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ORIGINAL RESEARCH ARTICLE

# Decoding carbon sequestration: The impact of agriculture, conservation policies, climate, and land use

**Muhammad Asif Khan[1,2], Muhammad Khalid Anser[3], Bushra Usman[4], Agha Amad Nabi[5], Ishfaq Ahmad[6], and Khalid Zaman[7]***

[1]Department of Forestry and Wildlife Management, Faculty of Physical and Applied Sciences, The University of Haripur, Haripur, Khyber Pakhtunkhwa, Pakistan
[2]Department of Research, The Sherwan Institute of Online Education (SIOE), Abbottabad, Khyber Pakhtunkhwa, Pakistan
[3]Department of Economics, Faculty of Economics and Administrative Sciences, Recep Tayyip Erdoğan University, Rize, Turkey
[4]Department of Business, School of Management, Forman Christian College (A Chartered University), Lahore, Pakistan
[5]Department of Business Administration, Faculty of Social Sciences, Government College University Hyderabad, Hyderabad Sindh, Pakistan
[6]Lahore Business School (LBS), Faculty of Management Sciences, The University of Lahore, Lahore, Pakistan
[7]Department of Economics, Faculty of Social and Administrative Sciences, The University of Haripur, Haripur, Pakistan
***Corresponding author:** Khalid Zaman (khalid.zaman@uoh.edu.pk)

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**Abstract:** Pakistan's forests play avital role in mitigating climate change by absorbing and storing carbon dioxide from the air, making them essential natural carbon sinks. Achieving a balance between logging and forest preservation is necessary for the country to meet global climate goals. This study employs a robust least squares regression approach to identify the components of carbon sequestration, using quarterly time series data from 1990 Quartile 1 to 2023 Quartile 4. The findings show that agricultural income, forest preservation legislation, rainfall variability, high temperatures, and land-use changes significantly affect carbon sequestration in Pakistan. Positive changes in forest cover highlight the need for continuous afforestation and replanting efforts. However, a decline in forest carbon sink capacity due to agricultural output and land-use changes hampers climate change mitigation. The results emphasize the delicate balance between economic growth and environmental conservation. These findings suggest that addressing the challenges of climate change and land use requires specialized policies that prioritize forest conservation while managing economic costs.

**Keywords:** Carbon storage potential; Sustainable forestry; Ecosystem resilience; Land management strategies; Climate variability; Environmental policy; Pakistan

## 1. Introduction

Globally, forests cover 4.06 billion acres or 31% of the Earth's land area.[1] They play a vital role in mitigating climate change by absorbing and storing carbon dioxide, thereby slowing the pace of global warming.[2] In Pakistan, maize is cultivated extensively in both rainfed and irrigated areas. Agriculture and forest management contribute to climate change mitigation by improving soil organic carbon through carbon sequestration.[3] Circular economy approaches have further enhanced forest management by promoting sustainable land use

and carbon sequestration. The Forest Carbon Benefit Indicator (FCBI) estimates the financial and ecological advantages of carbon sequestration in Pakistan's forests, along with the outcomes of conservation activities. Pakistan's efforts to minimize greenhouse gas (GHG) emissions, promote long-term carbon sequestration, and understand the influence of agricultural income on the carbon-protective function of forests are closely interconnected. Forest conservation methods, such as reforestation and establishing protected areas, are crucial for sustainable development.[4] This study explores the complex relationship between climate and carbon sequestration in these ecosystems. Given Pakistan's rapidly urbanizing population, understanding the demographic impact on forests and carbon sequestration is essential for addressing climate change. Urbanization and agricultural expansion significantly affect Pakistan's forest ecosystems and their capacity to sequester carbon, making sustainable land management vital for mitigating climate change.[5] Carbon sequestration is a key strategy in reducing global warming, as forest ecosystems not only absorb but also release carbon dioxide. Pakistan's 23.8 million hectares of fertile land are heavily used for agriculture. The Indus River and its tributaries support an irrigated agricultural sector encompassing 14.6 million hectares across Punjab, Sindh, and Khyber Pakhtunkhwa.[6]

