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Agricultural Footprint Dynamics: Capturing the Influence of Renewable Energy, Urbanization, and Ecological Resources

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ABSTRACT

Agriculture, a cornerstone of economic prosperity, is both a contributor to and a recipient of climate change. This study investigates the factors driving the agricultural footprint, considering land use, water use, pollution, greenhouse gas emissions, energy use, renewable energy consumption, urbanization growth rate, and ecological footprint components (fishing grounds, grazing land). Using principal component analysis, the study calculated an agricultural footprint index, weighting these factors. The study further estimated the impact of renewable energy consumption, urbanization growth rate, and ecological footprint components on the agricultural footprint. The stability of the model was assessed using CUSUM and CUSUM of squares calculations. The findings reveal that while renewable energy consumption and urbanization growth rate exert pressure on the agricultural footprint, ecological footprint components like fishing grounds, grazing land, and cropland contribute positively. To enhance the agricultural footprint and mitigate its environmental impact, the study proposed a multi-pronged approach: financial incentives, educational programs, consumer awareness campaigns, and the development of regulations and standards for sustainable agricultural practices. By implementing these strategies, society can promote a more sustainable and resilient agricultural sector that contributes to both economic prosperity and environmental protection.

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1. Introduction

In this present scenario the shift towards sustainable agriculture is vital not only for food security in the future but also to avert the disastrous effects of climate change (Huzenko & Kononenko, 2024; Rehman et al., 2022). However, this transition has its challenges are economic practicability as a main issue of concern along with economic sustainability; there may be some large up-front costs needed for sustainable agriculture in Pakistan (Raza et al., 2024; Yaqoob & Mujahid, 2023). Such actions and investments may lead reductions in yield in the early years but will bring long run benefits. According to the analysis of the acts and commitments, the constraints of binding costs and elements of risk and uncertainty associated with innovation and the alteration of traditional ways of farming impose encumbrance on many farmers (Blakeney, 2022; Manning, 2024).

Food production is necessary for people to feed themselves in the modern world while being one of the leaders in terms of ecological impact on the planet. Thereby the ecological footprint measures the areas of land and sea required to produce the resources used by man and to absorb the generated wastes (Dogan et al., 2019; Eufrasio Espinosa & Lenny Koh, 2024). (This footprint is greatly influenced by agriculture, given the huge reliance on natural resources most of which are characterized by their extensive use of land, water and energy, not to mention the production of greenhouse gases. These environment pressures are important to show the need to redress and change practice in agricultural that are more sustainable (Feng et al., 2022; Giampietro, 1997).

There are various studies that are trying to explore how agriculture interacts with a phenomenon known as ecological footprint with environmental problems associated with farming (Elahi et al., 2022; Popescu et al., 2022). Some studies explored ways on how sustainable agriculture can contribute in decreasing the sector's negative effects on the environment and at the same time, ensuring that it plays a significant function in feeding the world's increasing population facing the challenges of urbanization and energy transition (Chatterjee & Swarnakar, 2023). In this way, through such resource-saving approach, reducing emissions, and increasing ecosystem capacity, the agriculture industry will change from the role of the main destroyer of the environment to a creator of balanced and sustainable environment (Gamage et al., 2023; Muhie, 2022).

Furthermore, knowledge sharing to agriculture stakeholders is also assisting in the roll out of this transformation too. It is critical to share knowledge regarding the innovations with farmers, in areas with low literacy levels as wells as little access to information (Mendes et al., 2024; Zain et al., 2022). Another factor of the ecological change is behavior change – it is necessary to educate consumers and change their habits so that they buy only the tangible products made with the proper environmental approach when it comes to food production (Aslam et al., 2022; Halpern et al., 2022).

However, there are many areas where climate friendly measures for the promotion of sustainable agriculture in Pakistan. Government bears a significant responsibility as it could set up policies, financial programs and use its money to support the farmers and invest into the research consequently influencing sustainable practices (Jabbar et al., 2022; Raza et al., 2024). Some of the technological measures include precision agriculture, improvement of seeds through the breeding of crops that can withstand drought among other measures with regard to sustainable farming systems (Latif et al., 2024; Yaqoob & Mujahid, 2023). Further, there is a shift in the consciousness of individuals in terms of the environmental effects that their food choices bring thus increasing the demand for products from sustainability. The exponential rise in consumers' demand thus formative a virtuous cycle that leads more producers to embrace sustainable practices thus achieving the general cause of sustainable agriculture (Waseem et al., 2020).

