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MODELING THE IMPACT OF ANTHROPOGENIC AND CLIMATIC DYNAMICS ON FOREST AREAS USING ROBUST STATISTICAL METHODS

Original Research

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ABSTRACT

Background: Forests play a central role in climate regulation, biodiversity conservation, and ecosystem stability, yet they are increasingly threatened by anthropogenic and climate-related pressures. In developing countries such as Pakistan, low forest cover combined with rapid population growth, rising emissions, and land-use change has intensified forest degradation. Understanding how socio-economic and climatic variables jointly influence forest area is essential for evidence-based environmental planning and climate-adaptive forest management.

Objective: To quantitatively assess the effects of key anthropogenic and climatic variables on forest area in Pakistan and to identify the most robust predictors of forest change.

Methods: A quantitative, retrospective analytical design was adopted using 60 annual observations derived from a national-level dataset. Variables included forest area, carbon dioxide emissions, total greenhouse gas emissions, urban population, cereal yield, renewable energy consumption, rainfall, and agricultural land. Statistical analysis involved Pearson correlation, multiple linear regression, model reduction, and ANOVA-based model comparison. Diagnostic evaluation identified heteroscedasticity, non-linearity, and influential observations, prompting the application of robust regression with log-transformation of the dependent variable to ensure stable and reliable estimates.

Results: Correlation analysis revealed strong interrelationships among emissions, agricultural productivity, and urbanization. In the reduced regression model, carbon dioxide emissions, total greenhouse gas emissions, and urban population emerged as statistically significant predictors, jointly explaining 95.01% of the variation in forest area (adjusted R^2). Robust log-linear regression confirmed that both carbon dioxide and total greenhouse gas emissions were negatively associated with forest area, while urban population showed a statistically significant positive association. Diagnostic plots demonstrated improved variance stability and reduced influence of outliers following robust estimation.

Conclusion: The findings provide strong empirical evidence that emission-related factors are the principal drivers of forest decline in Pakistan, while urbanization exhibits a context-dependent relationship shaped by governance and land-use practices. The study underscores the urgency of emission mitigation and integrated urban environmental planning to support sustainable forest conservation.

Keywords: Carbon Dioxide, Climate Change, Forest Cover, Greenhouse Gases, Pakistan, Regression Analysis, Urban Population.

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INTRODUCTION

Forests represent one of the most critical life-support systems on Earth, underpinning climate regulation, carbon sequestration, hydrological balance, and the conservation of biological diversity (1). By acting as major sinks for atmospheric carbon dioxide, forest ecosystems play a central role in buffering the pace and intensity of climate change (1,2). Beyond their climatic function, forests sustain soil integrity, regulate watersheds, and provide livelihoods, food security, and cultural value to millions of people worldwide, particularly in low- and middle-income countries where human well-being is closely tied to natural resources (3,4). Despite these indispensable services, global forest systems are undergoing persistent decline, raising serious concerns for environmental stability, public health, and sustainable development. The degradation of forest ecosystems is largely driven by intensified human activity, including rapid urbanization, agricultural expansion, industrial growth, and unsustainable land-use practices (5,6). These anthropogenic pressures are increasingly compounded by climate-induced stressors such as rising temperatures, shifting precipitation regimes, and the growing frequency and severity of extreme weather events, including floods, droughts, heatwaves, and wildfires (4,7). Together, these interacting forces accelerate forest loss and weaken ecosystem resilience, particularly in regions already characterized by ecological fragility and socio-economic vulnerability (8). Pakistan exemplifies a highly vulnerable context where forest cover remains substantially below global and regional averages (9). Persistent population growth, rising energy demands, and economic pressures have intensified reliance on forest resources, leading to accelerated deforestation and degradation (10,11). At the same time, climate variability has increasingly disrupted socio-ecological systems across the country, manifesting through long-term shifts in temperature and precipitation patterns and through recurrent hydro-meteorological hazards that undermine ecosystem stability and human livelihoods (9,12). These dynamics underscore the importance of understanding forest change not as a single-factor phenomenon, but as the outcome of intertwined climatic and socio-economic processes.

