herders to adapt flexibly to the spatial and temporal heterogeneity of resources and climate variability in pastoral ecosystems (Goldman & Riosmena, 2013; Williams, 2002) and thus to promote the ecological sustainability of grasslands by maintaining a balance among humans, grasslands, and livestock (Dong et al., 2011; Hobbs et al., 2008). In Chinese pastoral areas, cooperation and migratory practices have historically served as effective disaster response strategies. However, with the shift toward sedentarization and more individualized herding practices, migration and consequent cooperative practices have significantly decreased (Yu & Farrell, 2013). Despite improvements in the market environment and infrastructure, the livestock industry remains highly susceptible to natural disasters (Yeh et al., 2014; Zhang et al., 2013).

New pasture ecology schools emphasize the influence of feedback mechanisms among climate, vegetation, and livestock on pasture ecosystems (Han, 2018; Scoones, 1998). From an adaptive management perspective, the ecological impacts of grazing vary based on the way how pasture resources are utilized and the way how grassland use is managed. In recent years, there has been increasing scholarly interest in adaptive grassland management strategies to mitigate impacts of natural disasters in pastoral areas. For example, Li & Tan (2018) found that grassland leasing can improve the ability of herders to cope with weather disasters by enabling access to additional resources during crises. In the event of weather disasters, pastoralists can overcome the limitations of natural pastures by engaging in grassland leasing or cooperative grazing arrangements (Li & Tan, 2020; Wang et al., 2013). Zhang et al. (2013) also reported that joint management is more effective than family management for coping with natural disasters in pasture areas. In summary, natural disasters significantly impact herders' livelihoods and grassland ecosystems, underscoring the need for adaptive management strategies to increase community resilience and ecological sustainability.

2.4. Potential ways to conserve grasslands in a complex system: A framework

Previous studies have highlighted diverse views on the ecological impacts of common versus private property rights. The way in which locals organize to utilize grasslands under varying property rights significantly influences the ecological outcomes of grasslands. Adaptive management strategies such as grassland leasing, joint management, and cooperatives have been shown to generate ecological benefits and enhance resilience to natural shocks. While these studies provide valuable empirical insights into how property rights, adaptive management strategies, and other social-economic conditions affect grassland ecosystems, several critical gaps remain in the literature. First, much of the existing studies relies on qualitative, case-based analysis, limiting the generalizability of findings. Second, the results have been inconsistent while some studies report positive ecological outcomes from privatization, others find negligible or even negative effects (Hou et al., 2022; Li & Huntsinger, 2011; Liu et al., 2024; Yu & Farrell, 2013). The influences of property right and adaptive strategies are deeply interwoven and context-dependent, yet such causal complexity is often underexplored.

To address these gaps, this study adopts a holistic analytical framework (Fig. 1) incorporating four key dimensions (i.e., grassland property rights, adaptive management strategies, the social-economic context, and natural disasters), in order to facilitate a more comprehensive understanding of strategies for promoting grassland ecological protection. Property rights play a central role in regulating access, use and transactions related to grassland resources. Adaptive management strategies further shape ecological outcomes through flexible and locally embedded practices. While most rural areas in China have access to basic infrastructure, such as water, electricity, internet, and transportation, variations in broader social-economic conditions (e.g., market integration) continue to influence how property regimes and management strategies affect herders' livelihoods, production decisions, and ecological behavior (Gongbuzeren et al., 2016; Gongbuzeren & Li, 2016; Kuminoto, 2010; Kunte et al., 2017). Additionally, natural disasters disturbances and climate variability play a role in affecting grassland quality (Feng et al., 2021; Goldman & Riosmena, 2013; Scoones, 1998). Building on this framework, this study seeks to examine the interactions of these factors with property right and to identify effective strategies for promoting the ecological sustainability of grasslands.

3. Data and methods

3.1. Data and operationalization

The village level social-economic data were sourced from the Chinese Pastoralist Household Tracking Survey Database (Hou et al., 2021), which was constructed by the China Centre for Agricultural Policy Research at Peking University (CCAP-PKU). To our knowledge, this is the first large-scale survey to cover most major pastoral provinces (Hou et al., 2021; Hou et al., 2022). This database includes 164 administrative villages across 27 banners and counties in pastoral regions of five provinces, Inner Mongolia, Qinghai, Tibet, Xinjiang and Gansu, from 2015 to 2020. We selected Inner Mongolia, Xinjiang, Qinghai, and Gansu as the study areas, focusing specifically on 2018, which was the year that all provinces (and autonomous regions) and most of the required information were included. The database employs a stratified random sampling method across the aforementioned four provinces. The dataset includes data from four counties in Gansu, five counties in Inner Mongolia, and six counties each in Qinghai and Xinjiang. Additionally, three main grassland types were identified, and the counties associated with each grassland type were categorized into two groups on the basis of per capita annual income. One county was randomly selected from each income quartile, and six sample counties were ultimately selected in addition to Gansu and Inner Mongolia. Gansu Province is relatively small and characterized primarily by alpine meadow grasslands, so all counties in Gansu Province were categorized into four income quartiles in the database, and one county from each quartile was randomly selected. Notably, one county from Inner Mongolia was excluded from the analysis because a significant number of pastoralists in that area have stopped grazing activities. Thus, a total of five counties were included in this study.

Ultimately, data from 21 counties in the four provinces were sampled from the database. Subsequently, all townships within these counties were categorized on the basis of per capita grassland area (generally divided into three equal parts, and those with particularly large area divided into four equal parts). One township was randomly selected from each division, resulting in a total of 65 selections. Among the 65 selected townships, the villages within each township were further divided into three equal parts based on the per capita grassland area. One village was randomly selected from the first third, and another village was randomly selected from the last third. Therefore, 2 villages were selected from each township. A total of 130 village samples were drawn from 21 counties in 4 provinces. However, since a significant amount of data was missing for one village in Inner Mongolia, we ultimately analyzed a total of 129 village cases from Inner Mongolia, Xinjiang, Qinghai, and Gansu Provinces (Fig. 2). The raw data were obtained from a questionnaire survey conducted in 2018 in which the respondents were village leaders. The collected data were then integrated and analyzed to compile village-level social-economic and natural data. The variables used to proxy our outcome and conditions are presented in Table 1.

