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Climate-Water Nexus and Livestock Production: Unraveling Dynamic Interactions in Pakistan

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Abstract

Pakistan's livestock sector is increasingly exposed to climate variability and water insecurity, yet the dynamic relationship between environmental conditions and livestock production remains insufficiently understood. This study examines the long-run and short-run effects of climate variability, water availability, and key socioeconomic and agricultural factors on livestock production in Pakistan. Using annual time-series data, the study employs the Augmented Dickey-Fuller and Phillips-Perron unit-root tests, followed by Johansen cointegration analysis and a Vector Error Correction Model (VECM) to capture both equilibrium relationships and short-run adjustments. The results reveal significant long-run relationships among livestock production, temperature, precipitation, water availability, forest area, cropped area, population, and inflation. Temperature and inflation negatively affect livestock production, whereas precipitation, water availability, forest area, and cropped area exert positive effects. Water availability demonstrates a particularly important positive association in both the long and short run. The significant negative error-correction coefficient indicates that approximately 59.5% of short-run disequilibrium is corrected within one period, confirming relatively rapid adjustment toward long-run equilibrium. The findings highlight the need for climate-resilient livestock policies, improved water-resource management, sustainable land use, and adaptive agricultural strategies to strengthen Pakistan's livestock production under increasing climatic and resource pressures.

Keywords: Climate Variability, Water Insecurity, Livestock Production, Pakistan, Vector Error Correction Model (VECM)

1. Introduction

Livestock production is a critical component of agricultural development, food security, rural livelihoods, and economic resilience, particularly in developing economies, where livestock provides income, nutrition, employment, and productive assets for rural households (Molina-Flores et al., 2022; Band & Tanganyika, 2021; Tiny et al., 2026). Globally, the livestock sector increasingly faces the dual challenge of meeting rising demand for animal-source foods while operating under growing environmental and climatic constraints (Morales et al., 2026). The Food and Agriculture Organization of the United Nations (2026) emphasizes that livestock systems contribute substantially to food security, nutrition, poverty reduction, and economic development, while simultaneously placing pressure on land, water, biodiversity, and the climate system. The livestock industry is essential to achieving several 'Sustainable Development Goals (SDGs)'. For example, it contributes to nutritious meals, revenue generation, livelihood assistance, and climate resilience. Livestock-related externalities include biodiversity loss, land degradation, and Climate Change (CC). To pursue the '2030 Agenda for Sustainable Development', member states must establish policies and an enabling environment to reduce the effects of climate change. Consequently, improving livestock productivity while strengthening the resilience of production systems has become an important component of sustainable agricultural development (Abdel-Wareth et al., 2026).

Climate variability has become a serious challenge for livestock production as it impacts livestock in several interrelated ways, including changes in temperature and precipitation (Birhanu & Destaw, 2026). Rising temperatures can cause heat stress, which reduces feed intake and productivity, harms reproduction, increases disease susceptibility, and raises the risk of death (Cheng et al., 2022; Jongbo et al., 2026; Mićić et al., 2025). Meanwhile, alterations in precipitation, droughts, floods, and extended dry spells may affect the availability of feed and water (Asghar et al., 2025). Previous research indicates that livestock are also affected indirectly by climate change through reduced-quality feed, reduced water availability, increased disease, declining land productivity, and changes in the broader livestock supply chain (Thornton et al., 2009; Rojas-Downing et al., 2017; Godde et al., 2021).

Among the various transmission mechanisms between climate and livestock productivity, water availability is highly significant (Mabhaudhi et al., 2025; Feleke et al., 2025). Water is used directly for drinking and cooling livestock, and a large amount is also used in the production of feed and other inputs (Wisser et al., 2024). Climate-induced warming can increase animals' water needs and, in turn, reduce water supply and inhibit livestock production and feed cultivation. Water availability is one of the most important ways climate change affects livestock systems, as noted by Rojas-Downing et al. (2017), and Mekonnen et al. (2016) highlight the need to consider water resources when assessing livestock production systems. Therefore, studying climatic variables alone may only partially explain the effects of climate variability on livestock production. However, these challenges are especially significant for Pakistan, where agriculture accounts for a large share of the economy and livestock dominates agricultural value added. The livestock sector contributes about 62% of Pakistan's agriculture and about 14% of national GDP (FAO, 2026), underscoring its importance to the overall economy. Livestock is also strongly linked to rural livelihoods, household income, food security, and agricultural production systems. As such, livestock productivity disruptions can affect more than food production, including rural livelihoods, food security, jobs, and economic resilience.

Pakistan is also one of the most climate-risk countries. The country is experiencing rising temperatures (TEMP) and climate-related pressures such as rainfall variability, recurrent floods, and droughts (Adnan et al., 2026). These changes pose hazards to agriculture and livestock production, as climate and weather play a significant role in livestock production, which is dependent on natural resources, water, and feed. (Edewor et al., 2026). FAO has declared Pakistan as one of the most climate-change-vulnerable countries and has also found that the changing climate and related impacts, including rising temperatures, fluctuations in precipitation, flooding, droughts, and glacier melt, have a strong influence on food and water security and the livelihoods of the rural population. In addition, livestock is a significant source of agricultural 'greenhouse gas emissions', meaning climate change threatens the agricultural sector while also contributing to the climate challenge (FAO, 2026). The importance of climatic conditions for livestock systems is further highlighted by the empirical evidence from Pakistan. The studies conducted in Punjab reveal that dairy farmers have been adversely affected by climate change, and they have identified climate stresses, such as increases in temperature and changes in rainfall patterns, water stress, and changes in weather, as major issues for livestock production (Haider et al., 2025; Abbas et al., 2025; Abbas et al., 2022). There has also been some research in Pakistan that has found that shifts in temperature and rainfall can have significant impacts on agriculture in a more general sense (Fahad & Wang, 2020); increases in temperature have been associated with negative outcomes for agriculture (Ali et al., 2017), while increases in rainfall have been associated with a variety of positive and negative outcomes across production systems (Gul et al., 2022). More recent findings from Punjab also suggest significant impacts of climatic stress on dairy production, further underscoring the importance of climate-smart livestock policies (Haider et al., 2025).

