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ARTICLE

Reforming livestock taxation for sustainable rangeland use: Macro-level analysis on Mongolia's livestock tax law implementation

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Abstract: This study evaluates the effectiveness of Mongolia's Livestock Tax Law (LTL), implemented in 2021, as an environmental policy instrument to mitigate desertification by regulating herd sizes and supporting rangeland rehabilitation. Specifically, it asks whether livestock taxation can influence livestock numbers and improve vegetation conditions. Panel data from 330 soums spanning the period from 2002 to 2024 were analyzed, integrating livestock and taxation records, satellite-derived Normalized Difference Vegetation Index (NDVI), and climate variables. Data prior to 2021 were used to establish a baseline and control for climatic variability and external shocks, enabling robust before-and-after comparisons of policy impacts.

Employing generalized least squares regression models, the present study examines the following: (1) the effect of tax collection on livestock numbers, and, (2) the relationship between livestock density, climate factors, and vegetation health measured by NDVI. Results show that tax collection has a statistically significant, but relatively weak positive association with livestock numbers (β = 0.0132, p = 0.039), while herd persistence over time remains strong, with recent declines likely driven by environmental and socio-economic shocks. Livestock density exerts a statistically insignificant effect on NDVI (β = -0.0019, p = 0.615). In contrast, precipitation and land surface temperature strongly enhance NDVI, underscoring the dominant influence of climate factors over grazing pressure.

Regional ecological zones significantly shape both livestock density and NDVI values, with temperate regions showing comparatively healthier vegetation. Further modeling of ecologically differentiated tax adjustments - based on rangeland carrying capacity and regional economic conditions - demonstrates potential gains in policy effectiveness.

Overall, the findings highlight the limited direct ecological impact of livestock taxation, but underscore its potential when combined with ecological differentiation and stronger compliance mechanisms. Strengthening these dimensions is critical for enhancing both the environmental and fiscal outcomes of the LTL.

Keyword: *Livestock taxation, Desertification, NDVI, Sustainable grazing;*

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INTRODUCTION

Mongolia's livestock sector remains a vital foundation for rural livelihoods and cultural identity, contributing to over 10% of the GDP and supporting about one-third of the country's population. Since the transition to a market economy in the early 1990s, national herd size has grown from approximately 25 million to nearly 70 million head, exerting unsustainable pressure on fragile rangeland ecosystems [1].

Similar patterns of herd expansion and rangeland degradation were observed in rangelands and systems across Central Asia and Sub-Saharan Africa, where market liberalization and weak regulatory frameworks have exacerbated overgrazing and ecosystem decline [2;3].

Desertification poses a critical environmental challenge in Mongolia, primarily driven by overuse of grasslands beyond their natural regenerative capacity. Indicators, such as stocking rates and vegetation responses to grazing, serve as key measures of rangeland sustainability, consistent with global research on grazing thresholds and carrying capacity [4;5]. Over time, declines in nutritious plant species, alongside proliferation of invasive and unpalatable species, have diminished rangeland productivity and ecosystem resilience. Falling hay yields further underscore difficulties in maintaining forage resources and the essential ecosystem services that support rangeland livelihoods. Foundational Mongolian research has provided important insights into the chemical composition of native forage species, aligning with international evidence that forage quality is crucial for livestock productivity [6; 7; 8; 9, 10, 11, 12; 13]. Despite these findings, overgrazing continues to degrade rangelands, reduce biodiversity, and increase vulnerability to climate shocks.

In response, the Mongolian Parliament enacted the Livestock Tax Law (LTL) in 2020, implemented in 2021, introducing a fiscal tool to regulate herd size, generate local revenue, and finance rangeland rehabilitation. Such fiscal mechanisms are increasingly advocated in environmental policy as instruments to align economic incentives with ecological outcomes [14;15]. The LTL empowers local governments to set species-specific tax rates through Citizens' Representative (local assembly) Meetings, with revenues designated for environmental restoration and rural infrastructure [16]. The law aims to discourage excessive livestock accumulation and promote sustainable rangeland management, reflecting comparable ecological tax policies in countries, such as New Zealand, Kenya, and parts of the European Union [17;18].

However, challenges remain. The tax is uniformly applied across regions without accounting for local ecological capacity, herd density, or climate vulnerability - factors identified in global case studies as crucial for effective grazing-related taxation [19;20]. Compliance is inconsistent, and the law's impacts on herder behavior, rangeland recovery, and desertification mitigation are not yet fully understood.

This study evaluates the macro-level effects of LTL on livestock numbers, tax revenues, and vegetation health by analyzing panel data from 330 soums spanning the period from 2002 to 2024. Satellite-derived NDVI and climate indicators are integrated, and econometric methods applied to assess relationships between taxation, grazing pressure, and pasture conditions. Data from the pre-implementation period (2002–2020) forms the baseline, enabling comparisons, while controlling climate variability and other external factors.

In this study, the "effectiveness of livestock taxation as an environmental policy instrument" is understood as a multifaceted concept, encompassing environmental outcomes (e.g., improvements in vegetation health measured by NDVI), economic outcomes (e.g., generation and sustainability of local tax revenues), and behavioral outcomes (e.g., changes in herder practices and livestock numbers). Clarifying these dimensions helps focus the analysis and

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provides a comprehensive understanding of policy impacts.

The study examines whether LTL has significantly influenced herd sizes, contributed to vegetation recovery, and increased local tax revenues. It also explores the potential benefits of an ecologically differentiated tax model. We hypothesize that LTL has helped reduced livestock numbers in high-density grazing areas and positively, though variably, impacted vegetation health; that tax revenues have risen but reinvestment in rangeland rehabilitation remains uneven; and that integrating ecological and regional factors into the tax framework would improve both environmental and fiscal outcomes.

