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ARTICLE

Statistical Relationships Between Agricultural Indicators and Annual Average Air Temperature in Mongolia

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Abstract

This study investigates the statistical relationships between agricultural indicators and annual average air temperature in Mongolia using long-term datasets covering the period 1975–2024. The analysis integrates linear algebra, mathematical statistics, probability distribution theory, correlation analysis, linear regression analysis, and Laplace-function-based spatial representation to evaluate associations between agricultural activities and temperature variability across representative agro-ecological regions of Mongolia. Five provinces representing the major agricultural zones were selected as sample regions. Distribution analysis confirmed the suitability of the datasets for subsequent statistical modeling. Correlation analysis revealed that livestock-related indicators generally exhibited stronger associations with annual average air temperature than crop-production indicators. Among livestock categories, goats, small livestock populations, and total livestock numbers showed the highest correlation coefficients and the broadest spatial representation within strong-correlation classes. Regression analysis further identified horse populations, goat populations, and vegetable production as indicators exhibiting relatively strong positive statistical relationships with annual average air temperature. The Laplace-function analysis enabled the spatial extrapolation of correlation and regression classes across representative agricultural regions, providing a probabilistic interpretation of the observed relationships. The results suggest that livestock dynamics are more closely associated with long-term temperature variability than crop-production activities in Mongolia. The proposed methodological framework provides a useful approach for investigating agricultural–climate interactions and may support future environmental assessment and sustainable agricultural policy development.

Keywords: annual average air temperature, agricultural indicators, correlation analysis, Laplace function, linear regression, Mongolia: spatial representation.

Introduction

Agriculture is one of the most important sectors of the Mongolian economy, contributing significantly to food production, employment, and rural livelihoods. Livestock husbandry and crop production constitute the foundation of the agricultural sector and play a crucial role in ensuring food security and supporting economic development. However, agricultural activities are also associated with environmental challenges, including land degradation, biodiversity loss, and greenhouse gas (GHG) emissions that contribute to climate change [1], [2].

Globally, agriculture is recognized as a major source of anthropogenic greenhouse gas emissions, particularly methane (CH_4) from enteric fermentation and manure management and nitrous oxide (N_2O) from agricultural soils [1], [3]. In Mongolia, where livestock production dominates the agricultural sector, understanding the relationships between agricultural activities and environmental change is essential for developing sustainable agricultural practices and climate change mitigation strategies.

Previous studies have demonstrated that agricultural production and climatic variables are closely interconnected. Variations in temperature and precipitation can influence agricultural productivity, while agricultural intensification may contribute to environmental pressures associated with greenhouse gas emissions [2], [4].

Nevertheless, quantitative assessments of long-term relationships between agricultural indicators and climatic variables remain limited in Mongolia, particularly at the regional level. Furthermore, detailed greenhouse gas emission inventories are available only for limited periods and primarily at the national scale, making long-term regional assessments challenging.

Mongolia is characterized by diverse climatic and agricultural conditions. For agricultural and environmental studies, the country can be broadly divided into five major agro-ecological regions: the Western Region, Khangai Region, Central Region, Steppe Region, and Gobi Region (Figure 1). These regions differ considerably in climate, vegetation, livestock composition, crop production systems, and land-use patterns, providing a suitable framework for evaluating regional variations in agriculture–climate relationships.

To address the existing knowledge gap, this study investigates the statistical relationships between agricultural indicators and annual average air temperature in Mongolia during the period 1975–2024. The analysis focuses on major agricultural subsectors, including livestock production and crop cultivation, using long-term datasets collected from representative agricultural regions. Correlation analysis, linear regression analysis, probability distribution theory, and Laplace-function-based spatial representation are employed to evaluate the strength and spatial distribution of associations between agricultural indicators and temperature variability.

To the best of our knowledge, this is the first study to integrate correlation analysis, regression analysis, probability distribution theory, and Laplace-function-based spatial representation to investigate long-term relationships between agricultural indicators and annual average air temperature across Mongolia's major agro-ecological regions. This integrated framework enables both statistical assessment and spatial interpretation of agriculture–climate relationships using long-term observational data.

Figure 1. Agro-ecological regions of Mongolia and representative provinces selected for the study.

Source: Institute of Geography and Geoecology, Mongolian Academy of Sciences.

To ensure representation of these major agro-ecological regions, the study considered five representative provinces: Khovd in the Western Region, Uvurkhangai in the Khangai Region, Selenge in the Central Region, Sukhbaatar in the Steppe Region, and Umnugovi in the Gobi Region. These provinces encompass distinct climatic conditions, agricultural production systems, and geographical characteristics while providing relatively complete long-term datasets for the study period.

Particular attention is given to identifying agricultural subsectors that exhibit relatively strong associations with long-term temperature variability and to examining how these relationships are distributed across representative agro-ecological regions. To achieve this, the study integrates correlation analysis, linear regression analysis, probability distribution theory, and a Laplace-function-based spatial representation approach. The resulting framework provides a quantitative basis for evaluating agriculture–environment interactions and contributes to a better understanding of long-term agricultural and climatic dynamics in Mongolia. The findings may support future environmental assessments, climate change mitigation strategies, and sustainable agricultural policy development.

Materials and Methods

Data Sources

This study utilized long-term agricultural and climatic datasets covering the period 1975–2024. Agricultural data were obtained from the National Statistics Office of Mongolia and included livestock population by species, crop production, harvested area, and other agricultural indicators. Climatic data consisted of annual average air temperature records obtained from the National Agency for Meteorology and Environmental Monitoring.

A total of 63 agricultural and climatic indicators were compiled and analyzed. The dataset covered approximately five decades, providing sufficient temporal coverage for investigating long-term statistical relationships between agricultural activities and climatic variables.

Agricultural greenhouse gas (GHG) emission data were available only at the national level for the period 1990–2014. These data were used to establish statistical relationships between annual average air temperature and agricultural GHG emissions.