Empirical evidence from Pakistan further illustrates this complexity. Spatial and temporal analyses in regions such as Murree have demonstrated that forest decline cannot be attributed solely to land-use change; significant increases in minimum temperatures alongside declining rainfall have coincided with measurable reductions in forest cover over recent decades (5,13). Similar findings globally suggest that climatic variability alone can trigger forest stress, mortality, and large-scale disturbance events, even in the absence of direct human clearing (6,7). Climate-driven vegetation and land-use models consistently highlight the sensitivity of forest systems to subtle environmental changes and the nonlinear interactions between climate and human activity (14,15). Recent research has further emphasized the role of anthropogenic greenhouse gas emissions in amplifying climate-related forest disturbances. Studies from different regions demonstrate that human-induced warming has substantially increased forest fire extent and intensity, contributing to long-term forest degradation and carbon feedback loops (5,6,10). Parallel econometric evidence indicates that broader macro-economic conditions, including unemployment, inflation, and population growth, are also closely linked to reductions in forest area, suggesting that economic stress can indirectly intensify environmental degradation (15). Urban expansion and agricultural intensification further reshape land-use patterns, often driving deforestation while simultaneously introducing complex trade-offs through localized greening initiatives and policy interventions (13). Despite this growing body of literature, a critical gap remains in quantitatively disentangling the combined effects of anthropogenic and climatic drivers on forest area using methodologies that are robust to the inherent noise, outliers, and structural irregularities common in environmental data. Conventional regression approaches may yield biased or unstable estimates under such conditions, potentially obscuring true relationships (11). Advances in robust statistical and machine-learning techniques offer promising alternatives, yet their application to forest dynamics in Pakistan remains limited (13,16). Addressing this gap is essential for generating evidence that can reliably inform forest management strategies, climate adaptation planning, and sustainable development policies. Against this backdrop, the objective of the present study is to systematically quantify the influence of selected anthropogenic and climatic variables on forest area in Pakistan using a combination of classical and robust statistical techniques. By mitigating the effects of outliers and data irregularities, this approach seeks to provide more reliable insights into the complex socio-environmental processes driving forest change, thereby supporting evidence-based policy formulation aimed at long-term ecological sustainability and climate resilience.

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METHODS

This study employed a quantitative, retrospective modeling design to examine the influence of selected anthropogenic and climatic variables on forest area in Pakistan. Secondary data comprising 60 annual observations were obtained from a previously published dataset compiled by Muhammad (2021). As the analysis relied exclusively on aggregated, country-level environmental and socio-economic indicators, no human participants were directly involved. Consequently, formal informed consent was not required. The use of anonymized secondary data exempted the study from institutional review board approval; however, the research protocol adhered to standard ethical principles for secondary data analysis, including transparency, data integrity, and responsible reporting of results. Prior to analysis, the dataset was systematically screened to ensure analytical suitability. Irrelevant attributes were removed, and all retained variables were converted into numeric form to ensure compatibility with statistical modeling procedures. Observations containing missing values were excluded using listwise deletion to prevent estimation bias and inconsistencies in model fitting. The final analytical dataset retained all variables deemed theoretically and empirically relevant to forest dynamics, including forest area, carbon dioxide emissions, total greenhouse gas emissions, urban population, and other socio-environmental indicators. Descriptive and exploratory analyses were first conducted to understand the underlying structure of the data. Pearson's correlation analysis was used to assess the strength and direction of linear associations between pairs of variables. The Pearson correlation coefficient between two variables, X and Y, was computed using the standard formulation based on the covariance of the variables normalized by their respective standard deviations. This preliminary assessment revealed several meaningful associations, including a strong positive correlation between carbon dioxide emissions and cereal yield, as well as a moderate positive association between urban population and total greenhouse gas emissions. These relationships, summarized in a full correlation matrix, informed subsequent model specification by highlighting potential interdependencies and multicollinearity among predictors.