We employ the normalized difference vegetation index (NDVI) as an indicator of grassland ecosystem condition. Although NDVI does not capture all dimensions of ecological complexity, its high sensitivity to vegetation status, coupled with its consistency, accessibility, and temporal coverage, make it capable for large-scale ecological assessments and community-level comparative studies (Piao et al., 2006; Hou et al., 2021; Hou et al., 2022; Tan et al., 2024). These characteristics are especially advantageous for analyzing ecological patterns across diverse and remote pastoral regions, where ground-based monitoring data is

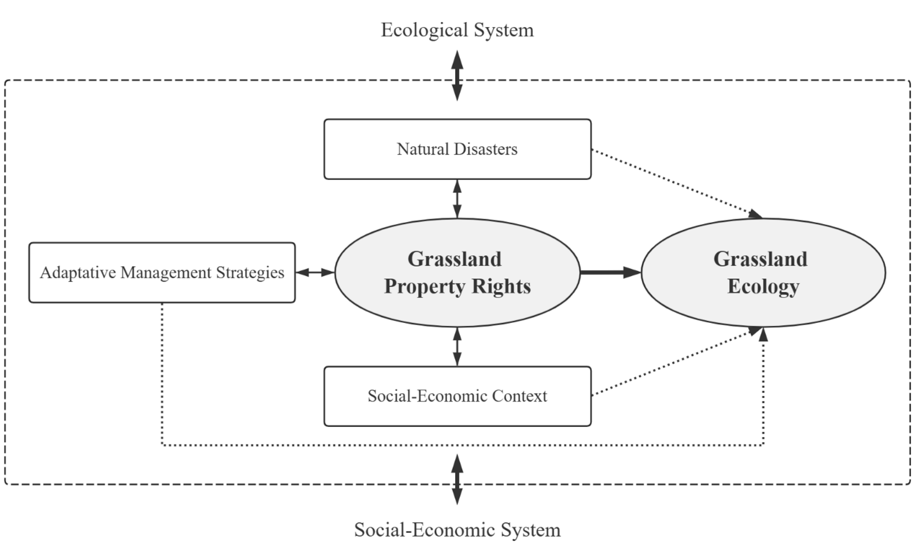

Fig. 1. Analytical framework for sustainable grasslands governance.

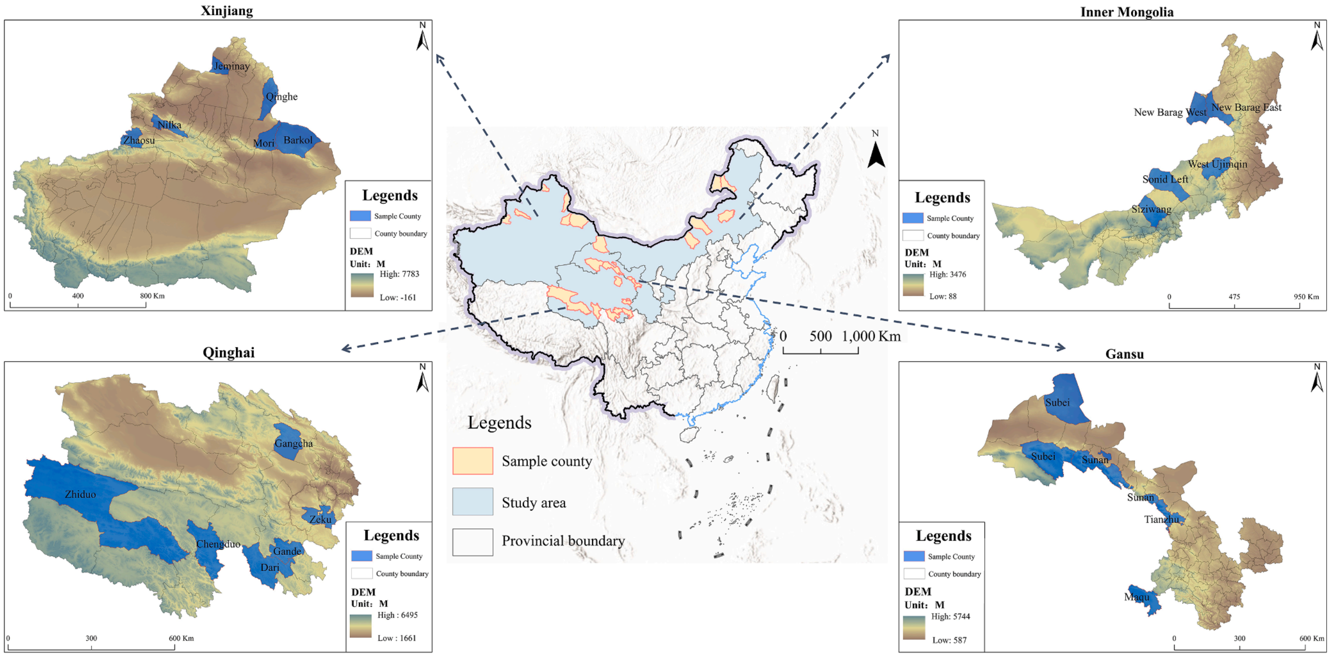

Fig. 2. Location map of sample counties.

Table 1
Measurement and descriptive statistics of outcomes and conditions.

Outcome and conditions	Proxy	Descriptive statistics			
		Mean	Std. dev.	Max.	Min.
Grassland ecosystems	The NDVI index within 20 km of the village committee in 2018.	0.559	0.211	0.833	0.110
Common property rights	The specific types of grass rights in the village in 2018. Value assigned: common grassland property rights = 1, private property rights = 0. The classification for grassland to joint households or village is 1, and the classification for the whole part of grassland to individual households is 0.	0.217	0.414	1.000	0.000
Joint management	Was there any joint management which refers to several pastoralist households grazing or cutting grass together on the same grassland in the village in 2018? Value assigned: Yes = 1, No = 0.	0.193	0.396	1.000	0.000
Cooperatives	Were there any pastoral cooperatives or associations in the village in 2018? Value assigned: Yes = 1, No = 0.	0.612	0.489	1.000	0.000
Grassland leasing	The proportion of total leased grassland to the total grassland area in the village (%).	0.104	0.149	1.000	0.000
Market connection	The maximum distance between the village committee and its superior county (banner) government in all samples minus the distance between the village committee and its superior government in this village (km).	275.503	57.309	340.000	0.000
Natural disasters	Has the village experienced any natural disasters in 2018? Value assigned: Yes = 1, No = 0.	0.482	0.502	1.000	0.000

often limited or unfeasible. The monthly NDVI data utilized in this study were obtained from the MOD13A3 product provided by the National Aeronautics and Space Administration (NASA) Earth Data, which offers a spatial resolution of 1×1 km^2. Using village-specific data, we calculated the NDVI values for areas within 10 km, 20 km and 40 km surrounding the village committee. Annual village-level NDVI data were subsequently derived from the maximum monthly NDVI values for each village. Consequently, the annual NDVI index for villages within a 20 km radius was used to represent grassland ecosystems as the outcome, and the NDVI within 10 and 40 km radius were used for robustness tests. Overall, the annual NDVI is greater under common property rights than under private property rights (Appendix A1).