Forest carbon stocks in the country have declined from 668 gigatons in 1990 to 662 gigatons in 2020, while carbon density increased from 159 to 163 tons per hectare.[7] Climate change, driven by rising GHG concentrations, is one of the most significant challenges of our time. A major global issue is fostering economic growth while simultaneously reducing GHG emissions, particularly carbon emissions.[8] Pakistan's economy has shifted from agriculture to industry, and this industry-led growth led to increased energy consumption and pollution.[9] He and Deng[10] found that natural resource quantities, mineral rents, and forest rents affect global finance unevenly. Forestry, fisheries, livestock, and crops are major agricultural subsectors in Pakistan, as they provide employment and income for low-income and disadvantaged families. Over half of the workforce and 62% of rural residents depend on agriculture for their livelihoods. However, Pakistan faces water shortages, low agricultural and livestock production, low wages, and extreme food insecurity.[11] Deforestation contributes to carbon emissions, exacerbating environmental issues and global warming. Since 1990, deforestation has resulted in the loss of 420 million acres of forest worldwide, although the rate has slowed. By 2020, the rate of deforestation was predicted to decrease to 10 million hectares per year, down from 12 million hectares between 2010 and 2015. Pakistan is combating the "Timber Mafia," a criminal group that illegally chops down and sells trees. Khalid *et al.*[12] found that illegal wood harvesting is four times higher than legal timber extraction. From 1990 to 2000, Pakistan lost 41,100 hectares of forest annually,[13] with an average annual deforestation rate of 1.63%. From 1990 to 2005, Pakistan lost 625,000 hectares, or 24.7% of its forest cover.[14] Forests in Pakistan now cover just 2.5% of the country, with deforestation occurring at 2.1% per year. This deforestation has hindered Pakistan's ability to meet the World Bank's Millennium Development Goal of increasing forest cover from 2.5% to 6% by 2015.[15] To mitigate deforestation, Pakistan has implemented various laws and initiatives aimed at conserving and expanding forest cover. With a deforestation rate of 4.6%, Pakistan ranks second globally in terms of deforestation. Forest managers and policy makers have long been concerned about the depletion of resources caused by human activity. Reforestation is essential in the fight against climate change and global warming.[16]

Without more and better-protected areas, sustainable growth is unattainable.[17] Pakistan needs to adopt sustainable forestry practices, such as plantation drives, to achieve long-term economic growth and mitigate climate change.[18] Globally, forests encompass 726 million acres of protected areas, with South America being unique among the world's six regions, as31% of its forests are protected.[19] Since 1990, the global forest cover in protected areas has expanded by 191 million hectares; however, it decreased between 2010 and 2020.[20,21] To safeguard both the environment and economy, Pakistan requires green mechanization in agriculture, sufficient investment in research and development, and integrated policies that promote economic development alongside environmental protection.[22] Integrated landscape solutions aimed at "reducing emissions from deforestation and forest degradation" (REDD+) are receiving increasing attention and funding.[23] Globally, multiple protected zones are being established to mitigate human-caused biodiversity loss. In Khyber Pakhtunkhwa, a province in Pakistan, free plants are now being provided for agroforestry and agricultural forestry.[24] Public forestry extension agents monitor the Billion Trees Afforestation Project (BTAP), which will continue under the newly announced 10-BTAP Project by the Government of Pakistan in 2023.[25]

Since 2000, the global average daily temperature has never exceeded 1.5°C above pre-industrial

levels.[26] Long-term fluctuations in annual rainfall and temperature, mainly driven by meteorological changes, may lead to floods and droughts.[27] Climate change is influenced by factors such as temperature, precipitation, humidity, carbon dioxide levels, air pollution, wind, and atmospheric pressure.[28] In hyper-arid and arid regions, droughts are common during the winter monsoon season (December – February) due to decreased seasonal rainfall and rising temperatures, which increase evapotranspiration.[29] Ahmed *et al*.[30] found that Pakistan's surface temperature rose by 0.1°C per decade from1960 to 2010, accompanied by highly variable precipitation patterns. Since 1990, private ownership of forests has increased, while public woodlands have decreased. China, Russia, Brazil, and Canada together own 54% of the world's forests, with the United States, Canada, and Russia collectively holding 46%. Heat waves – defined as annual temperatures of 29°C or higher – would affect approximately 5 times fewer people if global warming were limited to 1.5°C instead of 2.7°C. By the end of the century, climate change could force 3 – 6 billion people – roughly one-third to one-half of the global population, out of the habitable zone, leading to extreme heat, food shortages, and increased mortality.[31] Pakistan's land cover change maps show that most agricultural expansion is primarily occurring in rangeland and forest areas. Land use changes in Pakistan are driven by both economic growth and population growth.[32] Understanding the impact of urbanization and land use on regional and local climate, ecosystem services, biodiversity, and ecosystem functioning is essential. To balance climate change and food security, effective carbon sequestration – particularly land-based sequestration – is crucial.[33]

The preceding discussion raises the following research questions: First, what is Pakistan's forest cover-based carbon sequestration capacity? To achieve better carbon stewardship and climate change mitigation for sustainable development in Pakistan, it is crucial to understand its carbon sequestration potential. This knowledge will facilitate the development of policies and programs aimed at addressing these challenges. Second, how effectively have afforestation initiatives and protected area projects in Pakistan promoted long-term forest management and carbon sequestration? This question examines the effectiveness of forest management and conservation policies, particularly in protected areas and reforestation initiatives, to better understand their impact on carbon sequestration, sustainable practices, long-term environmental resilience, and biodiversity conservation in Pakistan. Finally, how do Pakistan's forests contribute to GHG reduction? This inquiry may reveal the factors that influence the carbon-capturing and carbon-storing potential of Pakistan's forests, which could guide strategies to enhance the country's climate change mitigation. The objectives of this study are as follows:

(i) To analyze Pakistan's FCBI, which assesses its forests' carbon sequestration capacity and their role in carbon management.
(ii) To evaluate the success of forest preservation and management initiatives, such as afforestation and protected areas, in enhancing carbon sequestration, and aligning with the Sustainable Development Goals.
(iii) To assess how agricultural income, annual deforestation rates, climate, population, and land use changes affect Pakistan's forest carbon sequestration capacity.

