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A high-resolution gridded dataset of livestock distribution on the Mongolian Plateau (2000–2020)

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Abstract. Accurate quantification of the geospatial distribution of livestock in pastoral regions is important for assessing and maintaining grassland ecological security and sustainable development. Statistical livestock data based on static and macro-level administrative units cannot characterize the fine-scale distribution of livestock across mobile geographic spaces. This study proposed a livestock spatial mapping framework that combined livestock inventory statistics of soum/banner counties with multi-source data (e.g., land cover, population, topography, and climate, etc) using the Random Forest model (RF). A series of high-resolution gridded spatial distribution datasets of total livestock, sheep & goats, and large livestock (cattle, horses, and camels) densities at five-year intervals were obtained for the Mongolian Plateau from 2000 to 2020. The fitting accuracy of this dataset with statistical data (R^2>0.85) is significantly better than that of the existing Gridded Livestock of the World (GLW) series dataset, and the spatial distribution is more accurate and detailed. At the same time, it also compensates for the lack of spatial information of large livestock such as camels in the GLW. This approach enables coarse-grained administrative division data transforming into high-resolution spatial gridded data, by solving the key problems of low spatial resolution, missing local details, and the spatial fusion of different data sources. Based on the acquired high-precision spatial distribution data of livestock density, it can be fused and analyzed with other geographic environment data, which is of great value for the ecological environment protection of grassland in nomadic grassland areas. Gridded livestock density datasets are freely available at https://doi.org/10.6084/m9.figshare.28695728 (Liu and Wang, 2025).

Keywords: Grassland conservation; gridding methods; animal husbandry; nomadic culture; Mongolian Plateau.

1 Introduction

Grasslands cover approximately 40% of the global land area (Bardgett et al., 2021). Animal husbandry serves as a pillar industry for regional sustainable development in vast grassland regions. Livestock, as direct carriers of anthropogenic

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disturbance in grasslands, have a direct impact on grassland ecosystems (Collishaw et al., 2023; Jones et al., 2013; Michler et al., 2019), and their spatial and temporal changes are a key issue for sustainable land management (Liu et al., 2024a). There are approximately 2.4 billion livestock in the world, providing livelihoods for 1 billion people who earn approximately $2 a day or less (Fetzel et al., 2017). Population explosion, dietary shifts from plant-based to animal-based consumption, globalization, and other socio-environmental changes have intensified the demand for meat and dairy products. Robust consumption demand has driven the rapid development of animal husbandry, leading to significant changes in livestock numbers and structure in many countries, especially in the Euro-Asian continent. For instance, Mongolia's livestock population surged from over 25 million in 1990 to more than 71 million in 2022 (Nso). However, the increase was not uniform across livestock types, with the highest growth observed in goats that produce high-value cashmere, further exacerbating grassland overloading (Sinclair et al., 2025; Science), directly impairing grassland health (Abazinab et al., 2022; Bouwman et al., 2013; Yuan et al., 2018). Over the past few decades, changes in livestock policies have introduced considerable uncertainty into environmental impact assessments and feedback analyses centred on pastoral systems (Liang et al., 2018).

The geospatial distribution characteristics of livestock can reflect forage utilization and grazing pressure (Huang et al., 2023). Compared to other factors affecting grassland ecosystem conservation, such as climate change and socio-economic conditions, livestock distribution is considered the only controllable and predictable factor (Chang et al., 2021). However, traditional livestock data are primarily collected based on administrative divisions, providing only the total number of livestock within each unit, which fails to accurately characterize the geospatial heterogeneity of livestock distribution (Zhu et al., 2022). Moreover, these administrative units are often too large in scale. Livestock statistics that are accurate to soum (the second-level administrative division unit) in Mongolia or banner county in Inner Mongolia of China face the problem of insufficient precision to represent fine-grained livestock spatial distribution characteristics. In addition, livestock statistical data suffer from low spatiotemporal resolution and implicit attribute information, making it difficult to integrate effectively with other geospatial datasets and thus limiting their applicability. Therefore, researchers are committed to developing gridded livestock density datasets at global, national, and regional scales, covering various resolutions and livestock species.

The Food and Agriculture Organization of the United Nations (FAO) launched the Gridded Livestock of the World (GLW) project, which successively developed global livestock density distribution datasets for 2002 (GLW1) and 2006 (GLW2) (Robinson et al., 2007; Robinson et al., 2014), mapping the spatial distribution of cattle, buffalo, goats, sheep, pigs, chickens and ducks. During this period, Prosser et al. (2011) generated gridded poultry density data for China by establishing relationship models between poultry census data and agro-ecological variables. To further improve the simulation accuracy, Gilbert et al. (2018) developed a 10km-resolution global spatial distribution map (GLW3) of cattle, buffaloes, sheep, goats, horses, pigs, chickens, and ducks by incorporating environmental factors and using Random Forest algorithms. The latest released version of GLW4 decomposes the statistical data into a grid dataset (2024) using the zonal density method and area weighting method to provide a global spatial distribution map of cattle, buffalo, horses, sheep, goats, pigs, chickens and ducks globally with a spatial resolution of approximately 10km in 2020. However, studies have shown that GLW datasets are less

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accurate in semi-arid regions and low-population density regions, and are mainly produced based on livestock statistics from first-level (provincial) administrative division units. Issues such as low resolution, limited temporal coverage, and lack of systematic validation significantly constrain their applicability in regional and local-scale studies (Robinson et al., 2014). Moreover, these datasets were primarily compiled and mapped from the perspective of poultry and meat food supply without considering the spatial distribution of non-captive livestock in pastoral nomadic regions or the influence of specific geographical environments. Additionally, GLW datasets exhibit significant gaps in livestock species coverage, particularly in their inadequate characterization of the spatial distribution of large livestock species such as camels, which further affects their applicability in fine livestock management and ecological assessment.

To address these limitations, studies have been conducted on the production of high-resolution regional datasets. Meisner et al. (2022) developed gridded datasets of cattle and pig densities in Malawi and Uganda from 2000 to 2020 with a resolution of approximately 1.88 km. Li et al. (2021) generated 1 km-resolution spatial distribution datasets of cattle and sheep in western China from 2000 to 2015. Meng et al. (2023) obtained a high-resolution grazing gridded dataset for the Tibetan Plateau from 1982 to 2015 based on the random forest algorithm. Kolluru et al. (2023) developed a gridded database of horses and small ruminants (sheep & goats) for 1 km from 2000 to 2019 in Kazakhstan. However, studies on the spatial griddedness of livestock on the Mongolian Plateau are lacking. As one of the three largest steppe livestock production regions in the world (Zhang et al., 2018), the Mongolian Plateau supported approximately 148 million livestock in 2022, sustaining the livelihoods of about 10 million low-income people. The ecological security situation in the region is complex, irrational land use practices such as overgrazing have caused degradation in approximately 70% of the grasslands (Miao et al., 2021). The dynamic changes in livestock distribution not only serve as important indicators of human activity intensity but also represent crucial factors in sustaining local livelihoods. Therefore, accurately obtaining livestock density datasets and identifying spatial distribution patterns and long-term temporal variations are of great significance for rational resource utilization, ecological restoration, and the sustainable development of animal husbandry.

To address the limitations of existing research, this study aimed to construct a 1 km-resolution gridded livestock density dataset for the Mongolian Plateau at five-year intervals from 2000 to 2020 (including total livestock density, sheep & goats density, and large livestock (cattle, horses, and camels)) densities, thereby facilitating the integrated application of livestock data. This study systematically collated the statistical data of livestock at the soum scale in Mongolia and banner county-level in Inner Mongolia of China, integrated multi-source remote sensing data, and established the spatial framework of livestock in the Mongolian Plateau, providing data basis for in-depth analysis of regional spatial differentiation of animal husbandry. The specific research objectives are: (1) to develop a livestock spatialization framework incorporating environmental indicators (e.g., climate, topography, land cover, population density, etc.) using Random Forest (RF) algorithms, enabling downscaling conversion of statistical data from soum/banner county administrative units; (2) to generate gridded datasets of total livestock density, sheep & goats density, and large livestock densities for the Mongolian Plateau from 2000 to 2020, with cross-validation and comparative analysis against statistical data and the GLW; (3) to quantify spatiotemporal evolution

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characteristics of livestock density using Mann-Kendall trend tests and Sen's slope estimator, while revealing centroid migration trajectories and directional patterns of livestock spatial distribution through centroid shift models and standard deviational ellipse analysis. The high-precision livestock density gridded data produced in this study can provide data support and a scientific basis for dynamic livestock distribution dynamically on the Mongolian Plateau or other large grassland nomadic areas in the world.

2 Study area and data

2.1 Study area

The Mongolian Plateau is situated in the centre of the Eurasian continent. It is one of the birthplaces of nomadic civilization, maintaining the grassland ecological security and ecological function services of the Eurasian continent. The core region comprises China's Inner Mongolia Autonomous Region (hereafter "Inner Mongolia") and Mongolia, geographically spanning 87°43′-126°04′E，37°22′-53°20′N, as shown in Fig. 1. This area encompasses approximately 2,749,500 km², with Inner Mongolia accounting for 1,183,000 km² and Mongolia occupying 1,566,500 km² (Xu et al., 2024). The terrain rises from west to east with an average elevation of 1,582 m. It mainly features grasslands, deserts, and the Gobi landscapes (Wang et al., 2025). The Mongolian Plateau is an important base for livestock development (Li, 2020; Qin, 2019; Wu et al., 2023). Animal husbandry is a fundamental component of Mongolia's national economy and supports approximately 25% of the population engaged in pastoralism. The traditional "five livestock" system (comprising sheep, goats, cattle, horses, and camels) remains predominant (Miao et al., 2016). The livestock industry in Mongolia has typical plateau ecological characteristics, but it also faces challenges such as climate change, grassland degradation and market fluctuations (Munkhbayasgalan, 2020). Inner Mongolia blends traditional methods with modern technology, it helps create intensive and semi-intensive systems for raising cattle, sheep, horses, and pigs. This hybrid approach has established the region as a significant contributor to national meat and dairy production (Niu et al., 2024).