MATERIALS AND METHODS

Study design and Data sources

This study employs a macro-level quantitative approach to assess the implementation and effects of LTL of Mongolia, using panel data regression across 330 soums from 2002 to 2024. Secondary data include: (1) Livestock and taxation data from the National Statistics Office and General Tax Authority, covering species-wise livestock populations and tax records (2021–2024); (2) Environmental data from MODIS and TerraClimate via Google Earth Engine [21], including NDVI, precipitation, temperature, wind speed, and vapor pressure deficit, with NDVI measured in late August to minimize seasonal variation; and (3) Carrying capacity estimates by species and soum, based on S.Serjkhuu's 2018 assessment [22].

Analytical framework

The analysis includes three components: (1) Descriptive analysis of livestock trends, tax compliance, and regional disparities; (2) Panel data regression with Model 1 using Generalized Least Squares (GLS) to examine tax collection's effects on livestock numbers, and Model 2 evaluating the impact of livestock, precipitation, and temperature on vegetation health (NDVI), focusing on grazing pressure versus climate variability; (3) Tax reform simulation, using an ecological and economic zone model to adjust tax rates based on carrying capacity and livestock density, aimed at improving policy targeting. Statistical analyses were performed in Stata, with spatial processing in the Google Earth Engine, and standard errors clustered at the soum level to account for heteroskedasticity and serial correlation.

The first random-effects GLS regression model was employed to assess the effect of collected tax on livestock numbers. The analysis used 969 observations from 333 soums over the period from 2002 to 2024. The model included the following key variables: collected tax, lagged livestock numbers (representing persistence in herding behavior), year effects (to account for any changes over time), and ecological zone dummies (to capture the effect of ecological zones on livestock numbers). The regression was conducted using a random-effects approach, which accounts for the variation between soums. The coefficients of the variables were estimated to understand how collected tax influences livestock numbers, controlling for temporal and spatial variation. The significance of the variables was evaluated using p-values, with values less than 0.05 considered statistically significant. The results from this model were reported along with their respective standard errors, t-statistics, p-values, and 95% confidence intervals.

The second regression model assessed the determinants of vegetation health, measured by the NDVI, using 4,387 observations collected from 323 soums. The model aimed to evaluate the influence of livestock numbers, precipitation, land surface temperature, lagged NDVI values, and ecological zones on NDVI. The dependent variable in this analysis was log-transformed NDVI, while independent variables included livestock numbers, precipitation, land surface temperature, and lagged NDVI. Yearly effects were included to control temporal variation. Ecological zones, such as the Steppe, Mountain Forest-Steppe, Desert, and High Mountain zones, were also incorporated to explore regional differences in vegetation health.

The tax adjustment mechanism is designed to modify livestock tax rates

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dynamically, ensuring that taxation reflects rangeland carrying capacity and regional economic conditions.

A regression-based approach is employed to estimate the adjusted tax rate, incorporating two key explanatory variables:

1. Carrying capacity, which provides optimal livestock numbers [22] for each of Mongolia's sub-provinces (soums). A higher carrying capacity is expected to correlate with lower tax rates, as rangeland can sustain more livestock without degradation. This allows for a tax rate that reflects regional variations in rangeland sustainability, rather than a uniform, one-size-fits-all approach.
2. Economic region classification, which accounts for regional economic disparities, allow for differentiated tax policies that prevent excessive financial burdens in less degraded areas.

To quantify these relationships, the following regression model is estimated:

$$Adjusted\ Tax\ Rate_{ir} = \beta_0 + \beta_1 \cdot Carrying\ Capacity_{ir} + \sum_{k=2}^{7} \gamma_k D_{ik} + \varepsilon$$

Where:

- $Adjusted\ Tax\ Rate$, tax rate for *i* type of livestock in *r* sub-province.
- β_0 , intercept (baseline tax rate).
- β_1, coefficient for carrying capacity, indicating how tax rate changes as carrying capacity increases.
- $Carrying\ Capacity_{ir}$ carrying capacity of *i* type of livestock in *r* sub-province.
- D_{ik} dummy variables for economic regions k (Central Highland, Central, Eastern, Gobi Desert, Northern, Western).
- γ_k, coefficients for economic region effects, capturing regional tax adjustments.
- ε error term.

Once the regression coefficients are estimated, the adjusted tax rate for each livestock type is computed using the regression results. To better reflect the scale of grazing pressure, an extended formula incorporates herd size through a logarithmic transformation:

$$Adjusted\ Tax\ Rate_{ir} = (\beta_0 + \beta_1 \cdot Carrying\ Capacity_{ir}) \times \log(Livestock\ Number_{ir})$$

Where:

- $Adjusted\ Tax\ Rate$, tax rate for *i* type of livestock in *r* sub-province.
- β_0 , intercept (baseline tax rate).
- β_1, coefficient for carrying capacity, indicating how tax rate changes as carrying capacity increases.
- $Carrying\ Capacity_{ir}$ carrying capacity of *i* type of livestock in *r* sub-province.
- $log(Livestock\ Number_{ir})$ introduces a logarithmic transformation of the livestock number for *i* type of livestock in *r* sub-province, capturing nonlinear effects and ensuring that taxation scales appropriately with herd size. The adjusted tax rate is aggregated to determine the mean tax rate across different economic regions. Based on the Livestock Density Index (LDI) classification, tax rates are further modified. In the Northern Region, where overgrazing pressure is high (mean LDI = 4.4), the tax rate is increased by 20%. In the Central Highland and Central Regions, which exhibit moderate livestock density (mean LDI = 1.2 and 1.7), the tax rate remains unchanged.