This research employs a robust least squares (RLS) regression technique that accounts for model outliers, ensuring accurate parameter estimations. The methodology enhances statistical rigor by identifying the most significant influencing factors. The research framework is structured as follows: Section 2 provides the literature review; Section 3 outlines the theoretical development; Section 4 presents the data and methods; and Sections 5 and 6 present the findings and conclusions, respectively.

## 2. Literature review

Environmental experts have studied the socioeconomic and environmental factors influencing forest carbon sequestration for decades.[34-36] It has long been recognized that forests are important "carbon sinks" that store substantial amounts of carbon dioxide.[2,37] Forests absorb 30% of the world's carbon dioxide emissions, helping to decrease climate change. Earlier studies have emphasized the need to preserve and expand forests to mitigate climate change.[38,39] However, most of these studies have focused on industrialized countries, then overlooking the unique dynamics of developing nations, where deforestation, land-use changes, and socioeconomic pressures pose significant challenges to forest management.[40,41] This study uses Pakistan as a case example of a nation where carbon sequestration capacity is substantially influenced by economic, environmental, and climatic factors. The academic literature also discusses how growing affluence and agricultural expansion contribute to deforestation and carbon sequestration.[42,43] Saleem *et al.*[44] demonstrated

that deforestation is primarily driven by the conversion of forests into agricultural land and pastures. This issue is particularly important in developing countries like Pakistan, where agriculture is the primary livelihood. This study empirically investigated how increasing agricultural income affects carbon sequestration, emphasizing the need for sustainable farming. Deforestation, another key factor, has been extensively studied. Bajoria *et al.*[45] demonstrated that global deforestation poses a serious threat to biodiversity, global warming, and carbon sequestration. Kinda and Thiombiano[46] argue that economic pressures and poor governance lead to deforestation in developing countries. Secondary forest growth may temporarily increase carbon sequestration after deforestation.[47]

Temperature and precipitation are crucial factors affecting forest carbon sequestration. Liu *et al.*[48] found that the carbon storage capacity of forests diminishes as temperature rises due to increased respiration and reduced biomass growth. Irregular precipitation patterns can also induce water stress, which harms forests.[49] Most prior studies have focused on temperate or boreal forests, overlooking issues specific to tropical and subtropical regions such as Pakistan.[50,51] This study showed how increasing temperatures and variable rainfall patterns have impacted carbon sequestration in Pakistan's forests, contributing to the global literature. It also underscores the importance of climate-resilient forestry practices tailored to local conditions. A large body of research has examined land-use dynamics and their environmental impacts, highlighting how land-use changes affect carbon sequestration.[52,53] Jiang *et al.*[54] and Ersoy Tonyaloğlu[55] found that urbanization and agricultural development reduce forest cover and carbon storage capacity. These studies emphasize the need for integrated land-use planning to balance economic growth and environmental sustainability. However, the literature has yet to explore how land-use changes, combined with meteorological, socioeconomic, and other factors, impact national carbon sequestration levels. This gap is addressed in this study, which analyzes the effects of land-use changes, agricultural income, and climate on carbon sequestration in Pakistan. Policy interventions to improve forest carbon sequestration in developing countries are underexplored. Mori[56] and Grant and Le Billon[57] suggest that REDD+ initiatives could promote sustainable forest management. Pakistan, however, faces challenges in implementing such programs due to institutional weaknesses, limited funding, and sociopolitical constraints. The study highlights the negative effects of agricultural income, temperature, and land-use changes, as well as the potential benefits of reforestation, which should inform policy makers seeking to promote carbon sequestration while fostering economic growth. By integrating economic, environmental, and meteorological factors, this study evaluates Pakistan's forest carbon sequestration potential. Although understanding of these processes has improved, significant gaps remain, particularly in rapidly developing countries like Pakistan, where economic growth and environmental sustainability are often in conflict. This research aims to assist practitioners and policy makers in enhancing carbon sequestration and mitigating climate change, while expanding the theoretical understanding of the complex relationship between socioeconomic, environmental, and climatic challenges.