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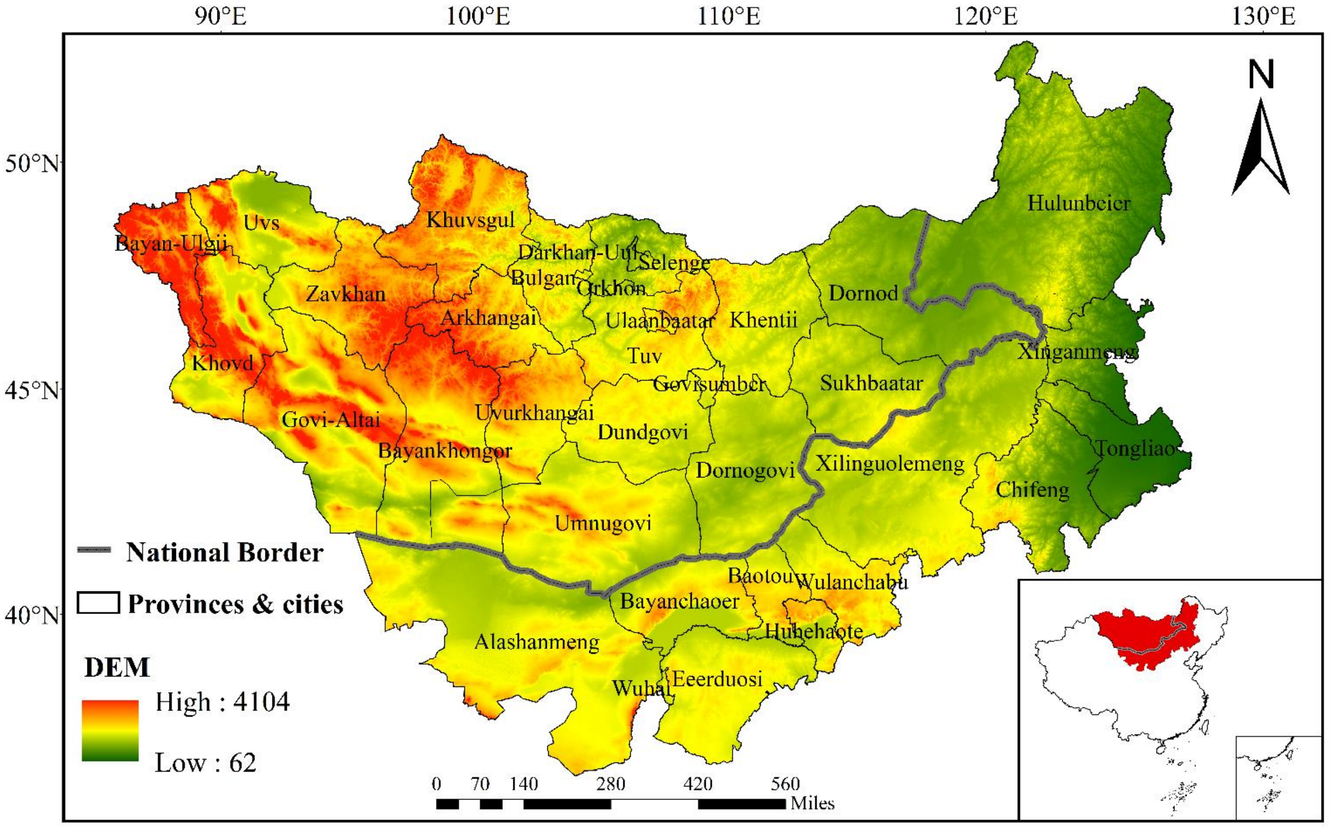

Figure 1: Geographical map of Mongolian Plateau.

2.2 Data source and preprocessing

To develop high-resolution gridded datasets based on statistical data, it is essential to integrate multiple driving factors to meet the requirements of spatial computation, methodologies, and modelling. This study gathered data on the spatial distribution of livestock from two main perspectives: socioeconomic and natural environmental factors. Based on the correlations among livestock spatial distribution and physiographic environment and socioeconomic factors, the primary data utilized in this study included: land use, population density, nighttime light, Normalized Difference Vegetation Index (NDVI), digital elevation model (DEM), and soil moisture. Table 1 provides a detailed list of all datasets used and their respective sources. To ensure consistent spatial referencing and accurate regional information, all datasets were projected onto WGS_1984 UTM_zone_48N. They were clipped to the extent of the Mongolian Plateau, with a uniform spatial resolution of 1 km.

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Table 1. Data sources for this study

Datasets	Factor variable	Time	Source
CRU TS	Average annual precipitation	2000-2020	(High-resolution gridded datasets (uea.ac.uk)
	Annual mean temperature	2000-2020	
Soil moisture	Soil moisture	2000-2020	(https://www.climatologylab.org/terraclimate.html)
MCD12Q1 GLC_FCS30D	Grassland coverage	2000-2020	(https://e4ftl01.cr.usgs.gov/MOTA/MCD12Q1.061/2015.01.01/)
	Cropland coverage	2000-2020	(https://essd.copernicus.org/articles/16/1353/2024/)
MOD13A3	NDVI	2000-2020	(https://ladsweb.modaps.eosdis.nasa.gov/search/order/1)
ASTER GDEM3	Slope	2010	(https://lpdaac.usgs.gov/products/astgtmv003/)
	Aspect		
WorldPop	Population density	2000-2020	(https://hub.worldpop.org/)
Settlement	Settlement density	2000-2020	(https://download.geofabrik.de/asia.html)
JRC Monthly Water History	Distance to river	2000-2020	(JRC Yearly Water Classification History, v1.4 Earth Engine Data Catalog | Google for Developers)
PCNL	Nightlight value	2000-2020	(https://zenodo.org/records/7612389)
Livestock statistics	Livestock density value	2000-2020	(https://www.1212.mn/) Inner Mongolia Banner county Statistics Bureau
Global suitability map for pastoral areas	/	/	(https://data.apps.fao.org/map/catalog)

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2.2.1 Extraction of environmental factors

Building upon existing research foundations and considering the fundamental socioeconomic conditions of the Mongolian Plateau (Gao et al., 2024; Wei et al., 2024; Wen et al., 2023), this study used measurable principles to identify 12 environmental factors that might affect livestock distribution. These indicators are highly representative and reflect multiple heterogeneous aspects of the spatial distribution of livestock. For data sources, we prioritised globally available variables. Thus, both the methods and findings can be reliably reproduced and applied to other regions. This selection strategy enhances the transferability and comparability of our study framework.

Land cover classification was extracted from the Global 30 m resolution Land Cover Dynamic Product (GLC_FCS30D), covering the period from 2000 to 2020. The ArcGIS software and Fishnet tools were used to determine the coverage of different land types in each grid cell. This helped us calculate the ratios of grassland to cropland coverage. The type of grassland was extracted by using ArcGIS software, which was converted into a vector and matched with the population density dataset for the grassland population density index extraction. The temperature and precipitation data were obtained from the monthly CRU TS data of the National Center for Atmospheric Sciences (NCAS) of the United Kingdom from 1901-2020 at 0.5° resolution. We selected temperature and precipitation data for every five years from 2000 to 2020 based on research needs. We then obtained the annual mean temperature and precipitation data by converting them to the NC format and combining monthly data. Soil moisture data were sourced from TerraClimate, the original values were adjusted using a scaling factor of 0.1. The Normalized Difference Vegetation Index (NDVI) was obtained from the MOD13A3 product of the National Aeronautios and Space Administration (NASA). We used MRT software for batch tasks like spatial clipping, removing background values, and detecting outliers. Then, we created annual maximum value composites using the Maximum Value Composite method. The slope and aspect raster indices were obtained from ASTER GDEM3 data with a spatial resolution of 30 m by using the ArcGIS Surface Analysis Tool. Human activities were characterized based on population density, nighttime light, settlement, and JCR water body data. The WorldPop global population density dataset with long time-series characteristics was selected with a spatial resolution of 100 m, and it was resampled to 1 km to ensure data consistency. Nighttime lighting data can effectively reflect the intensity and scope of human activities, and the data used in this study is the global long time-series nighttime lighting dataset with pixel-level correction (PCNL). The dataset is accurate, consistent in space and time, and is useful for socio-economic studies. Settlement data were obtained from OSM and corrected based on Google imagery, administrative boundary maps, and Wikipedia articles containing coordinates. We used a kernel density tool to generate settlement density raster data. The JCR water body data were combined to generate distance-to-river metrics.

2.2.2 Livestock statistics data

Inner Mongolia's statistical yearbook and data from banner counties focus on large livestock, sheep, goats, and pigs. Mongolia primarily records information on goats, sheep, cattle, horses, and camels. To minimize the country differences, this study collects the statistics of all types of livestock in Mongolia and Inner Mongolia separately, and combines them for processing.

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To build the spatialization model for livestock, we first added up all types of livestock. Since weight and age were not included in the data, we used the NY/T 3647-2020 Conversion Standard for Herbivorous Livestock to standardize livestock units into sheep units, along with relevant studies (Li et al., 2023). The conversion adopted was 1 sheep/goat = 1 sheep unit and 1 large livestock (cattle, horse, and camel) = 5 sheep units. The simulated data for sheep & goats and large livestock are not converted to sheep units; the count of sheep & goats are the total number of goats and sheep in the statistics; and the count of large livestock was the total number of cattle, horses, camels, and donkeys in the statistics. The livestock density was calculated by dividing the number of livestock by the area of each administrative division at the soum/banner county level. To ensure accuracy, the area data from the statistics was used as a reference for this study. Then, the livestock data were matched to the corresponding vector data of soum/banner county administrative divisions. There are different types of grazing on the Mongolian Plateau, like seasonal and year-round grazing. To keep things comparable, we counted the densities of all livestock over one year. This provided a database of total livestock, including sheep& goats, and large livestock. In total, we collected data from 436 sample points in each year.