Even with this growing evidence, an important empirical question remains unanswered. The current literature overwhelmingly focuses on individual climatic variables, specific livestock products (including milk), farmer perceptions, or specific geographic areas. The relationship between climate variability, water availability, resource constraints, and aggregate livestock production, including short-term adjustment dynamics and long-term equilibrium, in the context of Pakistan has been comparatively limited. This distinction matters because climatic shocks are not felt instantly. Temperature, precipitation, water availability, cultivated land, and forest resources can affect livestock production through cumulative and interconnected short- and long-term effects. Therefore, a purely short-run analysis may not capture the importance of long-run relationships, and a long-run analysis alone may not capture short-term adjustments in response to climatic and/or economic shocks. Also, livestock production is not independent of other socioeconomic and resource factors. Population changes can also increase demand for livestock products and affect land and water resources, and cropped area affects the availability of agricultural residues and feed resources. Forest resources may also support ecosystem services and livestock-supporting resources, while macroeconomic factors, like inflation, can affect the cost and availability of livestock inputs. Therefore, an integrated empirical framework that accounts for climatic, natural-resource, demographic, and macroeconomic determinants can support a more holistic analysis of the factors influencing livestock production in Pakistan.

In this light, the present study explores the linkages between climate variability, water availability, resource conditions and livestock production in Pakistan in a dynamic manner. In particular, the study involves an examination of the relationship of temperature and precipitation to livestock production in the long run and the short run, as well as an examination of the importance of water availability as a production resource and the importance of cropped area, forest area, population, and inflation as part of the livestock-production system. Using a multivariate time-series approach, the study identifies short-run adjustments and long-run equilibrium relationships based on annual data for Pakistan over the study period. This approach is especially relevant because livestock and climate dynamics may differ under long-term climate change from short-term climatic events.

The study has three major contributions to the literature. First, it builds on the Pakistan-specific literature by considering climate variables and resources together, not as separate entities. Second, water availability is explicitly incorporated with temperature and precipitation, representing the resource-mediated pathway by which climate variability can impact livestock production. Third, the study distinguishes between long-run linkages and short-run dynamics and presents a more advanced understanding of the effects of the climatic and socio-economic stresses on the livestock sector in Pakistan. The contributions are useful for developing policies that seek to sustain livestock production and enhance the resilience and resource use efficiency of livestock systems under growing climatic uncertainty. The results will have significant implications for water resource management, livestock development, and agricultural policies in Pakistan in the context of climate adaptation. Considering livestock's response to thermal stress, water security, feed and land resources, and overall socioeconomic conditions is key for policy interventions to enhance livestock resilience, given the economic and livelihood importance of the sector. This integrated approach is in line with FAO's priorities to make livestock systems more productive, resilient, resource-efficient, and environmentally friendly.

The study, therefore, seeks to answer the following research objectives:

1. To examine the long-run relationship between climate variability and livestock production in Pakistan.
2. To assess the short-run effects of temperature and precipitation on livestock production.
3. To investigate the role of water availability and other natural-resource conditions in determining livestock production.
4. To examine how demographic and macroeconomic conditions interact with climatic and resource factors in shaping livestock production.
5. To distinguish long-run equilibrium relationships from short-run adjustment dynamics and derive policy implications for climate-resilient livestock development in Pakistan.

2. Related Literature

Climate variability is now a significant challenge to agricultural production, especially in livestock-dependent economies where natural resources and climatic conditions play a critical role in agricultural activities (Thornton et al., 2014). In addition to the direct impact of heat stress, rising temperatures, altered precipitation patterns, repeated droughts, floods, and increased occurrence of extreme weather events have a cascading effect on livestock production by impacting feed availability, water availability, diseases, and grazing resources (Laghari et al., 2025; Assan, 2023). The Intergovernmental Panel on Climate Change (IPCC) identified agriculture as one of the sectors most vulnerable to climate change, and noted that impacts will vary depending on an area's climatic exposure, resources, and adaptive capacity. Livestock systems are therefore considered climate-sensitive production systems in which environmental variability can directly affect productivity and household welfare (Bashiru et al., 2025).A large and diverse literature shows direct and indirect links between temperature and precipitation variability and livestock productivity (Escarcha et al., 2018; Cheng et al., 2022; Baumgard et al., 2012). Heat stress can affect feed intake, fertility, potential growth rate, milk production, animal survival, and the long-term geographic suitability of livestock systems (Thornton et al., 2009; Rojas-Downing et al., 2017). Thornton et al. (2009) note that climate change can affect livestock in several ways: changes in feed resources, water availability, livestock health, and production conditions. Similarly, Rojas-Downing et al. (2017) show that climate change severely affects livestock health through heat stress and impacts on forage quality, water availability, and exposure to climate-sensitive diseases. Results show that average climatic conditions, as well as the variability and intensity of climatic shocks, affect livestock production.

