Journal of Integrative Agriculture 2023, 22(8): 2567–2576

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RESEARCH ARTICLE

Does nature-based solution sustain grassland quality? Evidence from rotational grazing practice in China

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Abstract

Rotational grazing is considered as one of the nature-based solutions (NbS) to grassland protection by natural scientists. However, its effects on improving grassland quality are still unclear when it is adopted by herders. Using a household-level panel data from field survey in two main pastoral provinces of China, empirical results from fixed-effect model and instrumental approach show that rotational grazing practices have insignificant short-term effects on grassland quality, but have positive long-term effects. In addition, rotational grazing practices can improve grassland quality when villages invest public infrastructure or herders have private supporting measures for more efficiency livestock production. Further analysis shows that herders adopting rotational grazing have higher grazing intensity, higher supplementary intensity and more livestock-house-feeding days, which indicate herders can utilize more efficient livestock management without increasing pressure on natural grassland. We also find that herders with pastoral income are more likely to adopt rotational grazing practice. These insightful findings offer policy implications on promoting grassroot NbS for ecosystem protection and resource utilization in developing pastoral countries.

Keywords: grassroots nature-based solutions, rotational grazing, grassland quality, pastoral region, China

1. Introduction

Grasslands is one of the most widely distributed vegetation types worldwide, which covers approximately 40% of the global terrestrial area and 69% of the world's agricultural area (Suttie *et al.* 2005; Zhao *et al.* 2020). Grassland ecosystem service also plays an important role in ecosystem conservation. For example, as one of the most important carbon sink, grassland store more 50% soil carbon than forest (Conant 2010). However, grasslands have suffered widespread and severe degradation in many parts of the world, which has threatened ecosystem services and socioeconomic development. It is generally believed that climate change and human activities are the two main drivers of grassland degradation (Liu *et al.* 2019; Bardgett *et al.* 2021). In particular, climate change will affect the vegetation growing season length and biodiversity, ultimately causing degradation of grasslands (Chen *et al.* 2019). Among human activities, intensive utilization such as overgrazing, leads to a decrease in primary productivity, is regarded as the dominant human cause (Andrade *et al.* 2015; Hou Q

Received 2 November, 2022 Accepted 15 May, 2023
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doi: 10.1016/j.jia.2023.07.001

et al. 2022). Therefore, developing effective and climate-smart grazing practices may be an economic-ecological solution to halting grassland degradation.

Nature-based solutions (NbS), which covers a range of approaches focusing on ecosystem services to address societal challenges, has the potential to provide effective grazing practices for grassland protection (Cohen-Shacham *et al.* 2019; Wang *et al.* 2022). NbS is committed to seeking more appropriate management measures to create social and economic benefits and realize the sustainable utilization of natural resources though making full use of ecosystem services provided by nature. With little costs and human intervention, it has been successfully applied into practice in many countries to address the issues of climate change, urban and rural ecosystems (Calliari *et al.* 2019; TNC 2021). There are also some successful examples of NbS in pastoral areas, which help to realize dual-objectives grassland protection and animal management. For instance, grassland bank was established in the United States, aiming at helping ranchers process alternative sites for grazing during the grassland restoration period. China has implemented the "grassland clever management" project in Inner Mongolia, which determines the reasonable grazing time by monitoring the grassland vegetation coupled with the meteorological data (TNC 2021).

Rotational grazing, taking livestock in turns to graze between different grassland units (Briske *et al.* 2011), is considered to be another convenient measure of NbS to conserve grassland by natural scientists (Cohen-Shacham *et al.* 2019). Technically, there is an optimal grass height that allows the maximum yield of fresh grass and the regrowth of grazing vegetations (Teutscherova *et al.* 2021; Baronti *et al.* 2022). For traditional continuous grazing, the animals eat as much as they want without human intervention. In this case, when the number of livestock expansion, it will lead to overgrazing, and when the number of livestock is insufficient, it will lead to grassland resource waste. Turning to rotational grazing, since the animals remain on each grassland units only for the time necessary for an optimal consumption of grass (Baronti *et al.* 2022), it is an efficient grazing practice for the utilization of grazing resources. Comparing with poor grazing practice, the good and efficient grazing contribute to local grassland ecosystem conservation theoretically (Chen *et al.* 2017).