In contrast, in the Eastern, Western, and Gobi Desert Regions, where livestock density is relatively low (mean LDI = 0.7 and 0.5), the tax rate is decreased accordingly.

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RESULTS AND DISCUSSION

Livestock trends and Tax collection (2021–2024)

Since the implementation of the LTL in 2021, tax compliance rose significantly—from 45.9% in 2021 to 92.5% in 2024, reflecting stronger enforcement and administrative improvements (Table 1). Despite this progress, policy consistency was challenged by external shocks, such as COVID-19 (2021) and a severe dzud winter (2024), both of which triggered partial tax exemptions. The number of taxpayers remained largely stable, increasing only 1.3% over the period. Meanwhile, total livestock numbers declined sharply by 13.9% in 2023 and 13.8% in 2024, especially among sheep and goats, due to both regulatory pressures and ecological stressors.

Table 1. Summary of Livestock Tax, 2021-2024.

Year	Number of Taxpayers	Number of Livestock (thousand)	Tax Payable (thousand)	Tax Paid (thousand)	Percentage%
2021	246,302	67,343.76	33,368,926.7	15,330,210.0	45.94
2022	248,296	71,121.45	23,819,132.1	19,832,083.7	83.26
2023	247,873	64,681.88	28,435,367.9	21,770,740.5	76.56
2024	249,450	57,647.94	21,716,970.1	20,085,459.2	92.48

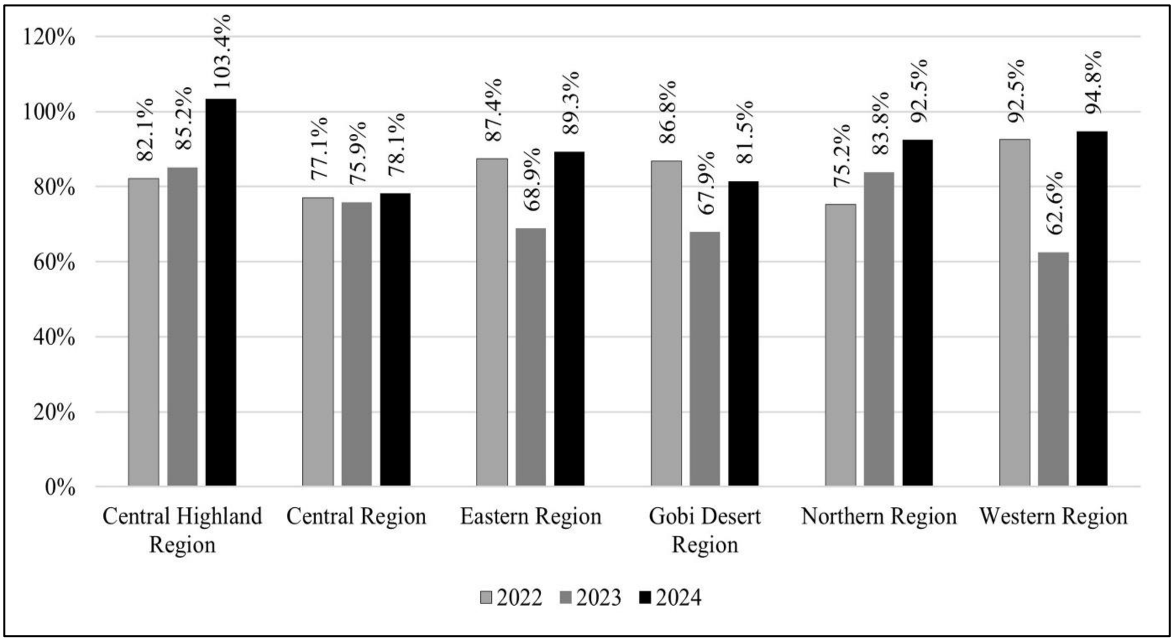

Figure 1. Percentage of Livestock tax paid by economic regions (2022–2024).

Regional disparities in tax compliance were substantial. In 2024, the Central Highland region exceeded expectations with a 103.4% collection rate (Figure 1). Notable high-performing provinces included Arkhangai (149.1%), Khentii (123.9%), and Orkhon (128.3%). In contrast, the Eastern and Gobi Desert regions lagged, with provinces, such as Sukhbaatar and Dornogovi reporting compliance rates below 60% in 2023.

These variations suggest that outcomes cannot be explained by taxation alone, which also reflect differences in governance quality, institutional capacity, and enforcement practices at the provincial level. Provinces with stronger local administrations and more transparent reinvestment of revenues, appear to have achieved higher compliance, while weaker institutional settings constrained tax effectiveness. Including indicators, such as the presence of local monitoring systems,

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frequency of inspections, or mechanisms for revenue redistribution, which could further throw light on how governance mediates policy performance.

Ecological pressure and Livestock density

The LDI, calculated as livestock units per hectare of agricultural land, was employed to evaluate grazing pressure across Mongolia.

An LDI above 3.0 indicates overgrazing, posing a threat to rangeland sustainability. In 2024, Orkhon province exhibited a critically high LDI of 9.4, signifying severe overuse of rangeland. Several other provinces reported moderate levels (LDI 1.0–3.0), while parts of the Gobi Desert and Western regions maintained sustainable grazing conditions (LDI < 1.0), suggesting regional variation in ecological carrying capacity and land management practices.