Following the exploratory phase, multiple linear regression analysis was performed using the ordinary least squares (OLS) method to estimate the joint effects of the selected predictors on forest area. The initial full model included all available explanatory variables to comprehensively assess their collective influence. Regression coefficients, associated standard errors, and significance levels were evaluated to determine the relative contribution of each predictor. Several variables were found to have limited explanatory power and lacked statistical significance. To enhance parsimony and interpretability, a reduced model was subsequently specified, retaining only carbon dioxide emissions, total greenhouse gas emissions, and urban population, which demonstrated both theoretical relevance and statistical significance. The adequacy of the reduced model relative to the full model was formally assessed using analysis of variance (ANOVA) for nested models. The comparison was based on differences in residual sum of squares and corresponding degrees of freedom. The resulting F-statistic indicated no statistically significant loss of explanatory power following the exclusion of non-informative variables, supporting the selection of the reduced specification as a more efficient representation of the data. This step ensured that the final model balanced explanatory adequacy with statistical simplicity. Post-estimation diagnostic analyses were conducted to evaluate compliance with key OLS assumptions. Visual inspection of residual-versus-fitted plots revealed clear evidence of heteroscedasticity, characterized by non-random dispersion of residuals across fitted values. Influence diagnostics using Cook's Distance identified several observations exceeding conventional thresholds, indicating the presence of influential outliers. In addition, quantile–quantile plots of residuals suggested mild departures from normality. Collectively, these findings indicated that OLS estimates were susceptible to distortion from extreme observations and non-constant error variance, a common issue in environmental time-series data.

To address these limitations, robust regression techniques were adopted using M-estimation. This approach replaced the traditional squared-error loss function of OLS with a bounded influence function, thereby reducing the impact of extreme residuals on parameter estimates (11,17). Robust estimates were obtained by iteratively reweighting observations based on a robust measure of scale, producing coefficient estimates that were more stable and resistant to outliers. In parallel, the dependent variable, forest area, was log-transformed to stabilize variance and improve linearity in the presence of heteroscedasticity. The resulting log-linear robust regression model demonstrated improved residual behavior and enhanced goodness-of-fit, as reflected in diagnostic and prediction accuracy plots presented later. Throughout the analytical process, graphical diagnostics played a central role in validating model assumptions and guiding methodological refinements. The correlation matrix, residual plots, quantile–quantile plots, Cook's Distance diagnostics, and actual-versus-predicted comparisons collectively ensured that the final modeling framework was statistically sound and substantively meaningful. This integrated approach strengthened the reliability of the findings and enhanced confidence in the inferred relationships between anthropogenic activity, climatic pressures, and forest area dynamics in Pakistan.

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RESULTS

The analytical findings demonstrated a clear statistical relationship between anthropogenic and climatic variables and forest area in Pakistan. Preliminary correlation analysis revealed several meaningful associations that informed subsequent modeling. Carbon dioxide emissions exhibited a strong positive correlation with cereal yield, while urban population showed a moderate positive correlation with total greenhouse gas emissions, indicating interlinked dynamics between economic activity, emissions, and demographic expansion. These associations confirmed sufficient linear structure within the data to justify multivariable regression analysis. The full multiple linear regression model incorporating eight predictors showed a high overall explanatory capacity; however, individual coefficient estimates indicated that several variables did not contribute significantly to explaining variation in forest area. Cereal yield, renewable energy consumption, mean rainfall, agricultural land, and other greenhouse gas indicators displayed non-significant coefficients, and their inclusion did not materially enhance model performance. Following systematic model reduction, a parsimonious specification retaining carbon dioxide emissions, total greenhouse gas emissions, and urban population was estimated. This reduced model accounted for a substantial proportion of variance in forest area, with an adjusted coefficient of determination of 0.9501, indicating that approximately 95% of the observed variability was explained by these three predictors. Model comparison using analysis of variance confirmed that exclusion of statistically insignificant variables did not result in a meaningful loss of explanatory power, supporting the adequacy of the reduced model. Diagnostic evaluation of the reduced ordinary least squares model revealed departures from key regression assumptions. Residual patterns indicated heteroscedasticity and mild non-linearity, while quantile–quantile assessment showed residuals largely followed a normal distribution with slight deviations in the tails. Influence diagnostics identified several observations exerting disproportionate leverage on coefficient estimates, suggesting susceptibility of ordinary least squares estimates to outliers. The initial analytical framework employed a full multiple linear regression specification in which forest area was modeled as a linear function of all selected anthropogenic and climatic predictors, expressed as