On the basis of this framework, four conditions were considered, namely, grassland property rights, adaptive management strategies, the natural disasters and social-economic conditions of the communities. In China, grassland is collectively or state-owned, whereas the use rights of grassland are typically contracted to individual households, groups of households, or remain with entire villages. Considering the diverse grassland property rights in practice (Hou et al., 2022; Li & Huntsinger, 2011; Liu et al., 2024; Yu & Farrell, 2013), we assigned the value of property rights as follows: common grassland property rights = 1 and private grassland property rights = 0. Any situation in which the use right of grassland was distributed to villages or joint households was classified as common grassland property right, whereas grassland that was divided into individual households was classified as private grassland property right.

Adaptive management strategies help to illuminate how locals define and implement actions at both the individual and collective levels. Among these strategies, joint management, pastoral cooperatives and grassland leasing have played significant roles in shaping the social and institutional transformation of pastoral regions. Drawing on insights from the existing literature, we focus on three specific strategies for adaptive management: (1) the presence or absence of joint management, (2) the existence of pastoral cooperatives within the village; and (3) the extent of grassland leasing measured by the proportion of total leased grassland to the total grassland area in the village.

The community background includes an indicator of the market connection of the village. With the increasing market integration of previously remote pastoral communities (Gongbuzeren & Li, 2016), pastoralists' market participation fosters the commercialization of livestock products, which may, in turn, impact grassland ecosystems. Market distance, such as the proximity between the village committee and the nearest market, township government, or county government (Sun et al., 2019), is key to the pastoral economy and ecosystem and thus should be considered in the study. As the distance between the village committee and its superior county government location increases, the market connection of this village decreases. Therefore, we use the village farthest from its county government as the benchmark, assigning it a market connection value of zero. For all other villages, the value is calculated as the difference in distance to the county government compared to the benchmark.

In addition, we consider the number of natural disasters experienced by each village as an indicator of natural conditions. The prevalence of natural disasters leads to vulnerable habitats in pastoral areas, which hinders sustainable livestock production. Thus, in this work, we evaluated the natural conditions of the case villages by systematically documenting the incidence or absence of natural disasters, including drought, snow disasters, high temperatures, wind disasters, sandstorms, floods, hail, rodent infestations, pests and diseases, and wolf infestations. We conducted descriptive statistics for each condition and outcome and present them in Table 1.

3.2. Methods

3.2.1. Fuzzy set quality comparative analysis (fsQCA)

We employed the fuzzy set qualitative comparative analysis (fsQCA) to analyze the complex causal relationships and mechanisms that affect the ecological outcomes of grassland. Designed to analyze conjunctural causation and equifinality, the idea that different combinations of conditions can lead to the same outcome, fsQCA is particularly well-suited for research involving complex social-ecological systems (Ragin, 1987; Eisenack & Roggero, 2022; Ragin, 2000; Ragin & Fiss, 2008). It enables the detection of multiple causal pathways across a large sample while accounting for the complexity and interdependence of variables. fsQCA also excels at identifying which conditions are necessary (i.e., must be present for an outcome to occur) and which configurations are systematically sufficient for achieving specific outcomes on the basis of sets and Boolean algebra (Ragin, 1987; Eisenack & Roggero, 2022). In this study, fsQCA is used to classify sample villages based on distinct configurations of conditions and to determine which configurations are systematically sufficient for achieving sustainable grassland ecosystems. In the fields of political science, sustainability research, and institutional analysis, fsQCA has increasingly proven effective in uncovering interdependent and complex causal mechanisms and interactive effects among conditions, making it an especially powerful tool for the study of complex governance and ecological systems (Rihoux et al., 2013; Rihoux & Ragin, 2008; Roggero et al., 2019).

Thus, the rationale for selecting this method is threefold. First, through cross-comparison between large scale samples, we are able to generalize the results compared with case studies and improved the external validity of the conclusions about grassland ecosystems (Ragin, 2000; Ragin & Fiss, 2008). Second, fsQCA can be used to analyze the complex causal relationships affecting grassland ecology from a systematic and holistic perspective (Ragin, 2000; Ragin & Fiss, 2008; Tian et al., 2023). Third, the empirical evidence that diverse combinations of conditions may lead to high-level grassland ecosystems (or vice versa) exemplifies a scenario in which different configurations of conditions may lead to equivalent outcomes (known as equifinality) as well as the same conditions can lead to various outcomes, which is referred to as causal asymmetry that fsQCA is adept at identifying (Fiss, 2011). In the supplementary Appendix A2, we explain the terminology in detail, including the affiliation score, necessity and sufficiency.

3.2.2. Data calibration

In fsQCA, calibration is the process of converting raw data into fuzzy set values that reflect the degree of affiliation to a particular condition or outcome (Ragin & Fiss, 2008). This process relies on theoretical and empirical justifications tailored to the specific context of a particular study and the nature of the data (Rihoux & Ragin, 2008; Schneider & Wagemann, 2012). Unlike binary methods, fsQCA uses affiliation scores ranging from 0 to 1 to represent varying degrees of belonging of a case to a certain set (Ragin, 2000; Ragin & Fiss, 2008): 0 indicates full exclusion and 1 indicates full inclusion. This allows researchers to capture the complexity of social phenomena that cannot be classified simply as "yes" or "no". A common approach is the Three Anchor Points method, which sets three key thresholds (low, medium and high) based on theory or experience, and then maps the raw data to the [0,1] interval using a non-linear function (Ragin & Fiss, 2008; Schneider & Wagemann, 2012).

We utilized fsQCA in response to the challenges associated with directly categorizing outcomes under multiple conditions as merely high or low. Specifically, in our analysis, grassland property rights are either common or privately owned, therefore the condition of common property rights is assigned a value of 1 or 0. The presence or absence of cooperatives and natural disasters is also recoded as a binary variable. We code other conditions with an affiliation scale ranging from 0 to 1, depending on their degree of belonging to a particular category. We apply the direct calibration method to all of the continuous variables (Ragin & Fiss, 2008), using the 10th, 50th, and 90th percentiles to indicate full non-membership, the crossover point, and full membership, respectively (see Appendix A3 for details). In order to ensure that cases located at fuzzy affiliations are not ignored, we added 0.001 to the affiliation for a condition or outcome set of 50 %. Additionally, three key thresholds were used to calibrate the robustness test are 25 %, 50 % and 75 %, which have been commonly used in previous research (Schneider & Wagemann, 2012).