The impact of agriculture is felt vis-a-vis the ecological footprint that embraces demands of land, water, and energy through pollution as well as generating greenhouse gases (Hassan et al., 2019; Ozturk et al., 2024). It is a well-known fact that agriculture is the leading land consumer worldwide, frequently to the detriment of forestry, wildlife, and huge losses in the levels of bio- diversity. Mono-cropping and high input farming practices compounded by poor soil management practices deepen the depletion of the soil fertility hence the need to expand more land for cultivation (Lago-Olveira et al., 2024; Manoj et al., 2022). Besides, the sector contributes to water scarcity mainly through irrigation, which consumes about three-fourth of freshwater withdrawals globally, and especially where water is scarce. Extraction of water goes further as it also has adverse effects on water, quantity of water available for other important uses. Fossil energy sources used in producing fertilizers and pesticides, in machinery, and transport within the modern agriculture plays a major role in the emission of greenhouse gases, hence climate change (Peng et al., 2023; Yilmaz et al., 2005). Also, it is reported that, agriculture is one of the significant sources of methane and nitrous oxide, both of which are highly effective greenhouse gases, and the clearance of lands for agricultural purposes causes the release of carbon dioxide into the atmosphere. High levels of synthetic fertilizers and pesticides cause leaching and pollute the water sources, and nutrients lead to algal blooms, thus has negative impacts on large bodies of water, making them 'dead' (Majeed et al., 2023).

Due to the industrialization of farming and negative impacts on the environment some practices have been developed like agro-ecology that applies ecosystems concepts in the management of farming systems and involves practices such as polyculture, agroforestry and crop livestock interaction to increase the agriculture sector's returns through improved agroecosystem health (Baker et al., 2023; Raihan, 2023). Some other practices of conservation agriculture techniques are no tillage, crop rotation, time of planting, soil is protected from compaction and loss through erosion is checked, and the water holding capacity of the soil can improve the agriculture productivity (Moldavan et al., 2024; Yang et al., 2023).

Precision agriculture entails the use of advanced technology to apply the right amount of inputs in the right place and right time by minimizing losses in a bid to enhance resource use efficiency. It seeks to address water scarcity by embracing water efficient ways of irrigation and management as well as undertaking right crop choice (Lakhiar et al., 2024; Ray & Majumder, 2024; Yang, Shafiq, Sharif, et al., 2024). Thus, on the one hand, organic farming makes use of less synthetic chemicals to farm and increase soil health and promote biodiversity all at once, while, on the other hand, regenerative agriculture specifically aims at improving soil health, increasing the biodiversity, and getting rid of carbon footprint.

Various strategies like using of rotational grazing system and better ways of disposing off cattle dung which is mostly a source of methane emission when decomposing have been put in place to advance the conservation of resources (Augustine et al., 2023; García et al., 2024; Jordon et al., 2022). Afforestation and Soil carbon sequestration, in particular, are used as important techniques for sequestering carbon from the atmosphere that aids in combating climate change while at the same time promoting the health of ecosystems. These, are some of the key eco efficient agricultural practices that are required in minimizing the environmental impacts that are associated with agriculture production and also in balancing the productive capacity of agriculture with that of protecting our natural resources (Rathore et al., 2024; Rebouh et al., 2023).

Prior works have quantified the energy use and the consequent GHG emissions linked with irrigation for particular regions, such as China (Zou et al., 2015), India (Rajan et al., 2020), and Pakistan (Siyal & Gerbens-Leenes, 2022). However, a massive information deficit is still manifested with regard to research that offers a global outlook to energy-referenced GHG emissions from irrigation. This missing link creates a major knowledge gap in the comprehensive evaluation of whether emissions of irrigation-induced GHG, contributes significantly to the overall emissions from the agricultural sector and how the issue maybe affecting global climate change mitigation plans. Thus, there is an urgent need of an extensive and comparative analysis of the global energy consumed and GHG emissions linked with irrigation and pumping systems (Ahmed et al., 2023; Fan & Fang, 2023). The very analysis is required to design proper adaption measures to transition agriculture toward the net-zero economy. Keeping in view of all these concerns, the significance of the current study is to link the agricultural footprint with ecological footprint in the presence of renewable energy consumption and urbanization in Pakistan. The calculation of agricultural footprint for Pakistan economy with respect to the determinants is also the novelty of this study.

