

Socio-economic drivers of deforestation in Sierra Leone

Forestry
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Review

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Abstract

Purpose – Deforestation remains a major environmental concern in Sierra Leone, with implications for biodiversity, climate change and livelihoods. This underscores the urgency for sustainable forest practices. The study investigated the socio-economic determinants of deforestation in Sierra Leone.

Design/methodology/approach – The study used annual time series data within a vector error correction and autoregressive distributed lag model to estimate both the short- and long-run drivers of deforestation in Sierra Leone. Forecast error variance decomposition and impulse response function were also employed to determine the magnitude and direction of shocks.

Findings – The decomposition of forecast error variance shows that biomass consumption (traditional renewable energy consumption) is the short-, medium- and long-term dominant factor. Income is found to reduce deforestation in the short term, while biomass consumption (traditional renewable energy consumption) increases it. Weak institutions, biomass consumption (traditional renewable energy consumption), natural resource rents and population increase deforestation in the long run.

Originality/value – The study contributes to the deforestation literature by providing new empirical evidence on the long- and short-run drivers of forest loss in Sierra Leone using a dynamic econometric framework that integrates institutional quality, income, population, natural resource rents and energy consumption. By distinguishing temporal effects and governance channels, the study advances understanding of how structural and policy factors interact over time to shape deforestation outcomes in resource-dependent developing economies, offering insights for sustainable forest management.

Keywords Deforestation, Sierra Leone, Income, Institutions, Population, Biomass

Paper type Research article

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1. Introduction

Forests are indispensable to the ecological balance of the planet, serving as carbon sinks, biodiversity reservoirs and sources of livelihood for millions. However, deforestation poses a serious threat to these functions globally. It contributes to climate change, biodiversity loss and disruption of water cycles (Armanto *et al.*, 2023). The situation is dire in Africa, with the continent experiencing some of the highest rates of forest loss as a result of the expansion of agricultural activities, logging and infrastructure development (Kassouri, 2024). Deforestation and its inherent challenges have not spared Sierra Leone, a country in West Africa rich in forest resources. Global Forest Watch (2025) reported that the country has lost approximately 25% of its forest cover over the past two decades. This rapid deforestation has implications for the country's environment, economy and the wellbeing of its population.

The drivers of deforestation vary across regions. Globally, the literature suggests that agricultural expansion is the primary driver of deforestation (Keenan *et al.*, 2015; Musienko *et al.*, 2020; Prevedello *et al.*, 2019; Qu *et al.*, 2024). This includes both subsistence farming and large-scale commercial agriculture, such as cattle ranching and the cultivation of crops like soy and oil palm. The situation in Africa mirrors that of the global trend, with agricultural expansion being the primary driver of deforestation (Taylor *et al.*, 2022). Many sub-Saharan

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African (SSA) countries rely on shifting cultivation due to poverty and population growth, which exacerbates deforestation. Furthermore, commercial logging, which is often unregulated, contributes significantly to deforestation (Salemi, 2021). In addition, the low level of development and income has left many households in SSA resorting to firewood and charcoal as primary sources of energy (Lawrence *et al.*, 2022).

In West Africa, the drivers of deforestation are multifaceted. Taylor *et al.* (2022) have noted that agricultural expansion, especially for cash crops like cocoa and palm oil, has caused extensive forest clearing. Studies have shown that significant portions of forests have been converted into agricultural land in Ivory Coast and Ghana (Adom *et al.*, 2024; Kouadio and Singh, 2021). Additionally, mining activities, urbanisation and infrastructure development contribute to the issues mentioned (Duku and Hein, 2021). Issues such as ineffective forest governance, land tenure insecurity and inadequate enforcement of environmental regulations have exacerbated deforestation in the region (Etongo *et al.*, 2015; Fasona *et al.*, 2022; Maina, 2022; Shittu *et al.*, 2018).

Sierra Leone's forests, comprising tropical rainforests like the Gola in the southeast, mangroves and savannah woodlands in the northwest, have been sources of biodiversity conservation and sustenance for local communities. However, the country has been experiencing rapid deforestation with an estimated 25% loss in tree cover over the past two decades (Global Forest Watch, 2025). Empirical studies have shown that the primary drivers include agricultural expansion, illegal logging, mining, urbanisation and charcoal production (Lemenkova, 2024; Mabey *et al.*, 2020; Mansaray *et al.*, 2016; Stevens *et al.*, 2025). Fayiah and Fayiah (2022) indicated that illegal logging accounts for approximately 30% of forest loss, while agricultural activities contribute 40%.

Lemenkova's (2024) recent study utilising satellite imagery highlighted increased landscape fragmentation and deforestation in Sierra Leone between 2013 and 2023. It has been observed that this fragmentation threatens wildlife habitats and undermines ecosystem services. Furthermore, Sola *et al.* (2017) found out that the country's reliance on forests for fuelwood and charcoal, driven by limited access to alternative energy sources, continues to pressure forest resources. Urban expansion, particularly around the coastal and mountainous areas of the capital, Freetown, has also been examined to be a major contributor to forest loss, often leading to increased vulnerability to natural disasters such as landslides and flooding (Jackson, 2015; Kainyande and Kainyande, 2024; Malan *et al.*, 2024; Wadsworth and Lebbie, 2019).

Although there is a growing body of literature on deforestation, the evidence indicates that the causes and determinants vary between different regions and countries. As noted above, there are studies on deforestation in Sierra Leone, but several research gaps persist. Previous studies have focused on quantifying deforestation, including forest loss, and identifying proximate causes. Nonetheless, there is a need for comprehensive analyses that integrate socio-economic determinants, such as income, resource exploitation, energy consumption patterns, institutional quality and population. Moreover, review of previous studies indicates that they often lack robust econometric analysis to capture both short-term dynamics and long-term equilibrium relationships between deforestation and its socio-economic determinants.