3.2.3. Configuration analysis

In fsQCA, sufficiency analysis identifies which configurations can lead to the occurrence of the outcome. The sufficiency of configurations needs to be assessed by defining both the consistency threshold and the frequency threshold. Existing studies indicate that the consistency threshold is typically established within the range of 0.75 to 0.85 (Schneider & Wagemann, 2012). Thus, we consider all configurations above the conventional 0.8 consistency threshold to be sufficient. To eliminate the occurrence of accidents and enhance the robustness of the results, we set the frequency threshold at 2. Additionally, to mitigate the occurrence of contradictory phenomena in which the same conditions cause different results, it is essential to set the proportional reduction in inconsistency (PRI) within a reasonable range. Although no consensus has been reached regarding the optimal PRI threshold, it is generally accepted to fall between 0.5 and 0.75 (Pappas & Woodside, 2021; Thomas et al., 2018). Thus, we opted to set the PRI threshold at 0.75, considering cases with a PRI value below 0.75 as out of the set (=0).

4. Results

4.1. Analysis of necessary conditions

We first identified the necessary conditions for high-level and non-high-level grassland ecosystems. The main observation for determining necessary conditions is consistency. Consistency refers to the degree of overlap between the condition and the outcome. A condition is considered necessary for the outcome when the consistency exceeds 0.90 (Ragin & Fiss, 2008). In addition, coverage represents the degree to which a condition can explain the outcome, that is how much of the outcome can be explained by that condition. The results of the necessity analysis for individual conditions are presented in Table 2, which shows that the consistency scores of all the variables did not exceed the threshold of 0.90. Thus, none of the selected conditions are necessary for high-level or non-high-level grassland ecosystems.

Table 2
Testing the necessary conditions for assessing grassland ecosystems.

Conditions	Grassland ecosystems		~Grassland ecosystems	
	Consistency	Coverage	Consistency	Coverage
Common property rights	0.270	0.646	0.126	0.354
Private property rights	0.730	0.416	0.874	0.584
Joint management	0.290	0.695	0.109	0.305
~Joint management	0.710	0.405	0.891	0.595
Cooperatives	0.713	0.560	0.479	0.440
~Cooperatives	0.287	0.320	0.521	0.680
Grassland leasing	0.557	0.570	0.557	0.668
~Grassland leasing	0.676	0.566	0.642	0.629
Market connection	0.714	0.643	0.574	0.606
~Market connection	0.562	0.530	0.661	0.730
Natural disasters	0.410	0.418	0.488	0.582
~Natural disasters	0.590	0.496	0.512	0.504

Note: The symbol ~ represents the non set of this condition.

4.2. *Sufficient configurations*

We conducted a sufficiency analysis of the configurations leading to high-level and non-high-level grassland ecosystems. Then, we identified the core conditions and peripheral conditions. Only those factors that appeared in both the parsimonious and intermediate solutions were considered core conditions, whereas factors that appeared only in the intermediate solution were classified as peripheral conditions (Ragin, 2000; Ragin & Fiss, 2008). It should also be noted that fsQCA has the multiple conjunctural causations, and multiple different configurations may collectively lead to the same outcome. Each configuration represents a pathway, and each pathway can independently explain the occurrence of the outcome (Rihoux et al., 2013). Ultimately, we identified five configurations leading to high-level grassland ecosystems and three configurations leading to non-high-level grassland ecosystems. The distributions of all configurations for high-level and non-high-level grassland ecosystems at the county level are shown in Fig. 3.

4.2.1. *Analysis of configurations for high-level grassland ecosystems*

Five configurations are involved in high-level grassland ecosystems (Table 3), achieving an overall consistency of 0.950 and a coverage of 0.288. In the sufficiency analysis, the consistency score reflects the degree to which a specific configuration is sufficient for the outcome. A greater intersection between conditions and outcomes correlates with greater consistency. When the consistency exceeds 0.8, the configuration is often considered sufficient for the outcome. The coverage score of a sufficiency claim is the proportion of the cases in which the outcome stands where the specific configuration holds, which means, in this case, these five configurations could explain 28.8 % of the outcome (i.e., high-level grassland ecosystems).

Based on the presence of both common and private property rights, we classified these configurations into two categories. Common property rights are identified as the core conditions in Configurations 1–3, whereas private property rights serve as the peripheral condition in Configurations 4–5. In general, the results show that both common and private property rights could contribute to high levels of grassland ecosystems, which supports our hypothesis that no ideal or single type of property right fits all contexts. The ways in which property rights influence grassland ecosystems depend on wider social-ecological conditions. The results also revealed that high-level pathways associated with common property rights (Configurations 1–3) are predominantly located in Qinghai Province and Gansu Province, and include counties such as Dari, Chengduo and Zeku in Qinghai, as well as Sunan and Tianzhu in Gansu (Fig. 3). Conversely, the pathways for private property rights (Configurations 4–5) are observed in Zhiduo in Qinghai, Tianzhu in Gansu, Nilka in Xinjiang and New Barag East Banner in Inner Mongolia. Overall, villages in Qinghai and Gansu demonstrate superior grassland ecosystems, with adaptive management—such as joint management, cooperatives and grassland leasing—playing a significant role.

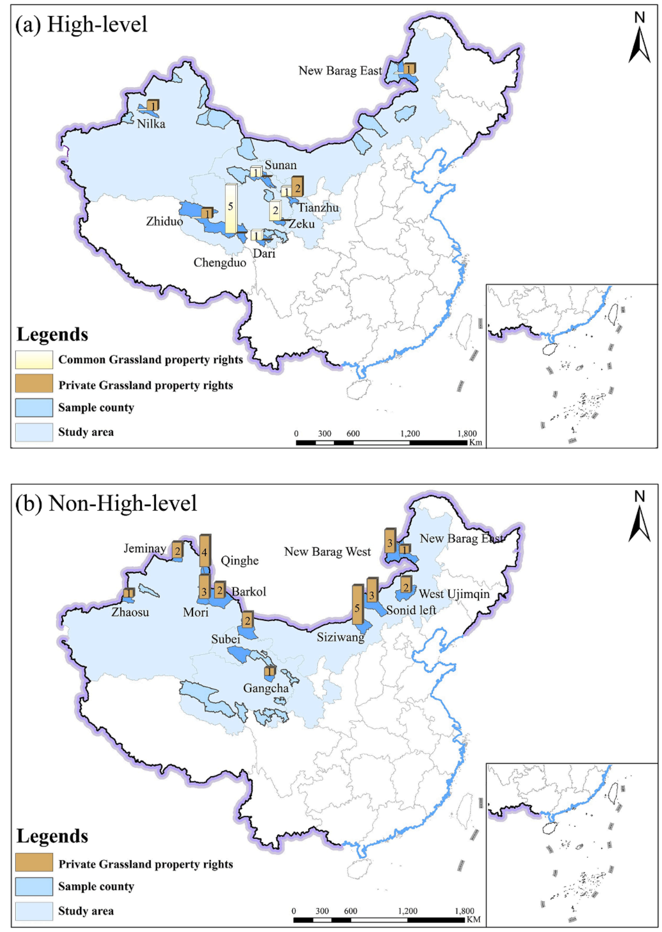

Fig. 3. Distribution map of configurations for high-level and non-high-level grassland ecosystems.