3 Methods

In this study, we combined multi-source data to produce livestock density gridded dataset based on the RF model. The main steps are mainly as follows (Fig. 2). (1) Data acquisition and processing. Sort out the livestock statistics at the soum/banner county scale because the smaller area has greater accuracy and can show more detailed changes in livestock distribution information (Saizen et al., 2010). The remote sensing data were prep-processed, including unified coordinate system, spatial resolution, and mask processing, to obtain suitable areas for livestock distribution. Covariance analysis and normalization were performed on the average annual precipitation, average annual temperature, soil moisture, grassland coverage, cropland coverage, NDVI, slope, aspect, grassland population density, settlement density, distance to the river, and nighttime light geo-environmental factors to avoid multiple covariance and mutation of the data. (3) Model construction and training. We used a RF model to create a spatial framework for livestock on the Mongolian Plateau. We took the average value of each indicator at the soum/banner county level as the independent variable for model training, and the logarithmic transformed value of livestock density as the dependent variable. (4) Zonal density mapping. To ensure that the livestock density obtained from the simulation aligned with the statistical data, we used the statistical data as a control. At the same time, the livestock density gridded data were compared with the livestock density statistics of the soum/banner county and the GLW dataset to verify the accuracy of results. (5) Analysis of spatial and temporal evolution of livestock density. Based on the spatialization results combined with the Sen+MK trend analysis, centre of gravity shift analysis, and other multi-dimensional analyses, the spatiotemporal evolution pattern of livestock density was revealed.

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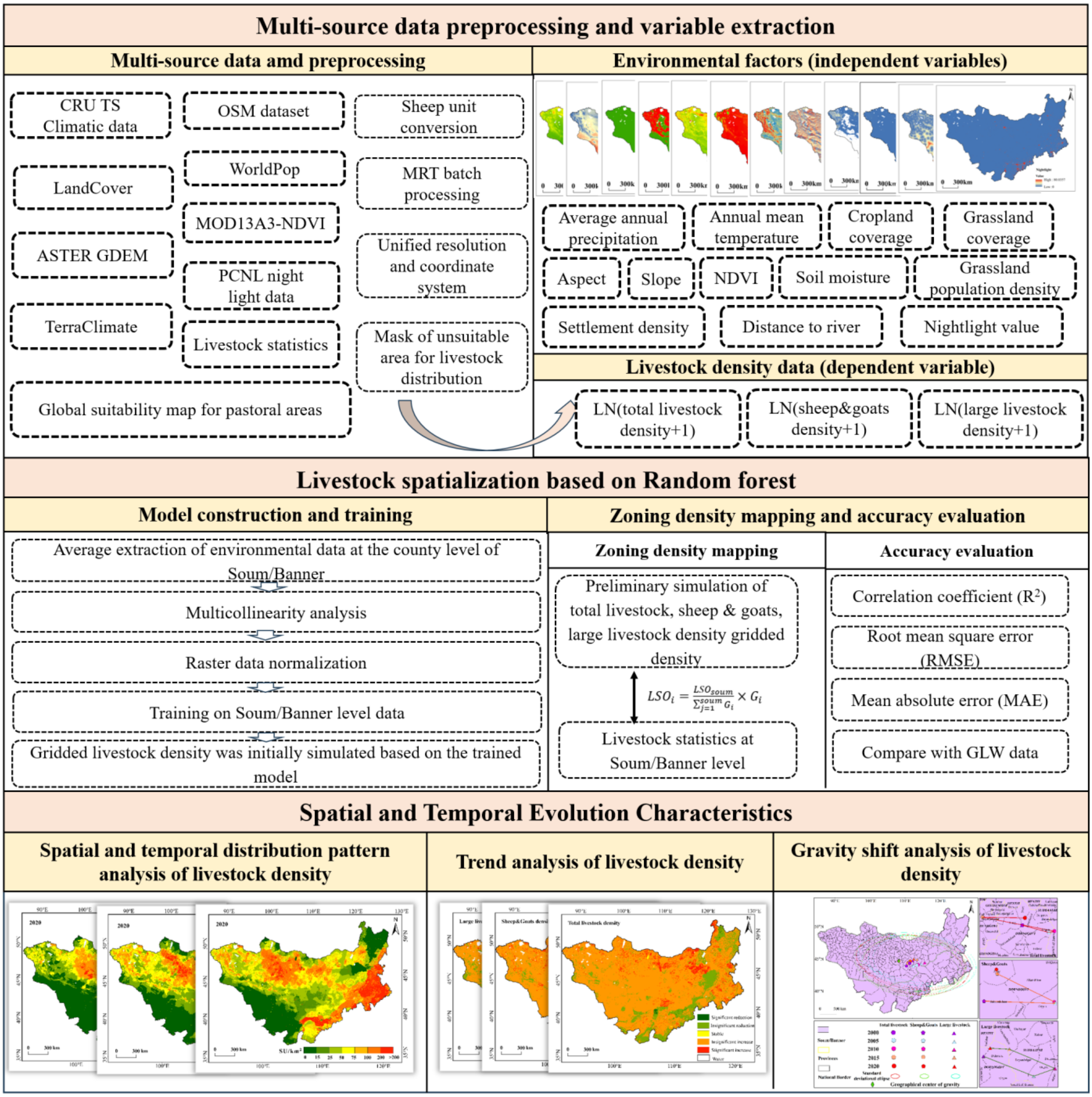

195 **Figure 2: The technical flowchart.**

3.1 Random Forest algorithm

This study employed the RF algorithm to simulate livestock density, primarily by leveraging its superior capability to process multisource environmental data. The RF model, first proposed by Leo Breiman (Breiman, 2001), is an ensemble learning

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method based on the decision tree theory. The algorithm builds several decision trees using a two-step random process and combines their predictions. First, the Bootstrap method creates different training subsets from the original dataset to form a single decision tree. Then, it randomly selects features for the best splits at each node. By constructing multiple such decision trees and finally taking the predicted mean of all trees as the output, this integration strategy effectively reduces the risk of easy overfitting of a single decision tree. It builds a collection of decision trees by randomly selecting samples and features multiple times, and then integrates the simulation capability of each sub-model to accurately estimate the livestock density at the spatial grid scale.

3.2 Model feature library construction

3.2.1 Covariance analysis

Strong correlations existed among the independent environmental variables used in the livestock spatialization model. When these variables are highly correlated, it will affect the regression coefficients. This makes the model overly sensitive to changes in the sample data, leading to instability during inference (Dong, 2023; Lebakula et al., 2025). Although the RF model can deal with covariance among multiple variables, it is still necessary to carefully avoid factors with Variance Inflation Factor (*VIF*) > 5 from entering the model to reduce the covariance interference among influences before proceeding with modeling. The *VIF* of each independent variable can be used to detect the covariance. All indicators in this experiment passed the covariance test with *VIF* < 5.

$$VIF_j = \frac{1}{1-R_j^2} \tag{1}$$

where, R_j^2 is the determination coefficient in the regression equation of the independent variable X_j, considering all other independent variables. The larger the *VIF* value is, the stronger the correlation between this independent variable and other independent variables is. In general, a *VIF* value exceeding 10 indicates severe collinearity.

3.2.2 Normalization of feature variables

In the livestock spatialization model, environmental indicators vary in units and value ranges. To remove bias from these differences, we used the MinMaxScaler () function in the Sklearn software package to normalize the factor values and scale the data to 0-1. The mathematical prototype of the function representation is as follows:

$$X_{Mms} = \frac{X-X_{min}}{(X-X_{max})-(X-X_{min})} \tag{2}$$

where X denotes the data value, X_{min} denotes the minimum value of the data, X_{max} denotes the maximum value of the data, and X_{Mms} is the normalized eigenvalue. The original data distribution is maintained using this approach.

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3.3 Model construction and training

In the Python programming environment, we built an RF model using the Scikit-learn framework. We trained the model by combining pre-processed 1 km raster data and the partition statistics from each soum/banner county level data samples. The mean values of the environmental factors for each soum/banner county served as the independent variable in the model. For the dependent variable, we first calculated the livestock density using the area of administrative divisions and livestock statistics. Then, we log-transformed this value to LN(n+1) to normalise its distribution. We used the RandomForestRegressor algorithm from the integrated learning method to construct the regression model. After importing the data, the original samples were randomly partitioned into a training set and a test set with a division ratio of 70% and 30%. To ensure the reproducibility of the experimental results, specific random seed parameters were set during the data partitioning process. This division strategy not only ensures the randomness of the data distribution, but also facilitates the subsequent enhancement of the model's accuracy through parameter tuning (Wang et al., 2022). This ensures the model performs at its best. In the process of model training, two important parameters need to be set: ntree and mtry. where ntree denotes the number of decision trees, and mtry denotes the selected feature dimensions of a single decision tree node split. Sampling is performed using the bootstrap method for sample selection. This approach generates several training subsets from a limited set of original data through repeatable random sampling with equal probabilities, thereby increasing the size of the sample data and enhancing the robustness and predictive consistency of the model. To obtain the best model performance, this study used RandomizedSearchCV to determine the optimal parameters. The best parameter combination from the results enhances and improves model performance.

3.4 Density mapping of zones

Livestock data spatialization is the process of converting data from the soum/banner county statistical scale to the geospatial grid scale. Because the livestock spatialization model is constructed based on the mean values of environmental factors and livestock densities at the soum/ banner county scale, it must be controlled using the livestock statistics of each soum/ banner county to achieve the redistribution of livestock at the soum/banner county scale to the grid scale (Kolluru et al., 2023; Zhou et al., 2023). The specific idea is to exponentiate the livestock gridded values predicted by the model to obtain the preliminary grid livestock prediction data. Then, the grid values are redistributed according to the total number of livestock in each soum/banner county. The indexed grid value data is used as the weight layer, and the livestock data were redistributed according to Eq. (3). The redistributed grid data is the spatialized result of 1 km of livestock on the Mongolian Plateau.

$$LSO_i = \frac{LSO_{soum}}{\sum_{j=1}^{soum} G_i} \times G_i \tag{3}$$

where LSO_i represents the adjusted livestock density value of the grid i; G_i represents the grid value after indexation of the original predicted value of the grid; $\sum_{j=1}^{soum} G_j$ represents the sum of the predicted values after indexation of all the grids within the soum in which the grid is located; and LSO_{soum} represents the total of the livestock statistics data within the soum/banner county.