The literature review led to the formulation of the study's research hypotheses:

*H1: Increased agricultural revenue in Pakistan diminishes carbon sequestration*

The agricultural sector in Pakistan is essential to the country's economic growth due to its contributions to employment and Gross domestic product. However, increased agricultural activity often leads to deforestation and land-use changes, which adversely affect carbon sequestration. As agricultural income rises, farmers and agribusinesses may convert forests in to croplands or pastures to increase production, thereby reducing carbon dioxide absorption. Practices such as mono cropping and the use of chemical fertilizer scan de grade soil quality and carbon storage. This hypothesis examines the tension between the economic benefits of agriculture and environmental sustainability, proposing policies that encourage sustainable land-use practices and safeguard the carbon sequestration potential of forests.

*H2: Land-use shifts and afforestation may mitigate the carbon sequestration losses caused by deforestation*

Deforestation is a major source of carbon loss, a sit depletes the carbon sink capacity of forest ecosystems and releases stored carbon into the atmosphere. The relationship between carbon sequestration and deforestation is not necessarily linear. Controlled land-use transitions, afforestation, and secondary forest regeneration can help restore carbon storage capacity following deforestation. Deforested land can be converted into sustainably managed plantations, agroforestry systems, or protected afforestation zones to recover a portion of the carbon sequestration potential.

However, these compensatory processes are typically insufficient and offer only temporary relief from widespread deforestation. Thus, this hypothesis aims to determine whether deforestation trends in Pakistan are accompanied by adequate reforestation and forest management practices that mitigate carbon losses or whether the continued degradation of Pakistan's forest cover further diminishes its ability to store carbon.

*H3: Rising temperatures and unpredictable rainfall reduce Pakistan's carbon sequestration*

The study suggests that high temperatures and variable precipitation negatively affect the health of forests, reducing their biomass production and making them less effective carbon sinks.

Carbon sequestration and the role of forests in mitigating climate change are topics of ongoing research. However, numerous questions remain, especially for developing countries like Pakistan.[58,59] Local socioeconomic and environmental factors significantly influence carbon sequestration, yet most studies focus on global trends or regional assessments, neglecting the specific dynamics at play in individual countries.[60,61] Many studies fail to consider the complex interactions between climatic factors, land-use changes, deforestation rates, and agricultural practices that shape carbon dynamics.[52,62] Pakistan, with its high rates of deforestation, unsustainable farming practices, and vulnerability to climate change, faces unique challenges that are often overlooked in global and regional research.[63,64] There is a lack of country-specific research on the policy-relevant impacts of socioeconomic factors on forest carbon benefits in Pakistan, which hinders the development of effective, evidence-based strategies for carbon sequestration.

This study addresses these gaps in understanding Pakistan's forest carbon sequestration capacity by examining the factors that affect it. The study incorporates agricultural income, deforestation rates, temperature, precipitation, and land-use improvements to present a comprehensive picture of carbon sequestration processes. Unlike previous research that treated these factors in isolation, this study examines their combined impact on carbon sequestration.[65,66] It also provides valuable data from Pakistan, which has been largely overlooked in international research on forest carbon dynamics, despite facing major concerns from deforestation and climate change.

The research advances theoretical understanding by linking its findings to economic and environmental concepts. It supports the environmental sustainability theory of carbon sequestration and deforestation, demonstrating how economic growth can degrade the environment but also how income and conservation efforts can promote sustainability.[67] The study also high light show theories of land-use change and agricultural growth affect carbon sequestration in Pakistan.[68] These theoretical contributions provide the groundwork for future research in other developing countries with similar environmental, social, and economic conditions, enhancing our understanding of carbon dynamics.

From a policy perspective, the study provides practical insights that bridge theoretical research to real-world applications. By illustrating how agricultural income and land-use changes diminish carbon sequestration, it advocates for sustainable farming practices and urban planning. The study also suggests targeted deforestation management strategies and climate-resilient forestry actions to improve carbon sequestration while balancing economic growth. Given its comprehensive approach and focus on Pakistan, this study is valuable for researchers, policymakers, and international organizations working on climate change and environmental degradation. It fills significant gaps in the literature and provides guidance for future research and policy development in this critical field.

## 3. Data source and methodology

Table 1 presents the variables used in the study. The time-series data were collected from the World Bank[69] and the Climate Change Knowledge Portal.[70] In addition, the data were converted into quarterly intervals, covering the period from 1990 Quartile 1 to 2023 Quartile 4.

The social-ecological systems theory helps explain the interaction between forest ecosystems and human systems, including social policies and activities.[71] Activities such as farming, development, tree cutting, and preservation have significant ecological impacts on forests. According to this theory, forests thrive through the dynamic interactions between human and natural systems.[72] Policies and initiatives that promote reforestation and establish protected areas directly influence forests' carbon sequestration capacity. The social-ecological systems theory also supports adaptive governance, which fosters sustainable policies through feedback loops between human and natural systems.[73] This theory aids in the sustainable and ethical management of forests by understanding how social, political, economic, and environmental factors affect carbon sequestration. Environmental determinism posits that climate, terrain, and resources shape human