Table 3
Configurations for high-level grassland ecosystems.

Conditions	Configurations				
	1	2	3	4	5
Common property rights	●	●	●	⊗	⊗
Joint management	●	⊗	●	●	⊗
Cooperatives	●	●	●	●	●
Grassland leasing	⊗	•	⊗	●	⊗
Market connection	⊗	⊗	•	⊗	⊗
Natural disasters	⊗	⊗	•	•	⊗
Consistency	0.973	1	0.945	1	0.906
Raw coverage	0.053	0.027	0.093	0.035	0.081
Unique coverage	0.053	0.027	0.093	0.035	0.081
Solution consistency			0.950		
Solution coverage			0.288		

Note: ● or • denotes the presence of the condition. ⊗ or ⊗ denotes the absence of the condition. ● and ⊗ denote core conditions. • and ⊗ denote peripheral conditions. Blank space indicates that the condition can exist or not exist.

Among the key conditions, adaptive management strategies are crucial for achieving high-level grassland ecosystems. Specifically, pastoral cooperatives consistently emerge as core conditions, indicating their positive role in protecting grassland ecosystems. As formal organizations, cooperatives are well positioned to coordinate the interests of pastoralists, minimize conflicts over grassland use, and facilitate collective decision-making. Through resource integration, risk sharing, technology promotion, market access and policy support, cooperatives act as effective mechanisms in pastoral settings. Notably, when natural disasters occur, both joint management and cooperatives are identified as core conditions for achieving high ecological quality, and these must be complemented by either convenient market connections or grassland leasing arrangements to achieve positive ecological outcomes. This demonstrates the importance of combining collective action with market integration to increase the resilience of communities. Overall, these findings suggest that flexible adaptive management strategies can effectively mitigate the impacts of natural disasters on grassland ecosystems.

4.2.2. *Analysis of configurations for non-high-level grassland ecosystems*

In this study, we also analyzed the configurations leading to non-high-level grassland ecosystems. Three configurations result in non-high-level grassland ecosystems (Table 4), with an overall consistency of 0.870 and coverage of 0.409, meaning that these configurations collectively explain approximately 41 % of village cases exhibiting non-high-level grassland ecosystems.

Specifically, all three pathways lack conditions of common property rights and joint management, reflecting the characteristics of private property rights and individual household management. Natural disasters are present as the core condition in Configurations 6–7, showing that in villages where grassland is privately contracted and independently managed, when suffering from natural disasters if market connection is poor (Configuration 6) or without cooperatives and grassland leasing (Configuration 7), the grassland ecosystem is likely to be non-high-level. Both configurations demonstrate a lack of cooperation and diverse management strategies which are essential for mitigating risks during disasters, ultimately resulting in non-high-level grassland ecosystems. Moreover, even in the absence of natural disasters, when no adaptive management strategies are implemented and market connections are weak (Configuration 8), grassland ecosystem is unlikely to reach a high level of sustainability.

These configurations are mostly located in Xinjiang and Inner Mongolia. Configuration 6 is mainly distributed in Siziwang Banner and Sonid Left Banner in Inner Mongolia, Configuration 7 mainly in Jeminay and Qinghe in Xinjiang. Configuration 8 mainly in Subei in Gansu and Qinghe in Xinjiang (Fig. 3). Villages in these regions have lower grassland quality, largely due to limited adaptive management and weak market connection, which reduce resilience to natural disasters.

In conclusion, under the conditions of private property rights, independent grassland management and severe disasters, the absence of cooperatives, grassland leasing or a supportive market environment leads to non-high-level grassland ecosystems. Furthermore, the lack of adaptive strategies such as cooperation and grassland leasing, along with poor market connections, also jeopardizes the ecological environment even without the impacts of natural disasters.

Table 4
Configurations for non-high-level grassland ecosystems.

Conditions	Configurations		
	6	7	8
Common property rights	⊗	⊗	⊗
Joint management	⨂	⨂	⊗
Cooperatives		⨂	⨂
Grassland leasing		⨂	⨂
Market connection	⨂		⨂
Natural disasters	●	●	
Consistency	0.902	0.883	0.891
Raw coverage	0.240	0.102	0.175
Unique coverage	0.186	0.048	0.121
Solution consistency		0.870	
Solution coverage		0.409	

Note: ● or • denotes the presence of the condition. ⨂ or ⊗ denotes the absence of the condition. ● and ⨂ denote core conditions. • and ⊗ denote peripheral conditions. Blank space indicates that the condition can exist or not exist.

4.3. *Heterogeneity analysis*

Previous studies show that herders with smaller grassland size are more likely to overgraze, causing grassland degradation (Zhou et al., 2019). To explore how grassland size shapes ecological outcomes, we divided the samples into two groups based on per capita grassland area, above or below the adjusted mean (excluding the top 5 % to reduce the influence of outliers). We then applied the same fsQCA procedure to each group.

The analysis identified two configurations linked to high ecological quality in the larger-area group and four in the smaller-area group (Table 5). In contexts with relatively large grassland areas, the results indicate that privatization and individual management can contribute to sustainable outcomes when natural disasters are absent and cooperative institutions are engaged. In contrast, the majority of configurations in the smaller-area group (Configurations 11–12, 14) emphasized common property rights and collective action, suggesting that these arrangements are more effective under land-scarce conditions. Importantly, in both land-rich and land-scarce contexts, the presence of cooperatives and joint management (Configurations 13–14) was critical in mitigating the ecological impacts of natural disasters.

Overall, our findings underscore the importance of tailoring governance strategies to local land conditions. In areas with relatively ample grassland resources, privatization and individualized management can foster ecological resilience. However, where grassland per capita is limited, sustainable outcomes are more likely to emerge through collective governance arrangements. In the face of environmental shocks, adaptive management and market connection are essential to maintain ecological quality.