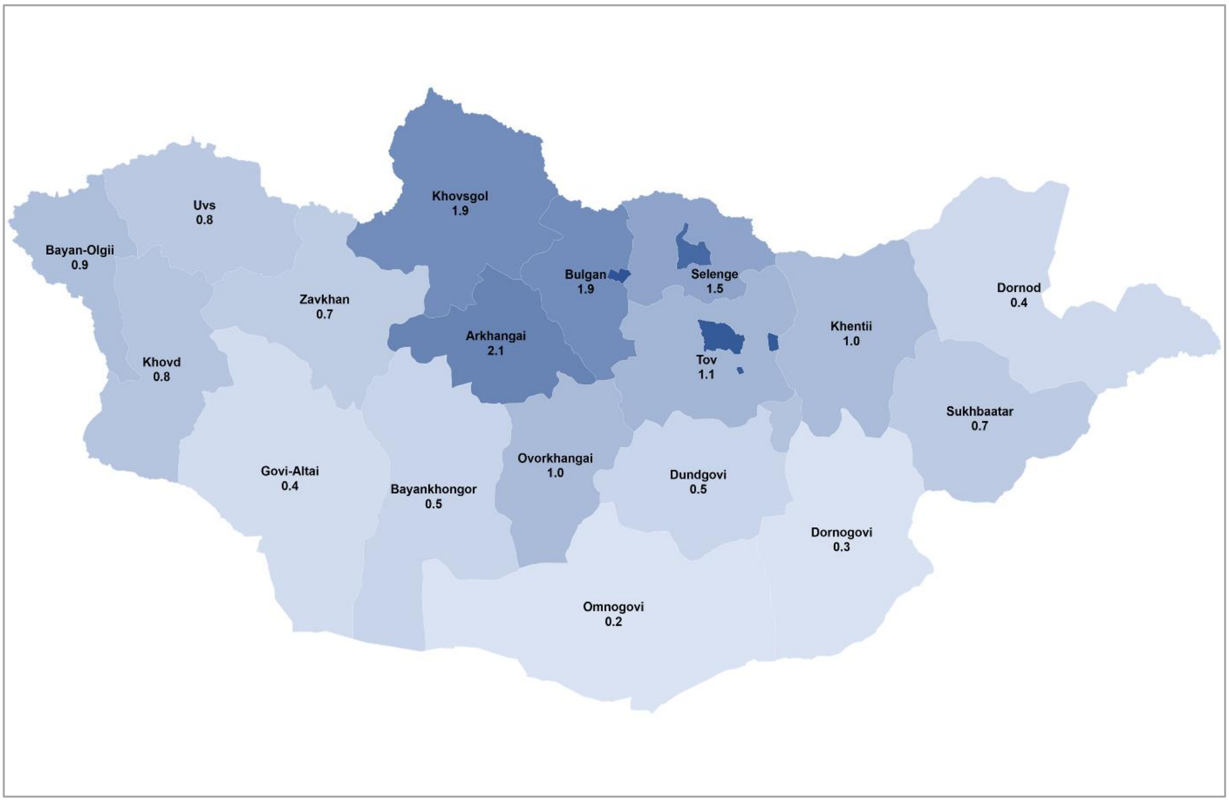

Figure 2. Livestock Density Index in Mongolia in 2024.

To address these disparities and align development with ecological capacity, Mongolia's government has introduced a regional specialization strategy. This approach segments provinces into zones based on comparative advantages, such as, traditional livestock husbandry, industrial development, eco-tourism, and renewable energy. As part of this strategy, differentiated tax policies are under consideration to support balanced regional growth and reinforce sustainable land use.

Table 2 illustrates the integration of regional specialization priorities with mean LDI values across economic regions, highlighting both congruence and tension between development goals and ecological realities.

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Table 2. Regional Specialization and LDI, 2024.

Region	Specialization	Sub-priority	Mean LDI	Provinces - LDI	
Central Highland Region	Traditional Livestock Husbandry Zone	Urban Development	1.2	Arkhangai	2.1
				Bayankhongor	0.5
				Ovorkhangai	1.0
Central Region	Agricultural Zone	Industrial Development	1.7	Darkhan-Uul	2.6
				Selenge	1.5
				Tov	1.1
Eastern Region	Cultural and Historical Tourism Zone	Intensive Agriculture	0.7	Dornod	0.4
				Khentii	1.0
				Sukhbaatar	0.7
Gobi Desert Region	Industrial Zone	Green Energy Development	0.5	Dornogovi	0.3
				Dundgovi	0.5
				Govisumber	0.9
				Omnogovi	0.2
Northern Region	Nature-Based Tourism Zone	Industrial Development	4.4	Bulgan	1.9
				Khovsgol	1.9
				Orkhon	9.4
Western Region	Energy Development Zone	Urban Development	0.7	Bayan-Olgii	0.9
				Govi-Altai	0.4
				Khovd	0.8
				Uvs	0.8
				Zavkhan	0.7

Table 2 demonstrates how each region's specialization is aligned with its mean LDI, suggesting that regions with higher grazing pressures may need to reconsider their economic and land use strategies to foster more sustainable practices.

Panel regression model 1: Tax and Livestock numbers

The regression results indicate that collected tax has a small but statistically significant positive association with livestock numbers ($\beta = 0.0132$, $p = 0.039$). This coefficient is modest in magnitude, and while statistically detectable, its practical significance is limited. For example, a one-unit increase in logged tax revenue corresponds to only about a 1.3% increase in logged livestock numbers, which is unlikely to represent a substantial driver of herd growth. This finding should, therefore not be interpreted as evidence that taxation causes herd expansion. Instead, several alternative mechanisms may explain the result. i. *Policy feedback effects*: In some localities, revenues from livestock tax may have been reinvested in programs that indirectly support herding (e.g., veterinary services, fodder support, or infrastructure). ii. *Delayed behavioral responses*: The positive effect could reflect short-term inertia, with herders maintaining or even expanding herd sizes in the initial years of the tax before longer-term adjustments emerge. iii. *Measurement limitations*: Collected tax may correlate with the size of herds already present, rather than exerting an independent influence on herd expansion.