**Table 1. List of variables**

| Variable type | Variable name | Symbol used | Measurement/formula | Unit | Data source |
|---|---|---|---|---|---|
| Dependent variable | Carbon sequestration capacity | FCBI | (Forest rents as % of GDP-net forest depletion as % of GNI)/$CO_2$emissions (metric tons per capita) | Index (dimensionless) | World Bank[69] |
| Independent variables | Agricultural income | AGRINC | Agriculture, forestry, and fishing value added (current USD) | USD (current) | World Bank[69] |
| | Annual deforestation rate | DEFORATE | ([Forest area year 2 -forest area year 1]/forest area year 1)×100 | Percentage (%) | World Bank[69] |
| | Forest management and conservation policies | FMCP | (Forest rents as % of GDP+Agricultural value added as % of GDP)/R&D expenditures as % of GDP | Index (dimensionless) | World Bank[69] |
| | Climatic variables — temperature change | TEMP | Annual mean temperature change | Degrees Celsius (°C) | CCKP[70] |
| | Climatic variables — rainfall | RAINFALL | Annual total precipitation | Millimeters (mm/year) | CCKP[70] |
| | Population and land use change — urban population | URBANPOP | Urban population as a percentage of total population | Percentage (%) | World Bank[69] |

Abbreviations: CCKP: Climate Change Knowledge Portal; CO2: Carbon dioxide; FCBI: Forest Carbon Benefit Indicator; GDP: Gross domestic product; GNI: Gross national income; R&D: Research and development; USD: United States dollars.

behavior, social development, and economic activities.[74] This concept is critical for understanding how plants store carbon in response to climate change. Temperature and precipitation regulate plant growth, soil fertility, and carbon sequestration, among other ecological processes. Moderate temperatures and abundant rainfall enhance forest carbon storage, while extreme heat waves and droughts reduce forest productivity and contribute to deforestation.[75] Human efforts to maintain and conserve forests are influenced by climate and geography,[76] particularly through factors such as urbanization, land use, and agriculture. This hypothesis can guide researchers in studying how environmental factors affect forest carbon sequestration and how societies have adapted to these constraints through sustainable policies and practices.

The study employed an analytical model to provide statistically robust insights into forest carbon benefits and critical socioeconomic and environmental challenges. RLS regression was used for empirical estimations. RLS regression effectively manages outliers and heteroskedasticity in complex datasets, making it especially useful when ordinary least squares (OLS) assumptions are violated.[77] Unlike OLS, which minimizes the sum of squared residuals, robust regression utilizes several optimization methods to reduce the influence of outliers on model predictions. As a result, RLS provides more reliable and unbiased parameter estimates for datasets with non-normal error distributions or extreme values.[78] This technique is particularly valuable when studying carbon sequestration, agricultural income, deforestation, forest management, climatic factors, and land use changes. In an OLS model, outliers often include extreme meteorological variables, such as precipitation and temperature, or rapid changes in forest cover, such as deforestation. The RLS approach improves the model by reducing extreme values, providing a clearer presentation of variable patterns and correlations.[79]

Environmental and socioeconomic variables typically exhibit varied error rates; therefore, robust regression accounts for this error.[80] Through the use of iteratively reweighted least squares, robust regression updates data weights, reducing the influence of observations with higher residuals to stabilize model fit. Despite such variations, robust regression ensures the validity of the study. Minimizing the impact of outliers in population growth, land use, and carbon sequestration policy

outcomes improves accuracy. **Equation I** presents the RLS equation for reference:

$$FCBI = \Omega_0 + \Omega_1 AGRIINC + \Omega_2 DEFORATE + \Omega_3 FMCP + \Omega_4 TEMP + \Omega_5 RAINFALL + \Omega_6 URBANPOP + \varepsilon \quad (I)$$

Where:
FCBI = Forest Carbon Benefit Indicator;
AGRINC = Agricultural income;
DEFORATE = Deforestation;
FMCP = Forest management and conservation policies;
TEMP = Extreme temperature;
RAINFALL = Rainfall vulnerability;
URBANPOP = Urban population; and
$\xi$ = Disturbance term.

RLS regression improves empirical validity and reduces bias by adhering to quantitative research standards for handling data outliers.[81] It provides a comprehensive and systematic assessment of the interrelationships between study variables, leading to practical, evidence-based solutions for sustainable forest management and climate change mitigation.

## 4. Results and discussion

Table 2 presents the descriptive statistics for the variables. In Pakistan, the FCBI fluctuated between 0.464 and 5.660 metric tons of carbon dioxide per year, with a mean value of 1.940 metric tons. Agriculture income improved carbon benefits by increasing the FCBI by 3,740 US dollars. The annual deforestation rate varied from 0.473% to 1.636%, with an average of 0.974%, placing pressure on forest carbon sequestration. The forest sustainability index trends fluctuated over the analyzed period, with an average of 4.780 US dollars, showing a decrease of 1.060 US dollars. Weather factors, such as temperature and rainfall, strongly influenced the FCBI. Forest carbon sequestration was affected by the average temperature increase of 0.567°C and annual precipitation of 293.558 mm. The average urban population was 6,110, with a range from 3,528 to 8,897. Urbanization patterns shifted and altered forest ecosystems and land use. The extreme values of each variable demonstrated the range of variability within the dataset. Kurtosis, skewness, and standard deviation provided insights into data distribution, symmetry, and dispersion. A kurtosis of 5.150 suggests a distribution with heavy tails and a large peak, whereas the FCBI's skewness of 1.574 indicates a right-skewed distribution.