Study Area and Sampling Design

Given the substantial climatic and agricultural heterogeneity of Mongolia, a stratified regional sampling approach was adopted to ensure representation of the country's principal agro-ecological zones. Based on the agricultural regionalization of Mongolia (Figure 1), five representative provinces were selected: Khovd from the Western Region, Uvurkhangai from the Khangai Region, Selenge from the Central Region, Sukhbaatar from the Steppe Region, and Umnugovi from the Gobi Region. These provinces were chosen because they represent distinct environmental and agricultural conditions while providing sufficiently complete long-term records of agricultural and climatic variables. The selected provinces were therefore treated as representative samples of their respective agro-ecological regions for the purposes of statistical analysis and spatial extrapolation.

Variables Used in the Analysis

Three categories of variables were considered in this study. Agricultural variables (z_i) included livestock populations by species, total livestock numbers, crop production indicators, harvested area, and crop yield variables. Annual average air temperature was used as the climatic variable (x), while agricultural greenhouse gas emissions were used as the environmental variable (y). Together, these variables provided the basis for assessing long-term statistical relationships between agricultural production systems, temperature variability, and greenhouse gas emissions in Mongolia. Their relationships were analyzed using a combination of mathematical and statistical techniques described in the subsequent sections.

Statistical and Mathematical Framework

The numerical variables used in this study were represented as vectors consisting of annual observations over the study period. Let zi denote an agricultural indicator (e.g., livestock population or crop production), x denote annual average air temperature, and y denote greenhouse gas (GHG) emissions.

To investigate the relationships among these variables, linear regression models were employed. The relationship between agricultural indicators and annual average air temperature was expressed as:

$$x = a1zi \quad (1)$$

where a1 is the regression coefficient describing the statistical association between an agricultural indicator and annual average air temperature.

Similarly, the relationship between annual average air temperature and greenhouse gas emissions was represented as:

$$y = a2x \quad (2)$$

where a2 is the regression coefficient relating annual average air temperature to greenhouse gas emissions.

Combining Equations (1) and (2) yields:

$$y = a2(a1zi)$$

or

$$y = (a_1 a_2) z_i \quad (3)$$

Equation (3) provides a simplified representation of the indirect statistical relationship between agricultural indicators and greenhouse gas emissions through annual average air temperature. An example of the analytical procedure is presented using livestock population (z_1) and crop production (z_2). The estimated relationship between greenhouse gas emissions and annual average air temperature was:

$$y = 4695.6x$$

For livestock population, the regression relationship with annual average air temperature was:

$$x = 0.0058z_1$$

Substituting this expression into the greenhouse gas emission model gives:

$$y = 4695.6(0.0058z_1)$$
$$y = 27.23z_1$$

Similarly, for crop production:

$$x = 0.000145z_2$$

which yields:

$$y = 4695.6(0.000145z_2)$$
$$y = 0.681z_2$$

These calculations indicate that livestock-related indicators exhibit larger regression coefficients than crop-production indicators, suggesting stronger statistical associations with annual average air temperature and estimated greenhouse gas emissions. It should be emphasized that these equations describe statistical relationships derived from observational data and do not imply direct causal effects among agricultural activities, temperature variability, and greenhouse gas emissions.

The relationships between annual average air temperature and the agricultural indicators were subsequently evaluated using correlation and regression analyses. Detailed statistical outputs are provided in the supplementary tables.

Distribution Analysis

Prior to correlation and regression analyses, the statistical distributions of all variables were examined. Measures of central tendency and variability were calculated, and distribution conformity was assessed using the Cramér–von Mises goodness-of-fit test [14]. The objective was to determine whether the variables approximated theoretical probability distributions and to evaluate their suitability for subsequent statistical analyses. The estimated distribution parameters were subsequently used to derive theoretical probability density functions and to support the application of the Laplace-function-based analysis.

Correlation Analysis

Pearson correlation analysis was employed to evaluate the strength and direction of the relationships between agricultural indicators and annual average air temperature [15]. The Pearson correlation coefficient was calculated as:

$$r = \Sigma[(x_i - \bar{x})(y_i - \bar{y})] / \sqrt{\Sigma(x_i - \bar{x})^2 \, \Sigma(y_i - \bar{y})^2} \quad (4)$$

where r is the correlation coefficient, x_i and y_i are individual observations, and $\bar{x}$ and $\bar{y}$ are the corresponding sample means.

Regression Analysis

Linear regression analysis was performed to quantify the statistical relationships between agricultural indicators and annual average air temperature. Regression coefficients and regression equations were estimated for each agricultural indicator.

$$y = a + bx \quad (5)$$

where a is the intercept and b is the regression coefficient.

Spatial Extrapolation Using the Laplace Function

To evaluate the spatial distribution of the observed statistical relationships, the Laplace function was applied to the correlation and regression coefficients obtained from the representative provinces.

$$\Phi(r) = (r_i - \bar{r}) / \sigma_r \quad (6)$$

The standard error was calculated as:

$$\sigma_r = \sqrt{[(\sigma^2/n)(1 - n/N)]} \quad (7)$$

The resulting standardized values were converted into probability values using the Laplace distribution table. These probability values were subsequently used to estimate the relative spatial representation of different correlation and regression classes across the representative agro-ecological regions.

Results and Discussion

Distribution Characteristics of the Sample Data

Before applying correlation, regression, and Laplace-function-based analyses, the distribution characteristics of the agricultural and climatic variables were evaluated using the Cramér–von Mises goodness-of-fit test. Distribution analysis was conducted to determine whether the observed data were compatible with the theoretical assumptions underlying the statistical framework employed in this study. The results indicate that annual average air temperature generally follows a normal distribution across the five representative provinces, whereas livestock and crop-production indicators exhibit a combination of normal, beta, gamma, and uniform distributions. Despite this variability, most variables demonstrated acceptable goodness-of-fit probabilities and were considered suitable for subsequent statistical analyses.

Table 1

Summary of Distribution Characteristics of Major Variables

Variable	Dominant Distribution	Average Probability
Temperature	Normal	0.93
Livestock	Beta / Normal	0.43
Crop Production	Beta / Normal	0.48
Large Livestock	Normal	0.77

Note: Distribution characteristics were evaluated using the Cramér–von Mises goodness-of-fit test. The values shown represent average goodness-of-fit probabilities across the five representative provinces. Detailed distribution parameters, probability distributions, and province-specific test results are provided in Appendix Table A1.