Water security is another key link between climate variability and livestock production (Matondo et al., 2026). Livestock need a constant water supply for drinking, and water is also required to make fodder and maintain pasture ecosystems. This can create a double burden on livestock systems, as climate-induced decreases in water availability can affect not only direct water use but also feed resources. Mekonnen and Hoekstra (2012) highlight the high-water requirements of livestock production and the importance of water resources in the production process. Further, water shortages can restrict livestock production in water-stressed regions where water needs for domestic, agricultural, industrial and ecological purposes are increasing. Water security is thus not just an environmental objective, but also an integral part of agricultural resilience (Keys et al., 2019).

Water availability and livestock productivity are particularly important in developing countries, where livestock producers are typically highly dependent on rains and lack access to irrigation water, water-storing facilities, better breeds, veterinary services, or financial markets. Herrero et al. (2010) find that the climate-related risks are particularly high for livestock systems in developing areas, as they depend on natural resources and have low adaptive capacity. During drought, climate variability can reduce pasture productivity and increase livestock mortality, whereas during periods of excess rain and flooding, pasture productivity can decline and disease risks can increase (Bogale et al., 2022). As a result, climatic shocks may affect production systems, regions, and farm households differently (Adeke et al., 2026). The literature also highlights that adaptive capacity plays an important role in the size of climate-related losses. Adaptation methods encompass selecting better livestock breeds, alternative management of livestock (reduction in livestock numbers, rotation, etc.), supplementary feeding, pasture management, water harvesting, alternative methods of water supply (irrigation), livestock mobility, diversification of income sources, and improved access to climate information, among others (Priyashantha et al., 2026). According to Seo and Mendelsohn (2008), livestock farmers can mitigate some negative economic impacts of climate change by choosing livestock species and production systems that adapt to climate conditions. But the effectiveness of adaptation depends on the availability of financial resources, technology, institutions, infrastructure and information. This highlights the importance of socioeconomic and institutional factors influencing biophysical climate/livestock production linkages as well.

In a country like Pakistan, where livestock production, rural livelihoods and agriculture systems are closely intertwined, these issues are important in other water-scarce South Asian economies as well. Climate variability seen in the region encompasses greater variability in precipitation, increased temperatures, droughts, and frequent floods. These shocks may have a negative impact on livestock production, such as pasture and crop residues, livestock infrastructure, water quality and animal health. The livestock-based communities are very sensitive to the extreme climatic events and the recent flooding in Pakistan has resulted in huge loss of livestock and agricultural assets. The importance of these risks is that livestock is a major part of the agricultural economy, rural livelihoods, food security, and rural resilience. This study then focuses on the most relevant topic that has policy implications. The study can be combined with water security to assess if there is a buffer against adverse impacts of climatic shocks on livestock production with increased water availability and water management. This is particularly relevant in the context of developing countries facing increasing climate and water stresses. The evidence that emerges can contribute to policies on climate-resilient livestock systems, sustainable water management, strengthening of irrigation and water storage systems, climate smart livestock systems and specific adaptation measures for vulnerable farming communities.

3. Methodology and Data

The study used a time-series dataset from 1980-2024, drawing on data from the World Development Indicators and the Economic Survey of Pakistan. The study variables include livestock production, annual mean temperature, annual mean precipitation, water, cropped area, forest area, inflation, and population. The figure below shows the study's conceptual framework.

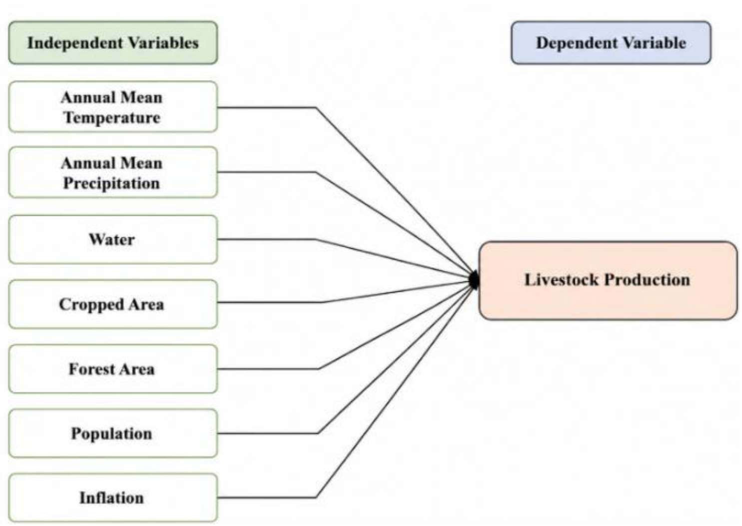

Figure 1: Conceptual framework

3.1. Econometric Model Specification

The following econometric model was used to establish the relationship among livestock production, annual mean temperature, annual mean precipitation, water, cropped area, forest area, inflation, and population. This econometric model is flexible and fits the economic estimation (Karlsson, 2013) and can be specified as:

$$\mathbf{y_t} = (\mathbf{LP_t}) = \mathbf{f}(\mathbf{TEMP_t}, \mathbf{PREP_t}, \mathbf{WT_t}, \mathbf{CA_t}, \mathbf{FA_t}, \mathbf{POP_t}, \mathbf{INF_t}) \quad (1)$$

Equation (1) clearly states that $\mathrm{TEMP_t}$ denotes temperature, $\mathrm{PREP_t}$ indicates precipitation as a proxy for rainfall, $\mathrm{WT_t}$ shows water, $\mathrm{CA_t}$ stands for cropped area, $\mathrm{FA_t}$ means forest area, $\mathrm{POP_t}$ indicates population and $\mathrm{INF_t}$ shows inflation. The t in the equation stands for the time dimension.

