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Balancing livelihoods and grassland sustainability: an analysis of biomass, stocking density, and income in Mongolian pastoralism

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Abstract
Mongolian pastoralism, a vital traditional livelihood, faces challenges from increasing livestock numbers, grassland degradation, and socio-economic disparities. This study explores the relationships between biomass, stocking density, and livestock-based income among Mongolian pastoralists, using a pooled dataset from socio-economic surveys and ecological data from 2010 to 2019. A two-stage least squares (2SLS) regression framework is employed, with biomass as an instrumental variable for stocking density. The results reveal that biomass positively correlates with stocking density, while stocking density is negatively associated with net income, suggesting overgrazing and heightened resource competition. Other variables such as livestock number and household size are positively associated with net income, highlighting their critical role in sustaining pastoral livelihoods. Cluster analysis further shows variations based on biomass and income levels. Low-biomass regions rely more on cashmere yield, while high-biomass regions face constraints due to competing land uses. Wealthier households managing larger herds can mitigate income losses, whereas poorer households experience more significant losses due to weakness in competition. Policy recommendations include regulating livestock numbers to prevent overgrazing and promoting cashmere productivity in low-biomass regions. Future research should focus on dynamic panel data analyses and policy evaluations for sustainable livestock management.

Introduction
Mongolian pastoralism is a traditional livelihood deeply intertwined with the region's ecological systems and socio-economic structures. Despite its resilience over millennia, this practice faces increasing pressures from growing livestock numbers, grassland degradation, and socio-economic disparities, exacerbated by market demands for products like cashmere. Studies have highlighted the environmental consequences of overgrazing and the socio-economic challenges faced by pastoralist households, yet there remains a gap in understanding the intricate relationships between biomass availability, stocking density, and household income. Specifically, the interplay of ecological constraints and socio-economic factors in shaping pastoral livelihoods has been under-explored from an economic perspective.

This study seeks to fill this gap by examining what relationships biomass, stocking density, and other socio-economic variables have with livestock-based income among Mongolian pastoralists. By leveraging a pooled dataset from household socio-economic surveys and ecological data spanning 2010 to 2019, this work employs regression analyses to investigate these relationships across ecological and income clusters. The objectives are to assess the role of biomass in associating stocking density and income, explore the disparities among households based on wealth, and provide insights for sustainable livestock management and policy development in Mongolia's pastoral systems.

Methods

This study integrates data from three sources to form a pooled dataset (See details for each variable in Table 1). The primary dataset originates from the Household Socio-Economic Survey (HSES) conducted in Mongolia in 2010, 2013, 2016, and 2019. Only households actively engaged in livestock production in the 12 months preceding the survey were included. The Rangeland Production Model (RPM) is a gridded ecosystem model. It integrates the Century ecosystem model to estimate herbaceous biomass production given climate, nutrient availability, and soil properties (Kowal et al. 2021). The rangeland area size for each province used to calculate stocking density is also derived from RPM. Cashmere market price and total livestock number data by province are sourced from the National Statistics Office (NSO).

Table 1. List of the final selected variables and their definition

Data source	Variables	Description	Unit
HSEH	Net income	Yearly net income for each household from doing livestock husbandry (net income = selling animal/products - expenditure on animals)	Tugrig*
HSEH	Household size	Number of household members in each household	People
HSEH	Livestock number	Total livestock number for each household converted to goat unit (GU)	Heads of GU
HSEH	Cashmere yield	100 grams of cashmere per goat in the household for each year	100g/goat
HSEH	Other income	Pension and benefits other than revenue from livestock production	Tugrig
HSEH	Location	Dummy to indicate whether the household is located in a settlement or the countryside	Code: 0. Countryside 1. Settlement
HSEH	Water condition	Dummy to indicate main water source types, divided by whether water sources are fixed in location or not. Examples of fixed water are centralized water supplies, dug wells, and springs. Unfixed water includes tanker trucks, rainwater, surface water…etc.	Code: 0. Unfixed 1. Fixed
NSO	Cashmere price	The average market price of cashmere per kilogram in each province for each year	Tugrig/kg
RPM	Biomass	The average potential biomass production in grassland for each province in a specific year	Kg/ha
NSO and RPM	Stocking density	Total number of goat units per hectare of each province's rangeland area in a specific year.	GU/ha