As shown in Table 1, annual average air temperature exhibited the strongest conformity to a normal distribution, with an average goodness-of-fit probability of 0.93 across the five representative provinces. Livestock and crop-production indicators demonstrated greater variability and were characterized by a combination of normal and beta distributions. Large livestock populations generally exhibited stable distribution characteristics with relatively high goodness-of-fit probabilities. Overall, the distribution analysis suggests that the datasets satisfy the statistical requirements for subsequent correlation, regression, and Laplace-function-based analyses.

The predominance of normal or near-normal distribution characteristics, particularly for annual average air temperature, supports the application of probability density functions and the Laplace-function-based framework employed in this study. Consequently, the analyzed datasets were considered suitable for further statistical modeling and interpretation.

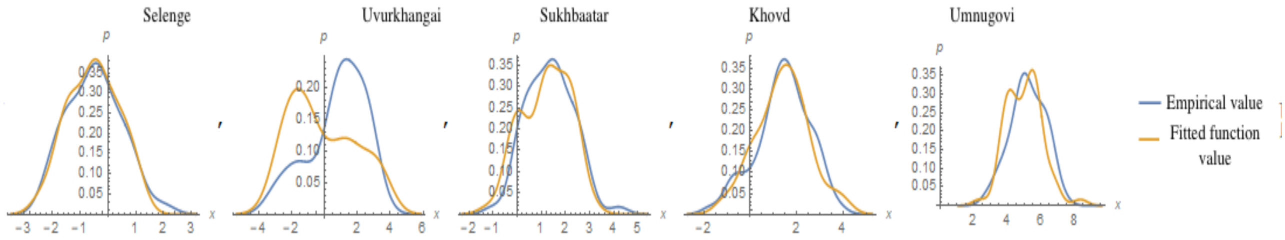


Figure 2. Empirical and fitted theoretical probability density functions of annual average air temperature for the selected provinces.

Figure 2 compares the empirical probability density functions derived from the observed annual air average temperature data with the corresponding theoretical density functions fitted to each representative province. The empirical density functions are shown in blue, while the fitted theoretical functions are shown in orange. The close agreement between the empirical and theoretical curves indicates that the selected probability distributions adequately describe the observed temperature data.

The fitted theoretical density functions were subsequently derived using the distribution parameters presented in Table 1. These functions provide a mathematical representation of the probability distribution of annual average air temperature and serve as the basis for subsequent statistical analyses.

Figure 3 presents the theoretical density functions of annual average air temperature for the five representative provinces on a common coordinate system. Differences in the location, spread, and shape of the distributions reflect regional variability in long-term temperature conditions. Umnugovi Province exhibits a distribution centered at relatively higher temperatures, whereas the remaining provinces show distributions concentrated around lower average temperature ranges.

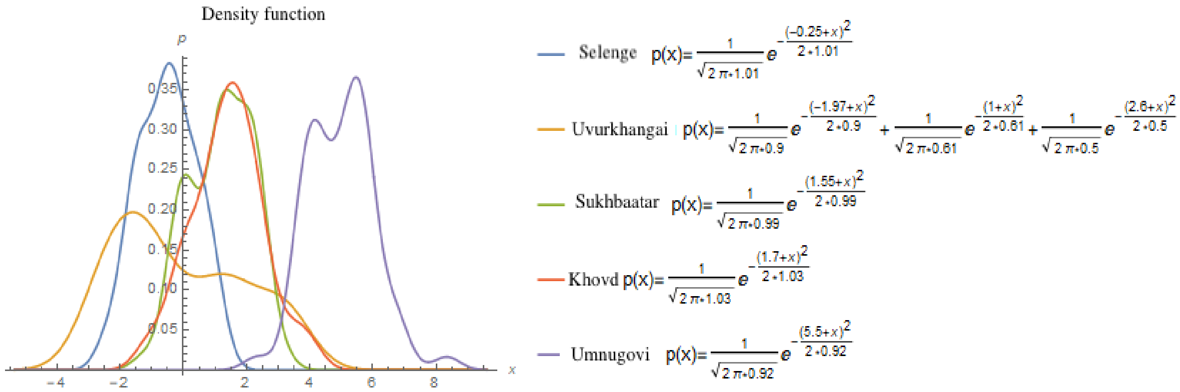


Figure 3. Comparison of fitted theoretical probability density functions of annual average air temperature across the selected provinces.

The successful estimation of theoretical probability density functions for the analyzed datasets demonstrates that the variables can be represented within a probabilistic framework. These results support the application of the Laplace-function-based approach used in the subsequent stages of the analysis and indicate that the statistical assumptions of the proposed methodology are reasonably satisfied.

Correlation Analysis

The relationships between annual average air temperature and agricultural indicators were evaluated using Pearson correlation analysis. The resulting correlation coefficients are presented in Table 2.

Table 2.

Pearson correlation coefficients between annual average air temperature and agricultural indicators across the selected provinces

Agricultural Sector		**Regional Sample**					**Sample Mean Correlation**
		Umnugovi	Sukhbaatar	Selenge	Uvurkhangai	Khovd	
Crop Production	Potatoes	0.46	-0.06	0.17	0.43	0.06	0.28
	Vegetables	0.65	-0.01	0.45	0.45	0.02	0.46
Crop Production Total		0.58	-0.05	0.3	0.44	0.04	0.37
Livestock	Horses	0.15	0.51	0.58	0.25	0.38	0.53
	Cattle	0.25	0.44	0.5	0.12	0.47	0.5
	Camels	-0.27	-0.57	0.48	-0.59	-0.16	-0.48
	Sheep	0.57	0.37	0.42	0.47	0.23	0.47
	Goats	0.72	0.51	0.53	0.63	0.23	0.61
	Large Livestock	-0.05	0.49	0.53	0.14	0.4	0.45
	Small Livestock	0.71	0.45	0.49	0.58	0.27	0.58
Livestock Total		0.7	0.46	0.5	0.56	0.29	0.58

Note: significance testing was not performed because the objective was exploratory pattern identification.