However, the practical impacts of rotational grazing on grassland quality are still ambiguous. One thread of literature concluded the positive effects of rotational grazing on grassland quality, specifically, improving plant biomass and soil properties in the short run (Li *et al.* 2020; Teutscherova *et al.* 2021), increasing vegetation, plant cover and species diversity in the long run. Another strand of literature showed that rotational grazing practices had no effective on improving grassland quality. In addition, most of existing literatures that were based on small regional experimental data (Enri *et al.* 2017; Vecchio *et al.* 2019; Li *et al.* 2020; Teutscherova *et al.* 2021), making it difficult to capture the long-scale effect of grassroot rotational grazing practices (Teague *et al.* 2013; Venter *et al.* 2019).

Given the mixed results and lack of causal effects, this paper identifies the impacts of rotational grazing on grassland quality based upon nearly 20 years of remote sensing and rotational grazing data covering two major pastoral provinces in China. Although the basic empirical results show insignificant short-term impacts of rotational grazing on grassland quality, the results from an event study reveal that rotational grazing has a positive long-term impacts on grassland quality. Moreover, the results also indicate that rotational grazing practices can bring more ecological benefits when public supporting infrastructure and private matched measures follow up. An analysis on the impacts of NbS on herder behavior may help us understand these results. Compared with households without rotational grazing practices, the households with rotational grazing have higher grazing intensity but higher supplementary feeding and more days of livestock-house-feeding. It means these rotational grazing households are more efficient in livestock management without increasing pressure on natural grassland. In addition, our results show that households relying more on pastoral income are more likely to adopt rotational grazing practice in their livestock management. This indicates that rotational grazing, as a grassroot NbS, could improve the efficiency of livestock management and grassland quality in the long-run.

The major contribution of this paper is that we empirically evaluate the impacts of rotational grazing, which is regarded as a grassroot NbS to halting grassland degradation beyond economic-ecological policies, from the perspective of economics. To explore ways to protect grassland, recent empirical literature focus on the impacts of economic–ecological policies, such as Grassland Ecological Compensation Policy (GECP) and Grassland Tenure Reform, and find the ecological outcomes of these formal institutions are limited (Hou *et al.* 2021; Hou L *et al.* 2022). Given this, we identify the effectivenesses of a grassroot NbS – rotational grazing – in the improvement of grassland quality. Previous studies mainly applied natural science approach to explore the outcomes of rotational grazing using field experimental methods, without exploring the causal association between rotational grazing practices and its outcomes from the perspective of economics. To the best of our knowledge, this paper is the first to explore the impacts of rotational grazing on grassland quality using household-level data and economic empirical method, which fills existing gaps. Our economic analysis results could be helpful to insight policy-makers who promote NbS practice applications in other countries with severe grassland degradation.

The remainder is organized as follows. Section 2 describes the data collection and presents the empirical model specification. Section 3 presents the results and mechanism analysis. Section 4 discusses and Section 5 concludes this paper.

2. Data and methods

2.1. Data

Qinghai and Gansu are two of five pastoral provinces and account for 20% of the total area of China's grassland (NBSC 2021). Grassland is the most major type of land use in these two provinces, accounting for 75 and 47% of the land area in Qinghai and Gansu, respectively (NBSC 2021). Besides, these two provinces also face high grassland degradation risks, with over 40 and 70% of grassland in Qinghai and Gansu suffering moderate to severe degradation (MOA 2017). Hence, exploring the effects of rotational grazing practices is essential for grassland conservation in these two provinces and even the whole nation. In order to investigate the impact of rotational grazing practices on grassland quality, we constructed a panel dataset based on a household and village survey conducted in the pastoral area of Qinghai and Gansu provinces of China in 2018. The household-level panel dataset includes grassland quality, rotational grazing practices and its supporting measures for the years 2000–2017; grassland utilization and herder income variables for the years 2015–2017. The village-level panel dataset includes control variables for the years 2000–2017.

We used a stratified random sampling method to identify and select the sample households from these two provinces. We first identified three main grassland types in each province and selected one or two counties within each grassland type according to per capita income of rural residents and spatial distribution. We then categorized the townships into three groups according to per-capita grassland area and randomly selected one township from each group. Finally, two villages were randomly sampled from each township and six households were randomly sampled from each village. In total, we sampled 358 households in 60 villages, 30 townships, and 10 counties (Appendix A). The research team conducted face-to-face interviews with the herders using a set of structured questionnaires.