Not only the agriculture is important in the production of food but it has something to offer to any economy as well as styles of living (Ali et al., 2024; Dogar, 2023). This industry generates many jobs and foremost in the rural areas where most farmers and other personnel related to farming are found. It also creates new employment opportunities, at the same time at farm, labor, processing, marketing, and distribution center level. Besides this, it stimulates economic growth through trade and export, thus enhance the national income and helps in sustaining food security on the global level (Adebayo et al., 2024; Saleem et al., 2024).

Besides, agriculture is totally indispensable to the further survival of our globe and the evolution of the ecosystem. Use of renewable energy and organic farming focuses on the health of the soil, has a positive impact on the diversity of species and uses water sparingly (Das et al., 2020; Willer et al., 2024; Yang, Shafiq, Nazir, et al., 2024). As most of the farming techniques like the use of organic farming, agroforestry, and precision farming the farmers have opportunities to minimize their use of toxic pesticides and fertilizers and control the erosion of the soil and the depletion of the natural resources (Gamage et al., 2023; Panday et al., 2024). There is also the ability also to promote or sponsored the production of renewable energy for the development of agriculture to form a more sustainable environment in future (Nazir et al., 2023). This may be done by use of methods which include bio-fuels production and the use of agricultural residuals in power production.

Due to further urbanization and escalation of ecological issues, there has been a number of academic debates in relation to urbanization and agriculture (Arshad et al., 2023; Kayani et al., 2023). The relevant studies are primarily divided into the various categories: first, there is the problem of creating an indicator measurement system to assess the general level of urbanization; secondly, the link between urbanization and agriculture; and, thirdly, both (Bao et al., 2024; Fertas et al., 2024). The Based on various elements, scholars often quantitatively assess the generic extent of urbanization from the economic structure, population distribution, social organization, environmental conditions and surveys in the geographical area (Wang et al., 2025; Yin et al., 2023; Zhang et al., 2024). This is so due to the reason that choices of data indicators are very many and diverse. Some research has shown that through dismantling variables in multiple dimensions including economic urbanization, demography urbanization, social urbanization, ecological urbanization and spatial urbanization it is easier and more credible to connect with the notion of new urbanization with people as the focal point (Kayani et al., 2023; Wang et al., 2024; Wang et al., 2023). Thus, they increase the reliability and effectiveness of evaluation of the level of comprehensive development of urbanization (Nasim et al., 2023).

The current study is conducted in order to attain the research objective that estimated agricultural footprint based on the determinants that are usage of water, land and energy, pollution and greenhouse gas emission by using principal component analysis and using the data from 1990-2024. The estimated agricultural footprint is affected by determinants of ecological footprint (fishing grounds, forest product, graze land, crop land), renewable energy consumption and urbanization.

2. Data and Methodology

The data is taken from WDI and GFPN for a time period of 1999-2024 for Pakistani economy. The attainment of objective the study is to calculate the agricultural footprint on the basis of its determinants. The following estimated model 1 is made:

$$Agricutural\ Footprint = \mathrm{f}\{\ Land\ Use,\ Water\ Use,\ Pollution, Energy\ Use,\ Green\ House\ Gas\ Emission$$

The equation representing this model can be formed as under:

$$AGFP = \ w_1 * Land\ Use + w_2 * Water\ Use + w_3 * Pollution + w_4 * Energy\ USe + w_5 * GHG\ Emissions$$

Principal Component Analysis (PCA) is a powerful dimensionality reduction technique that is commonly used to create composite indices, especially when dealing with multiple interrelated indicators. The agricultural footprint is calculated by using principal component analysis to get weights for indexation. The results are reported in Table 1.

Table 1: Agricultural Footprint

Indicators	Weights	Extracted Weights
Land Use	w_1	0.981
Water Use	w_2	0.938
Pollution	w_3	0.846
Energy Use	w_4	0.812
GHG	w_5	0.989

By using these weights, the variable of agricultural footprint is calculated. Furthermore, the study has to estimate the relationship between the ecological footprint and agricultural footprint considering the effect of renewable energy and urbanization. The next model of the study is formulated as Model 2 under:

$$\begin{aligned}&Agricultural\ Footprint\\&= f\{\ Fishing\ Grounds,\ Forest\ Product,\ Grazeland,\ Cropland, Renewable\ Energy,\ Urbanization\}\end{aligned}$$

The equation of this model is formulated as:

$$AGFP = \beta_1 +\ \beta_1 Fishing + \beta_2 Forest + \beta_3 Graze + \beta_4 Crop + \beta_5 Renewable\ energy + \beta_6 Urban + u_{\mathrm{i}}$$

3. Results and Discussion

The analysis further proceeds to calculate the descriptive analysis of the variables of the model 2. The result of the descriptive analysis is reported in Table 2.