The results indicate substantial variability among agricultural subsectors and regions. Crop-production indicators generally exhibited weak to moderate positive correlations with annual average air temperature, with vegetables showing stronger associations than potatoes. The average correlation coefficients for potatoes and vegetables across the selected provinces were 0.28 and 0.46, respectively. Among livestock categories, goats and small livestock demonstrated the strongest positive correlations with annual average air temperature. The average correlation coefficients for goats, small livestock, and total livestock population were 0.61, 0.58, and 0.58, respectively. In contrast, camels exhibited predominantly negative correlations, with an average coefficient of –0.48.

Overall, livestock-related indicators showed stronger associations with annual average air temperature than crop-production indicators. The strongest average correlation was observed for goats (r = 0.61), whereas the weakest relationship was observed for potatoes (r = 0.28). These findings suggest that livestock dynamics may be more closely associated with long-term temperature variability than crop-production indicators in the selected regions.

Application of the Laplace Function

To examine the spatial distribution of the observed statistical relationships across Mongolia, the Laplace function was applied to the correlation coefficients obtained from the representative provinces. The objective was to provide a probabilistic representation of the spatial distribution of agricultural indicators exhibiting different levels of association with annual average air temperature.

The standardized Laplace value was calculated as:

$$\Phi(r) = \frac{r_i - \bar{r}}{\sigma_r} \qquad (8)$$

where:

$\Phi(r)$= standardized Laplace value;

σ_r= standard error of the sample estimate;

r_i= observed correlation coefficient;

$\bar{r}$= mean correlation coefficient;

The standard error was calculated as:

$$\sigma_r = \sqrt{\frac{\sigma^2}{n}\left(1-\frac{n}{N}\right)} \qquad (9)$$

where:

σ^2= sample variance;
n= number of sample units;
N= number of units in the population.

As an illustrative example, the livestock sector was selected for analysis. The observed correlation coefficients for the five representative provinces were 0.70, 0.56, 0.50, 0.46, and 0.29. The corresponding variance was calculated as $\sigma^2 = 0.02232$, resulting in a standard error of $\sigma_r = 0.0578$.
Substituting the observed correlation coefficients into the Laplace-function equation produced standardized values ranging from approximately −4.94 to 2.04. These standardized values were subsequently converted into cumulative probability values using the Laplace (standard normal) distribution table. The resulting probabilities were then expressed as percentages and used to estimate the relative distribution of correlation-strength classes across the representative agro-ecological regions.
The use of the Laplace function is based on the assumption that standardized observations can be represented within the framework of the normal probability distribution. Similar approaches have been widely applied in probability theory and mathematical statistics for estimating cumulative probabilities and relative frequencies of standardized variables [9-11].
The resulting percentages provide a statistical representation of the relative occurrence of different correlation-strength classes among the selected regions. Therefore, the estimated percentages should be interpreted as relative distributions of statistical classes rather than direct measurements of physical land area.
The Laplace-function-based spatial representation should be interpreted as a probabilistic extrapolation of statistical classes rather than a direct measurement of physical land area. The approach provides an exploratory framework for examining the relative spatial distribution of observed statistical relationships and should therefore be interpreted with appropriate caution.
Detailed calculations and probability estimates derived from the Laplace-function analysis are presented in Appendix C.

Spatial Representation of Correlation Strength Based on the Laplace Function

The standardized Laplace-function values obtained from the correlation analysis were converted into probability areas under the Gaussian distribution curve. These probability areas were subsequently transformed into percentage values to facilitate interpretation of the spatial distribution of correlation strengths.
Figure 4 illustrates the Gaussian curve generated from the Laplace-function analysis for the livestock sector. The colored regions represent probability intervals corresponding to different ranges of correlation coefficients.

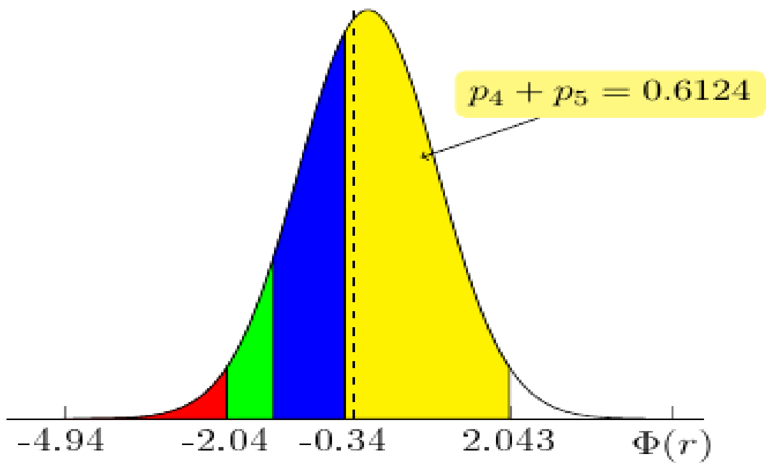


Figure 4. Gaussian curve showing probability areas derived from the Laplace-function analysis.

The probability areas obtained from the Gaussian distribution were subsequently transformed into percentage values to facilitate interpretation of the results. The resulting percentages provide an estimate of the relative spatial representation associated with different correlation-strength categories within the sampled regions.

The estimated distribution of correlation-strength classes is presented in Figure 5.