In contrast, the lagged livestock variable shows a very strong persistence effect ($\beta = 0.9676$, $p < 0.001$), suggesting that current herd sizes are overwhelmingly shaped by historical levels. This highlights the structural inertia of Mongolia’s pastoral economy, where herding decisions are path-dependent and resistant to short-term policy changes.

Year fixed effects indicate a significant decline in livestock numbers in 2023 and 2024 ($\beta = -0.1390$ and -0.1379, respectively, $p < 0.001$). These declines likely reflect broader environmental or socio-economic shocks, such as dzud disaster rather than taxation itself.

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Table 3. Random-effects GLS Regression results for Livestock number.

Variable	Coefficient	Std. Error	t-Statistic	p-Value	95% Confidence Interval
log_Collected_Tax	0.0132	0.0064	2.07	0.039	[0.0007, 0.0258]
log_Livestock_Number (L1)	0.9676	0.0123	78.46	0.000	[0.9434, 0.9918]
Year 2023	-0.1390	0.0066	-21.06	0.000	[-0.1519, -0.1261]
Year 2024	-0.1379	0.0148	-9.33	0.000	[-0.1669, -0.1089]
High Mountain Zone	-0.0243	0.0260	-0.94	0.350	[-0.0752, 0.0266]
Mountain Forest-Steppe Zone	-0.0694	0.0246	-2.82	0.005	[-0.1176, -0.0212]
Semi-Desert Steppe Zone	-0.0269	0.0295	-0.91	0.361	[-0.0847, 0.0308]
Steppe Zone	-0.0594	0.0275	-2.16	0.031	[-0.1134, -0.0055]
Intercept	0.1229	0.0639	1.92	0.054	[-0.0023, 0.2482]

Ecological zone coefficients provide additional nuance. The Mountain Forest-Steppe (β = -0.0694, p = 0.005) and Steppe zones (β = -0.0594, p = 0.031) show significantly lower livestock densities compared to other zones.

This may be attributed to ecological constraints, such as limited forage availability or stronger environmental degradation concerns, which restrict herd expansion despite policy incentives.

Panel regression Model 2: Livestock, Climate, and NDVI

The results of the regression model indicated that livestock numbers had a statistically insignificant effect[1] on NDVI (β = -0.0019, p = 0.615), suggesting there are no meaningful relationships between livestock densities and vegetation health. On the other hand, precipitation had the strongest positive effect on NDVI (β = 0.1028, $p < 0.001$), highlighting its critical role in supporting vegetation growth. Land surface temperature also showed a moderate positive effect (β = 0.0364, p = 0.002), which may reflect longer growing seasons, although excessive heat is likely to have negative impact in extreme years. Lagged NDVI displayed strong autocorrelation (β = 0.4401, $p< 0.001$), emphasizing that vegetation health is highly persistent over time and that previous vegetation conditions strongly influence current NDVI values. Yearly effects indicated that NDVI varied significantly over the years, with notable changes in 2004, 2010, 2015, 2018, and 2023. Specifically, the years 2010 and 2004 saw declines in NDVI, while 2015, 2018, and 2023 exhibited improvements.

From a policy perspective, the finding of an insignificant livestock–NDVI relationship does not imply that herds have no effect on rangeland health. Rather, it highlights the limitations of relying on NDVI alone for monitoring degradation and the importance of integrating multi-source data (remote sensing, ecological surveys, and herder knowledge). Policymakers should interpret NDVI trends with caution and avoid assuming that stable or improving NDVI automatically signals sustainable grazing. Effective rangeland management requires complementary indicators that can capture localized pressures and ecological thresholds more directly.

[1]The insignificant effect of livestock on NDVI likely reflects NDVI's limitations in dry lands, where sparse cover, soil reflectance, and coarse resolution, obscure localized grazing impacts and delayed ecological responses. More sensitive indices (e.g., EVI, SAVI, VOD), higher-resolution imagery, and field-based measures are needed for a more accurate assessment.

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Table 4. Random-effects GLS Regression results for log_mean_NDVI.

Variable	Coefficient (β)	Std. Error	t-Statistic	p-Value	95% Confidence Interval
log_Livestock_Number	-0.0019465	0.0038721	-0.50	0.615	[-0.0095357, 0.0056428]
log_Precipitation	0.1028043	0.0081696	12.58	0.000	[0.0867921, 0.1188164]
log_Land_Surface _Temperature	0.0364217	0.012035	3.03	0.002	[0.0128336, 0.0600099]
L.log_Mean_NDVI (Lagged)	0.4400857	0.0276123	15.94	0.000	[0.3859666, 0.4942048]
Year (2004)	-0.0236967	0.0066548	-3.56	0.000	[-0.0367398, -0.0106535]
Year (2010)	-0.0449407	0.0063076	-7.12	0.000	[-0.0573033, -0.0325781]
Year (2015)	0.0394634	0.0068270	5.78	0.000	[0.0260827, 0.0528441]
Year (2018)	0.0401676	0.0055439	7.25	0.000	[0.0293017, 0.0510336]
Year (2023)	0.0958530	0.0314518	3.05	0.002	[0.0342086, 0.1574973]
High Mountain Zone	-0.0160509	0.0071162	-2.26	0.024	[-0.0299984, -0.0021034]
Mountain Forest-Steppe Zone	0.0476677	0.0092088	5.18	0.000	[0.0296188, 0.0657167]
Steppe Zone	0.0305753	0.0068173	4.48	0.000	[0.0172137, 0.0439370]
Constant	-0.2581023	0.0452570	-5.70	0.000	[-0.3468045, -0.1694001]

Ecological zone variables revealed significant differences in vegetation health across regions. The Steppe and Mountain Forest-Steppe zones showed higher NDVI values compared to the Desert and High Mountain zones. This suggests that more temperate and moderate ecosystems tend to have healthier vegetation, likely due to better climatic conditions, such as higher precipitation and lower temperature extremes.