*Tugrig: Mongolian currency. One US dollar is roughly equivalent to 3500 Mongolian tugrig

Biomass does not have a direct relationship with income but influences it indirectly through livestock, which depends on forage availability (Herrero et al. 2013). The quantity of grassland biomass, measured in kilograms per hectare, determines the forage availability of the grassland, which directly impacts stocking density, the total number of livestock units a grazing area can support. Biomass serves as the basis for estimating potential stocking density and acts as an instrumental variable (IV) because it is exogenous determined by environmental and climatic factors, and is strongly correlated with actual stocking density (correlation coefficient = 0.62). Meanwhile, actual stocking density is treated as an endogenous variable, influenced largely by biomass and potentially by other management and environmental factors. I assume this structure stands and employed the two-stage least squares (2SLS) method. The model is described in equations (1) and (2). I used logarithm to treat heteroscedasticity on both the dependent variable and two major independent variables, biomass, and livestock number[11].

In the first stage, regress the endogenous variable of stocking density on the instrumental variable biomass to get the predicted values of stocking density (donated as $\widehat{SD}_{Jt}$). μ is the error term.

$$\widehat{SD}_{Jt} = \pi_0 + \pi_1 \, log\left(biomass_{jt}\right) + \mu_{jt} \qquad (1)$$

In the second stage, the dependent variable $log\ (Net\ income_{it})$ is regressed on the predicted stocking density from the last stage with other variables. Where the dependent variable is the net income of livestock production for a household i at province j in year t. Cashmere price, stocking density, and biomass are at province j in year t.

$$\begin{aligned} log\ (Net\ income_{jit}) &= \beta_0 + \beta_1 \, log\left(livestock\ number_{jit}\right) + \beta_2 \widehat{SD}_{Jt} + \beta_3 household\ size_{jit} \\ &+ \beta_4 cashmere\ price_{jt} + \beta_5 other\ income_{jit} + \beta_6 water\ condition_{jit} \\ &+ \beta_7 cashmere\ yeild_{jit} + \beta_8 location_{jit} + \epsilon_{jit} \qquad (2) \end{aligned}$$

Cluster analysis further is applied to this model. One cluster is based on biomass level and ecozones, another cluster is created based on net income and household size. Each cluster contains three groups to represent biomass and wealth status from low to high.

Results

The main results from equations (1) and (2) are summarized in Fig. 1 which are the coefficient (dots) and their confidence intervals (lines across dots). All results are significant. Except for stocking density, all other factors are positively related to it. Livestock number is most positively associated with net income. In the first stage regression, the relationship reveals that a 1% increase in biomass corresponds to a 0.005 GU/ha (0.507/100) increase in stocking density. Predicted stocking density, however, shows a negative relationship with net income in the second-stage regression. The coefficient indicates that an increase of 0.1 GU/ha in stocking density is associated with a 1.8% decrease in net income from livestock production.

[11] When doing the log transformation, I add 1 to handle zero values in those variables. By adding 1 does not change final interpretation since both net income, livestock number and biomass are large values.