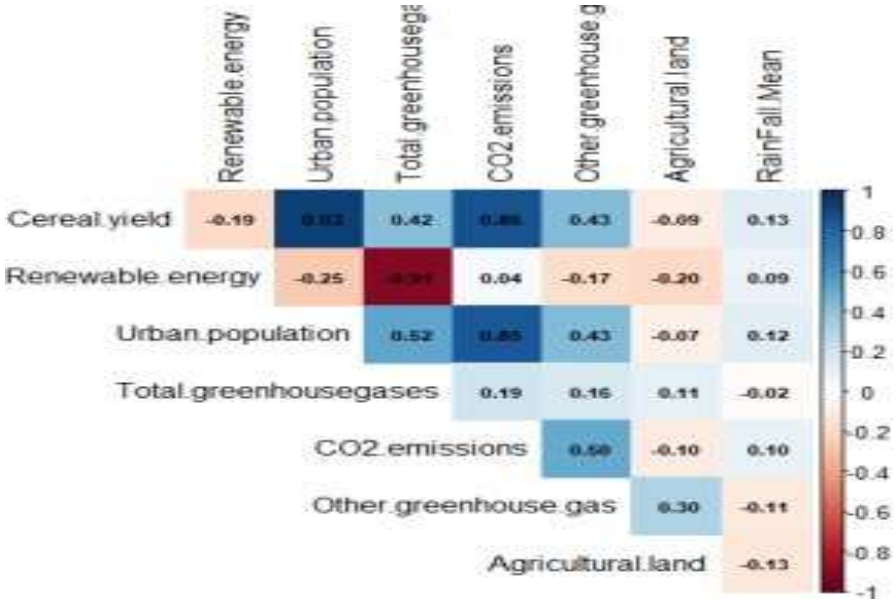
$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_8 X_8 + \varepsilon.$$

Subsequent statistical screening and model reduction resulted in a parsimonious specification retaining only the significant predictors, represented as

$$Y = \beta_0 + \beta_1(CO_2) + \beta_2(GHG) + \beta_3(Urban) + \varepsilon,$$

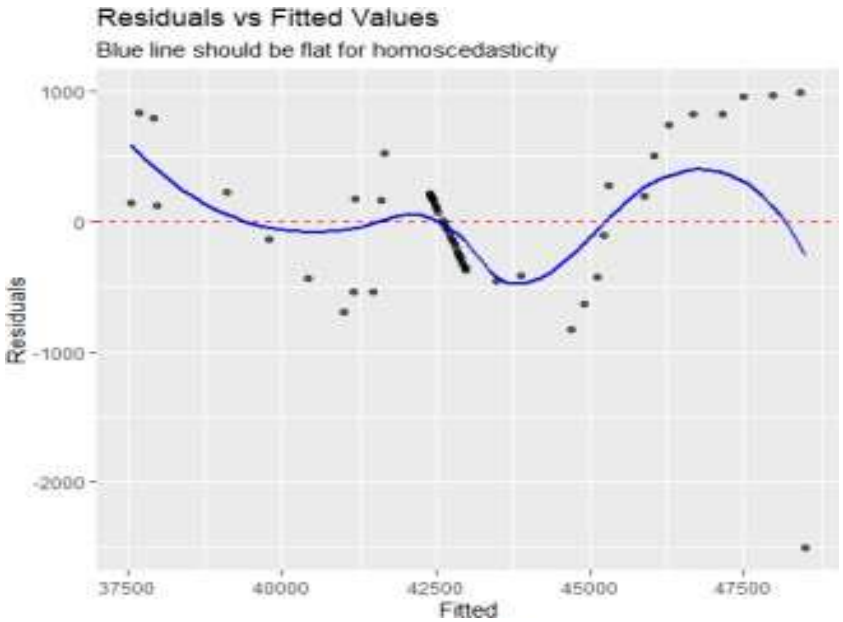
which demonstrated strong explanatory performance and formed the basis for further diagnostic and robust regression analyses.