Adjusted Tax rates results

An empirical analysis of the livestock tax reform was conducted using regression models to evaluate the determinants of tax rates for different livestock types and their adjustments based on economic regions and carrying capacity. The findings provide insights into how the tax structure aligns with pastureland sustainability and regional economic conditions.

Table 5. Regression results for Sheep tax rate

Variable	Coefficient	Std. Error	t-value	p-value	95% Confidence Interval
Sheep_Carrying Capacity	-0.0011478	0.0002329	-4.93	0.000	[-0.00160, -0.00069]
Central Region	442.8488	31.3456	14.13	0.000	[381.3554, 504.342]
Eastern Region	47.8051	33.7983	1.41	0.157	[-18.5002, 114.1103]
Gobi Desert Region	-33.3242	31.3346	-1.06	0.288	[-94.7961, 28.1478]
Northern Region	-114.5316	32.5846	-3.51	0.000	[-178.4556, -50.6075]
Western Region	-79.0529	27.0377	-2.92	0.004	[-132.0951, -26.0106]
Intercept (constant)	468.6701	25.7173	18.22	0.000	[418.2182, 519.1221]

Regression results indicate that livestock carrying capacity has a significant effect on tax rates. In the case of sheep, regions with higher carrying capacities tend to impose lower tax rates ($\beta = -0.00115$, $p < 0.001$), while the Central Region applies the highest taxation levels ($\beta = 442.85$, $p < 0.001$). The final tax revenue from sheep increased from 33.7 million MNT to 154 million MNT after adjustments.

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Table 6. Adjusted Sheep tax rate by Region.

Region	Original Tax Rate			Adjusted Tax Rate		
	Mean	Std. Dev.	Freq.	Mean	Std. Dev.	Freq.
Central Highland	395.25862	214.11031	232	1772.8585	178.64994	464
Central	861.73469	682.54054	196	3373.5909	617.31065	391
Eastern	391.33721	184.83425	172	1425.7171	234.69659	344
Gobi-Desert	359.89362	290.29026	188	1178.9474	153.49918	362
Northern	284.87805	119.69023	164	1498.4468	211.13592	328
Western	304.91573	165.63066	356	1008.9054	103.02933	712
Total	425.25526	380.35633	1,332	1641.1908	827.20238	2,601

For goats, the carrying capacity variable showed a weak negative correlation with tax rates ($\beta = -0.00052$, $p = 0.086$). The Central Region imposed the highest tax burden ($\beta = 513.62$, $p < 0.001$), while the Western Region had the lowest ($\beta = -197.75$, $p < 0.001$).

Table 7. Regression results for Goat tax rate.

Variable	Coefficient	Std. Error	t-value	p-value	95% Confidence Interval
Goat_Carrying Capacity	-0.0005164	0.0003008	-1.72	0.086	[-0.0011065, 0.0000737]
Central Region	513.6226	41.8805	12.26	0.000	[431.4619, 595.7833]
Eastern Region	25.3236	41.5756	0.61	0.543	[-56.2389, 106.8862]
Gobi Desert Region	-186.9172	41.4976	-4.50	0.000	[-268.3266, -105.5077]
Northern Region	-189.1672	42.9259	-4.41	0.000	[-273.3788, -104.9556]
Western Region	-197.7511	35.0291	-5.65	0.000	[-266.4707, -129.0315]
Intercept (constant)	703.3380	34.0148	20.68	0.000	[636.6081, 770.0678]

The adjusted mean tax rate was set at 2465.85 MNT, leading to an increase in total tax revenue from 44.4 million MNT to 200 million MNT.

Table 8. Adjusted Goat tax rate by Region.

Region	Original Tax Rate			Adjusted Tax Rate		
	Mean	Std. Dev.	Freq.	Mean	Std. Dev.	Freq.
Central Highland	668.10345	396.05176	232	2990.8513	274.0898	464
Central	1202.551	733.82987	196	4338.2689	847.62297	391
Eastern	692.7907	369.74355	172	2314.3557	316.09253	344
Gobi-Desert	466.01064	334.50345	188	1648.6906	165.21771	362
Northern	492.86585	206.4267	164	2456.921	436.05567	328
Western	464.49438	291.26537	356	1588.2444	144.69319	712
Total	645.99099	485.91088	1,332	2465.8526	1025.2416	2,601

Horses exhibited a statistically significant negative relationship between carrying capacity and taxation ($\beta = -0.00533$, $p = 0.006$). The Central Highland Region imposed relatively lower tax rates ($\beta = -623.81$, $p = 0.007$), whereas the Gobi Desert, Northern, and Western Regions experienced similarly reduced rates.

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Table 9. Regression results for Horse tax rate.