Figure 1 illustrates the influence statistics. These statistics revealed outliers and impactful observations within the dataset. The R Student and difference in fit(s) methods identified two extreme outliers that notably affected the regression analysis. The Hat Matrix approach also identified two highly leveraged observations that may significantly influence the regression findings. In addition, COVRATIO detected another outlier in the dataset. Given these results, RLS regression was the optimal choice for obtaining robust estimates.

Table 3 presents the RLS estimates. The results indicated a negative association between FCBI and agricultural income. As agricultural income increased, woodland carbon sequestration decreased. This conclusion emphasizes the conflict between forest protection and agricultural growth. Farming often leads to deforestation to make way for crops or livestock, reducing forest cover and carbon stored in soil and woody plants.[82] Agricultural activities such as soil tilling and fertilizer application release carbon into the atmosphere.[83] Pakistan, with an economy heavily dependent on agriculture, faces significant challenges in balancing economic growth and environmental sustainability.[84]

**Table 2. Descriptive statistics**

| Methods | FCBI | AGRINC | DEFORATE | FMCP | TEMP | RAINFALL | URBANPOP |
|---|---|---|---|---|---|---|---|
| Mean | 1.940 | 3.740 | 0.974 | 4.780 | 0.567 | 293.558 | 6110 |
| Maximum | 5.660 | 8.380 | 1.636 | 9.820 | 1.423 | 442.880 | 8897 |
| Minimum | 5.464 | 1.190 | 0.473 | 1.060 | -0.375 | 181.500 | 3528 |
| Std. dev. | 1.390 | 2.480 | 0.171 | 2.980 | 0.475 | 64.984 | 1615 |
| Skewness | 1.574 | 0.427 | 0.923 | 0.298 | -0.191 | 0.149 | 0.027 |
| Kurtosis | 5.150 | 1.766 | 9.793 | 1.594 | 2.481 | 2.215 | 1.787 |

Source: Authors' estimate. Abbreviations: AGRINC: Agricultural income; DEFORATE: Deforestation; FCBI: Forest Carbon Benefit Indicator; FMCP: Forest management and conservation policies; RAINFALL: Rainfall vulnerability; Std. dev.: Standard deviation; TEMP: Extreme temperature; URBANPOP: Urban population.

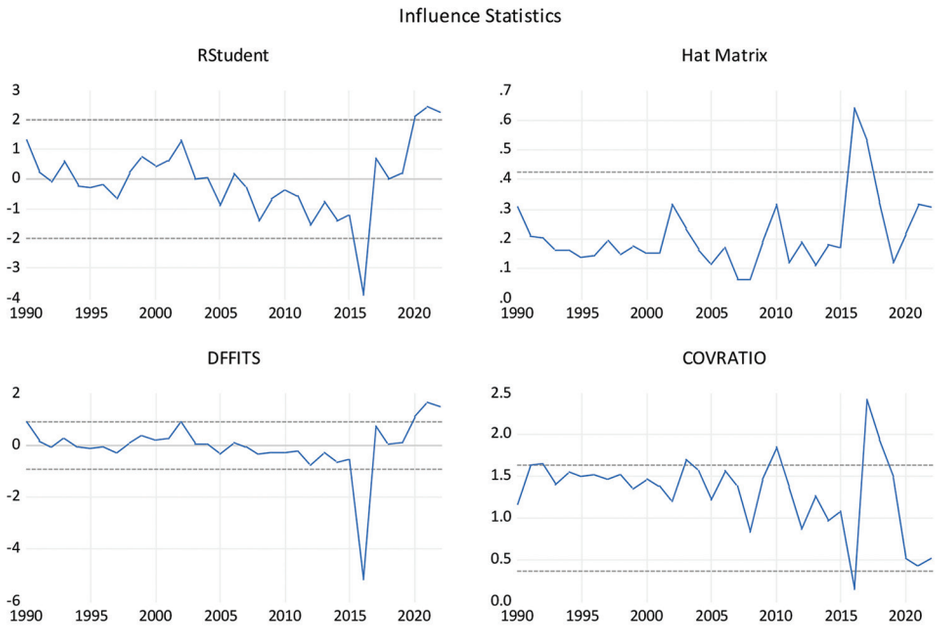


**Figure 1. Influence statistics**

Source: Authors' estimates. Abbreviation: DFFITS: Difference in fit(s).