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3.5 Accuracy verification

To further verify the accuracy of the simulation results, the simulated values of livestock density of all grids within each soum/banner county were counted in the subdistrict, and the error between the simulated data of livestock density and the statistical data was calculated. In this study, we used root mean square error (RMSE), absolute error (MAE), and coefficient of determination (R^2) to assess the accuracy of the simulation data, and the simulation result accuracy indexes were compared and analyzed with those of the GLW series of datasets to judge the accuracy of the spatialization results of livestock. This equation is expressed as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - R_i)^2} \tag{4}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|P_i - R_i| \tag{5}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(R_i - P_i)^2}{\sum_{i=1}^{n}(R_i - \bar{R})^2} \tag{6}$$

Where R_i is the statistical value of livestock density in the soum/banner county, P_i is the simulated value of livestock density in the soum/banner county, $\bar{R}$ is the statistical mean value of livestock density in the soum/ banner county, and n is the total number of samples. The smaller the RMSE and MAE are, the better the simulation results are; the closer R^2 is to 1, the closer the predicted value of the model is to the real value, and the higher the simulation accuracy is.

4 Results and discussion

4.1 Validation based on soum/banner county level statistics

This study utilized the Zonal Statistics as Table tool in ArcGIS to calculate the mean simulated livestock density values (excluding zero-density grids) for each soum/banner county based on unique identification codes, deriving the average spatial distribution values for different livestock types at the soum/banner county level. We used unique identification codes to match simulated density values with their statistical records and computed their discrepancies. Three evaluation metrics were obtained: MAE, RMSE, and R^2, with detailed results presented in Fig. 6. The validation results demonstrate high accuracy for all simulated outputs. The model excelled in simulating sheep & goats density, achieving an R^2 greater than 0.925, which shows strong explanatory power. Large livestock density came next, with an R^2 between 0.893 and 0.942. Total livestock density performed slightly lower but remained stable, with an R^2 ranging from 0.876 to 0.929. Error analysis showed lower MAE and RMSE values for large livestock simulation. This means it has higher precision. The sheep & goats density simulation had moderately higher error ranges, but they were still acceptable. In contrast, total livestock density had the highest uncertainty among the three categories. In general, the simulation results of the model for different types of livestock are good and very stable, and the spatial distribution of the livestock density simulated in this study was more realistic.

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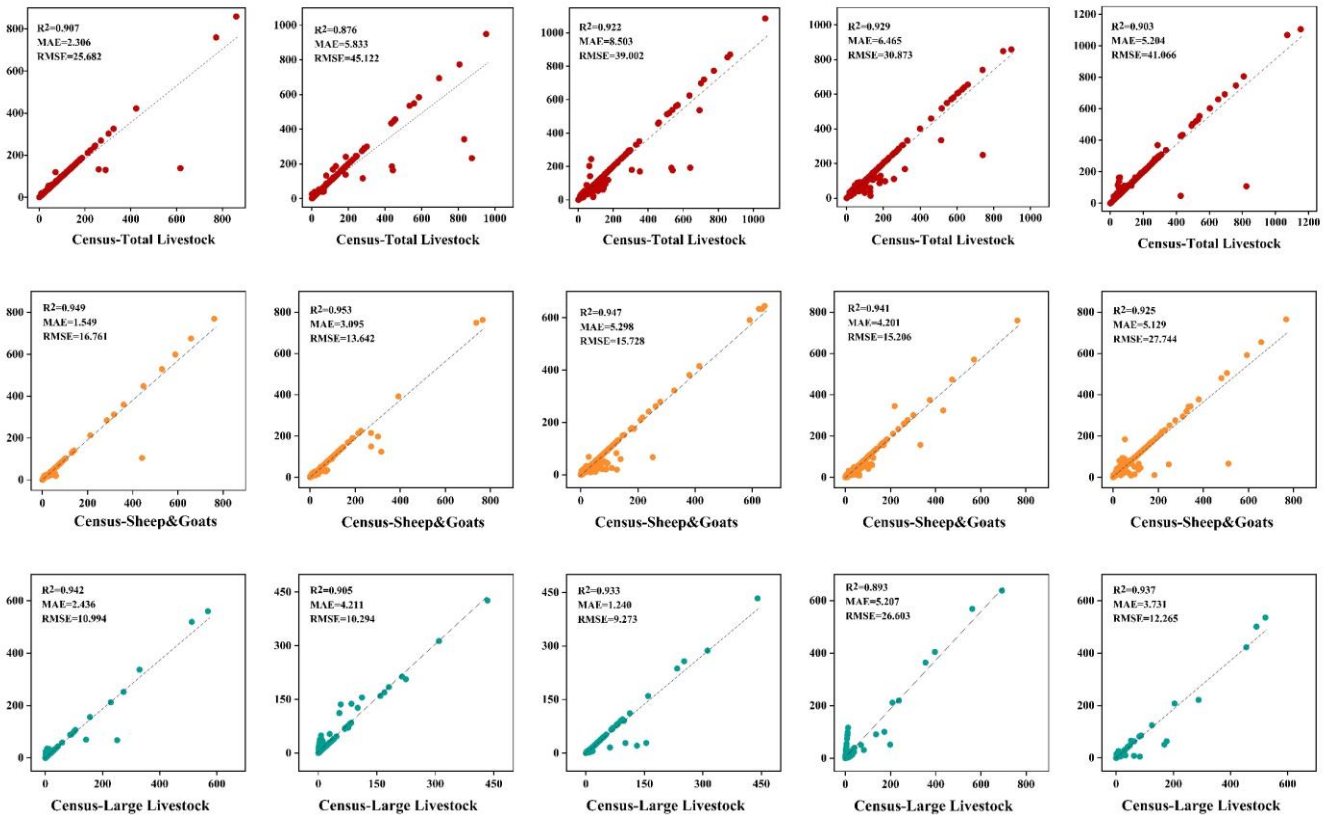

Figure 3: Accuracy verification results based on statistical data from 2000 to 2020.

We further assessed the 1 km×1 km livestock density results from the RF model. To better visualize the geographical patterns of relative errors, we show the relative error distribution maps at soum/banner county level for the total livestock, sheep & goats, and large livestock spatialization results of 2020 in Fig. 7. Results show that most soums in the Mongolian Plateau exhibit absolute relative errors below 5%, indicating good agreement between simulated and statistical values. All three livestock categories demonstrated similar error distribution patterns, with simulation results falling within reasonable ranges across the plateau. However, larger errors (5%-30%, exceeding 30% in some soums) occur in selected soums with substantial water bodies (e.g., Ulaan-Uul in Khövsgöl, Davst and Zavkhan soums in Uvs, and Buyant soum in Khovd city), where these areas were masked as unsuitable zones in simulations. Additionally, Xilingol League's West Ujimqin Banner, Taibus Banner, Xianghuang Banner, Zhengxiangbai Banner, Zhenglan Banner, Xilinhot City, and Abaga Banner had higher relative errors (>30%), which manifested themselves as overestimation of the total livestock density and the sheep & goats density. Conversely, Sonid Left Banner, Sonid Right Banner and East Ujimqin Banner showed lower errors (<-5%) with underestimation tendencies. These discrepancies primarily relate to inherent model assumptions. The grid-scale simulation assumes livestock presence in all suitable grids when aggregating geographical and socioeconomic inputs during random forest modeling. This premise diverges from reality where some suitable grids may remain unoccupied, creating systematic

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over/under-estimation biases. Despite the existence of local errors, the overall results still have a high degree of consistency with the actual situation, providing a scientific basis and important reference value for the study of the spatial distribution of livestock on the Mongolian Plateau.

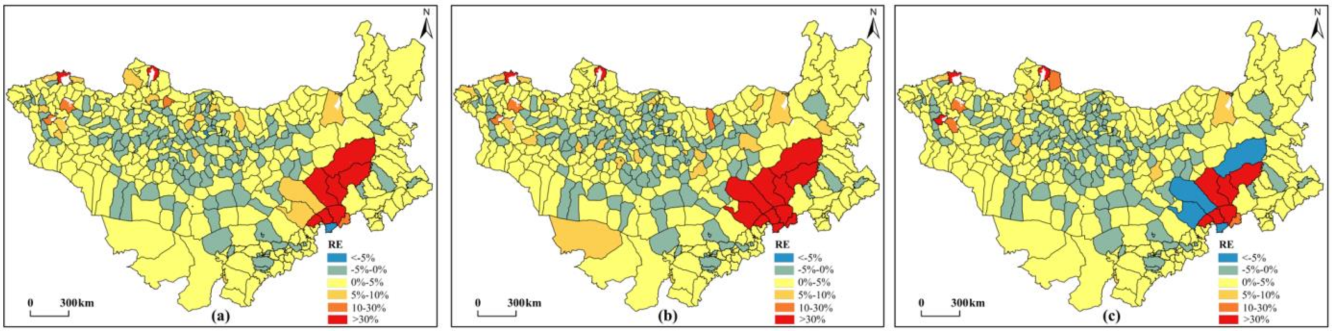

Figure 4: The spatial distribution of relative errors based on statistical data in 2020. ((a) Relative error plot of total livestock density relative error map for 2020; (b) Relative error plot of sheep & goats density; (c) Relative error map of large livestock density)).

4.2 Validation based on the Global Livestock Density Dataset (GLW)

4.2.1 Comparison with GLW series data spatial distribution

Currently available livestock spatial distribution datasets primarily include the GLW3 and GLW4 series. For this study, we conducted a comparative accuracy validation analysis of sheep & goats data using the corresponding years from these datasets, specifically the 2010 and 2015 GLW3 data and the 2020 GLW4 dataset.