The econometric specification of equation (1) can be written as under

$$(\mathrm{LP_t}) = \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \gamma_4 \\ \gamma_5 \\ \gamma_6 \\ \gamma_7 \end{bmatrix} + \sum_{i=1}^{k} \begin{bmatrix} \varsigma_{11} & \varsigma_{12} & \varsigma_{13} & \varsigma_{14} & \varsigma_{15} \\ \varsigma_{21} & \varsigma_{22} & \varsigma_{23} & \varsigma_{24} & \varsigma_{25} \\ \varsigma_{31} & \varsigma_{32} & \varsigma_{33} & \varsigma_{34} & \varsigma_{35} \\ \varsigma_{41} & \varsigma_{42} & \varsigma_{43} & \varsigma_{44} & \varsigma_{45} \\ \varsigma_{51} & \varsigma_{52} & \varsigma_{53} & \varsigma_{54} & \varsigma_{55} \\ \varsigma_{61} & \varsigma_{62} & \varsigma_{63} & \varsigma_{64} & \varsigma_{65} \\ \varsigma_{71} & \varsigma_{72} & \varsigma_{73} & \varsigma_{74} & \varsigma_{75} \end{bmatrix} \begin{bmatrix} LNTemp_{i-1} \\ LNPREP_{i-1} \\ LNWT_{i-1} \\ LNCA_{i-1} \\ LNFA_{i-1} \\ LNPOP_{i-1} \\ LNINF_{i-1} \end{bmatrix} + \begin{bmatrix} \epsilon_{1t} \\ \epsilon_{2t} \\ \epsilon_{3t} \\ \epsilon_{4t} \\ \epsilon_{5t} \\ \epsilon_{6t} \\ \epsilon_{7t} \end{bmatrix} \quad (2)$$

In equation (2) t= time dimensions, Ln=natural log, γ_i =matrix of the autoregressive (AR), ϵ_t= residual matrix. VAR(k) model is considered as

$$Z_t = \vartheta_i + \sum_{i=1}^{k} \beta_i X_{t-1} + \epsilon_t \quad (3)$$

The above equation (3), $\mathrm{X_{t-1}}$=nY1 indicates the vector of independent variables, β=nYn indicate the matrix of the autoregressive coefficient for l=1……k, ϑ= intercept vector, ϵ= error term. To examine the relationship between the variables, the econometric specification is written as below.

$$\Delta\mathrm{lnLP_t} = \alpha_0 + \sum_{h=1}^{e-1} \alpha_1 \Delta\mathrm{lnLP_{t-n}} + \sum_{h=1}^{e-1} \alpha_1 \Delta\mathrm{lnTEMP_{t-n}} +$$
$$\sum_{h=1}^{e-1} \alpha_2 \Delta\mathrm{lnPREP_{t-n}} + \sum_{h=1}^{e-1} \alpha_3 \Delta\mathrm{lnWT_{t-n}} + \sum_{h=1}^{e-1} \alpha_4 \Delta\mathrm{lnCA_{t-n}} + \sum_{h=1}^{e-1} \alpha_5 \Delta\mathrm{lnFA_{t-n}} + \sum_{t=1}^{e-1} \alpha_6 \Delta\mathrm{POP_T} +$$
$$\sum_{h=n}^{e-1} \alpha_7 \Delta\mathrm{INF_{t-N}} + \lambda_1 \Delta\mathrm{ECT_{t-1}} + \mu_t \quad (4)$$

$$\Delta\mathrm{lnTEMP_t} = \alpha_0 + \sum_{h=1}^{e-1} \xi_i \Delta\mathrm{lnTEMP_{t-n}} + \sum_{h=1}^{e-1} \xi_i \Delta\mathrm{lnLP_{t-n}} +$$
$$\sum_{h=1}^{e-1} \xi_i \Delta\mathrm{lnPREP_{t-n}} + \sum_{h=1}^{e-1} \xi_i \Delta\mathrm{lnWT_{t-n}} + \sum_{h=1}^{e-1} \xi_i \Delta\mathrm{lnCA_{t-n}} + \sum_{h=1}^{e-1} \xi_i \Delta\mathrm{lnFA_{t-n}} + \sum_{t=1}^{e-1} \xi_i \Delta\mathrm{POP_T} +$$
$$\sum_{h=n}^{e-1} \xi_i \Delta\mathrm{INF_{t-N}} + \lambda_2 \Delta\mathrm{ECT_{t-1}} + \mu_t \quad (5)$$