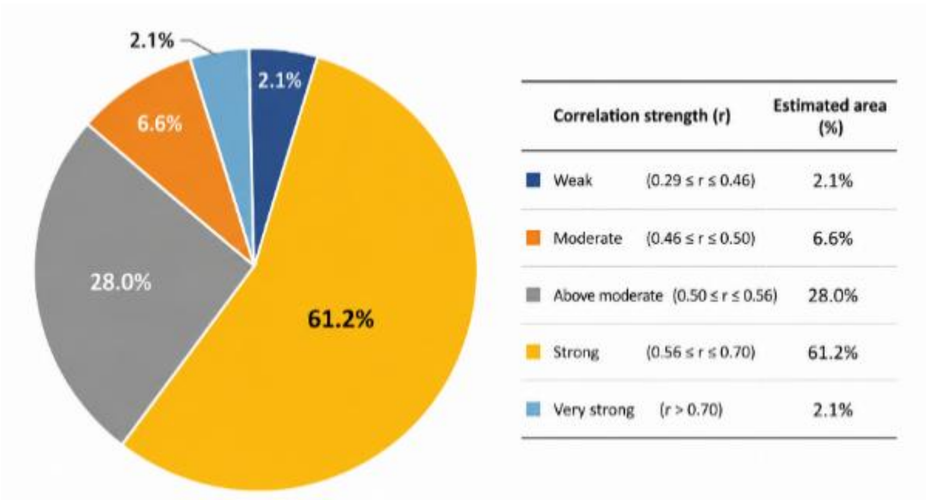


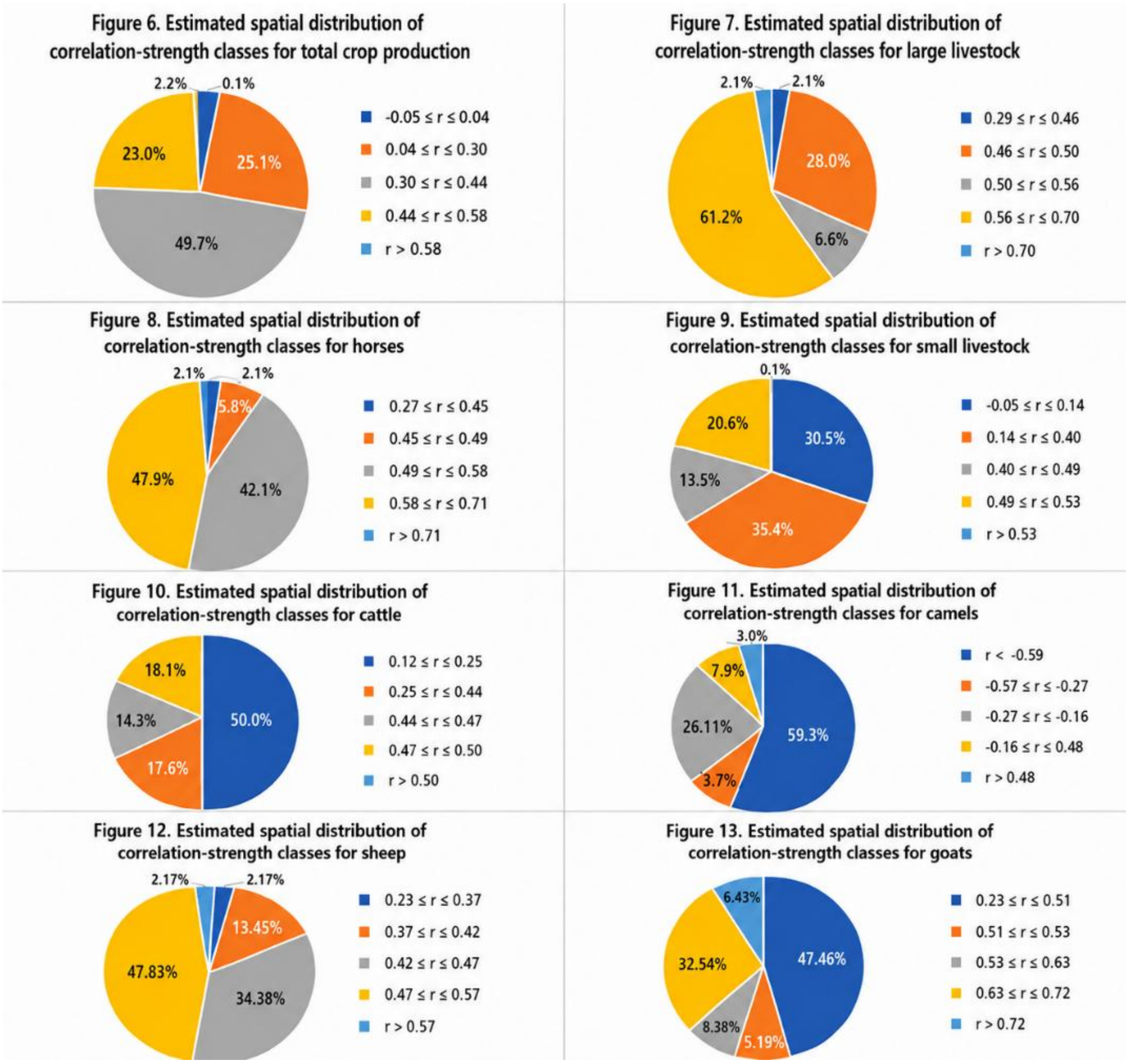
Figure 5. Estimated spatial distribution of correlation-strength classes for the livestock sector based on Laplace-function analysis.
Note: percentage may not sum to 100 due to rounding

The results indicate that approximately 61.2% of the estimated area falls within the strong-correlation class ($0.56 \leq r \leq 0.70$), while 28.0% is associated with above-moderate correlations ($0.50 \leq r \leq 0.56$). Moderate correlations ($0.46 \leq r \leq 0.50$) account for 6.6% of the estimated area, whereas weak correlations ($0.29 \leq r \leq 0.46$) and very strong correlations ($r > 0.70$) each represent approximately 2.1%. These findings suggest that livestock-related indicators exhibit a broadly distributed positive association with annual average air temperature across the selected regions.
The same procedure was applied to all agricultural indicators included in the study. The resulting probability distributions are illustrated in Figures 6–13, and the corresponding percentage values are summarized in Table 3.