Spatially, while both the GLW datasets and our produced data align with statistical trends in overall distribution, the GLW3 and GLW4 datasets exhibit significant limitations in accurately simulating the spatial patterns of sheep & goats density in the Mongolian Plateau, as illustrated in Fig. 8. The GLW dataset only roughly spreads the spatial distribution of sheep & goats in the Mongolian Plateau region. Although these datasets perform relatively well in low-density areas, substantial discrepancies exist between their simulated results and actual statistical data in medium-to-high density zones. Specifically, the GLW data significantly underestimates the density of sheep & goats in southeastern Inner Mongolia (Hinggan League, Tongliao City, Chifeng City), southern Bayannur City, and Hohhot City, while overestimating density in Baotou City and northern Ulanqab City. For Selenge River basin of Mongolia in 2010 and 2015, the GLW data shows limited density gradation and clear underestimation. In summary, compared to the spatial distribution of sheep & goats density in the GLW3 and GLW4 datasets, our results provide a more refined characterization of livestock density patterns across the Mongolian Plateau, demonstrating stronger consistency with statistical distribution patterns and greater simulation accuracy.

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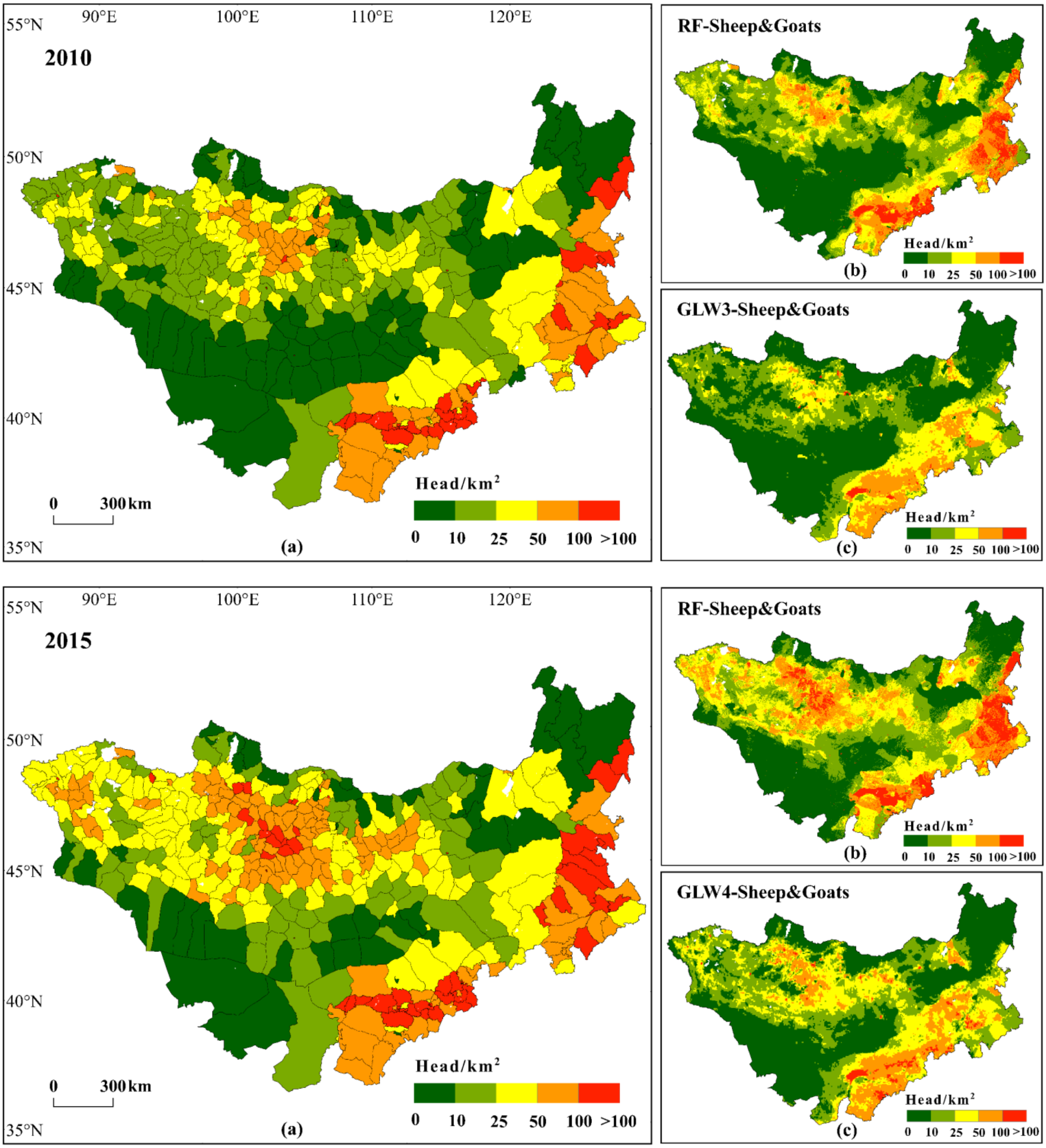

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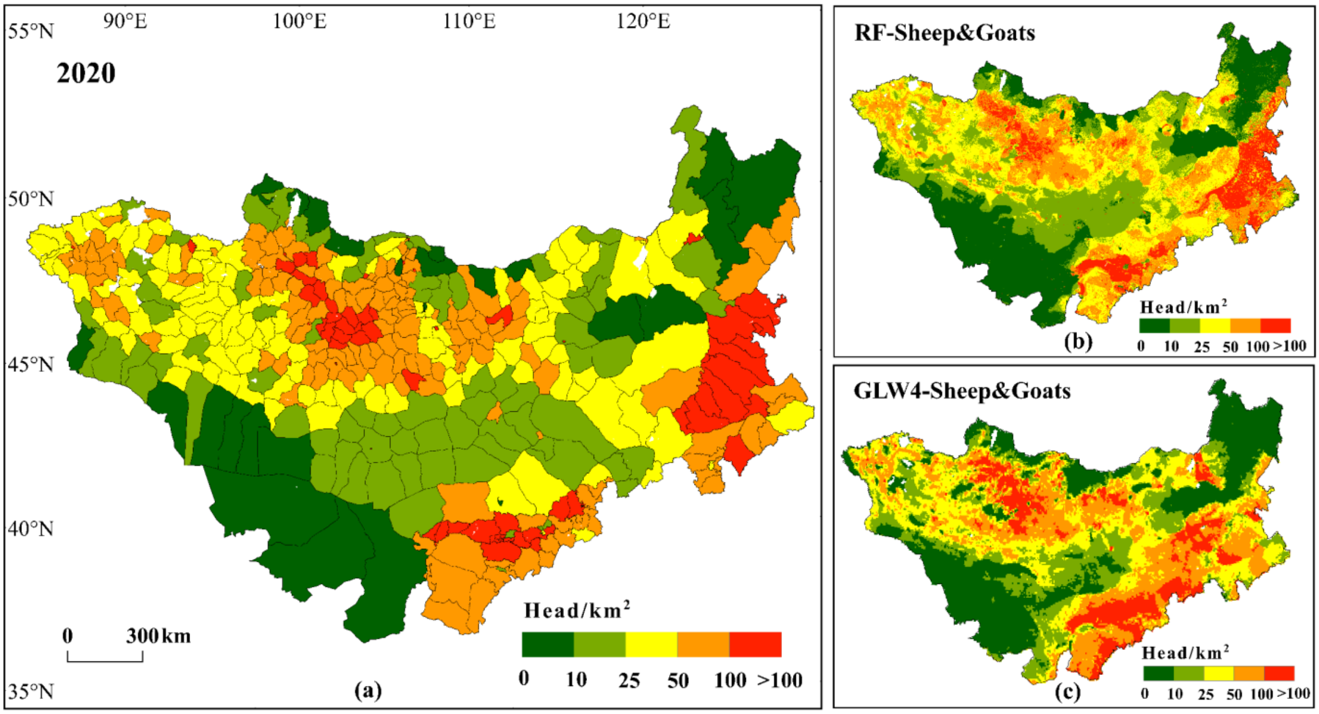

Figure 5: Spatialization of large livestock in the Mongolian Plateau from 2000 to 2020.

4.2.2 Accuracy validation and comparative analysis

Statistical analysis of the goodness-of-fit between GLW3/GLW4 livestock density data and soum/banner county statistical data (Fig. 9) yielded coefficients of determination (R^2) of 0.132, 0.415, and 0.403 for 2010, 2015, and 2020, respectively. Although the GLW4 dataset has improved the fitting accuracy compared with the GLW3 dataset, the R^2 is still relatively low and it is difficult to accurately describe the spatial distribution pattern of the livestock inventory at the end of the year. In contrast, our simulated livestock density data demonstrated significantly higher fitting accuracy with soum/banner county level statistical data, achieving R^2 consistently exceeding 0.85-substantially superior to those obtained from GLW3 and GLW4 datasets. This indicates that this study has higher accuracy in depicting the spatial distribution of sheep & goats on the Mongolian Plateau in comparison to the GLW3 and GLW4 datasets. Therefore, the simulation method of livestock spatial distribution based on random forest model showed excellent accuracy and applicability.

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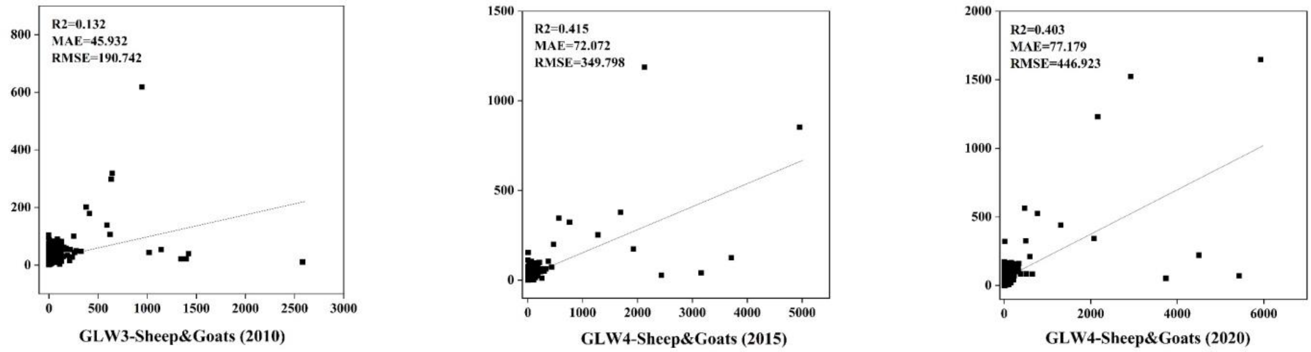

Figure 6: A comparative analysis of Gridded Livestock of the World (GLW) data and statistical data from the current study.

