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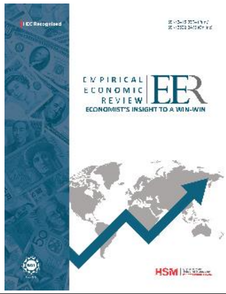

Title: **Environmental Degradation and Livestock Productivity under Climate Stress: Implications for Sustainable Agricultural Development**

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Environmental Degradation and Livestock Productivity under Climate Stress: Implications for Sustainable Agricultural Development

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Abstract

Environmental degradation is a multifaceted issue that drastically reduces production in Pakistan's agricultural sector. This study aims to investigate how environmental degradation affects cattle production in Pakistan, with implications for sustainable sectoral growth between 1980 and 2022. An autoregressive distributed lag estimator is used to determine how environmental deterioration (measured by CO_2) and other factors, such as water availability, heat stress, inflation, floods, crop and forest area, affect livestock productivity. The results show that inflation and CO_2 have long-term detrimental impacts on livestock productivity. Livestock productivity is positively and significantly affected by forest area, agricultural land, and water availability. The findings demonstrate that decreasing environmental deterioration and improving resource management and adaptability are necessary for Pakistan's cattle industry to thrive sustainably. The study also highlights the necessity of unified strategies focused on resource optimization, climate resilience, and environmental management.

***Keywords*:** climate stress, environmental degradation; heat stress, livestock productivity, Pakistan, sustainable agricultural development

JEL Codes: C22, O13, Q12, Q18, Q54, Q56

Introduction

In a developing country, the agricultural sector makes up the majority of the national economy (Awan & Abro, 2021; Campos-Requena et al., 2025; Win, 2023). It provides the majority of the labor force with jobs and ensures food security (Hafeez et al., 2020). Transforming the agricultural sector is essential for long-term, sustained increases in the economy's output. As a result, the quality of life for underprivileged populations improves, and food security increases (Farooq et al., 2025; Khryseva et al., 2026). Climate change directly affects the agricultural productivity (AP) function (Baris-

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Tuzemen & Lyhagen, 2026; Khalifa, 2025). Despite extensive studies demonstrating the detrimental effects of climate change on agricultural productivity, a gap remains in comprehending the nonlinear and asymmetric repercussions of environmental degradation (ED) over prolonged durations (Tan et al., 2022). In this study, livestock productivity is used as an indicator of agricultural performance due to its strong linkages with resource availability, climate conditions, and rural economic activity (Thornton et al., 2009; Zolotnytska et al., 2026).

It enhances the current research by utilizing a dynamic simulated ARDL model to evaluate the adverse and favorable productivity shocks. The global community is therefore endeavoring to mitigate climate change and pollution without threatening agricultural yields. Hence, CC significantly threatens agricultural output and food security (Abbas, 2022) and has detrimental effects on the macroeconomy (Chandio et al., 2024). While agricultural output suffers from ED, agriculture itself is a major source of environmental contamination. Ashraf et al. (2024) confirmed that food productivity significantly contributes to pollution in Pakistan. Agriculture remains Pakistan's predominant labor-intensive sector, directly or indirectly sustaining the livelihoods of the majority of its population. Nonetheless, its contribution to GDP has consistently declined in recent decades, now standing at 19.3%, despite an increase in its share of GDP due to enhanced productivity from improved agricultural technologies. This growth, facilitated by the sector's extensive industrial workforce and access to raw materials, reduces deprivation and supports the socio-economic framework of large-scale communities (Hussain & Rehman, 2022). The growth of the agricultural industry affects national economic development, employment prospects, and poverty incidence (GOP, 2024). Nevertheless, little empirical research has examined the effects of ED on livestock productivity (LP) in Pakistan.