The study filled the gaps by employing the vector error correction (VEC) and autoregressive distributed lag (ARDL) models to analyse the socio-economic determinants of deforestation in Sierra Leone. The integration of income, natural resource rents, biomass consumption (traditional renewable energy consumption), institutional quality and population, the study unravelled both the immediate and long-term effects of these factors on deforestation. The use of VEC and ARDL allowed for the examination of both short-run adjustments and long-run equilibrium relationships, providing a more distinctive perspective of the deforestation dynamics in Sierra Leone. The forecast error variance decomposition (FEVD) and the impulse response function (IRF) reaffirm the magnitude and direction of the determinants, respectively. Furthermore, the study's findings can guide sustainable forest

management policies that strike a balance between economic development and environmental conservation.

2. Materials and methods

2.1 Study area

Sierra Leone is the object of the study from the year 1990 to 2023. It is situated on the southwest coast of West Africa, bordered by Guinea to the north and east, Liberia to the southeast and the Atlantic Ocean to the west. The country encompasses an approximate area of 73,252 ha. Geographic coordinates span from approximately 7°N to 10°W longitude, with the central point near 8°30'N, 11°30'W (Mabey *et al.*, 2020).

The country's topography is diverse, featuring a coastal belt of mangrove swamps, wooded hill country, an upland plateau and mountains in the east, including Mount Bintumani, the highest peak at 1,948 metres. The geological structure comprises Precambrian basement complex rocks, with soils ranging from lateritic to alluvial types. The country is traversed by several rivers, including the Moa, Sewa and Rokel, contributing to its hydrographic network. Vegetation varies from tropical rainforests in the southeast to savanna in the north, reflecting the ecological diversity pertinent to the study. Figure 1 shows the map of Sierra Leone with primary forests and tree cover loss from the year 2000–2024.

2.2 Theoretical framework

Bager and Lambin (2020) noted that one single theory cannot explain the determinants of deforestation because it is a complex, multidimensional process influenced by interacting socio-economic, institutional and environmental factors which vary across regions, countries and time. As such, several theories guided this study. One is The Tragedy of the Commons (Hardin, 1968). The Tragedy of the Commons underscores the overexploitation of natural resources as a result of weak institutions, lack of environmental compliance and self-interest. This brings natural resource rent and quality of institutions. This shows how common pool resources like forests are depleted without effective management or collective action.

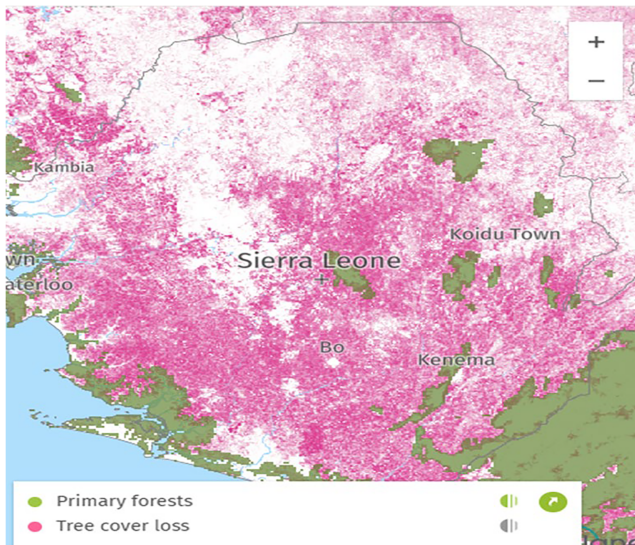


Figure 1. Map of forests and tree cover loss of Sierra Leone 2000–2024. **Source(s):** Global Forest Watch

Neo-classical growth theory suggests that economic growth driven by capital and labour may exert pressure on forests unless checked by regulations. Whilst property rights theory indicates that weak institutions and land tenure insecurity can accelerate deforestation, population pressure theory notes that an increase in population leads to higher land demand for agriculture and settlements. Based on the theories and literature, the deforestation model (D) includes income (Y) to capture expansion of economic activities which may cause deforestation, natural resource rents (N) to capture farming, mining and other resource activities which may reduce the forests, renewable energy (R) since traditional biomass energy – dominant in Sierra Leone – also increases deforestation (Kiley *et al.*, 2024), institution based on the notion that strong institutions protect the environment, and population (P) to capture how increase in both rural and urban population may affect the forests.

$$D = f(Y, N, R, I, P) \tag{1}$$

The functional form of the model is expressed as

$$D_t = \beta_0 + \beta_1 Y_t^2 + \beta_2 N_t + \beta_3 R_t + \beta_4 I_t + \beta_5 P_t + \varepsilon_t \tag{2}$$

2.3 Variable description and data sources

See [Table 1](#) for description of variables and sources of data.

Table 1. Variable description and data sources

Variable	Definition and measurement	Data source
Deforestation (D)	Deforestation including forest loss is calculated as the annual change (reduction) in the square kilometre of land that is covered by forest	Author’s calculation using FAOSTAT and Global Forest Watch
Income (Y)	Income is proxy economic activities. GDP per capita is used to account for economic activity per person. GDP per capita is gross domestic product (GDP) divided by midyear population. It is measured in current United States Dollars (USD)	World Bank World Development Indicators
Natural resource rent (N)	Natural resource rent is to account for farming, logging, mining and other natural resource activities which affect the forests. It is total natural resources’ rents which are the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents and forest rents. It is measured as a percentage of GDP	World Bank World Development Indicators
Renewable energy consumption (R)	Renewable energy consumption (% of total final energy consumption). It is measured as share of renewables (dominated by biomass as in Sierra Leone) in total energy consumption	World Bank World Development Indicators
Institutional quality (I)	Efficiency and effectiveness of public institutions. It includes rules of law, control of corruption, regulatory quality, government effectiveness and political stability. The measure ranges from 0 to 1 (worst to best)	University of Gothenburg Quality of Governance Institute
Total population (P)	Total number of residents in the country regardless of nationality per year. To capture both rural and urban population as they both affect the forest	World Bank World Development Indicators

Source(s): Global Forest Watch (2025), Teorell *et al.* (2025) and World Bank (2024)

2.4 Econometric model

Pre-estimation and post-estimation tests were conducted to justify and test for the robustness of the employed econometric model. The time series were tested for stationarity using Augmented Dickey Fuller (ADF: drift, trend and constant), and they are all integrated of order one ($I(1)$). Given that, the variables were tested for cointegration using Johansen's test, and the results revealed four cointegrating relationships satisfying the condition that the number of cointegrating relationships should be greater than zero but less than the number of variables, which are six in this study. That is the $0 < r < n$, where r is the number of cointegrating relationships and n is the number of variables. Before the cointegration test, appropriate lag length selection was done, and the likelihood ratio, Akaike Information Criterion and Hannan–Quinn Information Criterion all pointed to lag three as the appropriate lag.