4.3 Spatial distribution of the Livestock

After training and simulating the zonal density for total livestock, sheep & goats, and large livestock spatialization models based on the previous models, we successfully produced gridded density data for each type.

From 2000 to 2020, total livestock density on the Mongolian Plateau exhibited significant spatial heterogeneity and temporal dynamics (Fig. 3). Spatially, it showed a clear centre-edge pattern and formed a strip gradient distribution from southeast to northwest. High-density areas (>100 SU/km²) were concentrated in the northern Selenge River basin and the southeastern agro-pastoral intertwined zone (Hinggan League -Chifeng-Tongliao) and the Hetao Irrigation District (Delgerbayar, 2020). These areas have relatively abundant precipitation and rich forage resources (Marshall-Stochmal et al., 2020; Xu et al., 2019), has superior synergistic effects in the agricultural and animal husbandry systems. Crop straw can provide 50-65% of the winter forage supply (Nikzaad and Nusrathali, 2023; Wang et al.), providing favorable conditions for the survival of livestock. The medium-density area (25-100 SU/km²) is concentrated in the central and eastern parts of Mongolia, as well as the western part of Hulunbuir City, the northern part of the Xilingol League and Bayannur City in Inner Mongolia, forming a band-like connection between the high-value livestock area and the desert edge. The low-density area (<25 SU/km²) was distributed in the Gobi Desert area in the southwest. Limited by the extremely arid climate and the barren desert steppe ecosystems, the distribution of livestock is relatively small (Sternberg et al., 2011; Iegorova et al., 2019).

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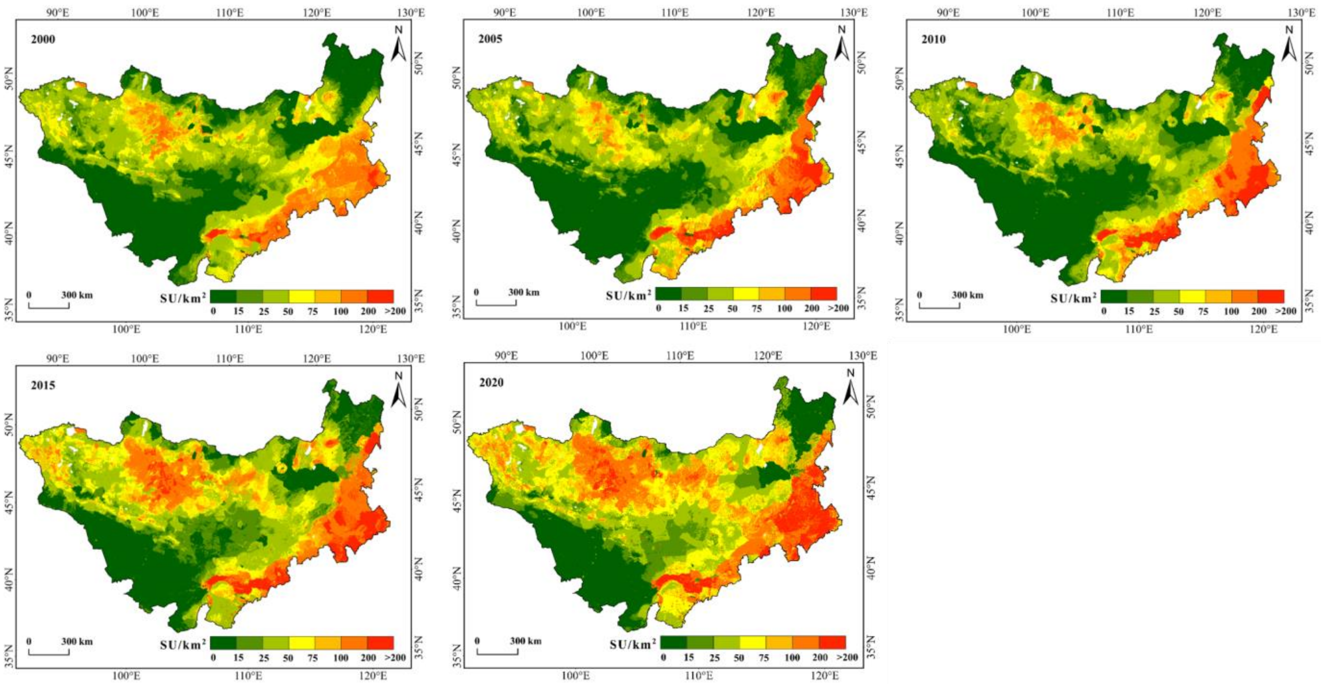

Figure 7: Spatialization of total livestock in the Mongolian Plateau from 2000 to 2020.

The simulation results for the spatial distribution of sheep & goats in the Mongolian Plateau are shown in Fig. 4. The distribution pattern of sheep & goats density matched that of total livestock density, showing a large and continuous distribution pattern in the study area. The study showed that sheep & goats density exhibited two significantly high-value areas (>50 heads/km²): the Khangai region in northern Mongolia and the agro-pastoral zone in the southeast (Horqin to Xilingol Grassland). These areas benefit from adequate precipitation and high quality pasture resources, forming a continuous belt of high density livestock. From 2015 to 2020, the density of sheep & goats in core pastoral areas such as Uvs, Zabkhan, Hinggan League, and Tongliao City increased significantly, reflecting the positive effects of the grassland restoration policy and the optimization of the agricultural and animal husbandry system. In contrast, the southwestern Gobi region was affected by extreme drought and low vegetation cover, and sheep& goats density was distributed below 25 heads/km² for a long time. This pattern of spatial differentiation profoundly reflects the multi-scale coupling mechanism of climate-vegetation-human activities, and provides an important scientific basis for the development of regional differentiated pasture management strategies based on resource carrying capacity.

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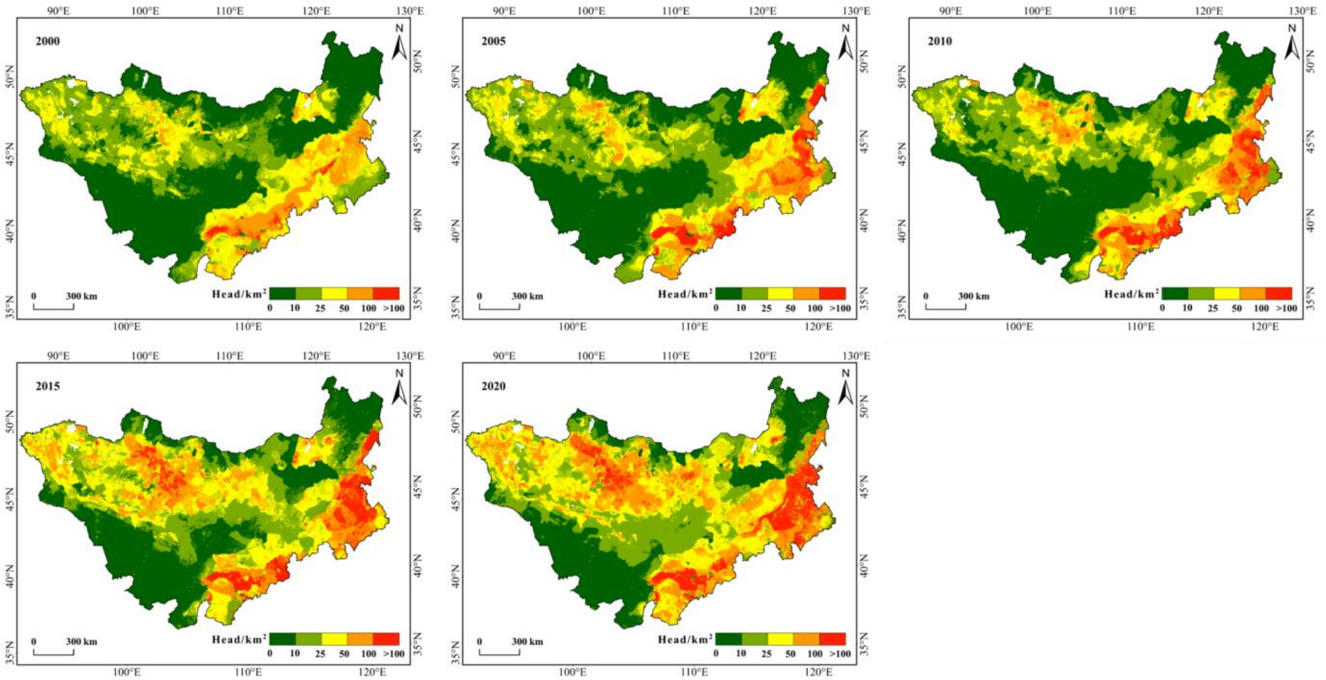

Figure 8: Spatialization of sheep & goats in the Mongolian Plateau from 2000 to 2020

In this study, large livestock primarily comprise horses, cattle, and camels. The Mongolian Plateau has relatively low livestock density as illustrated in Fig. 5. Spatially, a distinct distribution pattern emerges with higher concentrations in northern and eastern regions compared to relatively sparse distributions in southwestern and southern areas. High densities are found in southern Khovsgol, Arkhangai, Bulgan, Tov, northern Ovorkhangai, Khentii, and western Sükhbaatar provinces of Mongolia, especially true near the Khangai Mountain range. These traditional pastoralism-dominated areas have enough water and plenty of forage (Liu et al., 2024b). Eastern Inner Mongolia's Hinggan League, Tongliao City, Chifeng City, and southern Xilingol League also form significant clusters with densities exceeding 5 heads/km². These resource-rich areas have sufficientgrassland resources. They support cattle and horse farming, especially in the Xilingol and Horqin grasslands, which are key regional breeding zones (Yin, 2015). The southern Gobi Desert and nearby dry areas, like Mongolia's Omnogovi, Dornogovi, southern Govi-Altai provinces, and Alxa League, have low animal densities (0-5 heads/km²). This is due to low rainfall and limited plant life.