Prior studies, such as Gulalai and Nazir (2025), examined the impact of annual mean precipitation on livestock production in Pakistan. Hussain and Rehman (2022) employed ARDL on annual time series data from 1972 to 2019 to examine how carbon dioxide (CO_2) and temperature affect LP in Pakistan. Usman et al. (2023) conducted micro-level research, using primary data of livestock farmers in Punjab, collected via a multistage sampling technique, and analyzed it using Binary Logistic Regression and Partial Least Squares Path Modeling (PLS-PM) to evaluate the impacts of CC and adaptation strategies for livestock. The present study differs from prior literature by estimating the most recent impact for 1980-2022 and employing the ARDL technique for data analysis. The study aims to investigate both short- and long-run impacts, using carbon dioxide (CO_2) as a proxy for ED, with control variables including water availability, heat stress (proxy: number of hot days, temperature > 410), cropped area, inflation, and forest area. While a number of studies have examined the impact of climate change and LP, there is a lack of empirical research on the combined effects of ED and climate stress on LP, particularly in the long run. Existing studies in Pakistan primarily focus on a single climate variable (such as annual temperature and annual precipitation) (Hussain & Rehman, 2022) rather than other more comprehensive measures of ED (such as CO_2 emissions) and their interaction with resource-based factors (Chandio et al., 2024).

Additionally, the role of land-use variables, such as cropland and forest, is not adequately explored in the livestock productivity framework, despite their important role in livestock production and environmental health. Moreover, most past research has either used a short time frame or micro-level dimensions (Usman et al., 2023), leaving the results short on a long view. As a result, a time-series analysis is needed that includes ED climate and resource variables to better understand their effects on LP.

Literature Review

Theories of productivity and environmental economics provide a basis for examining ED's impact on agricultural productivity. The traditional productivity function (PF) states that agricultural productivity is determined by land (L), labor (L), capital (K), and technology (T). ED, represented by increased CO_2 emissions, along with these inputs, can also affect agricultural productivity (AD), depending on threshold levels of farmers' adoption behavior and input substitutability. The Environmental Kuznets Curve suggests an ED-productivity relationship in a U-shaped pattern, meaning that ED first increases with productivity and then decreases after a certain productivity threshold. This approach enables an estimation of ED's impact on LP in Pakistan (Jadoon et al., 2025).

Pakistan's agriculture is divided into four sub-sectors: livestock, forestry, crops, and fisheries (Government of Pakistan, 2024). Livestock are integral to the agricultural system and affected by ED. Environmental degradation and climate change are known to reduce livestock productivity due to heat stress (HS) and water and fodder scarcity (Abbas, 2022; Raza et al., 2021). Hussain and Rehman (2022) analyzed the effect of carbon dioxide (CO_2) emissions on cattle production in Pakistan (1972-2019). The ARDL model was estimated to examine associations among variables in both the short and long term. Long-term results show that LP has a positive impact on CO_2 emissions. Similarly, Khurshid et al. (2023) examined the impact of CO_2 emissions, annual mean temperature, and annual mean precipitation on LP in Pakistan by employing NARDL on time-series data from 1980 to 2021. CO_2 negatively affects the cattle sector's growth and output, as millions of animals suffer as a result. Ahmad et al. (2020) found that CC and CO_2 emissions hurt agricultural growth in Pakistan. The implications of CO_2 for agricultural growth suggest that it would affect all agricultural sub-sectors, especially livestock, which accounts for 62% of AP. Global warming directly reduces AP through melting glaciers, flooding, more frequent extreme weather events, and so on. CO_2 emissions cause animal health issues and lower output. CO_2 emissions from electricity, fuel use, and urban growth have elevated average temperatures in Pakistan, leading to stress, reduced reproductive rates, and higher livestock product prices, discouraging LP (Shahid et al., 2021). Pakistan's livestock sector has low productivity due to significant CO_2 emissions. Investing in improved management practices can increase milk yield and reduce emissions, thereby boosting milk and mutton productivity (Habib & Khan, 2018).

The study by Otim et al. (2023) examined the causal effect of CO_2 emissions on AP in East African countries using ARDL and fixed-effects methods from 1996 to 2019. The study found that LP itself is a major contributor to global warming, while livestock is the sector most affected by CO_2 emissions. Reduced crop yields, soil salinity, and arable land are the most serious repercussions of CO_2 emissions. Hence, it causes animal growth to stop and reduces milk production. Similarly, Liu et al. (2024) argued that CO_2 emissions negatively affect LP. At the individual level, rising temperatures beyond optimal ranges reduce the quality and quantity of cattle meat, with marginal productivity declines of up to 0.76% per 1°C of warming. Samad et al. (2025) also demonstrated that, for sustainable LP, reducing CO_2 is important. The livestock system itself emits a large quantity of CO2 through feed production and methane, thereby increasing exposure to CC, which ultimately creates pressure in LP.