**Table 3. Robust least squares regression estimates**

| Dependent variable: FCBI | | | | |
|---|---|---|---|---|
| **Method: Robust least squares** | | | | |
| **Variables** | **Coefficient** | **Standard error** | **z-statistic** | **Prob.** |
| AGRINC | −0.0029 | 0.0002 | −9.8422 | 0.0000 |
| DEFORATE | 3.5900 | 74,885 | 4.7960 | 0.0000 |
| FMCP | −0.0004 | 0.0002 | −1.9609 | 0.0499 |
| TEMP | −80,334 | 27,711 | −28,989 | 0.0037 |
| RAINFALL | −354,464.6 | 202,600.2 | −1.7495 | 0.0802 |
| URBANPOP | −4.2186 | 1.5262 | −2.7640 | 0.0057 |
| C | 4.3300 | 61,875 | 6.9899 | 0.0000 |
| Method: Robust statistics | | | | |
| $R^2$ | 0.5546 | Adjusted $R^2$ | 0.5086 | |
| $Rw^2$ | 0.8317 | Adjusted $Rw^2$ | 0.8317 | |
| $Rn^2$ statistic | 145.0428 | Prob ($Rn^2$) | 0.0000 | |

Source: Author's estimate. Abbreviations: AGRINC: Agricultural income; C: Constant; DEFORATE: Deforestation; FCBI: Forest Carbon Benefit Indicator; FMCP: Forest management and conservation policies; Prob: Probability; RAINFALL: Rainfall vulnerability; TEMP: Extreme temperature; URBANPOP: Urban population.

The annual deforestation rate showed a positive coefficient, indicating that the FCBI increases with deforestation. Afforestation programs that accompany deforestation may temporarily sequester carbon, which explains this paradoxical result. Although cutting down mature forests may release carbon, afforestation or restoration effort scan introduce younger trees that absorb more carbon.[85] According to Robinson,[86] planting trees provides greater short-term advantages than long-term costs to biodiversity and the ecosystem; hence, deforestation should not be condoned. The forest sustainability index displayed a negative coefficient, suggesting an inverse relationship with the FCBI. Sustainable forest management practices,

such as selective logging or reduced-impact logging, may initially lower overall carbon storage capability.[87] However, long-term sustainable forest management is crucial to preserving ecologically healthy forests that are more resilient to environmental pressures. This research emphasizes the need for a balanced forest management strategy that balances both short-term carbon sequestration and long-term sustainability.[88] The results demonstrated a strong negative relationship between temperature and FCBI. Forests are particularly vulnerable to climate change, as their carbon sequestration capacity declines with increasing temperatures.[89] Heat stress damages forest ecosystems, as Smigaj *et al.*[90] found. Elevated temperatures increase soil and plant respiration, releasing carbon into the atmosphere. Furthermore, extreme temperatures can reduce forest productivity and increase the risk of wildfires, further diminishing carbon stocks.[91] This research underscores the crucial need for adaptive forest management practices that improve forest resilience to heat stress in Pakistan, where temperatures have been rising due to climate change.

Rainfall has a negative coefficient, suggesting that excessive rainfall may hinder carbon sequestration. While precipitation is necessary for forest growth, excessive or irregular precipitation patterns can lead to soil erosion, waterlogging, and nutrient leaching, all of which harm forests. Sun *et al.*[92] stated that climate change-induced changes in precipitation patterns may disrupt the delicate balance of forest ecosystems. Climate variability is significantly altering Pakistan's rainfall patterns, adversely affecting forest ecosystems, and adaptation measures are needed to mitigate these effects. Another factor contributing to reduced carbon sequestration is human activity. Deforestation and carbon release often result from urbanization, infrastructure development, and agricultural conversion.[4] According to Qin *et al*.,[93] land-use change is a major driver of global carbon emissions. Pakistan's forest areas are under increasing pressure from urbanization and infrastructure growth. Deforestation not only degrades habitats and biodiversity but also reduces carbon sequestration.[94] Therefore, land-use planning and forest protection must be integrated to balance development with sustainability.

These findings have significant implications for Pakistan's climate change and carbon storage strategies. Deforestation, land-use changes, and agricultural activities contributed to nearly 200 million metric tons of carbon dioxide emissions in Pakistan in 2022. These emissions underscore the urgent need for focused efforts to mitigate carbon loss.[95] To prevent carbon sequestration from being hindered by agricultural growth, Pakistan could promote agroforestry, conservation tillage, and organic fertilizers. These approaches enhance soil health and increase carbon storage. Despite the benefits of afforestation in increasing carbon sequestration, long-term deforestation prevention remains critical. Expanding forest preserves, supporting community-based forest management, and curbing illegal logging are essential steps.[96] Adapting forests to changing rainfall patterns and rising temperatures is crucial. This may involve improving fire management practices, enhancing forest monitoring, and promoting the use of storm-resistant trees. Forest protection must be incorporated into sustainable land-use planning to reduce the impact of urbanization and infrastructure development on forest ecosystems.[97] Green infrastructure and park renovations could also contribute to carbon sequestration. Given that Pakistan is a signatory of the Paris Agreement, aggressive action is required to address climate change. Forest conservation efforts should align with broader climate and development goals, including renewable energy initiatives and sustainable waste management.[98]