$$\Delta\mathrm{lnPREP_t} = \alpha_0 + \sum_{h=1}^{e-1} \varpi_i \Delta\mathrm{lnPREP_t} + \sum_{h=1}^{e-1} \varpi_{i_i} \Delta\mathrm{lnTEMP_{t-n}} +$$
$$\sum_{h=1}^{e-1} \varpi_i \Delta\mathrm{lnLP_{t-n}} + \sum_{h=1}^{e-1} \varpi_{i_i} \Delta\mathrm{lnWT_{t-n}} + \sum_{h=1}^{e-1} \varpi_i \Delta\mathrm{lnCA_{t-n}} + \sum_{h=1}^{e-1} \varpi_i \Delta\mathrm{lnFA_{t-n}} + \sum_{t=1}^{e-1} \varpi_i \Delta\mathrm{POP_T} +$$
$$\sum_{h=n}^{e-1} \varpi_i \Delta\mathrm{INF_{t-N}} + \lambda_3 \Delta\mathrm{ECT_{t-1}} + \mu_t \quad (6)$$

$$\Delta\mathrm{lnWT_t} = \alpha_0 + \sum_{h=1}^{e-1} \eta_i \Delta\mathrm{lnWT_{t-n}} + \sum_{h=1}^{e-1} \eta_i \Delta\mathrm{lnPREP_t} + \sum_{h=1}^{e-1} \eta_i \mathrm{lnTEMP_{t-n}} +$$
$$\sum_{h=1}^{e-1} \eta_i \Delta\mathrm{lnLP_{t-n}} + \sum_{h=1}^{e-1} \eta_i \Delta\mathrm{lnCA_{t-n}} + \sum_{h=1}^{e-1} \eta_i \Delta\mathrm{lnFA_{t-n}} + \sum_{t=1}^{e-1} \eta_i \Delta\mathrm{POP_T} +$$
$$\sum_{h=n}^{e-1} \eta_i \Delta\mathrm{INF_{t-N}} + \lambda_4 \Delta\mathrm{ECT_{t-1}} + \mu_t \quad (7)$$

$$\Delta \ln CA_t = \alpha_0 + \sum_{h=1}^{e-1} \varphi_i \Delta \ln CA_{t-n} + \sum_{h=1}^{e-1} \varphi_i \Delta \ln PREP_t + \sum_{h=1}^{e-1} \varphi_i \Delta \ln TEMP_{t-n} + \sum_{h=1}^{e-1} \varphi_i \Delta \ln LP_{t-n} + \sum_{h=1}^{e-1} \varphi_i \Delta \ln WT_{t-n} + \sum_{h=1}^{e-1} \varphi_i \Delta \ln FA_{t-n} + \sum_{t=1}^{e-1} \varphi_i \Delta POP_T + \sum_{h=n}^{e-1} \varphi_i \Delta INF_{t-N} + \lambda_5 \Delta ECT_{t-1} + \mu_t \quad (8)$$

$$\Delta \ln FA_t = \alpha_0 + \sum_{h=1}^{e-1} \psi_i \Delta \ln FA_{t-n} + \sum_{h=1}^{e-1} \psi_i \Delta \ln CA_{t-n} + \sum_{h=1}^{e-1} \psi_i \Delta \ln PREP_t + \sum_{h=1}^{e-1} \psi_i \Delta \ln TEMP_{t-n} + \sum_{h=1}^{e-1} \psi_i \Delta \ln LP_{t-n} + \sum_{h=1}^{e-1} \psi_i \Delta \ln WT_{t-n} + \sum_{t=1}^{e-1} \psi_i \Delta POP_T + \sum_{h=n}^{e-1} \psi_i \Delta INF_{t-N} + \lambda_6 \Delta ECT_{t-1} + \mu_t \quad (9)$$

$$\Delta \ln POP_t = \alpha_0 + \sum_{t=1}^{e-1} \rho_i \Delta POP_T + \sum_{h=1}^{e-1} \rho_i \Delta \ln FA_{t-n} + \sum_{h=1}^{e-1} \rho_{i_i} \Delta \ln CA_{t-n} + \sum_{h=1}^{e-1} \rho_i \Delta \ln PREP_t + \sum_{h=1}^{e-1} \rho_{i_i} \Delta \ln TEMP_{t-n} + \sum_{h=1}^{e-1} \rho_i \Delta \ln LP_{t-n} + \sum_{h=1}^{e-1} \rho_i \Delta \ln WT_{t-n} + \sum_{t=1}^{e-1} \rho_i \Delta POP_T + \sum_{h=n}^{e-1} \rho_i \Delta INF_{t-N} + \lambda_7 \Delta ECT_{t-1} + \mu_t \quad (10$$

$$\Delta \ln INF_t = \alpha_0 + \sum_{h=n}^{e-1} \varrho_i \Delta INF_{t-N} + \sum_{h=1}^{e-1} \varrho_i \Delta POP_{t-n} + \sum_{h=1}^{e-1} \varrho_i \Delta \ln FA_{t-n} + \sum_{h=1}^{e-1} \varrho_i \Delta \ln CA_{t-n} + \sum_{h=1}^{e-1} \varrho_i \Delta \ln PREP_t + \sum_{h=1}^{e-1} \varrho_i \Delta \ln TEMP_{t-n} + \sum_{h=1}^{e-1} \varrho_i \Delta \ln LP_{t-n} + \sum_{h=1}^{e-1} \varrho_i \Delta \ln WT_{t-n} + \sum_{h=n}^{e-1} \varrho_i \Delta INF_{t-N} + \lambda_8 \Delta ECT_{t-1} + \mu_t \quad (11)$$

In equations (4-11) above, the optimal lag is reduced by 1, as indicated by b-1. $\alpha, \xi, \varpi, \eta, \varphi, \psi$, ρ and ϱ demonstrated the coefficients for short-run dynamics for adjustment in the model. Similarly, λ_1 expressed the level of change parameter, and ECT displays the error correction term.