The VEC model was considered appropriate for the study because the series is non-stationary ($I(1)$) and cointegrated ($0 < r < n$), coupled with its ability to capture both short-run dynamics and long-run equilibrium relationships (Engle and Granger, 1987; Nkoro and Uko, 2016). Following Lütkepohl (2005), the general form of the model is specified as

$$\Delta y_t = \alpha \beta y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta y_{t-i} + v + \delta t + \epsilon_t \quad (3)$$

y_t is a $K \times 1$ vector of endogenous variables, α is a $K \times r$ matrix of parameters, β is a $K \times r$ matrix of parameters, $\Gamma_1, \dots, \Gamma_{p-1}$ are $K \times K$ matrices of parameters, v is a $K \times 1$ vector of parameters, δ is a $K \times 1$ vector of coefficients and t is a linear time trend. Based on the specification of the trend and of constants and trends, the model can be reparametrized as

$$\Delta y_t = \alpha(\beta y_{t-1} + u + pt) + \sum_{i=1}^{p-1} \Gamma_i \Delta y_{t-i} + \gamma + \tau t + \epsilon_t \quad (4)$$

$\alpha(\beta y_{t-1} + u + pt)$ is the error correction term (ECT) or long-run equilibria with βy_{t-1} as the cointegrating vectors or long-run equilibrium relationships, u is constant or intercept of the cointegrating or long-run relationships and α is the adjustment (speed) coefficients which measure how quickly the deviations from equilibrium are corrected. $\sum_{i=1}^{p-1} \Gamma_i \Delta y_{t-i}$ is the short-run dynamics with Γ_i as the short-run coefficients for lagged first differences (Δy_{t-i}) and $p - 1$ is number of lags. $\gamma + \tau t$ are the deterministic terms outside the cointegrating relationships, with γ as the constant or intercept in the short-run equation and τt the linear trend in the short-run dynamics. Given that the study is only about the cointegrating vector among the variables:

$$D_t = \beta_0 + \beta_1 Y_t + \beta_2 N_t + \beta_3 R_t + \beta_4 I_t + \beta_5 P_t + u_t, \quad (5)$$

the vector error correction model (VECM) specification (short-run dynamics with ECT) for the deforestation variable is

$$\begin{aligned} \Delta D_t = & \gamma + \alpha ECT_{t-1} + \sum_{i=1}^{p-1} \Gamma_{1i} \Delta D_{t-i} + \sum_{i=1}^{p-1} \Gamma_{2i} \Delta Y_{t-i} + \sum_{i=1}^{p-1} \Gamma_{3i} \Delta N_{t-i} + \sum_{i=1}^{p-1} \Gamma_{4i} \Delta R_{t-i} \\ & + \sum_{i=1}^{p-1} \Gamma_{5i} \Delta I_{t-i} + \sum_{i=1}^{p-1} \Gamma_{6i} \Delta P_{t-i} + \epsilon_t \end{aligned} \quad (6)$$

FEVD was performed to explore the power of the other endogenous variables in explaining deforestation (Lanne and Nyberg, 2016). IRF was also performed to show the direction and magnitude of shocks from other endogenous variables on deforestation (Lütkepohl, 2018). Model robustness checks, including residual autocorrelation, normally distributed disturbances

and model stability, were also performed. When interpreting the long-run coefficients in the ECT, the signs are reversed because they are formed by subtracting the ECT from the right-hand side of the long-run equation from the dependent variable (see [equations 4 and 6](#)) ([Alogoskoufis and Smith, 1991](#)). ARDL model was also used for comparison and robustness.

3. Results

3.1 Summary descriptive statistics

The analysis starts with a summary descriptive statistic to help understand and verify the data, as noted by [Dong \(2023\)](#) (see [Table 2](#)).

The descriptive statistics in [Table 2](#) show that there is no missing data for any of the variables, as the 34-years period from 1990 to 2023 provides exactly 34 observations for all the variables. Complete data or no missing values avoid biases from interpolation or imputation which distort time series dynamics and in turn help ensure reliable parameter estimates, valid statistical inferences and precise long-run equilibrium relationships in the VEC model ([Kreindler and Lumsden, 2016](#)). Average annual deforestation is 197.28 km² with a standard deviation of 2.31, which is a serious concern given the size of the country. The standard deviation suggests year-to-year variation. Average annual income proxied by GDP per capita is 852.54 United States Dollars, confirming that Sierra Leone is a lower-income country. Natural resource rents have a mean of 12.05% of GDP, which confirms that Sierra Leone is a natural resource-dependent country. On average, 84.31% of energy consumption is renewable energy (dominated by traditional biomass), which is high and indicates unsustainable energy consumption coupled with its low variation. Average institutional quality is 0.3, which suggests weak institutions in the country. There is a steady increase in population, given a mean of 5.82 million with a wide range from 4.16 million to 8.64 million. Together, these statistics set the stage for analysing how these socio-economic indicators relate to the dynamics of deforestation in Sierra Leone.

3.2 Unit root results

The variables were tested for unit root to explore their order of integration to decide the appropriate econometric model to use. ADF was used to test all the variables for unit with all three models of constant, trend and drift. A unit root in any of the models suggests that the variable is non-stationary. The results in [Table 3](#) show that the null hypothesis of a unit root cannot be rejected in at least one of the models for all the variables at level but is rejected for all the models after first differencing. This shows that all the variables are integrated of order one, $I(1)$. See [Table 3](#) for the results.

3.3 Cointegration results

Given that the variables are $I(1)$, to determine if long-run relationships exist among the variables, cointegration tests were done using the Johansen cointegration test. See [Table 4](#) for results.