We use the normalized difference vegetation index (NDVI) to measure grassland quality. NDVI is commonly and widely used as an index of vegetation coverage (Jiang *et al.* 2006; Fern *et al.* 2018; Hou *et al.* 2021). The original NDVI data come from MOD13A3 product with 1 km×1 km spatial resolution. We calculate the monthly NDVI and use the maximum of NDVI in a year as the measurement of grassland quality for that year. We create household level NDVI data by combining the original NDVI data over 2000 to 2017 and the geographical coordinates of each household. The geographical coordinates of household were located by mobile phone during our field survey. Fig. 1 depicts the trend of mean NDVI for household sample. The mean NDVI shows a fluctuating and modestly increasing trend from 2000 to 2017.

We designed a structural survey questionnaire to elicit rotational grazing information by interviewing household heads. Household heads were asked since which year they started (and ended) rotational grazing. To clarity herders' understanding of rotational grazing in our case, we explained our definition to them during the survey, i.e., rotational grazing referred to a grazing type that herders took turns to utilize different plots and allowed part of plots to rest for any given period. In general, fences were used to divide a large grassland plot into small pieces for rotational grazing. We then generated a dummy variable indicating whether the herder adopted rotational grazing practice in a specific year from 2000 to 2017, with 1 indicating adopting rotational grazing and 0 otherwise. Fig. 2 shows that the proportion of households adopting rotational grazing practice had been stably increasing over time, from 6.7% in 2000 to 16.5% in 2017. It indicates that although rotational grazing practice become increasingly popular, the proportion of adoption

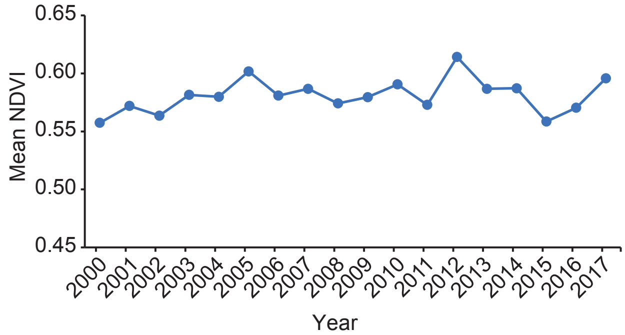

Fig. 1 Trend of mean normalized difference vegetation index (NDVI) at household level.

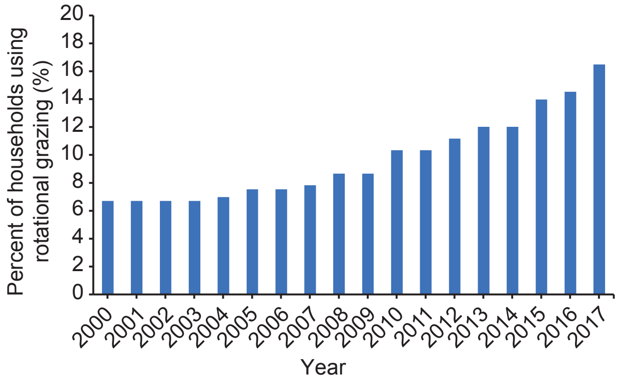

Fig. 2 Trend of rotational grazing in the sample.

is still low. It may be important and insightful if some households stopped using rotational grazing. However, no households answered they had ended rotational grazing during our study period.

The effects of rotational grazing on grassland quality may depend on different supporting measures, such as public infrastructure or private investment. Thus, we collected related supporting measures through interviewing village leaders and household members. Concretely, first, we collected data on public supporting measure by asking village leaders about whether their village invested public infrastructure, such as public fence for defining the village boundary and public well for villager using without exclusivity. Then, we collected private supporting measures data by inquiring household heads about whether the household had grassland farming (specially used for forage production but not for grazing, usually high yield than nature grassland), livestock shed (for livestock-house-feeding) or grassland shed (for the storage of grassland), respectively. It should be noted that the value of the variable "whether the household had grassland farming" only includes the years 2008–2010 and 2015–2017.

In order to explore the relationship between rotational grazing practice and other herder behaviors, we construct a series of variables for livestock management and income structure for the years 2015–2017. We use grazing intensity, days of shed feeding, and supplementary feed intensity to measure livestock management practice. Grazing intensity is calculated by the total number of livestock in equivalent sheep units divided by operated grassland size. It means the number of animals measured in equivalent sheep units living on a unit of grassland. Days of livestock-house-feeding are the number of days that feeding livestock in shed. Supplementary feed intensity is measured by total supplementary feeding cost divided by operated grassland size.