## 5. Conclusion and policy recommendation

This study analyzed the factors influencing Pakistan's carbon storage capacity, including climate, precipitation, land-use changes, deforestation, agricultural income, and forest preservation regulations. The RLS regression analysis revealed that these factors significantly affect the FCBI. The study demonstrated that environmental processes and societal activities are interconnected, with agricultural dependence driving deforestation and land conversion, which in turn threatens forest carbon sequestration. Climate change exacerbated this situation by reducing Pakistan's forest carbon sequestration capacity through rising temperatures and altered precipitation patterns. In addition, urbanization and infrastructure development contributed to decreased carbon absorption by forests. The findings also indicate that reforestation may offer temporary improvements in carbon absorption, highlighting the complex relationship between deforestation and carbon sequestration. However, the unsustainability of this strategy emphasizes the urgent need for proactive forest protection. Pakistan faces substantial challenges from climate change, urbanization, and economic expansion. The loss of forest carbon capacity due to anthropogenic activities undermines both ecological stability and efforts to mitigate climate change. Therefore, achieving Pakistan's carbon sequestration and sustainable development goals

requires a coordinated effort that balances social and economic growth with environmental preservation. The insights from this study on Pakistan's carbon sequestration dynamic scan guide more focused and effective governmental responses to these challenges.

The research recommends several policy actions aimed at reducing the human impact on Pakistan's forests and enhancing carbon sequestration. Policymakers should prioritize sustainable agricultural practices that do not compromise production for profit. Given the vital role of agriculture in the economy, it is crucial to promote farming techniques that support carbon sequestration. Initiatives like agroforestry, which involves growing crops alongside trees to enhance yields and store carbon, should be encouraged. Precision farming technologies can help reduce deforestation while increasing efficiency. Financial incentives should be provided to organic farmers to maintain soil carbon levels. These strategies require government subsidies, farmer education, and public awareness campaigns. Support for forest preservation initiatives is another key policy recommendation. As illegal logging and land conversion continue to threaten carbon sequestration, stronger regulations and enforcement are needed. Enhancing and expanding protected forests will help preserve biodiversity and carbon storage. Community-based forest management programs should be promoted, allowing local communities to participate in conservation and sustainable forest resource management. Policies should also encourage the replanting of native species to improve carbon absorption and maintain ecological stability. Furthermore, collaboration with international organizations and environmental agreements can provide additional financial and technical resources to strengthen conservation efforts.

Given that climate change is likely to further reduce forest carbon sequestration, adaptation and mitigation strategies are essential. Changes in precipitation and rising temperatures will continue to impact forest carbon storage. Climate-resilient forestry projects, such as improved forest management practices and the planting of drought-resistant trees, should be supported by the government. Studying these impacts will be key to mitigating the long-term effects of climate change on forest ecosystems. National development strategies must be aligned with climate change adaptation to ensure the health of both forests and economies. Communities must collaborate to mitigate the impacts of climate change on forests. As infrastructure development and urbanization continue to damage forest ecosystems, sustainable land-use planning becomes increasingly vital. Land-use changes hinder carbon sequestration, necessitating a comprehensive development policy that prioritizes forest conservation. Governments should incorporate forest preservation into zoning and urban development laws, providing incentives for businesses and developers to build sustainably and reduce land clearance. Furthermore, efforts to restore damaged through forestry and soil restoration initiatives should be encouraged, alongside robust monitoring systems to ensure efficacy and compliance with land-use regulations.

Finally, this research emphasizes the importance of global and regional cooperation in addressing climate change. Carbon trading mechanisms offer significant economic, technological, and scientific benefits to Pakistan. By participating in international carbon trading systems and partnering with environmental organizations, Pakistan can secure funding and expertise for forest conservation projects. Linking carbon sequestration goals with broader social and economic development objectives will help promote environmental sustainability. By adopting global environmental norms and seeking foreign financing, Pakistan can enhance its climate change mitigation efforts, strengthen its economy, and improve social well-being.

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## Conflict of interest

The authors declare no conflicts of interest.

## Author contributions

*Conceptualization:* Muhammad Asif Khan, Muhammad Khalid Anser, Khalid Zaman
*Investigation:* All authors
*Methodology:* All authors
*Writing-original draft:* All authors
*Writing-review & editing:* All authors

## Availability of data

The data are freely available at World Development Indicators published by World Bank (2024) at https://databank.worldbank.org/source/world-development-indicators, and

CCKP(2024)at:https://climateknowledgeportal.worldbank.org/country/pakistan (accessed on 13th September, 2024).

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