Given that the trace statistics exceed their corresponding critical values at 5% for ranks 0–3, the results indicate that there are four cointegrating relationships among the variables. This

Table 2. Descriptive statistics

Variable	Obs.	Mean	Std. dev.	Min	Max
Deforestation	34	197.3	2.31	17.42	22.04
Income	34	852.54	172.52	573.32	1,216.61
Natural resource rent	34	12.05	3.58	7.23	21.66
Renewable energy (biomass)	34	84.31	8.40	71.1	95
Institutional quality	34	0.30	0.09	0.17	0.44
Total population	34	5,824,632	1,440,126	4,157,130	8,460,512

Table 3. Unit root results

	Level			First difference		
	Constant Test statistic	Trend Test statistic	Drift Test statistic	Constant Test statistic	Trend Test statistic	Drift Test statistic
Deforestation	0.725	-1.78	-0.983	-3.815***	-3.898**	-3.841***
Income	-0.867	-3.340	-0.867	-4.683***	-4.687***	-4.683***
Natural resource rent	-1.048	-3.558	-2.716***	-4.798***	-4.764***	-4.786***
Renewables (biomass)	-0.192	-2.782	-0.192	-2.967**	-3.892**	-2.967***
Institutional quality	-0.308	-4.530***	-3.842***	-6.302***	-5.971***	-6.224***
Total population	1.829*	-4.653***	0.611	-3.539**	-3.629**	-3.300***

Note(s): *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 4. Johansen cointegration results

Maximum rank	Params	LL	Eigenvalue	Trace statistic	5% critical value
0	78	-438.31718		174.8735	94.15
1	89	-409.31828	0.84601	116.8758	68.52
2	98	-383.22704	0.81424	64.6933	47.21
3	105	-366.71876	0.65529	31.6767	29.68
4	110	-355.42916	0.51730	9.0975*	15.41
5	113	-350.92222	0.25231	0.0836	3.76
6	114	-350.88041	0.00269		

satisfies the condition of $0 < r < n$, where r is the rank and n is the number of variables. This indicates that there is a long-run equilibrium relationship among deforestation, income, natural resource rent, renewable energy consumption, institutional quality and population. As a robust test, the Johansen maximum eigenvalue test results also confirm the presence of cointegration among the variables (see Table 5).

The maximum eigenvalue statistics for ranks 0–3 are higher than the 5% critical value, which indicates the presence of four cointegrating relationships among the variables.

3.4 VECM results

The variables are integrated of order one ($I(1)$) and cointegrated ($0 < r < n$). As a result, the VECM is used to estimate both the short-run and long-run relationships between deforestation and its socio-economic determinants. See Table 6 for the model summary.

Table 5. Johansen maximum eigenvalue test

Maximum Rank	Params	LL	Eigenvalue	Critical value	
				Maximum	5%
0	78	-438.31718	.	57.9978	39.37
1	89	-409.31828	0.84601	52.1825	33.46
2	98	-383.22704	0.81424	33.0166	27.07
3	105	-366.71876	0.65529	22.5792	20.97
4	110	-355.42916	0.51730	9.0139	14.07
5	113	-350.92222	0.25231	0.0836	3.76
6	114	-350.88041	0.00269		

Table 6. Model summary

Equation	Parms	RMSE	R-sq	χ^2	$p > \chi^2$
D_Deforestation	14	0.004242	0.8202	77.54367	0.0000
D_Income	14	66.8625	0.5229	18.62978	0.1796
D_Natural Resource Rent	14	2.76844	0.5982	25.31194	0.0316
D_Renewables (Biomass)	14	1.62879	0.5717	22.6951	0.0654
D_Institutional Quality	14	0.027363	0.3814	10.48116	0.7262
D_Total Population	14	40141.4	0.9637	451.2576	0.0000

The results of the model summary in Table 6 reveal that the deforestation equation (D_Deforestation) has a high explanatory power, with an R-squared of 0.8202, indicating that approximately 82% of deforestation is explained by the lag of deforestation (own-effect) and the socio-economic variables included in the model. Overall, the model is statistically significant, as indicated by the chi-squared value of 77.54 and a p-value of 0.0000. This confirms that the joint effect of the determinants of deforestation is significant. In Table 7, the results are the short-run estimates.

The short-run VECM results in Table 7 offer insights into the short-run dynamics of the socio-economic determinants of deforestation in Sierra Leone. The ECT ($_{cel}$ L1) is negative and statistically significant ($-0.15, p < 0.01$). This confirms that the model has a long-run equilibrium adjustment. That is, 15% of the disequilibrium is corrected annually, which is a

Table 7. Results of short-run VECM estimates

	Coef.	Std. err.	Z	$p > |z|$	[95% Conf	Interval]	Sig
<i>D_Deforestation _cel</i>							
L1	-0.15	0.031	-4.89	0.001	-0.210	-0.090	***
LD	-0.624	0.196	3.18	0.001	1.009	0.239	***
L2D	-0.207	0.126	1.64	0.101	0.454	0.04	
<i>Income</i>							
LD	-0.004	0.121	3.31	0.001	1.010	0.241	***
L2D	-0.002	0.101	2.34	0.019	0.612	0.010	**
<i>Natural Resource Rent</i>							
LD	0.115	0.021	5.6	0.001	0.001	0.004	***
L2D	0.002	0.001	0.87	0.385	0.001	0.001	
<i>Renewables (Biomass)</i>							
LD	0.002	0.001	2.86	0.004	0.001	0.004	***
L2D	0.001	0.001	1.64	0.100	0.001	0.003	
<i>Institutional Quality</i>							
LD	-0.021	0.035	-0.60	0.551	-0.088	0.047	
L2D	-0.001	0.029	-0.02	0.982	-0.057	0.056	
<i>Total Population</i>							
LD	0.001	0.001	1.48	0.139	0.001	0.001	
L2D	-0.001	0.001	-0.67	0.501	0.001	0.001	
Constant	0.079	0.017	4.74	0.001	0.046	0.112	***
Mean dependent var	0.001		SD dependent var	0.007			
Number of obs	31.000		Akaike crit. (AIC)				