Moreover, we collected herders' total income, pastoral income and non-pastoral income information for the years 2015–2017 in the survey to reflect income structure. Household total income is the sum of pastoral income, non-pastoral income and other income (mainly from government transfers). Pastoral income refers to the gross income from grazing livestock, which is calculated by gross income from selling livestock and by-products. Non-pastoral income is calculated by adding the non-pastoral employment income from all family members.

We have one concern that during our data period, there might be other interventions implemented in the study area that may confuse our results. The most profound and lasting policy implemented in pastoral areas are Grassland Tenure Reform since 1980s and GECP since 2011. Thus, we collected some related village-level socioeconomic variables and use these variables as controls to eliminate the impact of these policies, including whether the village certificates grassland to household, whether the village has grazing ban or grass-livestock balance policy. The construction of infrastructure, such as roads, also has some effects on our results, so we collected whether the village connects to paved road as a control variable as well. We have data from 2000 to 2017 for these variables, which has consistent year span as that of grassland quality. Climate data at village level is used as control variables as well. The original daily climate data was collected from the National Meteorological Information Center of China. We create village-level mean precipitation and mean temperature by combining the original climate data over 2000 to 2017 and the geographical coordinates of each village. The descriptive statistics of the above variables are shown in Appendix B.

2.2. Empirical models

We firstly employ the following two-way fixed-effect regression model (TWFE) to identify the effects of rotational grazing practices on grassland quality:

$$Y_{i,j,t}=\beta R_{i,j,t}+\alpha Y_{i,j,t-1}+\theta X_{j,t}+\eta_i+\delta_t+\epsilon_{i,j,t} \quad (1)$$

where $Y_{i,j,t}$ is the log form of NDVI for household *i* village *j* at year *t* and $R_{i,j,t}$ is a dummy variable indicating whether household *i* in year *t* adopting rotational grazing practices. $Y_{i,j,t-1}$ denotes the first lag of log form of NDVI, which is used to control for the dynamics of NDVI. The vector $X_{j,t}$ represents a range of village-level controls, including whether the village certificated grassland to household, whether the village connected to paved road, whether the village had grazing ban or grass-livestock balance policy, mean precipitation and mean temperature. η_i stands for the household fixed effects, which absorbs the impact of any time-invariant household characteristics. δ_t denotes the year fixed effects, which are used to control the fluctuations over the years that are common to all households. The error term $\epsilon_{i,j,t}$ includes all other time-varying unobservable factors. The coefficient β is of our interest, which measures the effect of rotational grazing practices on NDVI. The coefficient α is a measure of temporal correlation of grassland quality, and θ is a coefficient vector that indicates the effects of control variables.

To test the possible endogeneity generated by time-varying omitted variables that may simultaneously affect the rotational grazing practice and NDVI, we introduce an instrument variable (IV). The change of grazing practices often occurs in local regional waves, thus, we use percentage of rotational grazing at the village level after excluding the respondent household as the IV. First, a village with higher proportion in rotational grazing usually has relatively mature rotational grazing practices. Households that do not adopt rotational grazing in this region may also have higher probability of practicing rotational grazing, which indicates that the relevance condition of IV is satisfied (Panel b, Table 1 shows the first stage estimators of IV). Second, as the wave of rotational grazing in the village doesn't directly affect the grassland quality at the household level, the conditional exogeneity of IV holds as well.

Table 1 Effects of rotational grazing on normalized difference vegetation index (NDVI)[1)]

Variables	OLS		IV	
	(1)	(2)	(3)	(4)
Panel a. Estimated result of OLS and IV, Y=log(NDVI)				
Rotational grazing	–0.005	–0.002	0.047	0.070
	(0.013)	(0.012)	(0.058)	(0.056)
NDVI-first lag	0.188***	0.169***	0.188***	0.168***
	(0.028)	(0.028)	(0.028)	(0.028)
Controls	No	Yes	No	Yes
Two-way fixed	Yes	Yes	Yes	Yes
R-squared	0.114	0.141	–	–
Endogeneity test	–	–	1.005	1.971
Panel b. First stage of IV, Y=Rotational grazing				
IV variables	–	–	0.896***	0.891***
	–	–	(0.057)	(0.057)
F-test	–	–	263.5***	263.5***
Observations	6 086	6 086	6 086	6 086
No. of sample	358	358	358	358

1) The IV is the rotational grazing proportion in the village. Endogeneity test is Chi-squared statistic, the null hypothesis is that the specified endogenous regressors can actually be treated as exogenous, failing to reject the null hypothesis suggested that the rotational grazing in the models (1) and (2) were exogenous.
Robust standard errors in parentheses are clustered by village. ***, P<0.01.