4.4. *Robustness tests*

We employed various methods to assess the robustness of the results derived from the main model. The supplementary calibration results, descriptive statistics and analysis of the necessary conditions for the newly added data are illustrative in the Appendix A4, A5, A6 and A7. As shown in A4 and A5, none of the newly added conditions are necessary for high-level or non-high-level grassland ecosystems.

First, precipitation plays a critical role in shaping pastoral ecosystem dynamics and vegetation productivity (Deguines et al., 2017; Liu et al., 2025; Zhang et al., 2017). To account for this key climatic factor, we included growing season precipitation (May to September) as an additional condition in our robustness tests, guided by the climate patterns and grass growth cycle of the study area (Yan et al., 2015). We used the China Monthly Precipitation Dataset at 1-km Resolution (2014–2018), obtained from the National Tibetan Plateau/Third Pole Environment

Table 5
Configurations for high-level grassland ecosystems based on different per capita grassland areas.

Conditions	Larger per capita grassland areas		Smaller per capita grassland areas			
	9	10	11	12	13	14
Common property rights	⊗	⊗	●	●	⊗	●
Joint management	⊗	⊗	●	⊗	●	●
Cooperatives	●	●	●	●	●	●
Grassland leasing	●	⨂	⊗	•	●	⊗
Market connection	⨂	•	⨂	⊗	⨂	•
Natural disasters	⨂	⨂	⊗	⊗	•	•
Consistency	0.923	0.984	0.886	1	0.913	0.876
Raw coverage	0.098	0.153	0.072	0.049	0.057	0.124
Unique coverage	0.063	0.118	0.072	0.049	0.057	0.124
Solution consistency	0.952		0.903			
Solution coverage	0.216		0.302			

Note: ● or • denotes the presence of the condition. ⨂ or ⊗ denotes the absence of the condition. ● and ⨂ denote core conditions. • and ⊗ denote peripheral conditions. Blank space denotes that the condition can exist or not exist.

Data Center (Peng, 2020). This high-resolution dataset provides monthly precipitation records from January 1901 to December 2023 at a spatial resolution of 0.0083333° (approximately 1 km at the equator) (Peng et al., 2019). The results aligned closely with the main model results, thereby strengthening the robustness and validity of our core findings. In addition, the results confirmed that precipitation consistently appeared as a contributing condition in configurations associated with high ecological quality (Robustness Test 1 in Appendix A8), reaffirming its ecological significance. However, precipitation was not identified as a necessary condition for achieving ecological sustainability (Appendix A5).

Second, we drew upon existing studies that utilized NDVI to assess grassland vegetation cover. We adjusted the NDVI index within 20 km of the grassland ecosystems to 10 km (Robustness Test 2 in A9) and 40 km (Robustness Test 3 in Appendix A9). The results remain consistently the same as those of the main model, which demonstrates that NDVIs with different radius ranges exhibit similar results.

Third, we validate the robustness of the results by changing the parameters and other conditions involved in the fsQCA method. We adjusted the calibration anchors of all of the continuous variables, with the 25 % quantile indicating no affiliation, the 75 % quantile indicating full affiliation and the 50 % quantile indicating fuzzy affiliation (Robustness Test 4 in Appendix A10). The results are consistent with the main model. Additionally, given the importance of grassland contracting rights certificates in defining property rights (Hou et al., 2022), we refined our classification of property rights: only grasslands allocated to individual households with certaificates were coded as private property rights (=0), whereas all other cases were classified as common property rights (=1) (Robustness Test 5 in Appendix A10). The results remain consistent with the main model, supporting the robustness of our findings.

Fourthly, to avoid a situation in which some village samples whose original NDVI values are completely located at fuzzy affiliations disrupting the results and configurations, we removed those samples and conducted empirical analysis (Robustness Test 6 in Appendix A10). This test results that were essentially consistent with those of the main model, confirming the robustness of the findings.

Lastly, we conducted regressions including interaction terms between common property rights and different adaptive management types. The results show that the interactions with joint management and cooperatives significantly improve grassland ecosystems (Appendix A11), supporting a synergistic link between adaptive management strategies and property rights, consistent with our hypothesis on condition coupling.

5. Conclusion

Grasslands constitute the world's largest ecosystem and are both economically and ecologically essential. However, they are fragile and vulnerable to climate variabilities. Although the impacts of property rights on grassland sustainability have long been debated (Hou et al., 2022; Li & Huntsinger, 2011; Li & Kerven, 2024), conclusions remain elusive, and empirical evidence shows mixed results. While common grasslands may carry the risk of the tragedy of the commons, they are able achieve sustainability through appropriate adaptive grassland management. Conversely, privatization cannot guarantee the sustainability of grasslands, as it may reduce reciprocity relationships and mutual trust in previously sustainable pastoral communities and increase overgrazing. In response to the increasing demand for grassland resources and challenges of degradation, adaptive grassland management practices, such as grassland leasing and joint management, have been developed as potential solutions. Could these approaches offer a sustainable path beyond the single solution of property rights management, and if so, under what conditions?

Using fsQCA methods with village-level data from 129 villages from four provinces in China, this study examined interactions among property rights, adaptive management strategies and other natural and social factors. Both privatized grasslands and common grasslands can be sustained or degraded, depending on the context, which confirms that the influence of grassland property rights varies significantly across contexts. Notably, adaptive grassland management strategies play a crucial role in sustaining grassland use across diverse property regimes, particularly in communities with limited grasslands or frequent natural disasters.

This study provides practical insights for local governments in promoting grassland property rights and adapting social-economic conditions to support adaptive management strategies and achieve a sustainability of grassland. As Cox (2024) emphasizes, property rights are not inherently sustainable or unsustainable; their effectiveness depends on how well they are matched to local ecological and institutional contexts. Our findings reinforce this perspective, suggesting that policies must be responsive to biophysical variability. For example, in areas with ample grassland, promoting grassland privatization and individualized grassland management and market-based mechanisms may enhance sustainability. Conversely, in areas with limited grasslands and frequent natural disasters, collective approaches, such as joint management and cooperatives, are more effective in protecting grasslands. Additionally, improvements in transportation infrastructure and market accessibility are essential for these communities to develop market-based solutions to address natural disasters and achieve sustainability.

CRediT authorship contribution statement

Lu Yu: Writing – original draft, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Siyuan Qiu:** Writing – original draft, Software, Formal analysis, Data curation. **Qi Chen:** Writing – original draft, Validation, Software, Data curation. **Lingling Hou:** Writing – original draft, Methodology, Investigation, Data curation.