Table 2: Descriptive Measures

	AGFP (M)	FISHING (M)	FOREST (M)	GRAZE (M)	REEC (%age)	URBAN GROWTH (%age)	CROP (M)
Mean	0.745	0.566	1.573	0.115	46.96	2.62	5.823
Median	0.734	0.580	1.588	0.104	46.90	2.69	5.789
Maximum	1.065	0.770	1.666	0.179	51.54	3.69	6.982
Minimum	0.479	0.372	1.414	0.086	42.10	1.78	5.010
Skewness	0.22	-0.59	-1.08	1.15	0.13	0.36	0.41
Kurtosis	1.88	2.87	3.09	3.15	2.36	2.70	3.39
Jarque-Bera	1.46	1.39	4.69	5.35	0.48	0.61	0.82
Probability	0.48	0.50	0.10	0.17	0.79	0.74	0.66

Table 2 reports the measures of central tendency. Table 2 also shows the normality of residual test results that are Jarque-Bera test and the resulting probability is showing the acceptance of null hypothesis that is residuals are normally distributed. The values of skewness and kurtosis are also shown in the table. The values for asymmetry and kurtosis between -2 and +2 are considered acceptable to prove normal univariate distribution (George & Mallery, 2010). Hair et al. (2010) and Bryne (2010) argued that data is considered to be normal if skewness is between -2 to +2 and kurtosis is between -7 to +7. The values of skewness show the shape of the distribution of each random variable. The value of skewness for all variables is lying in between the said values therefore the distribution is said to be approximately normal. Similarly, the kurtosis is measuring the tailedness of variable and therefore all variables of study showing value positive and indicating the normal distributions are mesokurtic.

The study uses the correlation matrix to see the severity of multicollinearity among the independent variables of the model 2. The results are presented in Table 3. The correlation matrix is a statistical tool to get the pairwise correlation to see the degree of relationship among independent variables. The high degree of correlation (e.g. more than 0.80) indicates the severity of multicollinearity and the high degree of association between variable create serious consequences in model estimation (Dziuban & Shirkey, 1974; Gogtay & Thatte, 2017). The estimated correlation coefficients are showing moderate or low degree of association and therefore the model can be estimated without any serious consequences of multicollinearity.

Table 3: Correlation Matrix

	AGFP	FISHING	FOREST	GRAZE	REEC	URBAN	CROP
AGFP	1.00						
FISHING	-0.53	1.00					
FOREST	0.58	-0.28	1.00				
GRAZE	-0.60	0.18	-0.51	1.00			
REEC	-0.83	0.34	-0.53	0.23	1.00		
URBAN	-0.73	0.09	-0.43	0.29	0.74	1.00	
CROP	0.67	-0.04	0.30	-0.34	-0.66	-0.55	1.00

The time series data is used in this study for empirical analysis therefore it is required to apply the unit root check. The application of Augmented Dickey Fuller test (Mushtaq, 2011) and Phillips-Perron (Perron, 1990) test is reported in table 4.

Table 4: Unit Root Tests

Variables	Augmented Dickey-Fuller Test		Phillips-Perron Test Equation		Order
	t-statistic	Prob.	Adj. t-stat	Prob.	
AGFP	-5.63841	0.0008**	-5.0951	0.0024**	Level
FISHING	-3.83425	0.009*	-4.13207	0.0045*	
FOREST	-6.0136	0.0004**	-5.25324	0.0017**	
GRAZE	-4.03063	0.0056*	-4.05893	0.0053*	
REEC	-3.85387	0.0083*	-3.41877	0.0734**	
URBAN	-4.80511	0.0047**	-3.97835	0.0255**	
CROP	-4.52048	0.008**	-3.1827	0.0343*	

Note: *with intercept, **with trend and intercept

The main objective of the study is to estimate the empirical model to see the impact of ecological footprint, renewable energy and urbanization on the agricultural footprint of Pakistan. Therefore, the empirics by least square measures are obtained and reported below in Table 5 as the unit root test indicates.