To address these issues, the dependent variable was log-transformed, and robust regression estimation was applied. The robust log-linear model yielded more stable coefficient estimates by down-weighting extreme observations and correcting for non-constant variance. In this specification, carbon dioxide emissions and total greenhouse gas emissions showed statistically significant negative associations with forest area, reflecting their dominant role in forest decline. Urban population retained a statistically significant positive association with forest area, indicating a contrasting directional effect relative to emissions-related variables. Model performance assessment using observed versus fitted values demonstrated close alignment between predicted and actual forest area, indicating strong predictive reliability under the final modeling framework. Visualization of standardized coefficient effects confirmed the relative magnitude and direction of influence, with emission-related variables exerting the strongest negative effects and urban population showing a moderate positive effect. Overall, the results consistently identified greenhouse gas emissions as the primary drivers of forest area reduction in Pakistan, while urban population exhibited a statistically significant positive association.



Correlation Matrix Showing Relationships Among Environmental and Socio-Economic Variables

Figure 1 Correlation Matrix Showing Relationships Among Environmental and Socio-Economic Variables



Residuals Versus Fitted Values Plot Showing Non-Linearity and Heteroscedasticity

Figure 2 Residuals Versus Fitted Values Plot Showing Non-Linearity and Heteroscedasticity

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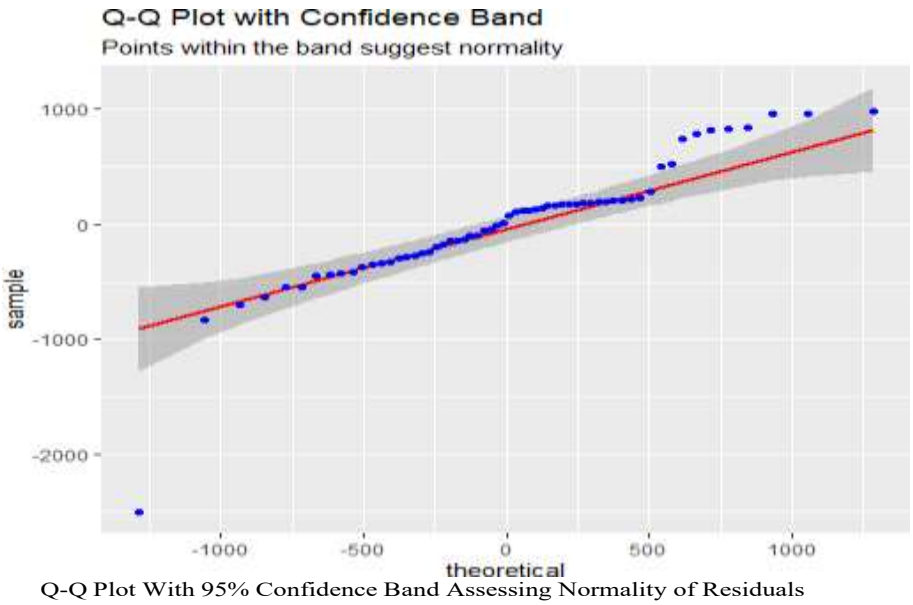
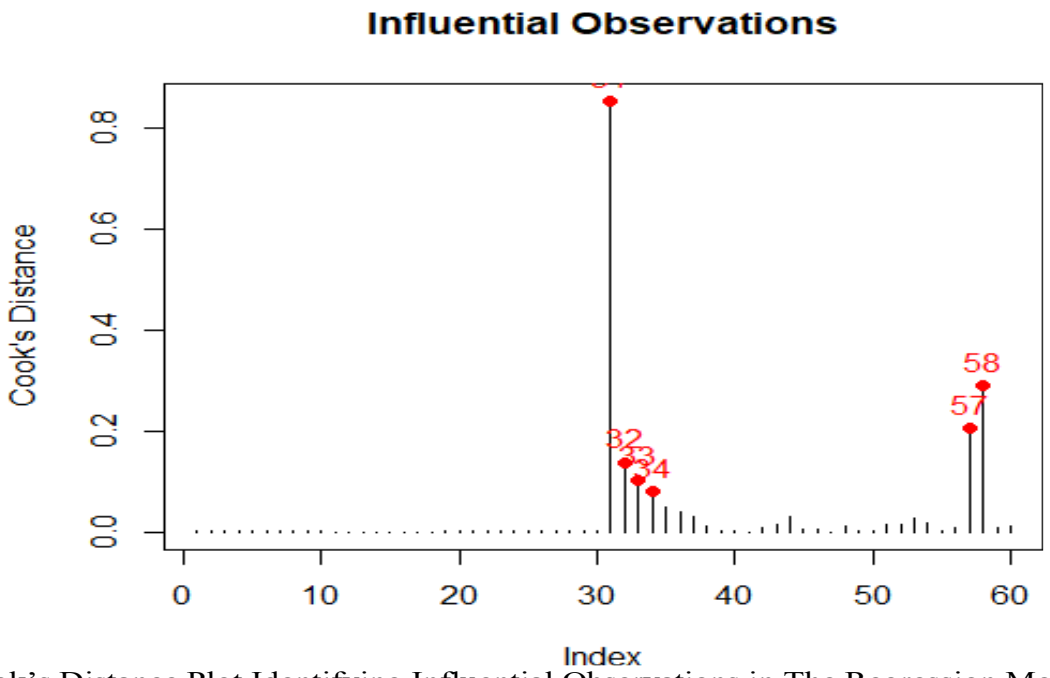