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.

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Appendix

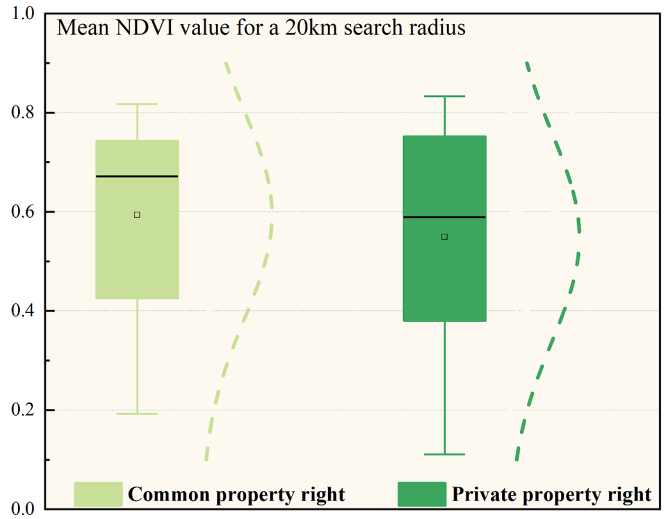

Fig. A1. Box plot of the NDVI with different types of property rights in the research area

Table A2
Definition of key terms in fsQCA (Ragin, 1987; Ragin, 2000; Ragin & Fiss, 2008).

Key terms	Definition
Fuzzy set	A mathematical tool that represents the degree to which a case belongs to a certain set through affiliation score.
Affiliation score	Usually between 0 and 1, it reflects the degree to which a case belongs to a certain set. 0 indicates that it does not belong to the set at all. 1 represents belonging entirely to the set. Values between 0 and 1 indicate that a portion belongs to the set.
Calibration	The process of converting continuous or categorical conditions into an affiliation score between 0 and 1 based on theoretical or empirical criteria.
Necessity	If a condition is necessary, it must exist in order for the result to occur. Without this condition, the result cannot occur.
Sufficiency	If a condition is sufficient, its existence is sufficient to ensure the occurrence of the result. As long as this condition exists, the result will occur.
Consistency	Indicate the degree of overlap between the condition and the outcome, that is whether the fuzzy set value of the condition is always lower than or equal to the fuzzy set value of the outcome. The consistency threshold for necessity is usually 0.9.
Coverage	The degree to which a condition can explain an outcome, that is how much of the outcome can be explained by that condition.
Frequency threshold	The minimum number of times that a condition combination (configuration) needs to appear in the sample in order to be considered meaningful and retained in the truth table. If the occurrence frequency of a configuration is below the frequency threshold, the configuration is considered unimportant and removed from the analysis.
PRI threshold	The proportional reduction in inconsistency threshold is an indicator that measures the consistency between a combination of conditions (configurations) and the outcome. It is used to evaluate whether a configuration is sufficiently correlated to be retained in the analysis. The higher the PRI value is, the stronger the relationship between configuration and outcome.
Complex solution	The complex solution contains all possible combinations of conditions that reflect the original structure of the data.
Parsimonious solution	The parsimonious solution retains only the simplest combination of conditions and reduces redundant conditions by introducing the counterfactual assumption.
Intermediate solution	The intermediate solution is between the complex solution and the parsimonious solutions. The choice of whether to introduce counterfactual assumptions is based on the researcher's preference.
Configuration	A holistic pattern or structure formed by combining multiple conditions in a specific way, used to describe the combination of conditions and their relationship with the outcome.

Table A3
Calibration standards for the outcomes and conditions.

Set	Fuzzy set calibration		
	Full affiliation	Fuzzy affiliation	No affiliation
Grassland ecosystems	0.808	0.604	0.223
Common property rights		Do not calibrate	
Joint management		Do not calibrate	
Cooperatives		Do not calibrate	
Grassland leasing	0.300	0.050	0.000
Market connection	333.100	285.500	214.600
Natural disasters		Do not calibrate	

Note: The four conditions that do not require calibration are all assigned values of 0 or 1.

Table A4
Calibration standards and descriptive statistics for the outcomes and conditions in robustness tests.

Set	Fuzzy set calibration (90–50-10)			Descriptive statistics			
	Full affiliation	Fuzzy affiliation	No affiliation	Mean	Std. dev.	Max.	Min.
Grassland ecosystems (10 km)	0.815	0.616	0.208	0.568	0.222	0.859	0.103
Grassland ecosystems (40 km)	0.784	0.553	0.194	0.538	0.207	0.835	0.130
Common property rights (certification)		Do not calibrate		0.333	0.473	1.000	0.000
Grassland leasing1		Do not calibrate		0.710	0.454	1.000	0.000
Precipitation (RS)	629.500	269.300	113.600	341.400	192.900	702.800	62.100

Note: The four conditions that do not require calibration are all assigned values of 0 or 1.

Table A5
Testing the supplemental conditions for assessing grassland ecosystems in the main model.

Conditions	Grassland ecosystems		~Grassland ecosystems	
	Consistency	Coverage	Consistency	Coverage
Common property rights (certification)	0.365	0.603	0.205	0.397
Private property rights (certification)	0.635	0.405	0.795	0.595
Precipitation (RS)	0.791	0.822	0.421	0.512
~Precipitation (RS)	0.530	0.438	0.854	0.827

Note: The consistency and coverage of the necessity tests for each condition shown in this table are based on the specific combination of conditions in the robustness test, that is, the conditions in the table do not appear separately. The symbol ~ represents the non set of this condition.

Table A6
Testing the necessary conditions for assessing grassland ecosystems (NDVI within a range of 10 km).

Conditions	Grassland ecosystems(10 km)		~Grassland ecosystems (10 km)	
	Consistency	Coverage	Consistency	Coverage
Common grassland property rights	0.263	0.647	0.129	0.354
Private grassland property rights	0.737	0.431	0.871	0.569
Joint management	0.292	0.718	0.103	0.282
~Joint management	0.708	0.414	0.897	0.586
Cooperatives	0.730	0.588	0.458	0.412
~Cooperatives	0.270	0.309	0.542	0.691
Grassland leasing	0.558	0.586	0.544	0.638
~Grassland leasing	0.656	0.563	0.647	0.620
Market connection	0.699	0.646	0.573	0.591
~Market connection	0.557	0.539	0.657	0.709
Natural disasters	0.403	0.421	0.496	0.579
~Natural disasters	0.597	0.515	0.504	0.485

Table A7
Testing the necessary conditions for assessing grassland ecosystems (NDVI within a range of 40 km).