Table 5: Least Square Estimates of Model

Variable	Coefficient	Std. Error	t-Statistic	Prob.
FISHING	0.6587	0.1322	4.9841	0.0001
FOREST	0.4629	0.1575	2.9385	0.0088
GRAZE	1.2586	0.4415	2.8505	0.0106
CROP	0.1587	0.0296	5.3683	0.0000
REEC	198.6498	583.8751	-0.3402	0.7376
URBAN	-1131.2620	3587.5130	3.1533	0.0055
R-squared		0.921	Adjusted R-squared	0.899
Durbin-Watson stat		2.025		

The least square estimates are reported in table 5 showing a clear measures of impact of ecological footprints on agricultural footprint (AGFP) (Banerjee et al., 2021). As the increasing value of agricultural footprint is indication of that agricultural activities are pressuring the environment. Keeping in view this fact the values of determinants of ecological footprint are associated with agricultural footprint positively and significantly, so it is alarming that as ecological footprint increases, the pressure by agricultural activities will also higher on environment. This positive association signals a dye need of transition towards sustainable agriculture so that environmental damage can be lessened (Kumar et al., 2019). Use of more renewable energy is showing a positive impact on AGFP that is not significant in the case of Pakistan. However, the positive impact is representing the more use of renewable energy causing more efficient use of land along with cleaner environment. It is showing more use of solar powered irrigation systems, biogas energy and solar drying technology. This shows that in Pakistan the transition towards renewable energy has not significant impact on AGFP (Kashif et al., 2020; Majeed et al., 2023). However, the impact of urbanization is negative and significant that is understood that increasing trend of urbanization is not suitable for agriculture land use (Fertas et al., 2024; Preusse et al., 2024).Particularly in Pakistan the cities are expanding towards their edges on agricultural land that is clearly evident.

Figure 1 shows the relationship between the actual and fitted values with time series regression model. Moreover, the residuals (the blue line) are also displayed that are the vertical distances between actual values and predicted ones. As the red and green lines are close to each other so it is referring to a general trend this model is fairly correct. It is due to the fact that, historically, real numbers have been showing a steady upward trend over time. The small, occasional divergence between the two lines is a sign of some prediction mistakes; however, they seem to be relatively small and non-systemic — that indicates the model does quite well in terms of following the behavior of the real data.

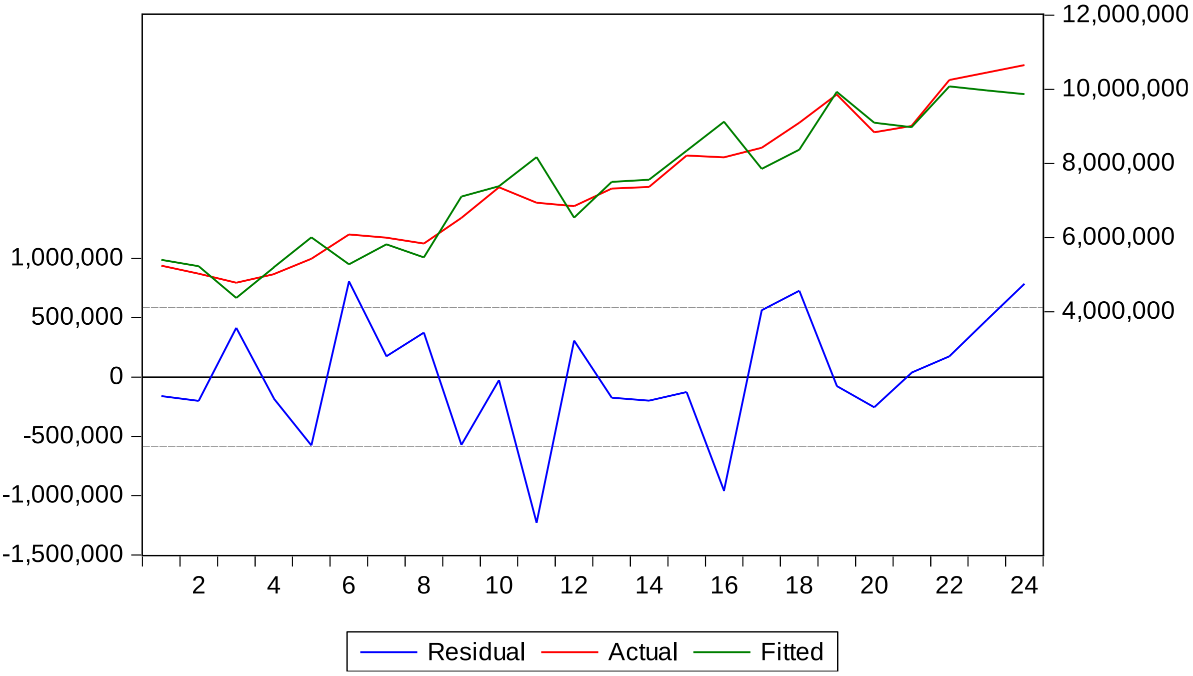
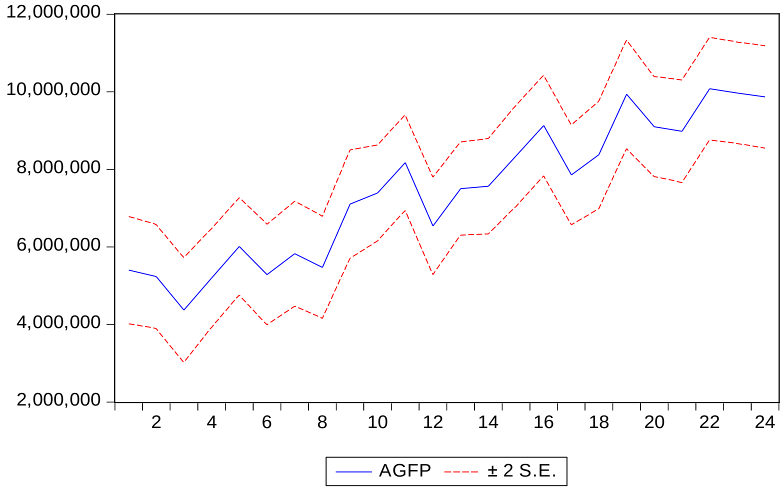