Note(s): *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

moderate speed of convergence toward long-run equilibrium. Also, lag 1 of the first difference of deforestation (LD) is negative and significant (0.62, $p < 0.01$). This indicates that deforestation is transient meaning that forests can be cleared and allowed to regrow. Income is negative and significant in both lags 1 and 2, which implies that an increase in income is associated with a decrease in deforestation. Natural resource rent is positive and significant indicating that increase in mining and other natural resource extraction from land could result in increase in deforestation. Renewable energy consumption (dominated by traditional biomass) is positive and significant, suggesting initial increase in deforestation which could be due to initial land requirements for renewable energy sources like biofuels. Given that the VECM is an unrestricted constant model, the short-term dynamics are also explained by the constant term, which is positive and significant, suggesting an upward trend in deforestation that is also accounted for after accounting for all explanatory variables. Overall, the results of the short-run estimates highlight natural resource rent, income or economic growth and traditional renewable energy consumption (biomass) as primary short-run drivers of deforestation in Sierra Leone.

As a robust test, the results in the cointegration test in Table 8 confirm a statistically long-run relationship among the variables in the VECM. The chi-squared statistic of 84.93 with 5 parameters and the associated p -value of 0.0000 indicate higher significance at the 1% level. See the results of the long-run estimates in Table 9.

The long-run VEC estimates in Table 9 reveal the equilibrium relationships between deforestation and its socio-economic determinants in Sierra Leone. Since these are normalised on deforestation, they are interpreted by inverting the signs of the coefficients to understand their long-run effect on deforestation. Natural resource rent is positive and significant indicating an increase in deforestation as natural resource rent increases. The same is for renewable energy consumption (dominated by biomass) and total population. Institutional quality is negative, indicating that weak institutions increase deforestation.

Furthermore, decomposition of forecast error variance, impulse response and post-estimation VEC diagnostics and tests, including autocorrelation, normality and stability, were done. See Table 10 for the results of the FEVD test.

Based on the FEVD result in Table 10, renewable energy consumption (dominated by biomass) is the dominant factor. It becomes the largest determinant of deforestation after year 3, peaking at 54.4% by the 30th year. It confirms the strong long-term relationship between

Table 8. Cointegration equation

Equation	Parms	χ^2	$p > \chi^2$
_ce1	5	84.92675	0.0000
Identification	beta is	exactly identified	

Table 9. Johansen normalisation restriction imposed VECM long-run

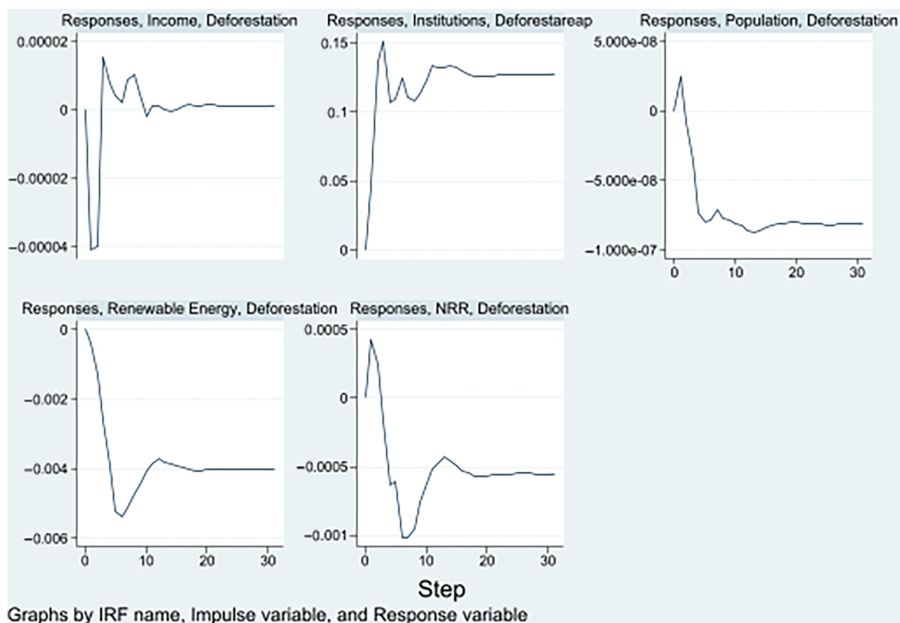
Beta	Coefficient	Std. err	Z	$p > z$	[95% conf	Interval]
_ce1						
Deforestation	1	.	.	.	.	.
Income	-0.0000413	0.000092	-0.45	0.653	-0.0002216	0.000139
Natural Resource Rent	-0.011252**	0.0030324	-3.71	0.011	-0.0481821	0.070686
Renewable Energy Con	-0.0189185***	0.003536	-5.35	0.000	0.0119881	0.0258489
Institutional Quality	0.4431736***	0.1305697	3.39	0.001	0.6990855	0.1872618
Total Population	-1.05e-07***	1.46e-08	-7.22	0.000	-7.68e-08	1.34e-07
_cons	-198.8184	.	.	.	.	.

Table 10. Results of forecast error decomposition (FEVD)

Step	Income	Natural resource rents	Renewable energy consumption	Institutional quality	Total population
1.	0.264	0.001	0.035	0.038	0.015
2.	0.200	0.000	0.122	0.233	0.008
3.	0.170	0.003	0.237	0.279	0.013
4.	0.182	0.004	0.350	0.236	0.030
5.	0.182	0.004	0.455	0.192	0.037
6.	0.180	0.012	0.502	0.173	0.038
7.	0.187	0.017	0.524	0.159	0.038
8.	0.193	0.018	0.532	0.152	0.040
9.	0.192	0.017	0.539	0.152	0.042
10.	0.188	0.016	0.542	0.156	0.044
11.	0.184	0.015	0.541	0.163	0.047
12.	0.181	0.014	0.538	0.169	0.050
13.	0.178	0.013	0.537	0.174	0.052
14.	0.175	0.012	0.536	0.179	0.055
15.	0.172	0.011	0.536	0.182	0.056
16.	0.171	0.011	0.536	0.184	0.057
17.	0.170	0.010	0.537	0.185	0.058
18.	0.169	0.010	0.538	0.186	0.059
19.	0.168	0.009	0.539	0.187	0.059
20.	0.167	0.009	0.540	0.188	0.060
21.	0.167	0.009	0.541	0.189	0.060
22.	0.166	0.008	0.541	0.190	0.061
23.	0.165	0.008	0.542	0.190	0.061
24.	0.165	0.008	0.542	0.191	0.062
25.	0.164	0.008	0.542	0.192	0.062
26.	0.164	0.007	0.543	0.193	0.062
27.	0.163	0.007	0.543	0.193	0.063
28.	0.163	0.007	0.543	0.194	0.063
29.	0.162	0.007	0.543	0.194	0.063
30.	0.162	0.007	0.544	0.195	0.064