For the process of learning by doing for a new grazing pattern, the impacts of rotational grazing practices may be dynamic and cumulative in the long run. To further analyze the dynamic effects of rotational grazing on grassland quality, we use $y^s_{i,j,t}(d)$ to denote the potential NDVI in log form at time $t+s$ for household i who started to adopt rotational grazing at time t. Specifically, for a household transitioning to adopting rotational grazing at time t, we have $d=1(R_{i,j,t}=1,\ R_{i,j,t-1}=0)$, and for one that remains not adopting rotational grazing, we have $d=0(R_{i,j,t}=R_{i,j,t-1}=0)$. Let $\Delta y^s_{i,j,t}(d)=y^s_{i,j,t}(d)-y_{i,j,t-1}$ denote the potential change in log NDVI from time t–1 to time $t+s$. We can regard d (0 or 1) as a "treatment" indicator and $\Delta y^s_{i,j,t}(d)$ as the potential outcomes affected by the treatment. The causal effect of a transition to adopting rotational grazing at time t on log NDVI at s periods thereafter for households that adopt rotational grazing is:

$$\beta^s=E[\Delta y^s_{i,j,t}(1)-\Delta y^s_{i,j,t}=(0)|R_{i,j,t}=1,\ R_{i,j,t-1}=0,\ X_{j,t},\ \delta_t];\quad s\epsilon[-10,\ 13] \tag{2}$$

Specifically, s can be chosen from –10 to 13, except 0, in our sample. The corresponding β^s indicates the impact of rotational grazing on grassland quality before –s (or after s) years of a household transitioning to adopting rotational grazing.

In order to examine the heterogeneous effects of rotational grazing with different supporting measures, we add interaction term of rotational grazing with variables that indicate public or private supporting measures in eq. (3):

$$Y_{i,j,t}=\alpha_1 R_{i,j,t}+\alpha_2 R_{i,j,t}P_{i,j,t}+\gamma P_{i,j,t}+\theta X_{j,t}+\eta_i+\delta_t+\epsilon_{i,j,t} \tag{3}$$

where $P_{i,j,t}$ represents whether the village invests public infrastructure, such as public fence and public well, when measuring village supporting measures; $P_{i,j,t}$ represents whether the household has grassland farming, livestock shed or grassland shed, respectively, when measuring herders private supporting measures. Other specifications are the same as eq. (1).

To further understand the association between rotational grazing and other grazing behaviors and the income differences between the groups with or without rotational grazing, we set up the following model:

$$Y_{i,j,t}=\beta R_{i,j,t}+\theta X_{j,t}+\delta_t+\epsilon_{i,j,t} \tag{4}$$

When measuring livestock management, the dependent variable is the grazing intensity (in log form), supplementary feed intensity (in log form), days of livestock-house-feeding (in log form), selling rate of livestock and working time per labor in pastoral sector (in log form). When measuring household income, we use household total income per capita (in log form), household pastoral income per capita (in log form), non-pastoral income per capita (in log form) as dependent variable, respectively. Other specifications are the same as eq. (1), expect for without household fixed effects.

3. Results

3.1. Impacts of rotational grazing on grassland quality

Basic results Table 1 presents the estimation results on the causal effects of the rotational grazing on grassland quality from OLS model and IV method. Results from OLS estimators in columns (1) and (2) show that rotational grazing has no significant short-term effects on grassland quality. As some omitted time-varying factors (e.g., natural disaster, the actual execution strength of ecological policy) may simultaneously affect the rotational grazing practice and NDVI, the OLS model may encounter endogeneity issues. We use IV approach for a robustness check. The Chi-squared statistics of endogeneity test in columns (3) and (4) are not significant, which suggests rotational grazing is exogenous. The above OLS panel fixed estimators can be trusted. Even after addressing this endogeneity concern using IV estimators, the effects of rotational grazing are still insignificant.