Variable	Coefficient	Std. Error	t-value	p-value	95% Confidence Interval
Horse_Carrying Capacity	-0.0053271	0.0019459	-2.74	0.006	[-0.009144, -0.001509]
Central Highland Region	-623.8125	230.6081	-2.71	0.007	[-1076.216, -171.4091]
Central Region	117.0923	231.0321	0.51	0.612	[-336.1429, 570.3275]
Eastern Region	-254.8346	232.4204	-1.10	0.273	[-710.7935, 201.1243]
Gobi Desert Region	-621.9905	231.0621	-2.69	0.007	[-1075.285, -168.6964]
Northern Region	-549.0453	231.4589	-2.37	0.018	[-1003.118, -94.9727]
Western Region	-670.1805	229.9531	-2.91	0.004	[-1121.299, -219.0621]

The adjusted mean tax rate was determined to be 2,123.3 MNT, contributing to a tax revenue surge from 11.9 million MNT to 33.1 million MNT.

Table 10. Adjusted Horse tax rate by Region.

Region	Original Tax Rate			Adjusted Tax Rate		
	Mean	Std. Dev.	Freq.	Mean	Std. Dev.	Freq.
Central Highland	680.17241	348.08563	232	2021.343	523.30741	464
Central	1432.6531	655.39583	196	3470.3604	927.15915	391
Eastern	982.32558	531.44771	172	2880.1443	571.69563	344
Gobi-Desert	680.42553	515.03785	188	1376.4209	311.63506	362
Northern	763.65854	366.79515	164	2654.5674	565.92507	328
Western	640.21067	338.60301	356	1225.1415	250.8956	712
Total	841.84309	542.31337	1,332	2123.2605	989.55988	2,603

In the case of cattle, carrying capacity had a positive impact on tax rates ($\beta = 0.00406$, $p = 0.019$). The Central and Eastern Regions levied higher taxes ($\beta = 476.70$, $p < 0.001$; $\beta = 81.18$, $p = 0.049$), while the Northern and Western Regions showed no significant variations.

Table 11. Regression results for Cattle tax rate.

Variable	Coefficient	Std. Error	t-value	p-value	95% Confidence Interval
Cattle_Carrying Capacity	0.0040646	0.0017324	2.35	0.019	[0.000666, 0.0074631]
Central Region	476.7042	37.7523	12.63	0.000	[402.6421, 550.7663]
Eastern Region	81.1839	41.2356	1.97	0.049	[0.2884, 162.0793]
Gobi Desert Region	68.7474	39.4352	1.74	0.082	[-8.6161, 146.111]
Northern Region	-3.3514	39.3997	-0.09	0.932	[-80.6454, 73.9426]
Western Region	3.8467	32.7443	0.12	0.906	[-60.3906, 68.0841]
Intercept (constant)	494.4910	30.9673	15.97	0.000	[433.7396, 555.2423]

The adjusted mean tax rate was 1,453.4 MNT, with total tax revenue increasing from 10.6 million MNT to 27 million MNT.

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Table 12. Adjusted Cattle tax rate by Region.

Region	Original Tax Rate			Adjusted Tax Rate		
	Mean	Std. Dev.	Freq.	Mean	Std. Dev.	Freq.
Central Highland	536.2069	310.84901	232	1450.4354	619.52282	464
Central	1002.0408	579.56298	196	2589.885	495.20466	391
Eastern	649.76744	347.52585	172	1569.0515	304.23384	344
Gobi-Desert	579.3617	504.44719	188	725.20117	283.25781	362
Northern	532.13415	239.48761	164	1941.3901	303.15985	328
Western	532.48596	288.00858	356	920.78556	313.32081	712
Total	636.0473	432.38689	1,332	1453.4021	737.8692	2,601

For camels, carrying capacity was not found to be a statistically significant determinant of tax rates (β = -0.00139, p = 0.779).

Table 13. Regression results for Camel tax rate.

Variable	Coefficient	Std. Error	t-value	p-value	95% Confidence Interval
Camel_Carrying Capacity	-0.0013915	0.0049479	-0.28	0.779	[-0.0110983, 0.0083153]
Central Highland Region	-951.9206	237.5390	-4.01	0.000	[-1417.922, -485.9194]
Central Region	-251.2953	238.1856	-1.06	0.292	[-718.565, 215.9743]
Eastern Region	-1125.513	238.4345	-4.72	0.000	[-1593.271, -657.7552]
Gobi Desert Region	-843.2039	238.0653	-3.54	0.000	[-1310.237, -376.1704]
Northern Region	-916.9470	238.6465	-3.84	0.000	[-1385.121, -448.7732]
Western Region	-933.2537	236.8695	-3.94	0.000	[-1397.941, -468.566]

However, economic regional disparities were evident, with significantly lower tax rates applied in the Central Highland, Eastern, Gobi Desert, Northern, and Western Regions (β ranging from -951.92 to -933.25, all p-values < 0.001).

Table 14. Adjusted Camel tax rate by Region.

Region	Original Tax Rate			Adjusted Tax Rate		
	Mean	Std. Dev.	Freq.	Mean	Std. Dev.	Freq.
Central Highland	250	331.89281	230	133.76395	174.80189	418
Central	952.55102	831.46064	196	88.160837	126.37313	323
Eastern	77.906977	209.37175	172	19.083398	12.327985	340
Gobi-Desert	354.25532	506.64882	188	405.03036	237.60472	362
Northern	286.89024	391.66401	164	33.079406	44.336296	295
Western	269.10112	358.08612	356	151.53393	134.02613	710
Total	371.39098	548.60719	1,330	144.83516	187.78694	2,450

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The adjusted mean tax rate was set at 144.83 MNT, and despite the lower tax rate, total revenue increased from 457,544 MNT to 788,098 MNT, mainly due to expanded taxation coverage.