renewable energy consumption and deforestation, as expressed in the results of the Johansen normalisation restriction imposed in Table 9 (VECM long-run estimates). Institutional quality shows signs of being a strong medium-term driver of deforestation. Though it peaks at 27.9% in the third year, it declines as renewable energy consumption becomes more dominant. Income shows a strong initial impact of 26.4% in the first year, after which it declines over time. Natural resource rents show minimal impact throughout the years. It never exceeded 1.8%. Similarly, total population is also consistently a minor contributor with a maximum of 6.4% at year 30. IRF results are shown in Figure 2.

The results of the IRF in Figure 3 show that a shock in income initially leads to a small negative effect on deforestation, which is followed by a quick positive spike. The response of deforestation to shock in income stabilises close to 0. This indicates that the income shock on deforestation is short-lived, which agrees with the VECM results of short-term negative results and no significant long-term impact. A shock in institutional quality is shown to have an initial sharp small negative impact on deforestation, after which it became significantly positive throughout. This indicates a short-term negative effect and a long-term positive impact, as in the results in the short- and long-run VECM estimates. Population shock causes an initial positive response in deforestation, which is short-lived. The shock in renewable energy consumption initially leads to a positive response in deforestation. Shock in natural resource rent causes a positive response in deforestation.



Graphs by IRF name, Impulse variable, and Response variable

Figure 2. Results of the impulse response functions. **Source(s):** Author's computation using Stata 17

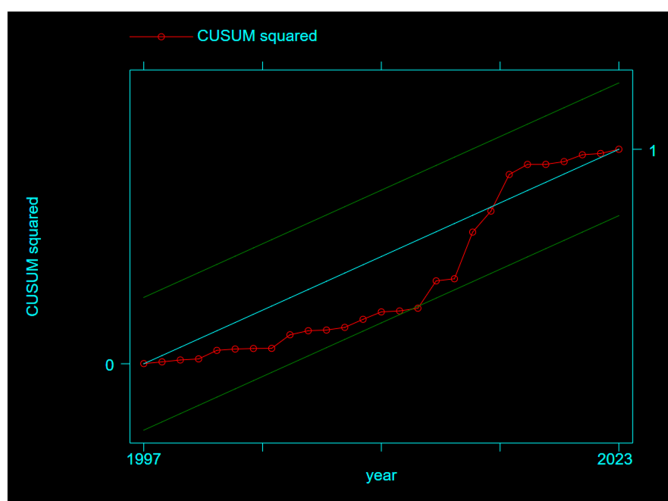


Figure 3. Results of cumulative sum (CUSUM) Test. **Source(s):** Author's computation using Stata 17

The results of the Lagrange-multiplier (LM) test for autocorrelation in [Table 11](#) examine whether the residuals of the VECM are autocorrelated. The model estimation used 3 lags, so the LM test was conducted for lags 1 to 3. Given that the p -values are all greater than 0.05, particularly for lag 3 used in the model estimate, the null hypothesis of no autocorrelation is accepted. This indicates that the lag length of 3 is appropriate which is also important for the standard errors, the estimates and the model specification ([Le Gallo et al., 2020](#)). Also, the

Table 11. Results of Lagrange-multiplier test for autocorrelation

Lag	χ^2	Df	Prob > χ^2
1	35.941	36	0.471
2	50.881	36	0.051
3	30.371	36	0.733

results of the Jarque–Bera test for whether the residuals are normally distributed are shown in [Table 11](#).

The results of the Jarque–Bera test for normality of residuals in [Table 12](#) assess the residuals from each equation, particularly the D_Deforestation, which is the equation of interest. The residuals of the all the equations are normally distributed except for D_Institutional Quality. Overall, the residuals for the equations together (ALL) are normally distributed with a p -value greater than 0.05. This robust check satisfies the condition for valid inference in time series models. Finally, it is the test for model stability. See the result in [Table 13](#).

The eigenvalue stability condition which assesses the stability of VECM requires that for a VECM to be stable and dynamically well specified, all moduli (absolute values of

Table 12. Results of Jarque–Bera test for normality of residuals

Equation	χ^2	Df	Prob > χ^2
D_Deforestation	0.121	2	0.941
D_Income	0.463	2	0.793
D_Natural Resource Rent	2.809	2	0.245
D_Renwable Energy Consumption	1.404	2	0.495
D_Institutional Quality	6.184	2	0.045
D_Population	0.240	2	0.887
ALL (all, joint, or overall)	11.222	12	0.510

Table 13. Results of Eigenvalue stability condition

Eigenvalue	Modulus
1	1
1	1
1	1
1	1
−0.7799278	0.779928
0.07353846	0.759088i
0.07353846	−0.759088i
0.6937292	0.3025697i
0.6937292	−0.3025697i
0.6231969	0.413359i
0.6231969	−0.413359i
−0.474184	0.5499402i
−0.474184	0.5499402i
−0.3706649	0.158952i
−0.3706649	−0.158952i
0.2933783	0.2224261i
0.2933783	−0.2224261i

eigenvalues), except for as many unit roots as there are cointegration relationships, must lie strictly inside the unit circle (i.e. have modulus <1) (Johansen, 1995). The results in Table 13 indicate that the system has 4-unit roots, which is equal to the four cointegration relationships found in the Johansen test. Since all non-unit eigenvalues lie within the unit circle (modulus <1) and the number of unit roots corresponds to the number of cointegration vectors, the VECM satisfies the eigenvalue stability condition. This means that the model is stable, and its long-run relationships and short-term dynamics are reliable, which is important for inference.