Dey (2023) examined CC's effects on livestock output in Bangladesh from 1971 to 2020, including economic repercussions, using the FMOLS method. Results indicated that rising temperatures, precipitation, and CO_2 emissions negatively affect LP. CO_2 emissions cause global warming and increased cattle mortality. Higher temperatures can lead to lower metabolism, feed intake, and HS. High rainfall leads to wet, humid conditions that promote many ailments. Conversely, cattle productivity benefits from colder conditions and inundated areas. Lower temperatures help improve water quality, reduce illness and parasite burdens, and boost cattle breeding performance. Floods can increase water availability, nutrient availability, and pasture, but better management, water systems, resilient breeds, and alternative feed are required to reduce the impacts of climate change on Bangladesh's livestock.

Jadoon et al. (2025) found that environmental degradation significantly affects agricultural productivity in Pakistan. Although their study focused on crop productivity, it supports the argument that environmental degradation harms Pakistan's agricultural sector. Conversely, Orach et al. (2025) examined the impact of CO_2 emissions on agricultural production indicators in Sub-Saharan African countries. Their findings support the view that environmental degradation can reduce agricultural performance. (Jongbo et al., 2026) explained that heat stress is a major constraint in tropical livestock systems because high temperature, humidity, solar radiation, and weak wind conditions increase thermal pressure on animals. This supports the present study because Pakistan's livestock sector is also exposed to heat stress and climate variability.

Recent studies have improved the understanding of climate change, heat stress, and sustainable livestock systems, but important gaps remain in the context of Pakistan. Studies such as Malek & See (2026), Neira et al. (2026), and Palandri et al. (2025) provide strong international evidence that heat stress and future warming threaten cattle and dairy productivity. However, these studies are global or region-specific and do not directly estimate the long-run relationship between environmental degradation and livestock productivity in Pakistan.

In Pakistan, recent studies such as Arshad and Abdulai (2025) focused on climate-smart agriculture, farmer welfare, and supply-chain resilience. These studies are useful, but they do not directly test the long- and short-run effects of CO2 emissions, heat stress, floods, water availability, agricultural land, forest area, and inflation on livestock productivity within a single combined model. Therefore, the present study fills this gap by applying the ARDL approach to annual data from 1980 to 2022. This makes the study distinct from previous research by combining environmental, climatic, resource-based, and macroeconomic variables within a single framework. The present study employed the ARDL model to estimate the impact of ED on LP while accounting for control variables. Multiple studies have employed linear and panel data regressions. This paper fills the aforementioned research gap. Consequently, it makes a valuable addition to the literature in forecasting the effects of explanatory factors in reaction to positive and negative shocks over a 40-year period.

Methods

The present study estimates the impact of ED on LP in Pakistan via ARDL analysis. The value added (VA) to LP in Pakistan from 1980 to 2022 varied significantly. Equation 1 presents the functional relationship, and Table 1 describes the variables and data sources.

$$\mathrm{LP_t = f(ED_t, HS_t, Floods_t, AL_t, FA_t, Wav_t, INF_t)} \quad (1)$$

The dependent variable, LP, indicates the major livestock production (milk, meat, bones, leather). Likewise, the selection of control variables: $DFloods_t$, $LnCA_t$, $LnCO_{2t}$, $Ln\text{-}HS_t$, $LnFA_t$, $LnWA_t$, $LnInfl_t$ is based on the literature and is important in examining the role of LP following, (Hussain & Rehman, 2022; Khurshid et al., 2023; Monteiro et al., 2024; Orach et al., 2025; Otim et al., 2023).