The introduction of the Livestock Tax Law (LTL) in 2021 produced a dual outcome: substantial improvements in tax compliance and administrative efficiency, alongside a reduction in livestock numbers, but limited evidence of ecological restoration. Tax compliance rose sharply from 45.9% in 2021 to 92.5% in 2024, reflecting strengthened enforcement and administrative capacity [15;19]. However, external shocks ,such as the COVID-19 pandemic in 2021 and the severe dzud winter in 2024, necessitated partial tax exemptions, underscoring that taxation interacts with ecological and socio-economic stressors, rather than serving as a stand-alone determinant of herd dynamics [20].

Total livestock numbers declined by nearly 14% in 2023 and 2024, particularly among small ruminants. Regression analysis confirmed that taxation had only a small but statistically significant association with livestock numbers ($\beta = 0.0132$, $p = 0.039$), while herd persistence remained very strong ($\beta = 0.9676$, $p < 0.001$). These results align with earlier findings that *dzud* remains the most decisive factor shaping herd dynamics [23]. The persistence of herd sizes reflects structural inertia in Mongolia's rangeland economy, where livestock remain central to livelihoods and social security [4]. Despite herd reductions, panel regression results reveal no statistically significant relationship between livestock density and vegetation recovery, as measured by NDVI ($\beta = -0.0019$, $p = 0.615$). Instead, precipitation ($\beta = 0.1028$, $p < 0.001$) and land surface temperature ($\beta = 0.0364$, $p = 0.002$) strongly determined vegetation health, with lagged NDVI values ($\beta = 0.4401$, $p < 0.001$) highlighting temporal persistence. These findings suggest that vegetation dynamics are primarily climate-driven, consistent with prior studies in arid and semi-arid ecosystems [24, 25]. While grazing pressure is not irrelevant, NDVI alone cannot capture its short-term impacts, reinforcing global calls for integrating remote sensing with field-based assessments and local ecological knowledge [5, 7].

Regional disparities further complicate the ecological assessment of the LTL. The Livestock Density Index (LDI) shows critical overgrazing pressures in Orkhon and Central regions, while parts of the Gobi Desert and Western regions remain within ecological thresholds. NDVI outcomes also varied across ecological zones, with Steppe and Mountain Forest-Steppe regions showing higher productivity than Desert and High Mountain zones, reflecting differences in precipitation and biophysical resilience [26, 27]. These spatial patterns highlight the limitations of a flat-rate tax structure, which ignores ecological gradients and produces inequities in tax burdens.

Policy simulations demonstrate that differentiated taxation - adjusting rates by ecological carrying capacity and livestock species - can enhance both fiscal and ecological outcomes. Adjusted rates for sheep, goats, cattle, and horses increased revenues, while better aligning tax burdens with ecological realities, though further refinement is required for species, such as camels. These findings support international evidence that ecological fiscal reform can generate efficiency gains, while promoting sustainability [15, 18]. However, successful implementation requires local monitoring systems that integrate ecological indicators with fiscal administration, alongside transparent revenue management. Establishing a "Rangeland Restoration Fund" under the Local Development Fund, with annual reporting and participatory budgeting, could enhance legitimacy and trust among herders [20].

International experiences illustrate possible pathways. In Australia, land-use levies and environmental service payments link taxation to ecological outcomes, ensuring that high-impact users bear proportionate costs [28]. In New Zealand, livestock emissions levies directly tie taxation to greenhouse gas outputs, internalizing ecological costs into herding systems [29]. While Mongolia's unique rangeland mobility and limited enforcement capacity preclude direct replication, the underlying principle of spatially adaptive taxation remains highly relevant. Simulation results confirm that such adaptive adjustments can simultaneously raise revenue and reduce grazing pressure on degraded rangelands.

Overall, this study demonstrates that LTL has improved compliance and reduced livestock numbers, but ecological benefits remain limited, with vegetation recovery driven mainly by climate variability. These findings resonate with broader debates on ecological taxation: fiscal tools can incentivize compliance and strengthen institutions, but are insufficient without complementary reforms in governance, revenue reinvestment, and livelihood diversification [3,15]. For Mongolia, advancing sustainable pastoralism requires embedding taxation within a broader policy framework that balances equity, efficiency, and ecological resilience.

CONCLUSIONS

The analysis highlights both the achievements and limitations of Mongolia's Livestock Tax Law since its adoption in 2021. On one hand, tax compliance improved markedly due to stronger enforcement and institutional capacity, generating stable revenues. On the other hand, the law's direct influence on livestock numbers turned out to be limited, as herd sizes remain path-dependent and heavily influenced by environmental shocks, such as dzud. Vegetation health, as measured by NDVI, was determined more by precipitation and climatic variability than by grazing intensity, underscoring the need for complementary monitoring tools beyond remote sensing indices alone.

The tax reform simulations demonstrate that aligning tax rates with carrying capacity and regional economic conditions can significantly enhance fiscal outcomes, while promoting ecological sustainability. Regions with high grazing pressure, such as the Northern provinces, require stricter adjustments, whereas areas with low livestock density may sustain lower rates without ecological harm. These differentiated approaches not only improve equity, but also reinforce the principle of "taxing where pressure is highest."

Overall, the study came to the conclusion that Mongolia's livestock taxation can become an effective policy instrument if embedded within a broader framework of adaptive rangeland governance, regional specialization strategies, and transparent reinvestment of revenues into rangeland resilience. Such integration is essential in balancing the economic role of herding with the ecological imperative of safeguarding fragile rangeland ecosystems.

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Ethical approval

There are no ethical issues with the publication of this article.

Author contribution

The authors confirm contribution to the paper as follows: Study conception and design, investigation, writing, review and formal analysis OE; Study conception and design, investigation, review and editing, supervision JZh; investigation, review& editing TN; review& editing SCh. All authors reviewed the results and approved the final version of the article.

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Conflict of interest

The authors declare that there is no conflict of interest.

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