As a robustness check, the ARDL model was employed, and the result is shown in Table 14.

The results of the ARDL estimates are in Table 14. The results are similar to the long- and short-run VEC model estimates in Tables 9 and 7. In the short term, natural resource rent and renewable energy consumption (traditional biomass) increase deforestation while income reduces it. Similarly, in the long run, natural resource rent, renewable energy consumption (traditional biomass) and population increase deforestation while strong institutions reduce deforestation.

The results of the ARDL model post-estimation tests also indicate that the model is stable, reliable and valid. The CUSUM squared plot in Figure 2 shows that the red CUSUM squared

Table 14. Results of long- and short-run ARDL estimates

D. Deforestation	Coefficient	Std. err.	T	p > t	[95% conf. Interval]	
<i>ADJ</i>						
<i>Deforestation</i>						
L1	-1.180	0.334	-3.530	0.003	-1.895 -0.464	
<i>LR</i>						
Income	-0.033	0.027	-1.240	0.235	-0.091 0.024	
Natural resource rent	2.517**	0.773	3.260	0.006	4.176 -0.859	
Renewables (biomass)	1.694**	0.871	1.950	0.045	0.174 3.563	
Institutional quality	-1.306**	0.375	-3.483	0.004	-4.949 2.564	
Total population	2.641***	0.540	4.891	0.000	5.231 0.843	
<i>SR</i>						
<i>Deforestation</i>						
LD.	-1.003***	0.205	-4.893	0.000	-0.437 0.443	
<i>Income</i>						
D1	-0.050**	0.015	-3.333	0.002	-0.003 0.103	
LD.	0.023	0.020	1.140	0.271	-0.020 0.067	
<i>Natural resource rent</i>						
D1	1.665**	0.060	2.775	0.027	-1.022 3.953	
LD.	0.554	0.654	0.850	0.411	-0.848 1.956	
<i>Renewables (biomass)</i>						
D1	0.216***	0.049	4.408	0.001	-1.948 2.381	
LD.	0.203	0.899	0.230	0.825	-1.726 2.132	
<i>Institutional quality</i>						
D1	-53.068	59.845	-0.890	0.390	-181.423 75.286	
LD.	13.203	42.523	0.310	0.761	-77.999 104.405	
<i>Total population</i>						
D1	-3.035	2.852	-1.064	0.333	-0.002 -0.201	
LD.	-2.415	3.421	-5.966	0.637	-0.000 0.000	
_cons	-142.622	143.019	-1.000	0.336	-449.368 164.124	

Note(s): ***p < 0.01, **p < 0.05, *p < 0.1

line stays within the green boundaries (the critical bound of 5% significance) throughout the sample period (1990–2023). This is the evidence of no structural break in the data and indicates that the model’s estimated coefficients are stable over time (Brown *et al.*, 1975; Kripfganz *et al.*, 2016). Though Sierra Leone experienced a civil war from 1991 to 2000, political instability, using aggregated annual data, may have reduced the impact of those shocks.

The results of the Breusch–Godfrey LM test for autocorrelation in Table 15 show that the *p*-value of 0.09 is greater than 0.05, indicating that the residuals are not serially correlated which may bias the estimates. Similarly, the results of the White’s test in Table 16 with a *p*-value greater than 0.05 indicate that there is homoscedasticity (no heteroscedasticity).

The results in Table 17 show that there is no skewness or kurtosis in the residuals, and the joint, which combines both kurtosis and skewness, also shows that the residuals are normally distributed.

4. Discussion

The study examined the socio-economic drivers of deforestation in Sierra Leone using VEC and ARDL models. The results reveal both short-run and long-run significant relationships that align with the existing theoretical explanations and existing literature within Sierra Leone, across West Africa, SSA and globally. The evidence also contributes to the sparsely available empirical literature on deforestation and socio-economic linkages in Sierra Leone. The short-run VECM estimates indicate that income, natural resource rents and renewable energy consumption (traditional biomass consumption) are statistically significant drivers of deforestation in Sierra Leone. The significance of the ECT confirms a stable long-term equilibrium relationship among the variables, and any disequilibrium adjusts gradually over time. This interpretation is in line with the use of the VECM econometric approach. This is also supported by the ARDL estimates.

The lag of deforestation is significant and negative indicating that past deforestation reduces current deforestation. This could be due to socio-ecological feedback and structural changes in land use as Caron *et al.* (2021) observed that as forests are cleared and remaining forest becomes scarcer, the marginal returns to further clear forests decline. It also aligns with

Table 15. Results of Breusch–Godfrey LM test for autocorrelation

Lags (p)	χ^2	Df	Prob > χ^2
1	2.85	1	0.09

Table 16. Results of White’s test

χ^2	Prob > χ^2
28.41	0.010

Table 17. Result of Jarque–Bera test for normality

Variable	Obs	Pr (skewness)	Pr (kurtosis)	Joint test Adj.	$\chi^2(2)$
Residual	32	0.612	0.623	0.520	0.773

the finding of [Caron et al. \(2021\)](#) that natural forest regrowth occurs when land is cleared and left to fallow or abandoned.

The significance and negative sign of income in the short run is similar to a U- or N-shaped curve, which, contrary to the inverted U-shaped curve by Kuznets, observes that environmental degradation initially decreases with a rise in income. This is similar to the suggestions of [Caporin et al. \(2024\)](#), who observed a linear relationship in Central Asia and suggested the possibility of the countries being in the first phase of the N- and U-shaped curve. Also, in the developed world, [Dogan and Inglesi-Lotz \(2020\)](#) observed in their studies of European countries that the industrial share of economic growth reduces environmental degradation through the adoption of technologies that are energy efficient and environment friendly. Though income shows a strong initial impact based on the FEVD analysis, accounting for 26.4% of the variation in deforestation, the IRF curve shows that the response of deforestation to an income shock stabilises near 0, supporting the VECM estimates that the effect of income on deforestation is short-lived. This is in line with [Seri and Fernandez \(2021\)](#), who found out that most countries in Latin America do not exhibit any long-run relationship between income and the environment.