One limitation of the estimators in Table 1 is that it only captures the short-term effects rather than long-term effects. The event study based on eq. (2) can identify the dynamic change of the estimated effects of rotational grazing practices. The results shown in Fig. 3 illustrate two key points: first, the parallel trend assumption is hold, i.e., the grassland quality between rotational grazing group and non-rotational grazing group experiences the same trend before adopting rotational grazing practices. Second, the impact of rotational grazing on grassland quality gradually turns to positive in the long run. As shown by the results, the change of the NDVI is waved before the household adopt rotational grazing, with no stable trends in grassland quality prior to rotational grazing practices (time from –10 to 0). Although still fluctuating, the change of NDVI nearly stays above zero and gradually moves upgrade after having rotational grazing practice. Moreover, after 10 years of rotational grazing, the impact on NDVI is significant and positive. Specifically, we calculate the average of the last two significant point estimators in Fig. 3 as the long run estimator. The magnitude of the long run estimator is 5.6, which means that rotational grazing improves grassland quality by 5.6% after at least ten years adoption. Given the GECP has improved grassland quality by 3–5% during 2011–2020 (Hou *et al.* 2021), a 5.6% improvement of grassland quality from rotational grazing is rather considerable.

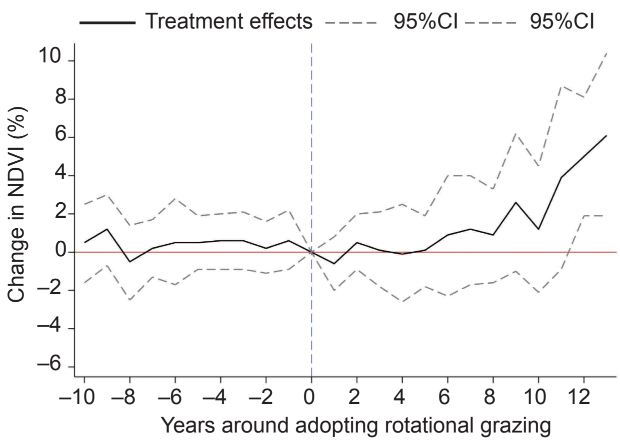

Fig. 3 Dynamic changes of the estimated effects. NDVI, normalized difference vegetation index.

Heterogeneity analysis A well-functioned NbS calls for supporting policy, such as public and private supporting measures (Tanneberger *et al.* 2021). We, therefore, firstly explore the heterogenous effects of rotational grazing by public infrastructure status. The results in column (2) in Table 2 show that rotational grazing has a significant positive effect when a village has public infrastructure such as village borders and public wells. It contributes to a 2.8% increase of NDVI, compared to the villages without public infrastructure. This indicates that investing public infrastructure can promote the benefits from adopting grazing intensity. However, in our sample village, only 57% villages have invested public infrastructure for supporting herders' livestock product, indicating that public

Table 2 Heterogeneous effects of rotational grazing on normalized difference vegetation index (NDVI)

Variables	Interaction term			
	Public infrastructure	Grassland farming[1)]	Livestock shed	Fodder shed
	(1)	(2)	(3)	(4)
Rotational grazing	–0.021	–0.012	–0.004	–0.003
	(0.012)	(0.007)	(0.005)	(0.005)
Interaction term	0.028*	0.022**	0.008*	0.020**
	(0.014)	(0.009)	(0.005)	(0.008)
Controls	Yes	Yes	Yes	Yes
Two-way fixed	Yes	Yes	Yes	Yes
R-squared	0.139	0.248	0.138	0.139
Observations	6 086	2 148	6 086	6 086
No. of villages	358	358	358	358

[1)] The observation in column (2) is different from others, as grassland farming only includes data from 2008–2010 and 2015–2017.

Robust standard errors in parentheses are clustered by village. **, P<0.05; *, P<0.1.

infrastructure in pastoral areas needs more investment.

Secondly, we explore the heterogenous effects of rotational grazing by different private supporting measures. We use three indicators, whether herders having grassland farming or not, having livestock shed or not, and having grassland shed or not, as the measurement for private supporting measures. Results in columns 2–4 in Table 2 show that if households have grassland farming, livestock shed or grassland shed when conducting rotational grazing, their rotational grazing practices can bring a significant 2.2, 0.8 and 2% increase of NDVI, respectively, compared to the households without these private supporting measures. This indicates that rotational practice is not a single practice that can work effectively alone. Matching other measures such as planting fodder and investing livestock shed and grass shed are also important in improving the ecological benefits from adopting rotational grazing. These matched measures allow grassland to recover at the key growth period. When grassland recovers, livestock could be fed in shed with supplementary grass and fodder. In our rotational grazing sample, 70% households have livestock shed, however, only 25% households have grassland shed and 10% households plant grass. This indicates that it is necessary to invest grassland shed and increase grassland farming to ensure the ecological benefits from adopting rotational grazing.