4. Results And Discussions

We have started from analyzing descriptive statistics, correlation, unit root test below section describes one by one the systematic procedure of results analysis.

4.1. Descriptive Statistics, Correlation Analysis and Unit Root

Table 1: Descriptive statistics

	LP	POP	WT	TEMP	PREP	INF	CA	FA
Mean	29.288	18.829	97.582	104.756	86.953	162.041	178.0742	173.904
Median	30.376	18.885	96.766	104.677	90.041	160.856	179.945	183.576
Maximum	51.850	19.2785	99.922	109.502	131.223	343.627	255.090	225.399
Minimum	11.307	18.2053	96.421	99.507	53.777	42.844	93.224	97.909
Std. Dev.	9.9192	0.3202	1.290	2.7391	17.844	58.252	48.675	39.912
Skewness	-0.062	-0.359	0.652	-0.160	0.115	0.886	-0.302	-0.7793
Kurtosis	2.490	1.889	1.787	2.140	2.385	5.427	1.682	2.317
Jarque-Bera	0.492	3.134	5.687	1.507	0.771	16.188	3.763	5.18671
Probability	0.781	0.2086	0.0582	0.470	0.679	0.000	0.152	0.074
Sum	1259.425	809.678	4196.046	4504.529	3738.986	6967.763	7657.191	7477.884
Observations	45	45	45	45	45	45	45	45

Descriptive statistics are presented in Table 1. Overall, most of these variables are reasonably well spread and have roughly normal distributions. Again, the Jarque-Bera probabilities of LP, POP, TEMP, PREP, CA, and FA are greater than 0.05. Only INF is clearly inconsistent with the normality assumption, with a probability of 0.000. There is generally little difference between the means and medians, except for PREP, INF, and FA, where the dispersion or skewness is relatively large. Descriptive statistics help provide a first impression of the data before further econometric analysis. Similarly, Table 2 presents the correlation matrix among the variables (namely livestock production, population, water, mean annual temperature, mean annual precipitation, inflation, cropped area, and forest area). All variables selected for the study show dynamic correlation.

Table 2: Correlation Matrix

	LP	POP	WT	TEMP	PREP	INF	CA	FA
LP	1							
POP	-0.617	1						
WT	0.530	0.428	1					
TEMP	-0.351	-0.703	-0.594	1				
PREP	0.282	0.056	0.049	0.191	1			
INF	-0.541	-0.008	-0.149	-0.0777	0.4043	1		
CA	0.304	0.566	0.443	0.301	0.089	0.091	1	
FA	0.503	0.506	0.424	0.219	-0.057	0.0581	0.498	1

The findings of the ‘Phillips-Perron (PP)’ and ‘Augmented Dickey-Fuller (ADF)’ unit root tests on the research variables are shown in Table 3. The results suggest that all the variables are non-stationary at levels since the reported probability values are mostly above the 5% significance level. However, after taking first differences, both ADF and PP tests yield statistically significant p-values ($p < 0.05$) for all variables, implying that the unit-root hypothesis is rejected. Hence, LP, POP, WA, TEMP, PREP, INF, CA and FA are integrated of I (1). Importantly, none of the variables are found to be I (2) variables, indicating that Johansen cointegration test and VECM framework is applicable.

Table 3: Unit root test

Variables	ADF (Prob)		PP(Prob)	
	I (0) **With trend**	I (1) **Without Trend**	I (0) **With trend**	I (1) **Without Trend**
LP	0.751	0.008	0.377	0.000
POP	0.793	0.006	0.865	0.020
WA	0.750	0.0000	0.795	0.000
TEMP	0.110	0.0000	0.119	0.000
PREP	0.319	0.0000	0.256	0.0000
INF	0.218	0.0000	0.105	0.0000
CA	0.773	0.0000	0.661	0.0000
FA	0.140	0.0000	0.791	0.0000

4.2. Optimal Lag Determination and Cointegration Tests for the Model

Lütkepohl (2006) Studied that AIC usually gives better and more consistent information for lag selection. The study chose an acceptable lag order using the vector autoregression (VAR) model's optimal lag order. The study used VAR (3), which makes sense for this investigation. This is because a lag that is too small could misspecify the model. In contrast, an extremely long lag order may reduce degrees of freedom.

Table 4: Lag Selection Criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-316.700	NA	3.59e+10	-15.058	-14.724	14.936
1	631.8174	491.891*	2.02e-22*	-27.308*	-24.298*	-26.212*
2	694.9558	73.9181	3.04e-22	-27.266	-21.582	-25.196

4.3. Johansen Cointegration Tests for the Model

After selecting an appropriate lag order for VAR, the next step is to run the Johansen cointegration (Johansen & Juselius, 1990) tests using the maximal eigenvalue and trace test stochastic matrices as in Table 5. The Johansen cointegration test measures the strength of long-term co-integrating interaction among the variables. In the table, the trace and max-eigenvalue statistics exceed the critical value at the 5% significance level, indicating a long-run co-integration relationship among the variables. In the short run, deviations from the equilibrium point are correlated. The variables exhibit causal and long-term co-relationship. Therefore, the Vector Error Correction Model (VECM) is the most appropriate method.