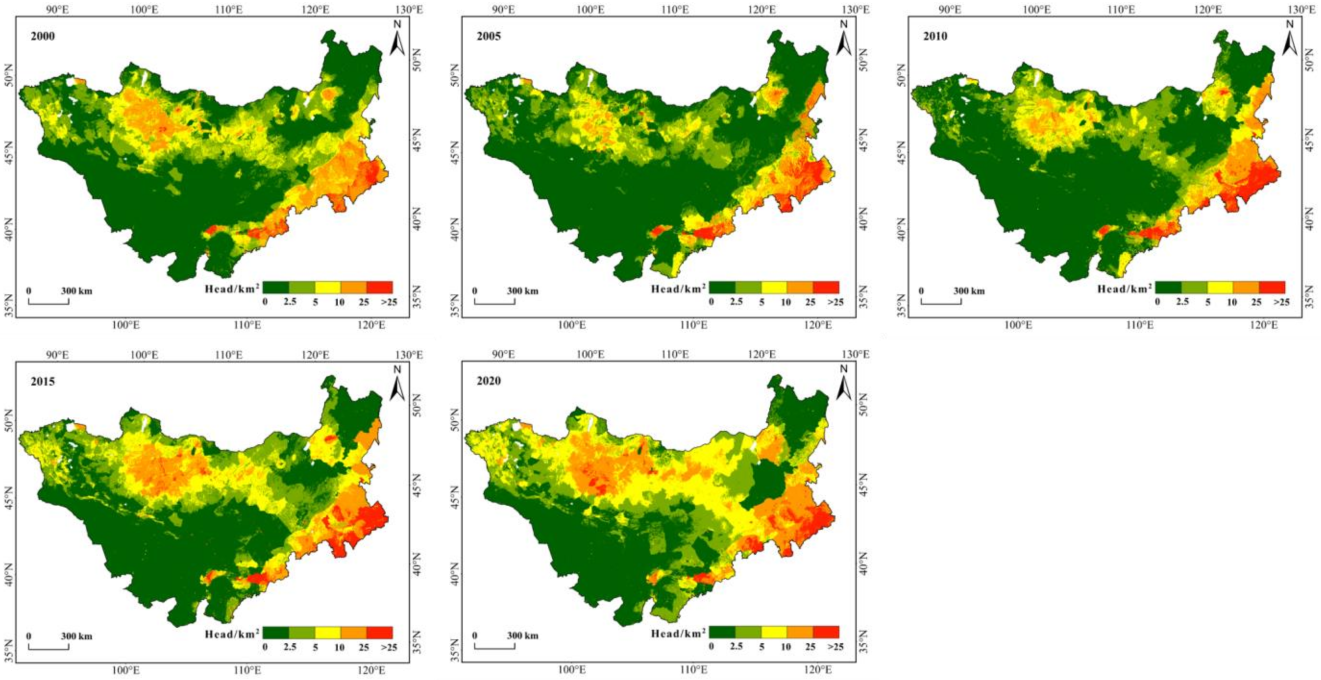

Figure 9: Spatialization of large livestock in the Mongolian Plateau from 2000 to 2020.

From a temporal perspective, the livestock density on the Mongolian Plateau shows a fluctuating trend of "increase - decrease - increase", which was mainly the result of the combined effect of the natural environment and social conditions. The severe and persistent drought in the summer of 2009 resulted in a significant reduction in pasture productivity, severely affecting overwintering livestock resource reserves. Subsequently, the extreme blizzard disaster that occurred from January to February in 2010 led to the large-scale freezing of forage resources. Livestock were unable to obtain food normally, resulting in a large number of deaths. The loss rate in some severely affected provinces was as high as 50% (Rao et al., 2015). These effects are more severe in the arid southern region, particularly in ecologically fragile areas. These regions have less precipitation, sparse vegetation, longer recovery time for pasture resources, and longer disaster durations. Socio-environmental conditions are also important drivers of the evolution of livestock distribution dynamics. The long history of nomadic instability of income and the traditional management philosophy of herders have also made herders less likely to take measures to mitigate disasters, such as artificial supplemental feeding and migratory grazing. With the gradual improvement in climatic conditions, the gradual recovery of rangeland vegetation and the strengthening of government support, the densities of various types of livestock gradually increased during the following decade, gradually presenting a new dynamic equilibrium of the regional livestock-ecosystem. This change reflects the sensitivity and vulnerability of livestock development in the complex ecological environment of the Mongolian Plateau (Marin, 2010; Nandintsetseg et al., 2021), and highlights the significant impacts of natural disasters on pastoral production and livelihoods.

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4.4 Spatial trends in Livestock density

Based on the trend analysis method of Sen+MK from 2000 to 2020 (confidence level $p<0.05$), this study revealed the spatio-temporal evolution characteristics of livestock density on the Mongolian Plateau (Figure 10). The classification characteristics and the areas of each category are shown in Table 2: 85.75% of the study area showed an increasing trend in total livestock density ($\beta > 0.0001$). Among them, the significantly increased areas ($|Z| \geqslant 1.96$) are mainly concentrated in the northern part of the Eastern Province of Mongolia (such as Chuluunkhoroot, Choibalsan, Bulgan and Matad soum) and some soums of the Tov Province. This is mainly attributed to the superior natural conditions and effective policy support. The urbanized areas in the western part of Inner Mongolia (such as Alxa Left Banner, Otog Front Banner, etc.) and the southern part (eg., Jingcheng County of Hohhot City, etc.) show a significant decreasing trend (13.78%). These areas are mainly distributed in the key implementation zones of ecological protection policies in Inner Mongolia, and they are also the core areas where urbanization and industrialization are advancing rapidly. In addition, these regions are also affected by natural environmental changes such as climate change and grassland degradation, resulting in a decline in the production capacity of animal husbandry. The changes in sheep &goats density and the large livestock density showed a similar spatial differentiation pattern, with regional increases of 83.26% and 81.20% respectively. However, the areas with significantly increased sheep &goats density were more prominent in Khentii Province and the northern part of Sukhbaatar Province. This difference may be related to the response mechanisms of different livestock breeds to climate adaptation and management models. The research results highlight a new pattern of livestock industry development that is jointly shaped by climate change, policy regulation and human activities, providing an important scientific basis for regional sustainable development.

Table 2. Livestock density change trend analysis

β	Z	Trend change characteristics	Total livestock density		Sheep & goats density		Large livestock density	
			area	percentage	area	percentage	area	percentage
>0.0001	≥1.96	significantly increasing	169973	6.24%	313874	11.52%	127444	4.68%
>0.0001	-1.96-1.96	non-significantly increasing	2167212	79.51%	1955347	71.74%	2085668	76.52%
=0.0001	-1.96-1.96	stable and unchanging	12834	0.47%	12929	0.47%	13466	0.49%
<0.0001	-1.96-1.96	non-significantly decreasing	368854	13.53%	432098	15.85%	491807	18.04%
<0.0001	≤-1.96	significantly decreasing	6883	0.25%	11508	0.42%	7371	0.27%

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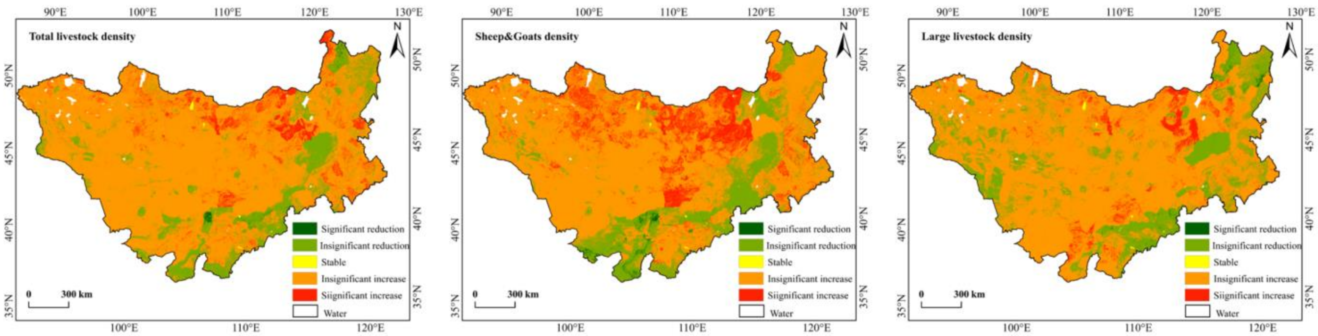

Figure 10: Trends in livestock density.

4.5 Spatial-temporal evolution of the centre of gravity of livestock density

From 2000 to 2020, the livestock density on the Mongolian Plateau showed a movement from southeast to northwest first. The degree of movement in the east-west direction was significantly higher than that in the south-north direction. This is mainly due to the meridian gradient differences in resources between the eastern grassland area and the western desert zone, the influence of the implementation of regional differentiation policies, and the imbalance of infrastructure distribution. At the same time, the north-south movement is relatively limited owing to the constraints of terrain barriers and precipitation patterns. As shown in Table 3. Sheep & goats had the shortest migration distances and the slowest speeds among the four phases. Their migration speed shows a changing trend of increasing first and then decreasing. This pattern likely relates to their dependence on pasture resources and distinctive husbandry practices. Sheep & goats herds primarily rely on short-distance movements between grazing pastures to obtain forage, resulting in more spatially constrained adaptability compared to large livestock and consequently shorter migration distances. Furthermore, the initial acceleration in migration speed may have been driven by increasing pasture resource pressures and intensifying grazing utilization in the early stages. After implementing pasture management policies, improving resource use, and slowly reducing grassland degradation, the migration speed of sheep & goats herds went down.