3.2. Herders' livestock management and income structure

The results from exploring the relationship between rotational grazing and other grazing behaviors show that herders who adopt rotational grazing are more likely to improve animal management (Teague *et al.* 2013), i.e., increasing grazing intensity, supplementary feeding intensity and number of livestock-house-feeding days, without degrading grassland quality. Column (1) in Table 3 shows that the grazing intensity for the households adopting rotational grazing practice is higher than that for those without rotational grazing practices. Given other measures unchanged, higher grazing intensity indicates more pressure on grassland for rotational grazing households. Fortunately, column (2) in Table 3 shows that supplementary feeding intensity for households adopting rotational grazing practice is higher than the households without rotational grazing. Higher supplementary feeding intensity for the herders using rotational grazing indicates that supplementary feeding mitigates the pressure from increasing grazing intensity. Column (3) in Table 3 shows that days of livestock-house-feeding for households adopting rotational grazing practice are also more than the households without rotational grazing. It implies more time for grassland to replenish during rotational grazing practice, which may benefit grassland conservation in the long run.

The results from exploring the relationship between herders' income and rotational grazing show that herders, whose pastoral income accounts for a larger share, are more likely to adopt rotational grazing. Column (1) in Table 4 shows that herders who adopt rotational grazing have higher pastoral income than those who do not adopt. It indicates that herders, who rely on pastoral income for livelihood, may have more knowledge on livestock management and rotational grazing. Column (2) in Table 4 shows that herders who adopt rotational grazing have lower non-pastoral income. The main reason may be that rotational grazing is a labor-intensive grazing practice and need more labor input. Herders who are skilled in rotational grazing may spend more time in the pastoral sector rather than making a living in the non-

Table 3 Relationship between rotational grazing and livestock management[1)]

Variables	Grazing intensity	Supplementary feeding intensity	Days of livestock-house-feeding
	(1)	(2)	(3)
Rotational grazing	0.229***	0.653***	0.350*
	(0.068)	(0.180)	(0.196)
Controls	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes
R-squared	0.273	0.094	0.126
Observations	1 074	1 074	1 074
No. of sample	358	358	358

[1)] To avoid the influence of extreme value, the dependent variables are in log form.
Robust standard errors in parentheses are clustered by village.
***, $P<0.01$; *, $P<0.1$.

Table 4 Relationship between rotational grazing and herders' income[1)]

Variables	Pastoral income per capita	Non-husbandry income per capita	Total income per capita
	(1)	(2)	(3)
Rotational grazing	0.662***	–0.623*	0.052
	(0.238)	(0.369)	(0.077)
Controls	Yes	Yes	Yes
Time fixed	Yes	Yes	Yes
R-squared	0.258	0.016	0.384
Observations	1 074	1 074	1 074
No. of sample	358	358	358

[1)] To avoid the influence of extreme value, the dependent variables are in log form.
Robust standard errors in parentheses are clustered by village.
***, $P<0.01$; *, $P<0.1$.

pastoral sector. From our field survey, working time per capita spending on the pastoral sector is nearly 15% higher in a household with rotational grazing practice. Overall, column (3) in Table 4 shows there is no significant difference in total income per capita between those who adopt and do not adopt rotational grazing. These results may be different from some literature that evaluate the effects of ecological policy on herders' livelihood. For example, to reduce the pressure on the grassland, GECP may release herders from the pastoral sector and allow them to take on non-pastoral jobs through policy force and subsides (Hou *et al.* 2021). However, the NbS indicates another path that herders can be free to develop their comparative advantages at pastoral or non-pastoral sector in the process of grassland conservation.

4. Discussion

The basic results from fixed-effect model show that rotational grazing has insignificant short-term effects on grassland quality indicated by NDVI. Our basic results may not be consistent with some short-time rotational grazing experiments (Li *et al.* 2020; Teutscherova *et al.* 2021), which found an immediate improved grassland quality effects in a few years. However, we found positive long-term effects that are consistent with other rotational grazing experiments. For example, in an 8-year experiment, Vecchio *et al.* (2019) found increased vegetation for rotational grazing plots compared with continuous grazing plots. Our basic results indicate that the ecological effect of production behavior change is progressive and cumulative. When controlling the impact of short-term weather, the coverage of vegetation and plant mainly depend on the long-term improvement of grassland soil nutrient status. Benefiting from rotational grazing practices, the soil nutrient of grassland improves gradually (Li *et al.* 2020; Teutscherova *et al.* 2021). Hence, it may be hard to see obvious difference of plant coverage in the short term.