Table 3.
Summary of spatial distributions of correlation-strength classes derived from the Laplace-function analysis

Indicator	Dominant correlation class	Largest proportion (%)
Total crop production	Weak to moderate	49.7
Potatoes	Strong	61.2
Vegetables	Moderate to strong	47.9
Horses	Weak to moderate	35.4
Cattle	Strong	50.0
Camels	Negative to weak	59.3
Sheep	Moderate to strong	47.8
Goats	Moderate to strong	47.5

The following figures 6–13 reveal substantial differences among agricultural subsectors in their associations with annual average air temperature. Livestock-related indicators generally exhibited broader distributions within the moderate-to-strong correlation classes, whereas crop-production indicators were more frequently concentrated within weak-to-moderate correlation ranges.



Note: r – correlation coefficient. The percentage values indicate the estimated proportion of the total territory represented by each correlation-strength class

Among livestock categories, goats, sheep, cattle, and total livestock populations demonstrated the largest proportions within the strong-correlation classes, indicating widespread positive associations with long-term temperature variability. In contrast, camel populations displayed a distinctly different pattern, with the majority of the estimated area occurring within weak or negative correlation classes. This result suggests that camel population dynamics may respond differently to climatic conditions than other livestock species.

Overall, the Laplace-function analysis supports the results of the Pearson correlation analysis by indicating that livestock-related indicators exhibit stronger and more spatially extensive associations with annual average air temperature than crop-production indicators. These findings suggest that long-term temperature variability may exert a greater influence on livestock dynamics than on crop production within Mongolia's agricultural system.

The results summarized in Table 4 consolidate the spatial distributions of correlation-strength classes derived from the Laplace-function analysis for all agricultural indicators. The percentages represent the estimated proportion of the sampled agro-ecological regions associated with each correlation-strength category.

Table 4.

Estimated spatial distribution of correlation-strength classes between annual average air temperature and agricultural indicators

Agricultural Sector		Correlation Strength					
		Very Weak	Weak	Moderate	Above Moderate	Strong	Very Strong
Crop Production	Potatoes	NA	10.22%	86.85%	2.22%	NA	NA
	Vegetables	NA	NA	46.41%	48.64%	4.95%	NA
Crop Production Total		NA	25.1%	71.7%	2.17%	NA	NA
Livestock	Horses	NA	1.58%	37.01%	37.83%	23.58%	NA
	Cattle	NA	0.01%	50%	49.99%	NA	NA
	Camels	NA	NA	NA	NA	NA	NA
	Sheep	NA	2.17%	47.83%	47.83%	2.17%	NA
	Goats	NA	NA	13.75%	47.46%	32.54%	6.43%
	Large Livestock	0.1%	30.5%	35.41%	34.06%	NA	NA
	Small Livestock	NA	NA	2.1%	47.88%	47.88%	2.12%
Livestock Total		NA	NA	7.92%	42.07%	47.88%	2.12%

The results indicate that livestock-related indicators generally exhibit stronger associations with annual average air temperature than crop-production indicators. For total livestock population, approximately 47.9% of the estimated area falls within the strong-correlation class, while an additional 42.1% is classified as above moderate. In contrast, total crop production is predominantly concentrated within the weak-to-moderate correlation classes.

Among the livestock categories, small livestock populations exhibit the broadest spatial representation within the strong-correlation class, accounting for approximately 47.9% of the estimated area, with a further 47.9% occurring within the above-moderate class. Goat populations also demonstrate strong associations with temperature variability, with 32.5% of the estimated area classified as strong and 6.4% as very strong.

Horse populations display a more balanced distribution across moderate, above-moderate, and strong correlation classes, whereas cattle populations are concentrated primarily within the moderate and above-moderate categories. In contrast, large livestock populations show predominantly weak-to-moderate relationships with annual average air temperature.

Crop-production indicators exhibit comparatively weaker associations. Potato production is concentrated almost entirely within the weak and moderate correlation classes, whereas vegetable production demonstrates stronger relationships, with approximately 48.6% of the estimated area falling within the above-moderate class.

Camel populations exhibit a distinct pattern compared with other livestock categories, reflecting the negative average correlation observed in the Pearson correlation analysis. This result suggests that camel population dynamics may respond differently to climatic conditions than other livestock species.

Overall, the Laplace-function analysis indicates that livestock-related variables, particularly small livestock and goats, exhibit broader and stronger spatial associations with annual average air temperature than crop-production indicators. These findings are consistent with the correlation analysis presented in Table 2 and suggest that livestock dynamics may be more closely associated with long-term temperature variability across Mongolia's agricultural regions.

Regression Coefficient Analysis

While correlation analysis provides information on the strength and direction of statistical associations, regression analysis enables quantification of the expected change in annual average air temperature associated with variation in agricultural indicators. the representative regions and the corresponding Therefore, linear regression models were developed for each agricultural sector and subsector. The estimated regression coefficients, representing the magnitude and direction of these statistical relationships, are presented in Table 5 for national averages.

Table 5.
Linear regression coefficients between annual average air temperature and agricultural indicators

Agricultural Sector		Regional Sample					Mean Regression Coefficient
		Umnugovi	Sukhbaatar	Selenge	Uvurkhangai	Khovd	
Crop Production	Potatoes	0.00136	-0.00084	0.00002	0.00044	0.00022	0.00006
	Vegetables	0.00203	NA	0.000036	0.00075	0.00021	0.000124
Crop Production Total		0.00092	-0.000194	0.000011	0.00042	0.00011	0.000046
Livestock	Horses	0.0714	0.0082	0.023	0.0067	0.02526	0.01428
	Cattle	0.02513	0.01	0.0097	0.0082	0.01365	0.01418
	Camels	-0.0085	-0.131	2.312	-0.104	-0.0254	-0.0448
	Sheep	0.0049	0.00094	0.00236	0.0014	0.0014	0.00183
	Goats	0.0015	0.00136	0.00237	0.0013	0.00053	0.00138
	Large Livestock	NA	0.005	0.007	0.0032	0.008	0.018
	Small Livestock	0.00446	0.0011	0.0013	0.001	0.001	0.0034
Livestock Total		0.0012	0.001	0.0011	0.0007	0.001	0.00394