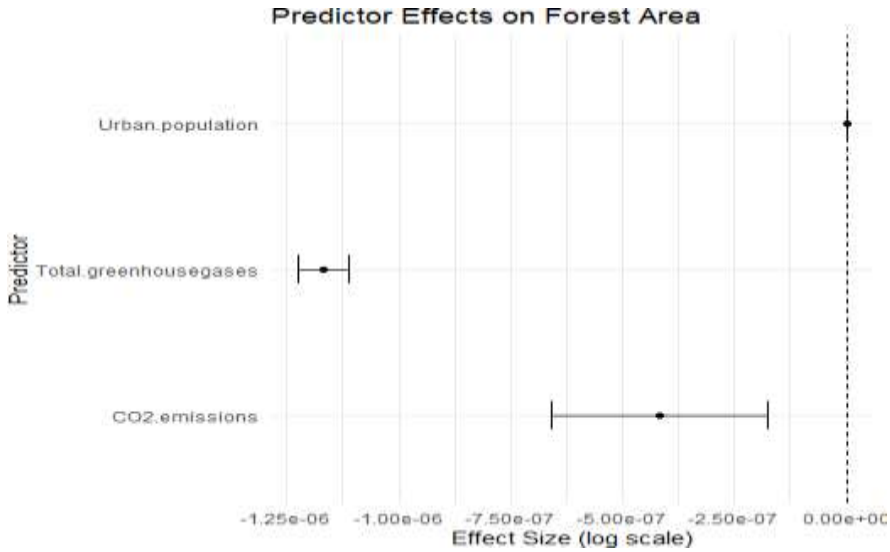
Q-Q Plot With 95% Confidence Band Assessing Normality of Residuals

Figure 3 Q-Q Plot with 96% Confidence Band Assessing Normality of Residuals



Cook's Distance Plot Identifying Influential Observations in The Regression Model

Figure 4 Cooks Distance Plot Identifying Influential Observations in The Regression Model



Comparison Of Actual and Predicted Forest Area Values Under the Final Model

Figure 5 Comparison of Actual and Predicted Forest Area Values Under the Final Model

DISCUSSION

The findings of this study provided compelling empirical evidence that anthropogenic emissions, particularly total greenhouse gas emissions and carbon dioxide emissions, were the dominant drivers of forest area decline in Pakistan. These variables consistently emerged as statistically significant determinants across both the reduced multiple regression model and the robust log-linear specification, underscoring the strength and stability of their association with forest loss. This pattern aligned closely with the broader body of global and regional literature, which has demonstrated that elevated emission levels intensify temperature rise, disrupt precipitation regimes, increase drought frequency, and ultimately weaken ecosystem integrity, leading to accelerated forest degradation (16). Similar evidence from developing regions has shown that rising atmospheric carbon concentrations contribute to land degradation and reduced vegetation productivity, lending further support to the robustness of the present findings (17,18). A notable and somewhat counterintuitive outcome was the statistically significant positive association between urban population and forest area. Classical land-use theories often suggest that urban expansion accelerates deforestation through infrastructure development and land conversion. However, emerging empirical evidence from countries undergoing rapid socio-economic transition has reported comparable trends, where urbanization reduces pressure on rural forests by lowering dependence on biomass fuels, promoting modern energy use, and concentrating populations within urban centers (19,20). In the Pakistani context, ongoing urban greening initiatives, the preservation of green belts, and the gradual strengthening of environmental regulations may collectively explain this positive relationship. These results highlighted that urbanization does not exert a uniform effect on forest systems; rather, its environmental consequences are mediated by governance quality, policy enforcement, and broader socio-economic transformations.