Table 5: Johansen cointegration tests

Hypothesized no of CE(s)	**Trace statistics**			**Hypothesized no of CE(s)**	**Maximum eigen- value statistics**		
	t-stats	**0.05 critical value**	**p-value**		**t-stats**	**0.05 critical value**	**p-value**
None	438.814	159.529	0.000	**None**	235.234	52.362	0.000
At most 1	203.580	125.615	0.000	**At most 1**	78.577	46.231	0.000
At most 2	125.002	95.753	0.000	**At most 2**	40.276	37.077	0.100
At most 3	87.725	69.818	0.001	**At most 3**	33.833	31.876	0.086
At most 4	55.892	47.856	0.007	**At most 4**	27.987	26.584	0.059
At most 5	28.904	29.797	0.063	**At most 5**	16.056	21.131	0.221
At most 6	15.848	12.494	0.120	**At most 6**	12.109	14.264	0.106
At most 7	5.738	3.84	0.390	**At most 7**	0.738	3.841	0.3900

4.4.Vector Error Correction (VECM) Estimation

Table 5 shows the VECM estimates, which indicate significant long-run and short-run relationships between livestock production (LP) and climate, water, demographic, and agricultural factors in Pakistan. The statistically significant negative error correction term is COINTEQ (-0.595), indicating a stable adjustment process toward long-run equilibrium. Specifically, approximately 59.5% of the previous period's disequilibrium in livestock production is corrected within one period, or there is relatively fast convergence to the long-run equilibrium in livestock production. The negative and significant value of the vector error correction term suggests that the model is suitable for future simulation and policy recommendations (Rehman et al., 2021). The negative and significant error correction coefficient is an important characteristic of the stable adjustment process in the VECM framework (Engle & Granger, 1987; Johansen, 1995). This result supports the VECM framework for analyzing the dynamic interaction between the livestock production sector and the forest area. Forest area (FA) exhibited a positive and statistically significant relationship with livestock production in the long run which suggests that more forest resources may provide ecosystem services that increase livestock production, such as forage production and improved environmental conditions. Persistent price pressures (INF) have a significant negative impact indicating that if the inflation rate continues to rise, production costs could increase, reducing the performance of livestock sector. Temperature (TEMP) has a negative relationship with livestock production, which indicates the negative effects of climatic stress and high temperatures on livestock. Animals suffer from heat stress as the temperatures increase, and will eat less feed, produce less milk, have poor reproductive efficiency and have increased maintenance needs. Their effects are manifested as a decline in production factor productivity, which is reflected in a decline in the productivity of the sector and its profitability. An economic point of view will show that as temperatures increase, the economic costs of production will increase, but the productive efficiency will decrease. Nardone et al. (2010) demonstrate that elevated temperatures have negative effects on growth, milk production, reproduction and animal welfare. Similarly, Rojas-Downing et al. (2017) note the direct and indirect impacts of climate change on the cattle, including impacts on heat stress and feed availability and disease dynamics. However, PREP can also have a positive and significant impact, with enough rain potentially resulting in better feed and water availability, and therefore production conditions for livestock. Good rainfall is needed to restore the surface water and ground water sources that are vital for animals to drink, to digest food and maintain their body temperature, as well as for lactation. Evidence indicates that water stress results in a lower milk production and growth rates, especially in dairy systems (Megersa et al., 2014; Rojas-Downing et al., 2017). The impact of rainfall on the growth of cattle is mainly through the change in the condition of the pastures, and the availability of feed bases, which supports the findings of Ndesanjo et al. (2023) that the impact of rainfall on livestock production is mainly through the resource and forage channel.