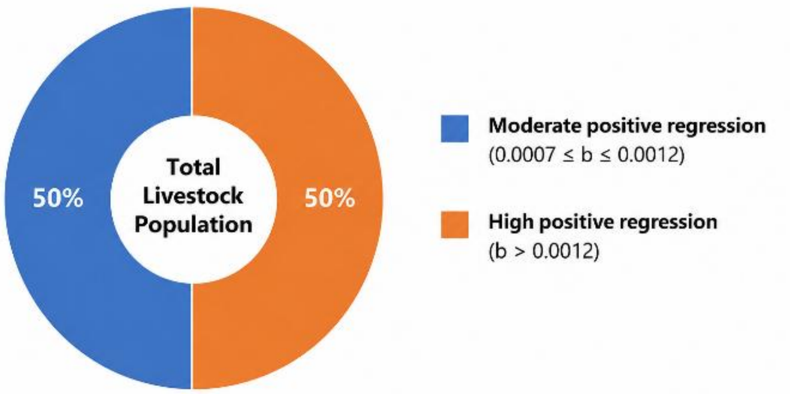


Figure 14. Estimated spatial distribution of regression-coefficient classes for total livestock population derived from Laplace-function analysis.
Note: Regression-coefficient classes were derived using the Laplace-function classification procedure. Percentages indicate the estimated spatial representation of each coefficient class.

Figure 14 presents the estimated spatial distribution of regression-coefficient classes for total livestock population. Approximately 50% of the estimated area is associated with regression coefficients ranging from 0.0007 to 0.0012, while the remaining 50% is associated with coefficients greater than 0.0012.

The predominance of positive regression coefficients across all classes indicates a consistently positive statistical relationship between total livestock population and annual average air ngmitemperature throughout the representative agro-ecological regions included in the study. Furthermore, the equal distribution between the two coefficient classes suggests that both moderate and relatively strong regression relationships are widely represented across the sampled regions.

These findings are consistent with the results of the correlation and Laplace-function analyses, which identified the livestock sector as one of the agricultural components most strongly associated with long-term temperature variability.

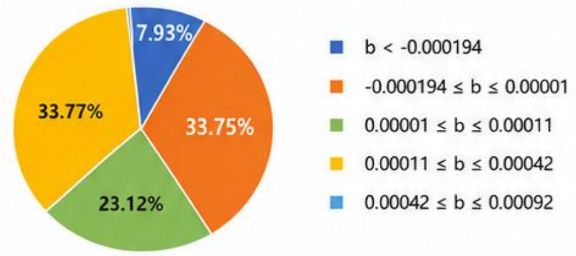


Figure 15. Estimated spatial distribution of regression-coefficient classes for crop production (total)

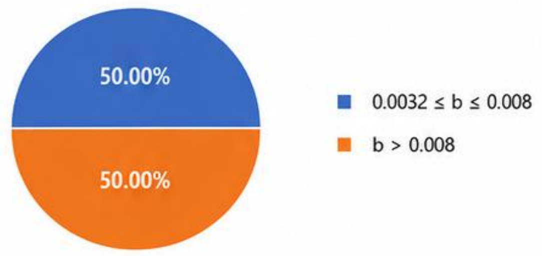


Figure 16. Estimated spatial distribution of regression-coefficient classes for large livestock

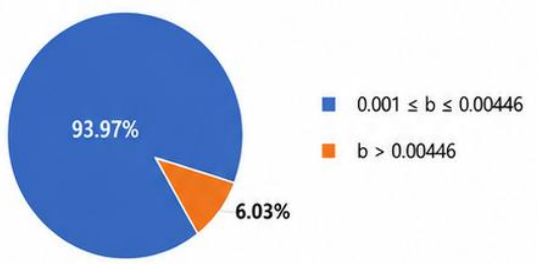


Figure 17. Estimated spatial distribution of regression-coefficient classes for small livestock

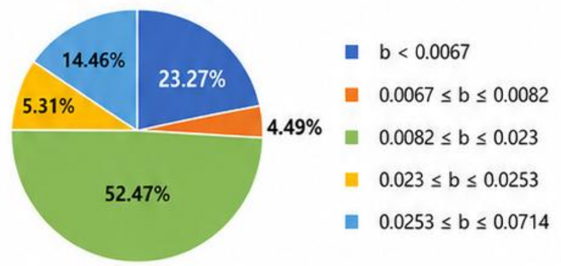


Figure 18. Estimated spatial distribution of regression-coefficient classes for horses

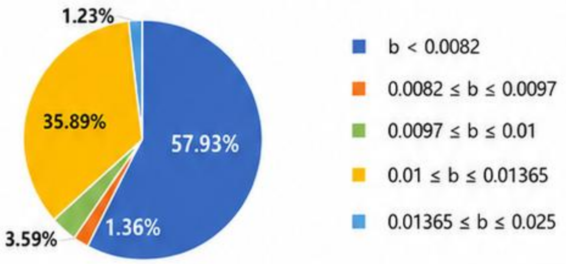


Figure 19. Estimated spatial distribution of regression-coefficient classes for cattle

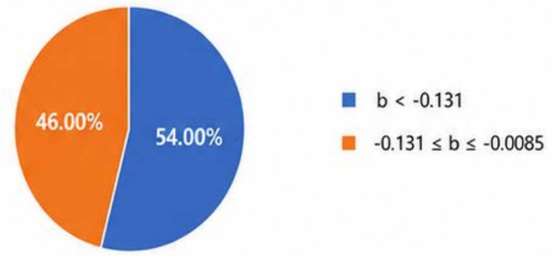


Figure 20. Estimated spatial distribution of regression-coefficient classes for camels

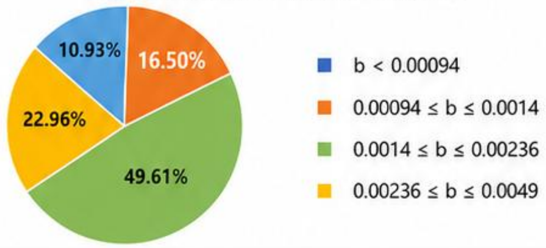


Figure 21. Estimated spatial distribution of regression-coefficient classes for sheep