Our heterogeneity analysis results show both public investment on infrastructure and private-matched measures can help improve the ecological benefits of rotational grazing practices. These matched measures, such as livestock shed or grassland shed, allow herders to keep animals in shed leaving natural grassland to recover at key growth period without destruction from livestock. Moreover, comparing herders' other grazing behaviors and the income differences between herders with or without rotational grazing, we find some linkages. First, the herders who adopt rotational grazing practices are more likely to have higher grazing intensity and more supplementary feeding. This indicates an improved livestock management without increasing pressure on natural grassland in the short run. Besides, more days of livestock-house-feeding mean fewer days for grazing and contribute to grassland restoration in the long run. Second, herders who are more likely to adopt rotational grazing may be more dependent on pastoral income, suffering non-pastoral chance, but without total income lose.

These results provide a "long-run ecological benefits and pastoral income improvement" grassroot NbS mode for grassland utilization and protection. However, the rotational grazing adoption rate is still low, only 16.5% in 2017. From our field survey, three main constrain factors restrict herders from pursuing this more environment-friendly practice. Firstly, public infrastructure and private matched measures need large investment, and herders face liquidity constraint to invest these infrastructures. In order to make small herders be available to rotational grazing practices, it offers policy-makers the insights on increasing governmental financial supporting for public and private supporting infrastructures. It should be noted that, the positive effect of rotational grazing on environment is not an overnight process, thus, the funds and policy support provided by the government should be continuous, stable and sustainable to stimulate the enthusiasm of herdsmen for long-term participation.

Secondly, linking rotational grazing to economic benefits (productivity or profitability) is also essential for herders to accept it, but the total economic grain from rotational grazing may be uncertain. Grassland not only provides important ecosystem services, but also supports the livelihoods of millions of small herders. When transforming grazing pattern, the local small herders have no obligation to put the potential environmental benefits into first place, conversely, they may view general economic indicators such as return on grazing pattern as important criteria. One of the strongest motivations for herders to maintain these environment-friendly practices is perceiving positive economic outcomes of the improved ecological environment in the long term. This offers policy-makers another insights on strengthening small herders' economic benefits from grassroot NbS. Thus, a series of policy measures that can help herders get more expected economic outcomes, such as demonstration, training and risk-sharing mechanisms (Boz 2016), are needed to promote rotational grazing.

In addition to liquidity constraint and uncertain economic benefits, thirdly, insufficient grassland size is another important factor that hinders rotational grazing adoptions. Current rotational grazing technology requires a large enough grassland plot to be able to divide it into small pieces (Shi *et al.* 2021; Baronti *et al.* 2022), but herders are always allocated several small plots that are geographically disconnected according to grassland tenure reform (Hou Q *et al.* 2022). To breakthrough this constraint, on the one hand, grassland rental supporting policy may contribute to concentrate land on capable herders. As a result, these capable herders have more chance to choose rotational grazing with sufficient grassland size. On the other hand, given that establishing a thriving land market is a long-term process, it is also insightful to design some incentive policy to promote new rotational grazing technology, such as convenient electronic fence suitable for medium grassland size.

While our study has explored the casual effects of rotational grazing on grassland quality and linked rotational grazing to herders' economic benefits, several limitations need to be acknowledged. Firstly, as some literatures have discussed the impacts of formal institutions (e.g., ecological policy (Hou *et al.* 2021) and grassland tenure reform (Hou Q *et al.* 2022)) and informal institutions (Li *et al.* 2021) on grassland quality, it may be meaningful to put formal institutions, informal institutions and grassroot NbS within one framework for future research. Secondly, given data availability, we have not identified the casual effects of rotational grazing on herders' other economic behaviors. These limitations provide scope for future research.

5. Conclusion

Nature-based solutions has the potential to protect ecosystem but with few empirical evidences. Using household-level panel data from field survey in two main pastoral provinces of China, this paper empirically evaluates the effects of a grassroot NbS practice-rotational grazing on grassland quality. Our results indicate a positive and progressive long-term ecological benefit from rotational grazing. These insightful evidences offer policy-makers on promoting grassroot NbS for ecosystem protection and resource utilization in developing regions.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (72173004 and 71773003) and the Major Consulting Project of Chinese Academy of Engineering (2022-HZ-09).

Declaration of competing interest

The authors declare that they have no conflict of interest.

Appendices associated with this paper are available on https://doi.org/10.1016/j.jia.2023.07.001

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