Conditions	Grassland ecosystems (40 km)		~Grassland ecosystems (40 km)	
	Consistency	Coverage	Consistency	Coverage
Common grassland property rights	0.258	0.659	0.129	0.341
Private grassland property rights	0.742	0.452	0.871	0.548
Joint management	0.269	0.688	0.118	0.313
~Joint management	0.731	0.445	0.882	0.555
Cooperatives	0.712	0.560	0.466	0.404
~Cooperatives	0.288	0.343	0.534	0.657
Grassland leasing	0.564	0.616	0.551	0.623
~Grassland leasing	0.655	0.585	0.661	0.611
Market connection	0.699	0.672	0.587	0.584
~Market connection	0.568	0.571	0.670	0.698
Natural disasters	0.412	0.448	0.491	0.552
~Natural disasters	0.588	0.528	0.509	0.472

Table A8
Robustness test of configurations for high-level grassland ecosystems: adding conditions of precipitation.

Conditions	Robustness Test 1: Adding the total precipitation from May to September obtained from remote sensing data as a new condition				
	1′	2′	3′	4′	5′
Common property rights	●		●	⊗	⊗
Joint management	●	⊗	●	●	⊗
Cooperatives	●	●	●	●	•
Grassland leasing	⊗	•	⊗	•	⊗
Market connection	⊗	⊗	●	⊗	•
Natural disasters	⊗	⊗	•	•	⊗
Precipitation	●	●	•	●	●
Consistency	0.971	0.996	0.970	1	0.995
Raw coverage	0.049	0.111	0.093	0.035	0.117
Unique coverage	0.049	0.062	0.093	0.035	0.068
Solution consistency	0.986				
Solution coverage	0.356				

Note: ● or • denotes the presence of the condition. ⊗ or ⊗ denotes the absence of the condition. ● and ⊗ denote core conditions. • and ⊗ denote peripheral conditions. Blank space denotes the condition can exist or not exist.

Table A9
Robustness tests of configurations for high-level grassland ecosystems: adjusting the distance range of the NDVI.

Conditions	Robustness Test 2:Using the NDVI index within a 10 km radius of the village committee as the center to characterize grassland ecosystems in the village during the year					Robustness Test 3:Using the NDVI index within a 40 km radius of the village committee as the center to characterize grassland ecosystems in the village during the year				
	1″	2″	3″	4″	5″	1‴	2‴	3‴	4‴	5‴
Common property rights	●	●	●	⊗	⊗	●	●	●	⊗	⊗
Joint management	●	⊗	●	●	⊗	●	⊗	●	●	⊗
Cooperatives	●	●	●	●	●	●	●	●	●	●
Grassland leasing	⊗	•	⊗	●	⊗	⊗	•	⊗	●	⊗
Market connection	⊗	⊗	•	⊗	⊗	⊗	⊗	•	⊗	⊗
Natural disasters	⊗	⊗	•	•	⊗	⊗	⊗	•	•	⊗
Consistency	1	1	0.875	0.958	0.887	0.911	1	0.949	0.958	1
Raw coverage	0.053	0.026	0.084	0.033	0.077	0.046	0.025	0.088	0.032	0.083
Unique coverage	0.053	0.026	0.084	0.033	0.077	0.046	0.025	0.088	0.032	0.083
Solution consistency	0.921					0.963				
Solution coverage	0.273					0.274				

Note: ● or • denotes the presence of the condition. ⊗ or ⊗ denotes the absence of the condition. ● and ⊗ denote core conditions. • and ⊗ denote peripheral conditions. Blank space denotes the condition can exist or not exist.

Table A10
Robustness tests of configurations for high-level grassland ecosystems: other adjustments.

Conditions	Robustness Test 4: 75-50-25 quantile calibration					Robustness Test 5: Taking into account the registration and certification of grassland					Robustness Test 6: Removing the samples whose original NDVI outcome values are located completely at fuzzy affiliations				
	1''''	2''''	3''''	4''''	5''''	1'''''	2'''''	3'''''	4'''''	5'''''	1''''''	2''''''	3''''''	4''''''	5''''''
Common property rights	●	●	●	⊗	⊗	●	●	•	⊗	⊗	●	●	●	⊗	⊗
Joint management	●	⊗	●	●	⊗	●	⊗	●	●	⊗	●	⊗	●	●	⊗
Cooperatives	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Grassland leasing	⊗	•	⊗	●	⊗	⊗	•	⊗	•	⊗	⊗	•	⊗	●	⊗
Market connection	⊗	⊗	•	⊗	⊗	⊗	⊗	•	⊗	⊗	⊗	⊗	•	⊗	⊗
Natural disasters	⊗	⊗	•	•	⊗	⊗	⊗	•	•	⊗	⊗	⊗	•	•	⊗
Consistency	0.946	1	0.969	1	0.897	0.973	0.814	0.933	1	0.959	0.973	1	0.945	1	0.906
Raw coverage	0.057	0.035	0.102	0.040	0.053	0.053	0.029	0.075	0.025	0.078	0.053	0.027	0.094	0.035	0.081
Unique coverage	0.057	0.035	0.102	0.040	0.053	0.053	0.029	0.075	0.025	0.078	0.053	0.027	0.094	0.035	0.081
Solution consistency	0.958					0.939					0.950				
Solution coverage	0.287					0.260					0.291				

Note: ● or • denotes the presence of the condition. ⊗ or ⊗ denotes the absence of the condition. ● and ⊗ denote core conditions. • and ⊗ denote peripheral conditions. Blank space denotes the condition can exist or not exist.

Table A11
Regression results.

Variables	Grassland ecosystems			
	(1)	(2)	(3)	(4)
Common property rights	−0.035	−0.099**	−0.134**	−0.027
	(−1.06)	(−2.19)	(−2.41)	(−0.53)
Common property rights* Joint management		0.157***		
		(2.97)		
Common property rights* Cooperatives			0.171***	
			(2.75)	
Common property rights* Grassland leasing1				−0.013
				(−0.20)
Control variables	YES			
N	105	105	105	105
Adj. R2	0.49	0.50	0.51	0.49

Note: Other control variables include “joint management”, “cooperatives”, “grassland leasing1”, “market connection”, “natural disasters” and “precipitation”. Among them, “grassland leasing1” is a 0/1 variable. When there is grassland leasing in this village, the variable is assigned a value of 1. Otherwise, assign a value of 0. The definition and assignment of the remaining control variables are exactly the same as those in the fsQCA method.

Data availability

Data will be made available on request.

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