In time series analysis, understanding the processes of unit root series is essential, since it influences the appropriateness of the analytical technique employed (Dickey & Fuller, 1979; Phillips & Perron, 1988). Tests are used to determine the integration order of the time series in this example. Following Pesaran et al. 2001), the functional relationship expressed in Equation 1 is now presented in Equation 2 for ARDL estimation. For economic analysis, it is important to have fewer than 80 years; for this, the bound test is very conservative (Philips, 1988). Furthermore, the difference between I (0) and I (1) is important. Phillips and Perron (1988) emphasize that the dependent variable's I (1) criterion is that the order of integration of the explanatory variables must not surpass I (1), and the model's innovations must not exhibit autocorrelation (AC).

$$\mathrm{lnLP_t} = \alpha_0 + \alpha_1 \mathrm{lnED_t} + \alpha_2 \mathrm{lnInfl_t} + \alpha_3 \mathrm{lnWAv_t} + \alpha_4 \mathrm{lnHS_t} + \alpha_5 \mathrm{lnFA_t} + \alpha_6 \mathrm{lnAL_t} + \alpha_7 \mathrm{lnFlood}_{\,t} + \mu_t \quad \textbf{(2)}$$

$$\begin{aligned}\Delta \mathrm{lnLP_t} = \alpha_0 + \sum_{i=1}^{k} \alpha_1 \Delta \mathrm{ED_{t-1}} \\ + \sum_{i=1}^{k} \alpha_2 \Delta \mathrm{lnInfl_{t-1}} + \sum_{i=1}^{k} \alpha_3 \Delta \mathrm{lnWAv_{t-1}} + \sum_{i=1}^{k} \alpha_4 \Delta \mathrm{lnHS_{t-1}} \\ + \sum_{i=1}^{k} \alpha_5 \Delta \mathrm{lnFA_{t-1}} + \sum_{i=1}^{k} \alpha_6 \Delta \mathrm{AL_T} + \sum_{i=1}^{k} \alpha_7 \Delta \mathrm{Flood_t} + \varphi_1 \Delta \mathrm{lnED_{t-1}} \\ + \varphi_2 \Delta \mathrm{lnInfl_{t-1}} + \varphi_3 \Delta \mathrm{lnWAv_{t-1}} + \varphi_4 \Delta \mathrm{lnHS_{t-1}} + \varphi_5 \Delta \mathrm{lnFA_{t-1}} \\ + \varphi_6 \Delta \mathrm{AL_{t-1}} + \varphi_7 \Delta \mathrm{Flood_{t-1}} + \ \mu\mathrm{t}\end{aligned} \quad (3)$$

After establishing a long-run relationship in the study, we will estimate the short-run relationship between the variables using an error correction model based on the ARDL technique. The following expression for ECM is given in (Eq 4).

$$\begin{aligned}\Delta \mathrm{lnLP_t} = \alpha_0 + \sum_{i=1}^{k} \alpha_1 \Delta \mathrm{lnED_{t-1}} \\ + \sum_{i=1}^{k} \alpha_2 \Delta \mathrm{lnInfl_{t-1}} + \sum_{i=1}^{k} \alpha_3 \Delta \mathrm{lnWAv_{t-1}} + \sum_{i=1}^{k} \alpha_4 \Delta \mathrm{lnHS_{t-1}} \\ + \sum_{i=1}^{k} \alpha_5 \Delta \mathrm{lnFA_{t-1}} + \sum_{i=1}^{k} \alpha_6 \Delta \mathrm{AL_T} + \sum_{i=1}^{k} \alpha_7 \Delta \mathrm{Flood_t} + \varphi_1 \Delta \mathrm{lnED_{t-1}} \\ + \varphi_2 \Delta \mathrm{lnInfl_{t-1}} + \varphi_3 \Delta \mathrm{lnWAv_{t-1}} + \varphi_4 \Delta \mathrm{lnHS_{t-1}} + \varphi_5 \Delta \mathrm{lnFA_{t-1}} \\ + \varphi_6 \Delta \mathrm{AL_{t-1}} + \varphi_7 \Delta \mathrm{Flood_{t-1}} + \varphi \mathrm{ECM_{t-1}} + \mu_t\end{aligned} \quad (4)$$

The coefficients $\beta_j, \gamma_j, \emptyset_j, \xi_j, \eta_j, \varphi_j, \varpi_j$ and ψ_j represent the short-run dynamics of the variables, while the coefficients of $\sigma_i (i = 1,2,3,4,5,6,7)$ indicate long-term dynamics. θ represents the coefficients of the correction for disequilibrium.