Table 3 Statistical table on the shift in the center of gravity of livestock density on the Mongolian plateau

Time span	Species of livestock	Migration direction	Total distance /km	Average velocity (km/year)
2000-2005	total livestock	southeast	133.824	26.765
	sheep & goats	southeast	125.366	25.073
	large livestock	southeast	163.994	32.799
2005-2010	total livestock	northeast	26.045	5.209
	sheep & goats	northwest	3.310	0.662
	large livestock	northeast	68.555	13.711
2010-2015	total livestock	northwest	352.926	70.585
	sheep & goats	northwest	111.848	22.370

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	large livestock	northwest	150.135	30.027
	total livestock	southeast	204.390	40.878
2015-2020	sheep & goats	northwest	8.113	1.623
	large livestock	northwest	58.561	11.712

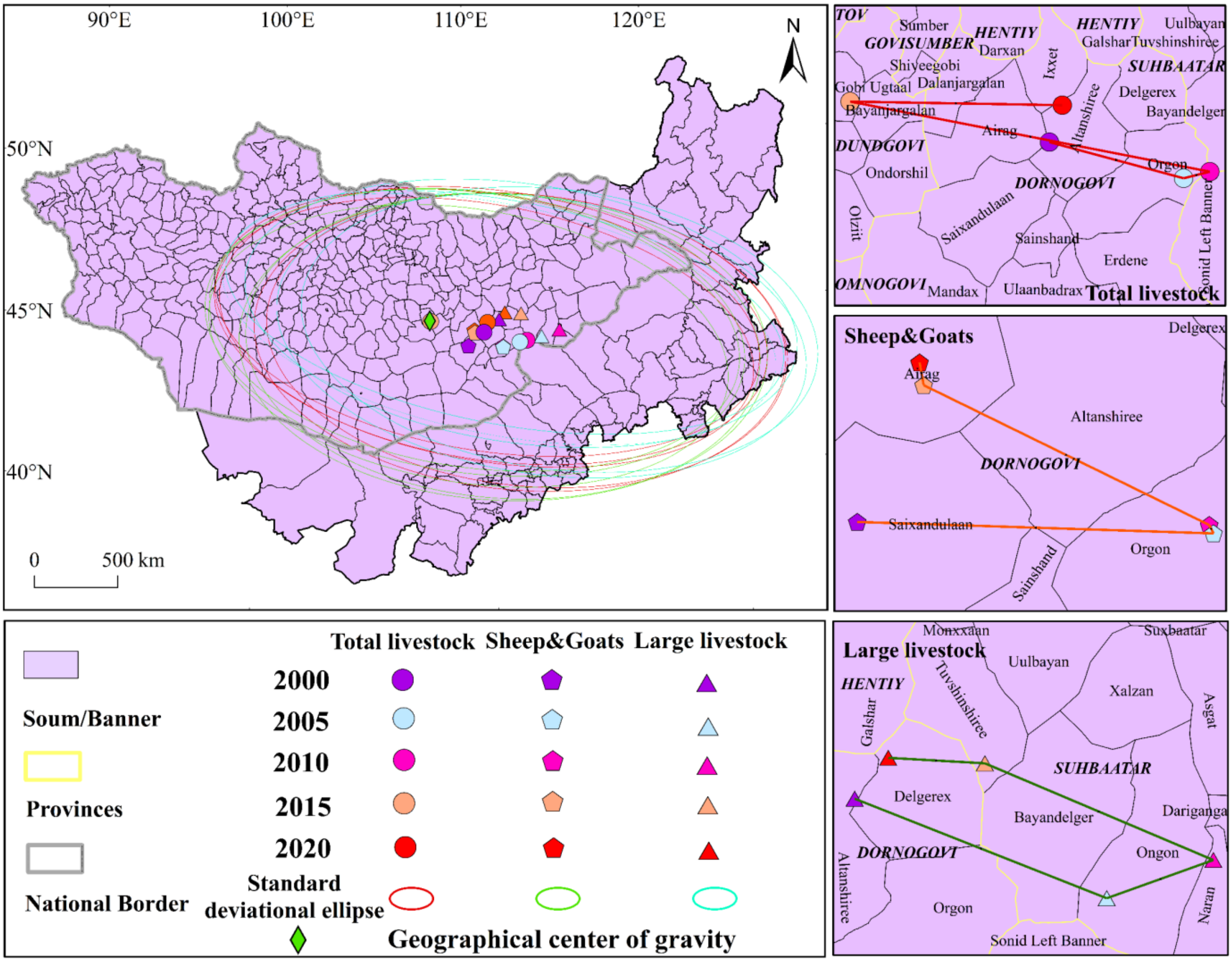

Figure 11: Map of the shift in the centre of gravity of livestock density.

Figure 9 reveals that the density centres of various livestock deviate from the centre of gravity of the Mongolian Plateau (107°35'5"E, 45°53'17"N). As time goes by, the offset trend between the centre of gravity of livestock density and the geometric centre of gravity becomes increasingly obvious, indicating that the imbalance of livestock distribution in the region is intensifying day by day. The distribution of livestock density in the eastern and western regions varies greatly, which mainly stems from the dual action mechanism of natural geographical conditions and socio-economic factors. At the natural geographical level, there are significant differences in grassland resources between the eastern and western regions of the region: the Gobi Desert area in the southwest is limited by the scarcity of grassland resources and land carrying capacity (Tong et al., 2022; Zhang et al., 2023; Zhao et al., 2023), resulting in the livestock density remaining at a relatively low level, and the eastern region has vast grassland resources, which are suitable for the survival of livestock and have a relatively high density of livestock. This difference in geographical condition is the core reason for the difference in livestock density between the eastern and western regions, and it further leads to the offset between the centre of gravity of livestock density and the geometric centre of gravity. At the socio-economic level, the eastern region has promoted the intensive development of animal husbandry through policies such as subsidies for returning grazing land to grassland, promotion of high-quality breeds, and support for mechanization, as well as technological innovations (Chaorattanakawee et al., 2022; Miao et al., 2021), while in the western region, constrained by ecological protection policies and restricted management of grasslands, the development of animal husbandry lags behind relatively. The differentiated implementation of such regional development policies has further strengthened the spatial differentiation of livestock density between the east and the west, thereby intensifying the shift trend between the centre of gravity of livestock density and the geometric centre of gravity.

5 Conclusions

This study developed a 1km-resolution gridded dataset (2000–2020) of total livestock, sheep & goats, and large livestock densities on the Mongolian Plateau by integrating multi-source remote sensing data with soum/banner county level livestock statistics using a random forest model. This study significantly improves the spatial expression accuracy of traditional statistical data and shows obvious advantages compared with the GLW dataset. Spatially, although the GLW3 and GLW4 datasets can roughly reflect the livestock distribution patterns on the Mongolian Plateau, there are obvious underestimates and overestimates in some local areas. In contrast, this study delineated the spatial heterogeneity of livestock densities more accurately, showing high accuracy in the global region and high consistency with the distribution patterns observed in soum/banner county level statistics. In terms of statistical verification, the R^2 between the GLW dataset and the statistical data was only 0.132-0.415. The R^2 of the livestock density gridded data with a resolution of 1 km was constructed in this study and the statistical data both exceeded 0.85. This result not only verifies the superiority of the RF model in the spatial simulation of livestock, but also indicates that the integration of multi-source remote sensing data (e.g., land use, climate, terrain and population, etc.) can effectively improve the simulation accuracy. Furthermore, this study fills the gap in the spatial distribution information of large livestock (e.g., camels) in the GLW dataset, providing a basic dataset with stronger spatio-temporal continuity and more accurate spatial expression for the research on the ecosystem of the Mongolian Plateau.

This research revealed that the livestock density on the Mongolian Plateau shows a gradient differentiation pattern from southeast to northwest. High-value areas are concentrated in regions such as Khovsgol provinces and Hinggan League, which have superior water and heat conditions. However, limited by conditions such as scarce precipitation and low vegetation coverage, the density of livestock in the Gobi Desert area in the southwest is relatively low. Under the combined effects of natural factors such as climate change and grassland degradation, and socioeconomic drivers such as policy interventions and market demand, the study period witnessed significant increases in livestock density in Mongolia's Dornod Province and China's Inner Mongolia regions (e.g., Alxa Left Banner and Otog Front Banner), while significant decreases occurred in Hohhot and Ulanqab areas. The center of gravity of livestock density shows a migration trend from southeast to northwest first, and the migration amplitude in the east-west direction is significantly greater than that in the north-south direction, further indicating the synergistic effect of nature-social factors on the spatial distribution of livestock. This dataset can provide a scientific basis for the optimal allocation of livestock resources and the assessment of ecological carrying capacity in the Mongolian Plateau, and offer reliable data to support the protection of regional grassland ecosystems, dynamic early warning of overgrazing risks, and the balanced development of humans, livestock and grass.

Although this study achieved a good simulation effect at the 1 km scale, there are still some limitations: First, the error in the local complex area needs to be optimized through higher-resolution (eg., 30 m) remote sensing data; Second, this research model does not subdivide livestock types (such as sheep and goats), making it difficult to accurately reflect the impact of livestock species structure adjustment. Future work will focus on the following directions: (1) introducing higher-resolution data such as Sentinel-2 and combining deep learning algorithms to improve the ability to depict local details; and (2) establish spatial models for subdivided livestock species (goats, sheep, cattle, horses, and camels), with particular attention to the phenomenon of a sharp increase in the number of goats in Mongolia and providing more precise decision support for regional adaptive management.

6 Code availability

The code is fully operational under Visual Studio Code 1.74 for environment variable normalization, data reading, model training, simulation and zonal density mapping. The complete code and example datasets are publicly available through the figshare repository (https://doi.org/10.6084/m9.figshare.28695728).

7 Data availability

Gridded livestock density datasets are freely available at the figshare repository （https://doi.org/10.6084/m9.figshare.28695728） (Liu and Wang, 2025). The repository contains four folders. These include data for total livestock, sheep and goats, and large livestock as well as example code and data for the spatial distribution simulation of total livestock density in 2020. Each file is saved in GeoTiff format with a spatial resolution of 1 km and a projection of WGS_1984 UTM_zone_48N. Each file is labeled with the acronyms "Total" for total livestock, "SG" for sheep & goats, and "LA" for large livestock, followed by an underscore and the year. Missing data are indicated by "No data".

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Author contributions

Conceptualization, Methodology, Investigation, Resources, Liu Y.P. and W.-J.L.; Software, Validation, Data curation, Writing—original draft preparation, Liu Y.P.; Writing—review & editing, W.-J.L., Liu Y.P., Ochir A. and Zou W.H. All authors have read and agreed to the published version of the manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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