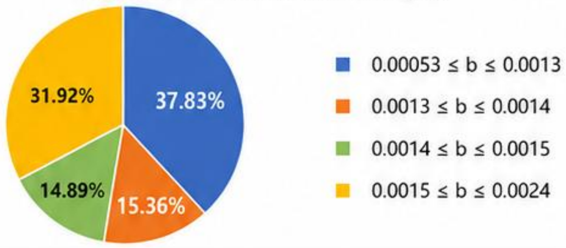


Figure 22. Estimated spatial distribution of regression-coefficient classes for goats

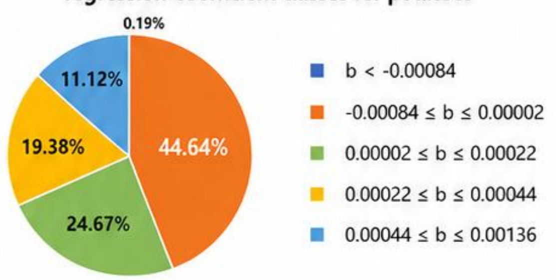


Figure 23. Estimated spatial distribution of regression-coefficient classes for potatoes

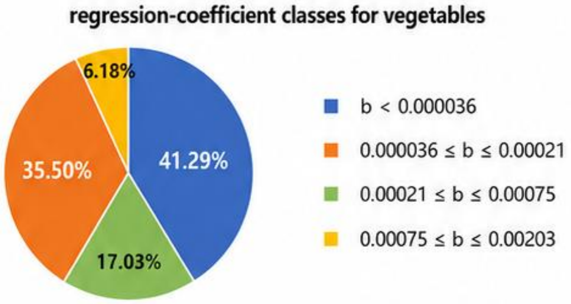


Figure 24. Estimated spatial distribution of regression-coefficient classes for vegetables

Note: b-regression coefficient (slope). The percentage indicate the estimated proportion of the total territory represented by each regression-coefficient class.

Table 6

Estimated spatial distribution of regression-coefficient classes derived from Laplace-function analysis

Agricultural Sector		Regression Coefficient				
		Subsector	**Inverse**	**Low**	**Moderate**	**High**
Crop Production	Potatoes	0.2%	44.64%	24.67%	19.38%	11.12%
	Vegetables	NA	41.29%	17.03%	35.5%	6.18%
Crop Production Total		7.93%	33.75%	23.12%	33.77%	1.43%
Livestock	Horses	NA	23.27%	4.49%	57.78%	14.46%
	Cattle	NA	6.18%	35.89%	57.93%	NA
	Camels	54%	46%	NA	NA	NA
	Sheep	NA	27.43%	49.61%	22.96%	NA
	Goats	NA	37.83%	15.36%	14.89%	31.92%
	Large Livestock	NA	50%	50%	NA	NA
	Small Livestock	NA	NA	93.7%	6.03%	NA
Livestock Total		NA	50%	50%	NA	NA

According to Table 6, substantial variation exists among agricultural indicators in the spatial distribution of regression-coefficient classes. Vegetable production, horse populations, and goat populations exhibit relatively large proportions within the high-regression category, indicating stronger positive statistical associations with annual average air temperature than many other agricultural indicators.

Cattle (57.9%) and horse populations (57.8%) exhibited the largest proportions within the high-regression class. Goat populations showed a more heterogeneous distribution, with substantial proportions occurring in both low- and high-regression classes. In contrast, camel populations were characterized predominantly by inverse relationships, consistent with the negative correlations observed in the previous analyses.

Overall, the regression analysis supports the findings of the correlation and Laplace-function analyses, indicating that livestock-related indicators generally exhibit stronger statistical associations with annual average air temperature than crop-production indicators.

Conclusions

This study investigated the statistical relationships between agricultural indicators and annual average air temperature in Mongolia using long-term datasets covering the period 1975–2024. By integrating correlation analysis, linear regression analysis, probability distribution theory, and Laplace-function-based spatial representation, the study evaluated the strength and spatial distribution of associations between agricultural activities and temperature variability across representative agro-ecological regions of Mongolia.

The results revealed that livestock-related indicators generally exhibited stronger associations with annual average air temperature than crop-production indicators. Among the livestock categories, goat populations, small livestock populations, and total livestock population exhibited the strongest average correlations with annual average air temperature and the largest spatial representation within the strong-correlation classes. In contrast, crop-production indicators were predominantly concentrated within weak-to-moderate correlation categories.

Regression analysis further supported these findings. Horse populations, goat populations, and vegetable production displayed relatively large proportions within the high-regression classes, indicating stronger positive statistical relationships with annual average air temperature than many other agricultural indicators. In contrast, camel populations exhibited predominantly inverse relationships, suggesting a different pattern of association with long-term temperature variability.

The Laplace-function analysis provided a spatial interpretation of the observed statistical relationships by estimating the distribution of correlation and regression classes across Mongolia's representative agricultural regions. The results suggest that livestock-related variables, particularly goat populations and small livestock populations, exhibit broader and stronger spatial associations with long-term temperature variability than crop production variables.

Based on the estimated statistical relationship between annual average air temperature and agricultural greenhouse gas emissions ($y = 4695.6x$), agricultural indicators exhibiting stronger associations with temperature variability may also be associated with higher estimated greenhouse gas emissions. In particular, goat populations, horse populations, and vegetable production demonstrated the strongest combined temperature and regression relationships among the indicators analyzed.

Overall, the findings highlight the importance of considering livestock dynamics when evaluating agriculture–environment interactions in Mongolia. The methodological framework developed in this study, combining correlation analysis, regression analysis, probability distribution theory, and Laplace-function-based spatial representation, provides a useful approach for investigating long-term agricultural–climate relationships and may support future environmental assessment, climate change mitigation planning, and sustainable agricultural policy development.

Author's Contribution

E.Ya. collected and compiled the agricultural and climatic data, performed the statistical analyses (distribution testing, correlation, regression, and Laplace-function computations), and drafted the manuscript. Ts.D. conceived and supervised the study, developed the statistical and mathematical framework, contributed to the interpretation of the results, and critically revised the manuscript for important intellectual content. Both authors read and approved the final manuscript.

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