Table 1

Variables, Symbols, and Data Source

Variables	Symbols	Definition	Sources
Livestock Productivity	$LnLP_t$	It measures livestock production	Pakistan's economic survey issues
Environmental Degradation	$LnCO_{2t}$	Proxied by emissions from gaseous fuel consumption (% of total CO_2 emissions)	WDI*
Heat Stress	$LnHS_t$	Number of days where the temperature exceeds 41 °	WDI
Floods	$Floods_t$	Dummy variables assume the value of 1 when flood is 1 and 0 when flood is 0.	FFC*
Agricultural Land	$LnAL_t$	Agricultural Land (% of land area)	Pakistan's economic survey issues
Forest Area	$LnFA_t$	Forest area (% of forest area)	Pakistan's economic survey issues
Water Availability	$LnWAv_t$	Ln of the total amount of water availability to the agriculture sector measured by MAF	Pakistan's economic survey issues
Inflation	$LnInfl_t$	Consumer price index, % annual	WDI

Note. CCP* stands for Climate Change Knowledge Portal, WDI* stands for World Development Indicator, and FFC*stands for Federal Flood Commission, mh=million hectares

Results and Discussions

Descriptive data indicate that LSP exhibits moderate variability, with a mean of 29.288. Wav demonstrates stability and is expected to correlate favorably with LP, whereas CO_2 and Infl exhibit significant volatility and exert a negative effect. HS, FA, and AL demonstrate considerable variability and are expected to positively impact LP via resource availability.

Table 2

Summary Statistics (N = 43)

	LP	Wav	Infl	HS	FA	AL	Floods	CO_2
Mean	29.29	98.62	162.04	135.39	173.90	178.07	0.627	14.89
Median	30.12	96.77	160.86	158.65	183.57	179.94	1	11.79
Maximum	49.92	136.46	343.63	187.04	225.40	255.09	1	12.20
Minimum	11	96.42	42.84	62.07	97.91	93.22	0	11.32
Std. Dev.	10.07	6.08	58.25	42.946	39.91	48.68	0.489	0.24

Table 2 summarizes the correlation matrix among the variables. The correlation results indicate that CO_2, LnCA, LnFA, and LnHS are positively associated with the dependent variable. LnAL and LnFA have a robust positive correlation. Conversely, LnWav and Floods exhibit a negative correlation with LP, indicating an inverse effect. The negative coefficient of Wav indicates potential inefficiencies or resource limitations. The results demonstrate a complex interplay between environmental and economic factors and livestock productivity.

Table 3

Correlation Matrix

	LP	CO_2	AL	WAv	Floods	FA	HS	Infl
LP	1							
CO_2	-0.265	1						
AL	0.733	0.212	1					
Wav	0.408	-0.016	0.672	1				
Floods	-0.195	0.122	-0.077	0.015	1			
FA	0.716	-0.037	0.526	-0.244	-0.287	1		
HS	0.442	-0.273	0.002	0.088	-0.489	0.512	1	
Infl	-0.662	-0.443	-0.216	-0.036	0.070	0.186	0.094	1

Table 3 presents the unit roots using the PP error test and the ADF test. The unit root analysis shows that the variables LP, CO_2, HS, FA, and AL are integrated of order I(1), while the variables Infl, Wav, and Floods are integrated of order I(0). This means that the variables are of mixed I (1) and I (0) orders, which is a prerequisite for ARDL.

Table 4

Unit Root Test

				ADF				
Variables	LP	CO_2	Infl	WA	HS	FA	AL	Floods
Level	3.653	-1.728	-5.362 ***	-3.441***	-1.427	-1.542	-1.519	-3.193**
1st diff	-4.997***	-4.755***	-4.427***	-8.044***	-3.214**	-6.882***	-5.715***	-9.886***
				PP				
Level	3.854***	-1.968	-2.800	-5.974***	-1.227	-1.513	-1.592	-3.253*
1st diff	-6.310***	-6.353***	-6.862***	-8.541***	-8.753***	-6.509***	5.715***	-9.885***
	I(1)	I(1)	I(0)	I(0)	I(1)	I(1)	I(1)	I(0)

Note. * denotes the probabilities; authors' calculation using EViews 13

The optimal lag numbers were 1 and 3, respectively. Appropriate lag length criteria are important for the ARDL model. After several lag lengths, Table 5 was estimated for some of these lag length criteria. The AIC lag-length criteria indicate that lag lengths 1 and 3 are the most appropriate.