There is a highly significant negative long run association between Population (POP) and Livestock Production. This may be a sign of stress due to population growth, resulting in limited land and other farm resources. Water availability, on the other hand, has a positive and significant relationship, highlighting the significance of water security in livestock production. Assessing livestock production systems and supply chains is all about water productivity and water availability. The importance of water in relation to livestock systems has been discussed in recent literature, where water is seen to affect the productivity of agricultural systems, both in terms of productivity and sustainability. Similarly, livestock production is closely and positively associated with cropped area (CA) perhaps due to the greater availability of agricultural land, crop residues, and feed resources. Recent evidence on integrated crop-livestock systems shows that such systems improve resource-use efficiency, resilience, and sustainable production, supporting the positive role of cropped area in livestock output (Sekaran et al., 2021). Similarly, research on sustainable livestock consumption emphasizes that livestock production depends strongly on the availability of grass resources and biomass streams, supporting the importance of land and feed-resource availability. Musalia et al. (2016) found that most animal feeds came from crop residues such as millet straw, maize stalk, pigeon peas, beans, and sorghum. These findings reflect the short-run estimates, which also suggest that livestock production is highly sensitive to changes in these factors. Lagged livestock production has a positive impact, indicating continuity of livestock-sector dynamics. Forest area and precipitation are positively related to short-run livestock production, and inflation and temperature are negatively related. Based on previous research, forest ecosystems have the potential to positively affect livestock production in a variety of ways, both ecological and productive. Additional forage resources include forest areas with tree leaves and understory vegetation, which are significant food sources when pasture is limiting. Empirical research on silvo-pastoral systems indicates that integrating trees within grazing landscapes improves forage biomass, enhances feed quality, and supports higher animal performance compared to an open pasture system (Dos Santos et al., 2025). In addition to providing feed, forest cover contributes to livestock production by regulating the microclimate. Trees reduce temperature extremes and provide shade, thereby mitigating heat stress, a major constraint on livestock productivity. Cooke & Rivero (2023) found that heat stress affects animals' overall health and productivity, which in turn impacts farmers economically. As conditions change, global temperatures are likely to rise, and most areas, particularly dry ones, will receive less precipitation. In the short run, population shows a significant negative correlation, while water availability and cropped area positively affect livestock production. The results suggest that short-term climate conditions and water availability matter for livestock production, and that their influence is part of a longer-term ecological and agricultural balance. Overall, the VECM findings indicate that livestock production in Pakistan is highly sensitive to climate and resource factors. In particular, the negative temperature response and positive responses to precipitation and water availability reflect the importance of climate variability and water security in sustaining livestock production. Concurrently, forest area and cropped area contribute positively, indicating that land-based ecological and agricultural resources complement livestock production. The integrated crop-livestock system fosters sustainable production intensification while minimizing negative environmental effects and supporting both crop and animal product supply (Baiyeri et al., 2019). Cropped area also affects livestock production via the impact on feed stability and resilience. Naturally growing pasture is available and changes from season to season in regions vulnerable to climate change. Crop residues provide protection during dry spells, decreasing feed fluctuations and stabilizing livestock production (McDermott et al., 2010). Furthermore, an enlarged cropped land leads to additional income for the farmers; higher income from crop production is utilized for livestock production, including payments for better breeds, veterinary care, and supplementary feeds. The income-mediated effect adds to livestock growth (Herrero et al., 2010). The error-correction mechanism also highlights that a short-run shock can't permanently affect the economy as the economy realigns itself with the long-run equilibrium.

Table 6: Vector Error Correction (VECM) Results

Regressors	Coef.	Standard errors	t-stats
Long Run			
LnLP	1.000		
LnFA	0.601	0.052	11.491
LnINF	-0.046	0.003	-15.333
LnTEMP	-2.692	0.7855	-3.427
LnPREP	0.484	0.091	5.317
LnPOP	-0.970	0.171	-5.672
LnWT	3.565	1.190	2.995
LnCA	1.520	0.143	10.629
COINTEQ	-0.595	0.031	-19.135
D (Ln-LP (-1))	0.329	0.046	7.608
D (Ln-FA (-1))	0.350	0.0373	9.383
D (Ln-INF (-1)	-0.022	0.002	-10.476
D (Ln-TEMP (-1))	-0.663	0.1587	-4.177
D (Ln-PREP (-1))	0.103	0.0161	6.397
D (Ln-POP (-1))	-5.191	0.446	-11.639
D (Ln-WT (-1))	1.861	0.220	8.459
D (Ln-CA (-1))	0.274	0.079	3.468
C	0.127	0.115	1.101
R –Square	0.660	Log Likelihood	14.908
Adj-R-Squared	0.457	Akaike AIC	-0.239
SUM sq. resids	1.160	Schwarz SC	0.178
S.E. equation	0.193	Mean dependent	0.021

F-statistics	1.212	S.D. dependent	0.198

5. Conclusion

In this study, the dynamic linkages between climate variability, water security and livestock production are explored. Data are annual time-series and a Vector Error Correction Model (VECM) is used for analysis. The results create important long-run and short-run relationships between livestock production and important climatic, environmental, agricultural, demographic and macroeconomic factors. The negative error-correction coefficient is quite large in absolute terms (-0.595), reinforcing this that the mechanism of adjustment is stable and in effect about 59.5% of short-run deviations from the long-run equilibrium are corrected in one period. The findings also indicate that livestock production decreases with increase in temperature and inflation while the opposite is true with an increase in precipitation, water availability, forest area, and cropped area. Population is negatively associated with livestock production in both the long and short run. In general, the evidence shows that production of livestock is well correlated with climate and availability of essential natural resources including water resources in Pakistan.

The results have a number of policy implications. First, water security must be at the heart of livestock development strategies, since the availability of water has always had a positive impact on livestock production. Investment in efficient irrigation, water storage systems, rainwater harvesting, and improved water management will boost livestock producers' resilience to water stress. Second, the negative impacts of temperature emphasize the need for livestock systems adapted to climate change, such as heat-resistant breeds, improved animal protection, shade, cooling, and climate-adapted feeding systems. Third, the positive influence of precipitation, forest area, and cropped area highlights the need for integrated management of land and forests, agricultural and livestock production, rather than managing these sectors separately. Lastly, policies should be put in place to shield livestock producers from rising feed, energy, veterinary, and other input costs driven by inflationary pressures. Therefore, the study offers future research opportunities. This analysis could be expanded to generate provincial- or district-level panel datasets that capture spatial variation in climate- and water-related livestock vulnerability. Future research could also explore non-linear and asymmetric effects of temperature, droughts, floods, and rainfall shocks, since moderate climatic conditions can affect livestock differently than extreme conditions. Livestock-specific indicators such as feed availability, animal diseases, breeds, productivity-enhancing technologies, and water-use efficiency could provide a more complete picture of production dynamics. Future studies could also examine whether adaptation mechanisms, agri-technology, institutional quality, and climate-smart livestock practices buffer the negative impacts of climate variability. Such extensions would provide robust support for designing specific, climate-smart livestock policies in Pakistan.

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