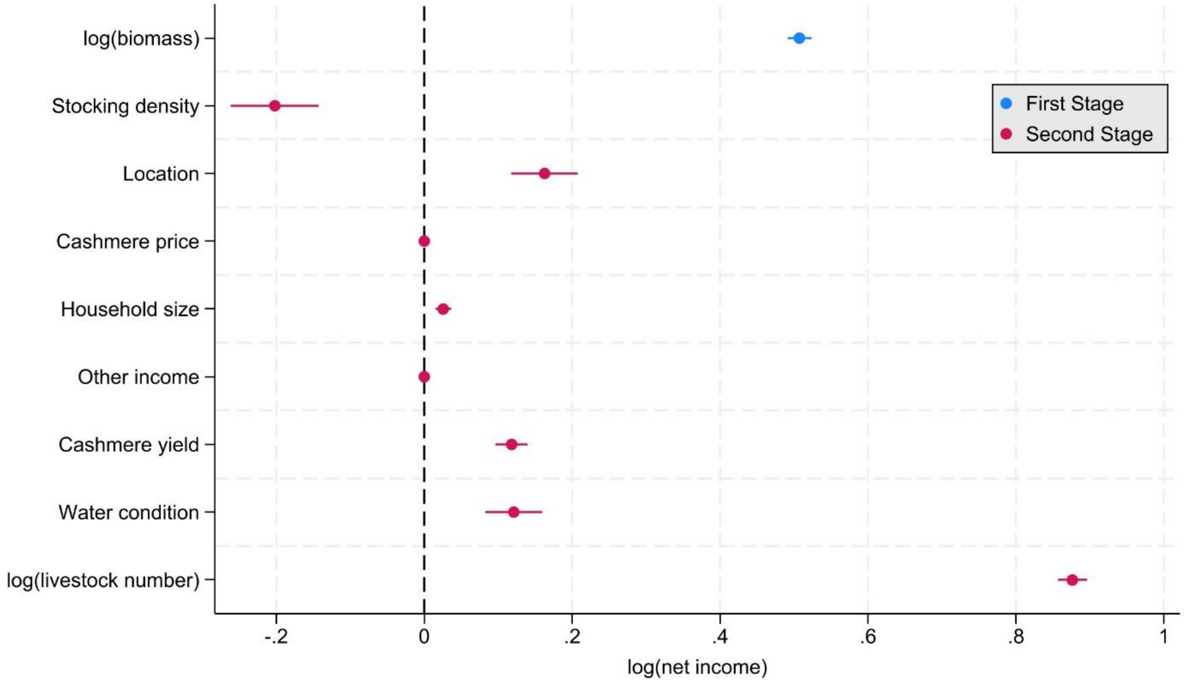

Fig. 1. General results from IV regression. Factors correlated with net income

Most results are also significant in all cluster analyses. I chose the most important variables and the main takeaway in each cluster group to be reported in Table 2. The first stage column reports the relationships between biomass and stocking density and the second stage column displays the relationship between predicted stocking density and the net income of livestock production.

Table 2. The main results from IV regressions by each biomass or wealth cluster group

Cluster group	First stage (Log (biomass) on stocking density)	Second stage (Stocking density on net income)	Interpretation of main results
Low-biomass	0.41	-0.232	Income response to cashmere yields more than other variables
Middle-biomass	0.888	0.367	Stocking density correlates positively with net income
High-biomass	-2.544	0.122	Stocking density is potentially constrained by the availability of or access to grazing land
Low-wealth	0.478	-0.169	Decreased net income is associated with stocking density increase
Middle-wealth	0.55	-0.076	Net income increases by higher biomass but possibly unreliable results due to low R squared
High-wealth	0.6	-0.03*	Stocking density is not related to net income

Note: Numbers are coefficients and * means statistically insignificant

Discussion

In the general results, the positive relationship between biomass and stocking density shows the basic idea that the more biomass, the more livestock the rangeland can support. This declining relationship between stocking density and net income is likely due to the increased demand for grass resources and heightened competition among livestock for adequate forage, reducing the per-unit livestock production. This negative association further suggests overgrazing which is a classic example of the tragedy of the commons, a concept articulated by Garrett Hardin in 1968. Increasing stocking density often leads to overgrazing since it exceeds the carrying capacity of grassland (Piipponen et al. 2022), then the degraded rangelands due to overgrazing disrupt the balance between livestock and their environment, leading to decreased livestock productivity and income, harming all users in the overgrazed areas (Silayi et al. 2024).

When breaking down the relationships by different clusters, the results suggest that regardless of the wealth status, increasing stocking density is related to less net income for livestock production. However, richer households can cope with it by keeping the larger scale of herds and having access to the market and more resources. Poorer households with less livestock will have a larger loss in net income since they are too weak to compete with richer households.

Low-biomass cluster suggests that overgrazing has happened but not for middle-biomass regions. The negative association between biomass and stocking density could mean some constraints prevent animals from grazing on land in the high-biomass group. Given the high biomass regions have the highest forest, cropland cover, and population density, lands may be turned to other uses than rangelands so fewer pastoralist households live in those areas resulting in less stocking density whereas the biomass is high.

All results suggest that livestock numbers should be regulated from overgrazing yet Mongolia currently does not have a systematic policy to control livestock numbers (ADB 2018). A higher positive association between cashmere yield and net income in low-biomass areas highlights that the decision-making in production and policy should help pastoralists focus on improving cashmere productivity instead of increasing the quantity of goats. Future studies should build on this study by using panel data to analyze effects between biomass, stocking density, and economic returns in a geographic spilite and dynamic format. Further policy analysis on livestock management and its impact is requested from this paper.

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