Table 5

Lag Selection Criteria

Lag	Log	LR	FPE	AIC	SC	HQ
0	-1024.026	NA	3.55e+12	51.60128	51.93906	51.72341
1	-819.5606	316.9209*	3.37e+09*	44.57803	47.61801*	45.67719*
2	-749.3501	80.74207	5.30e+09	44.26750	50.00970	46.34370
3	-676.8936	54.34234	8.58e+09	43.84468*	52.28908	46.89791

Note. * denotes the optimal lag; author's calculation using EViews 13

The long-run relationship can be assessed by a cointegration test. The computed F-statistic is 29.052, exceeding both the lower limit of 2.450 and the upper limit of 3.61 at the 5% significance level, thus affirming the long-term relationship and co-integration among the variables.

Table 6

ARDL Bound Test

F-statistics	29.052	
Significance	Lower Bound I (0)	Upper Bound I (1)
10%	2.10	3.230
5%	2.450	3.610
1%	3.150	4.430

The main variable in this case is the percentage of total gaseous fuel consumption, which indicates environmental degradation. The coefficient value of CO_2 in the long-term dynamics is -0.394 and is significant at the 5% level. This data indicates that a 1% rise in CO_2 results in a 0.39% decline in LP over the long term. The results are supported by Jadoon et al. (2025). The effect of inflation is considerable and favorable, quantified at 0.078. A 1% rise in inflation results in a 0.17% decrease in LP in the long term. Likewise, WA's influence on LP is both favorable and significant over the long term (Jadhav & Sonawane, 2024). HS exerts a detrimental, statistically significant impact on animal output at the 10% level over the long term. FA exhibits a substantial and positive correlation with livestock productivity. A 1% increase in AL leads to a 0.25% rise in LP over the long term. (Ahmadzai et al., 2025; Musalia et al., 2016) determined that most animal feed originates from agricultural byproducts, such as millet straw, maize stalks, pigeon peas, beans, and sorghum. The semi-intensive agro-pastoral system encompasses small-scale crop production combined with a less extensive approach to pastoral animal husbandry (Olsen et al., 2025; Sileshi et al., 2001). The short-run dynamics demonstrate a considerable correlation between changes in water and in LP. Additionally, AL exerts a detrimental influence: a 1% rise in CL results in a 0.24% increase in LP in the near run. The flood exhibits a negligible but adverse near-term correlation, with a 1% increase in flooding leading to a 0.28% decrease in LP. The ECM coefficient must be significant and negative to characterize the short-run dynamics. The findings were verified by a study conducted by Dey (2023) and Headey & Fan 2008). Consequently, in the present investigation, the ECM probability value is markedly significant, and ECM possesses a negative coefficient. The coefficient value of -0.754 indicates that livestock output will improve if long-term issues are resolved for 75% of the year.

Table 7

Estimated Coefficients of ARDL model (1,0,1,0,0,1,0)

Variables	Coefficient	*t*-statistics	Prob
ED	-0.394***	-3.094	0.000
Infl	-0.078***	-6.083	0.000
WA	4.720***	2.930	0.005
HS	-0.040*	-1.907	0.064
FA	0.114***	6.514	0.000
AL	0.248***	4.578	0.000

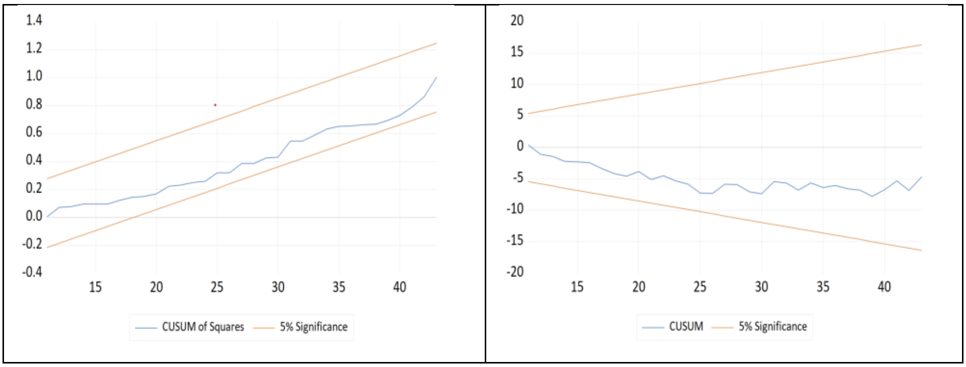
Δ WA	0.014	0.2497	0.804
Δ AL	0.243	0.618	0.540
Floods	-0.281	-0.450	0.655
COINTEQ*	-0.754***	-24.122	0.000
Breusch-Pagan Godfrey Test	1.393(0.241)	Jarque-Bera Test	0.123(0.940)
ARCH Test	0.393(0.534)	Ramsey Test	3.195(0.083)