Figure 1: Actual, Fitted and Residual Plot

Additionally, the residuals (in blue) fluctuate around zero. This means that in some cases (for the negative residuals) the model over-estimate and in other cases (for the positive residual), it underestimates the real values. Some locations have larger deviations, which means the model could be improved in order to better generalize such patterns. Most of the residuals are pretty low but there are a couple of points that have high deviation. One can see that the residuals do not follow a pattern or trend, meaning that there is no systematic error in the model. That suggests no further improvements can be made without increasing the model complexity or adding more features to capture unexplained variability.

Figure 2 is concerned, the forecasted series of AGFP is plotted with standard deviation of 2. The results also represent the value of Theil Inequality coefficient that is used to measure the accuracy of a forecasting model by comparing actual and fitted values. As the value of Theil's U statistic is closer to zero so it is an indication towards a perfect fit as there are very small variations between actual and fitted values. Similarly, bias proportion is one of Theil inequality coefficient that measures the size of forecast error and estimated value is showing the systematic error is minimal and forecast is close to real values. On the other hand, since the residuals do not show some evident shape or curvature so this would mean that the model is free of bias and misspecification.



Forecast: AGFP
Actual: AGFP
Forecast sample: 1 24
Included observations: 24

Root Mean Squared Error	506597.9
Mean Absolute Error	399027.5
Mean Abs. Percent Error	5.603923
Theil Inequality Coefficient	0.033088
Bias Proportion	0.000084
Variance Proportion	0.010845
Covariance Proportion	0.989070

Figure 2: Forecasted Agricultural footprint

Dynamic stability or the extent to which a model keeps consistent parameter estimates over time. This capability enables the model to provide reliable predictions. A visually stable model has coefficients that do not change a lot and for this, testing methods like the Cumulative Sum (CUSUM) and CUSUM of Squares (CUSUMSQ) are often employed to verify if the system is stable. At each time point, the pure residual is added to those from earlier times and this cumulative sum is tested with the CUSUM test against 95% confidence boundaries in order to see if it continues within these boundaries. If the CUSUM plot exceeds these bounds, it means that the model parameters might be unstable and can change over time. Similarly, CUSUMSQ test monitors the cumulative sum of squares residuals and looks for stability in the error variance. When the boundaries of a CUSUMSQ plot are crossed for a stable model, it can mean there could be problems such as heteroscedasticity or increases in error variance over time. For the uses of this test in time series and econometric analysis, both tests are necessary since they contribute to judging whether or not your model will hold in predicting the future without experiencing massive drifts in parameters. This ensures that the model is robust against structural changes in the data.