The results also reveal significant short- and long-run relationships between renewable energy consumption and deforestation in Sierra Leone. Both the short- and long-run estimates reveal a positive relationship indicating that renewable energy consumption dominated by traditional biomass increases deforestation. This is also supported by the IRF, which shows a positive shock. The increase in deforestation could be attributed to the falling down of trees for biomass firewood consumption as noted by [Weston \(2024\)](#) in the global case and [Stevens et al. \(2025\)](#) in the Sierra Leone context.

The significant negative relationship between institutional quality and deforestation is in line with the property right theory that quality institutions reduce deforestation. This could be due clear property rights, robust enforcement of environmental laws and low corruption which increase the costs and risk of illegal clearing leading to forest protection. This was confirmed by [Bösch \(2021\)](#) in a cross-national study and found out that weak institutions allow illegal logging and [Fischer et al. \(2020\)](#) observed that governance indicators correlate with decreased deforestation. Similarly, in the context of Sierra Leone, the analyses by [Mihaylova \(2023\)](#) underscored how politico-legal institutional settings, including the authority of traditional rulers (chiefs), and governance quality affect the forest.

Natural resource rent is significant and positive in both the short- and long run. This could be due to reliance on revenue from mineral extraction and other natural resources which creates incentives for deforestation. This is supported by empirical studies in resource-rich developing countries where high extractive industry rents correlate with high forest cover loss mainly for minerals and other natural resource rents ([Butsic et al., 2015](#); [Keneck-Massil and Foudjo, 2025](#); [Tunde et al., 2016](#)). This includes clearing of forests for roads and settlements. This could be long term due to natural resource dependence. Previous studies in Sierra Leone have also observed that mining of gold and iron ore extraction significantly drive deforestation and other environmental change ([Samura, 2024](#); [Stevens et al., 2025](#); [Wadsworth and Lebbie, 2019](#)).

The results of both the VEC and ARDL estimates indicate that increase in population is correlated with increase in deforestation in the long run. This suggests that rapid population growth leads to increased deforestation in the long run because of expansion of agriculture, settlements and other infrastructure. It is well established in the environmental science literature that demographic expansion is associated with forest loss. In Sierra Leone, after the civil war, demographic growth led to increase in the demand for land contributing to forest loss ([Adom et al., 2024](#); [Aleman et al., 2017](#); [Stevens et al., 2025](#); [Yumantoko et al., 2016](#)).

In summary, this study contributes to the literature in several ways. It identifies distinct short-run and long-run relationships between deforestation and its socio-economic determinants, highlighting the dynamic nature of deforestation. Secondly, the evidence put forward by the study aligns with the global views of the effect of income, renewable energy

consumption (traditional biomass), institutional quality, natural resource rents, income and population on deforestation, demonstrating the need for deeper reforms and modernisation efforts. Also, the study bridges local evidence with global discourse on environmental sustainability by situating the findings within broader theoretical and regional frameworks.

5. Conclusion and policy recommendations

This study has empirically investigated the long- and short-run socio-economic determinants of deforestation in Sierra Leone using the Johansen cointegration framework within a VEC and an autoregressive distributive lag (ARDL) models. Drawing on annual time series data, the analysis focused on key variables including income, natural resource rents, renewable energy consumption, institutional quality and population, providing important insights into the underlying forces driving deforestation in the country. The results confirm the presence of a long-run equilibrium relationship among the variables, as indicated by the significance of the ECT, which reflects the system's tendency to return to equilibrium after short-run deviations.

In the short-run dynamics, income, natural resource rents and renewable energy consumption were found to significantly influence deforestation, indicating that economic growth, natural resource extraction and energy consumption patterns are critical in understanding fluctuations in forest cover over time. Whilst an increase in income in the short run is found to reduce deforestation due to a possible shift away from subsistence agriculture and firewood use, inertia is observed in renewable energy consumption, which might be due to the scale effect in initial set-ups. However, it persists in the long run possibly due to dominance of traditional biomass in renewable energy consumption in Sierra Leone. The significant negative relationship between institutional quality and deforestation suggests that strong institutions reduce deforestation either through prioritisation of environmental sustainability, transparency in forest management or effective implementation of penalties for forest illegal forest clearing. Furthermore, the inference that can be drawn from the long-run significant positive relationship between total population and deforestation is that as population intensifies, demand for land, food, energy and infrastructure intensifies and expand on agriculture, settlements and transport networks into forest areas reduces fallow periods, making deforestation persistent rather than temporary.

From a policy perspective, the results call for a re-evaluation of current energy strategies to shift from traditional biomass to modern renewable alternatives, such as solar and wind, for sustainable forest practices. Policymakers could also consider income incentives to shift from subsistence farming and the use of firewood to reduce deforestation. Furthermore, the government should prioritise forest protection by institutionalising and implementing forest protection regulations. For an increase in population not to increase deforestation, the government should complement the reforestation and afforestation efforts of NGOs. Moreover, there is a need to integrate population policy into environmental planning, promoting sustainable land use and reducing forest dependence among rural populations.

The findings of this study contribute significantly to the existing literature by offering empirical evidence specific to Sierra Leone, a country with limited econometric research on environmental degradation like deforestation. The forecast error decomposition (FED) shows the magnitude of the effects of the variables on deforestation, whilst the IRFs show the shocks and direction. Furthermore, the use of VEC and ARDL frameworks allows for a distinction between short-run shocks and long-run equilibrium dynamics, enriching the analytical rigour. However, the study is limited to Sierra Leone, which may affect the generalisability of the findings. Furthermore, future studies should consider disaggregated population data to separate rural and urban population effects. Income could also be disaggregated into industrial and non-industrial or agricultural income to capture their individual effect on deforestation. Lastly, a comparative analysis with Guinea and Liberia, who share the same forest (Gola Forest) with Sierra Leone, would be valuable, as lessons could be learnt from the assessment of their similarities and differences.

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