Note. Floods is a static variable. Sources: Calculations based on the data taken from: World Bank Indicator, Economic Survey of Pakistan, Federal Flood Commission of Pakistan, Pakistan Meteorological Department, Climate Change Knowledge Portal.

In the final stage, the stability of these results was verified using the CUSUM and CUSUM of Squares tests (Figure 1). The model is considered stable if the line lies within a 5% confidence interval. Figure 1 illustrates that the model was stable in this instance. The Ramsey RESET test indicates that the model is free of specification errors.

Figure 1

CUSUM of Squares and CUSUM



Conclusion

This study demonstrates that the LP in Pakistan is significantly reduced by ED, Infl, and CC, but is significantly enhanced by resource endowments. Our findings highlight the need for better resource management, climate change adaptation, and environmental protection in sustainable sectoral development. Therefore, to achieve economic growth, food security, and sustainable productivity, it is critical to adopt policy interventions. The findings of this study have significant ramifications for the sustainable growth of the Pakistan livestock sector, which relates to the United Nations Sustainable Development Goals (SDGs). The negative impact of ED on LP highlights the urgency of adopting environmentally sustainable practices and directly supports SDG 13 (Climate Action). It is important to address climate vulnerabilities and enhance long-term productivity by limiting greenhouse gas emissions through climate-smart agriculture, manure management, and renewable energy sources. The climate vulnerability of livestock systems is further underscored by heat stress, highlighting the need for adaptation measures, including developing heat-tolerant livestock breeds, improving farm facilities, and enhancing veterinary services. Maintaining livestock productivity and food security goes beyond SDG 13 (Climate Action) and also impacts SDG 2 (Zero Hunger).

Implications for Sustainable Agricultural Development

The significance of sustainable resource management is underscored by the benefits of water availability, agricultural land, and forest resources, which align with SDG 15 (Life on Land) and SDG 12 (Responsible Consumption and Production). By implementing sustainable land practices, afforestation initiatives, and efficient water use, it is possible to improve feed availability, maintain environmental balance, and enhance ecosystem services, thereby promoting ecological sustainability and LP. Macroeconomic stability is crucial for achieving sustainable agricultural growth, as inflation can undermine LP. Policies designed to stabilize input prices, provide subsidies, and strengthen rural financial systems contribute to SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth) by safeguarding farmers' incomes and fostering inclusive economic development. Overall, the research indicates that an integrated policy framework that simultaneously addresses economic stability, resource efficiency, climate resilience, and environmental sustainability is necessary to achieve sustainable growth in Pakistan's livestock sector. In addition to enhancing LP, this comprehensive approach guarantees long-term food security, environmental preservation, and socio-economic development by advancing numerous SDGs. These findings align with global sustainability priorities, particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land), by emphasizing the need for climate-resilient livestock systems, sustainable resource management, and reduced ED.

Future Directions

This study can be further developed by incorporating disaggregated regional or farm-level data to capture heterogeneity in LP. Furthermore, broader forms of ED, including land degradation and methane emissions, should be taken into account. Advanced econometric methods, such as nonlinear and panel models, may offer more profound insights into intricate relationships. Lastly, future research should investigate the effectiveness of policies and adaptation strategies in improving climate resilience and advancing sustainable livestock systems.

Author Contribution

Gulalai: conceptualization, formal analysis, software, resources, methodology, investigation, writing-original draft. **Nazish Kanval:** validation, supervision, writing - review &editing.

Conflict of Interest

The authors of the manuscript have no financial or non-financial conflict of interest in the subject matter or materials discussed in this manuscript.

Data Availability Statement

Data supporting the findings of this study will be made available by the corresponding author upon request.

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Generative AI Disclosure Statement

The authors did not use any type of generative artificial intelligence software for this research.

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