Methodological diagnostics revealed the presence of non-linearity, heteroscedasticity, and influential observations, which are common characteristics of environmental and climate-related datasets. The adoption of robust regression techniques combined with logarithmic transformation substantially improved model stability and reliability by reducing the influence of extreme values and correcting variance instability. This methodological rigor strengthened confidence in the estimated relationships and demonstrated the practical value of assumption-resistant statistical approaches in environmental modeling, particularly in contexts characterized by data irregularities and limited sample sizes (21,22). The high explanatory power of the reduced model further supported the internal consistency of the analytical framework, while the robust log-linear results confirmed the persistence of key effects after adjusting for violations of classical regression assumptions. From a policy and planning perspective, the findings emphasized the necessity of integrated strategies that simultaneously address emission reduction and land-use management. While urbanization may generate conditional environmental co-

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benefits under effective governance structures, unchecked growth in greenhouse gas emissions remained the most substantial threat to forest sustainability. The interaction between emissions, population dynamics, and land management illustrated the complexity of designing effective forest conservation policies in Pakistan, where climatic vulnerability and socio-economic pressures intersect. The results reinforced the importance of prioritizing emission mitigation alongside sustainable urban planning to safeguard remaining forest resources.

Despite its contributions, the study had several limitations that warrant consideration. The analysis was based on a relatively small sample of 60 observations, which may constrain statistical power and limit generalizability. In addition, the absence of potentially relevant variables, such as temperature anomalies, soil quality indicators, and historical land-use transitions, restricted the ability to capture the full spectrum of drivers influencing forest dynamics. The use of aggregated national-level data also precluded assessment of spatial heterogeneity across provinces or districts, where forest pressures and governance capacities may differ substantially. Future research would benefit from incorporating longer multi-decadal datasets, integrating additional climatic and biophysical indicators, and applying non-linear or machine-learning approaches to better capture complex interactions. Spatially disaggregated analyses at provincial or district levels could further enhance understanding of localized forest dynamics and policy effectiveness. Such extensions would improve predictive accuracy and deepen insight into the mechanisms linking anthropogenic activity, climate variability, and forest change (23,24). Overall, this study contributed valuable data-driven evidence on the determinants of forest degradation in Pakistan, reinforcing the central role of emission control while highlighting the nuanced effects of urbanization under evolving governance conditions. By situating the findings within existing literature and employing robust statistical techniques, the study offered a credible and policy-relevant contribution to national and regional discussions on forest conservation and environmental sustainability.

CONCLUSION

This study demonstrated that forest degradation in Pakistan is closely linked to anthropogenic pressures, with emissions emerging as the most critical threat to forest sustainability, while urbanization showed a more nuanced role shaped by governance and environmental management practices. By applying rigorous and assumption-resistant statistical methods, the analysis strengthened confidence in the identified relationships and highlighted the importance of addressing both environmental and socio-economic drivers of land-use change. The findings underscored the need for coordinated policy approaches that prioritize emission control alongside climate-adaptive forest conservation and responsible urban planning. Overall, the study contributed meaningful, evidence-based insight to the national discourse on sustainable land management and reinforced the urgency of integrated strategies to protect and restore forest ecosystems under growing climatic stress.

AUTHOR CONTRIBUTIONS

Author	Contribution
Sohail Abbas*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Sara Tehreem	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Ayesha Akram	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published
Dilawar Khan	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published

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Author	Contribution
Rabia Rashid	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published
Fatima Batool	Substantial Contribution to study design and Data Analysis Has given Final Approval of the version to be published

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