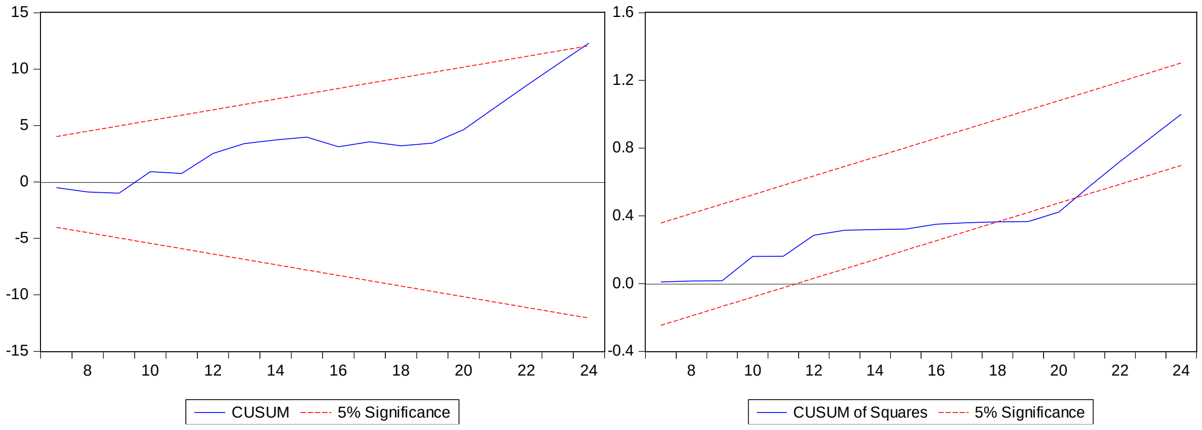


Figure 3: Dynamic Stability Tests

The figure 3 is explaining the picture of a stable model in a clear way. The CUSUM test is predicting the positive deviations and slope is showing an increasing process. However, the CUSUM SQ graph is indicating there may be problem of heteroscedasticity due to variation in error variance.

4. Conclusion

The primary purpose of the study is to estimate the empirical model in order to determine the influence that urbanization, renewable energy, and ecological footprint have on the agricultural footprint of Pakistan. The agricultural footprint is calculated by using the principal component analysis on the basis of the factors that are land, water and energy use, and pollution. The further study estimated the long run relationship of ecological footprints, renewable energy and urbanization with agricultural footprint in Pakistan by using data series ranges from 1999-2024. After the unit root assessment and descriptive analysis, the ordinary least square method is employed for long run results.

The outcomes of the study show that the increasing value of agricultural footprint indicates that agricultural activities are pressuring the environment. The determinants of ecological footprint are positively and significantly associated with agricultural footprint, indicating a need for a transition towards sustainable agriculture to reduce environmental damage. The use of renewable energy has a positive impact on AGFP, but not significantly in Pakistan. The transition towards renewable energy has no significant impact on AGFP. However, urbanization has a negative and significant impact on agricultural land use, particularly in Pakistan, where cities are expanding towards agricultural land edges. This highlights the need for a transition towards sustainable agriculture to minimize environmental damage. The robustness of estimated model is analyzed by the graph of fitted, actual and residuals. The graphical depiction of model allows to rely on estimated model for forecasting. Dynamic stability test also conducted to check the health of model.

The actual implementation of the policy proposals calls for a concerted effort on the part of governments, academics, farmers, and consumers to work together to implement renewable energy technologies in agriculture. By encouraging responsible consumption, boosting resource efficiency, and supporting sustainable farming methods, the study can lessen the impact that agriculture has on the environment and contribute to the development of a global food system that is in a better position to be resilient and sustainable. In addition, the urbanization should be restricted also horizontally. The areas that are not suitable for farming should be used for the expansion of cities so that the pressure on agriculture can be minimized.

Authors Contribution

Ismat Nasim: Prepare the initial draft of the paper including results
Furrukh Bashir: Explained the results and policy recommendations
Muhammad Ramzan: Revised overall quality, and proof read the whole paper

Conflict of Interests/Disclosures

The authors declared no potential conflicts of interest w.r.t the research, authorship and/or publication of this article.

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