

# The Role of Forest Areas as Carbon Sinks in Türkiye: The Impact of Industrialization and Energy Consumption on Greenhouse Gas Emissions

Serkan ŞENGÜL 

Mudanya University, Economics and Finance, Mudanya, Bursa, TÜRKİYE  
Corresponding Author: [serkan.sengul@mudanya.edu.tr](mailto:serkan.sengul@mudanya.edu.tr)

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## Abstract

*Aim of study:* This study examines the impact of forest area expansion on greenhouse gas (GHG) emissions in Türkiye, focusing on the roles of industrial production, energy consumption, and economic growth.

*Area of study:* The analysis covers Türkiye using annual data for the period 1990–2021. Data on GHG emissions, forest areas, industrial production, energy consumption, and economic growth were obtained from the Turkish Statistical Institute (TurkStat) and other official sources.

*Material and method:* The study employs the autoregressive distributed lag (ARDL) model and Johansen cointegration approach to analyze the long-run relationships among the variables. Unit root tests were conducted to examine the stationarity properties of the series.

*Main results:* The findings indicate that forest area expansion significantly reduces GHG emissions in the long run, highlighting the role of forests as carbon sinks. In contrast, industrial production, energy consumption, and GDP per capita exert statistically significant positive effects on emissions. The Johansen cointegration results confirm a stable long-run equilibrium relationship among the variables.

*Research highlights:* Achieving Türkiye's emission reduction targets requires strengthening forest management policies and aligning industrial production and energy consumption with environmental sustainability.

**Keywords:** Greenhouse Gas Emissions, Forest Areas, Energy Consumption, Industrialization, Türkiye

## Türkiye'de Orman Alanlarının Karbon Yutakları Olarak Rolü:

## Sanayileşmenin ve Enerji Tüketiminin Sera Gazı Emisyonlarına Etkisi

### Öz

*Çalışmanın amacı:* Bu çalışma, Türkiye'de orman alanlarının genişlemesinin sera gazı emisyonları üzerindeki etkisini incelemekte; özellikle sanayi üretimi, enerji tüketimi ve ekonomik büyümenin rolünü analiz etmektedir.

*Çalışma alanı:* Analiz, 1990–2021 dönemine ait yıllık veriler kullanılarak Türkiye için gerçekleştirilmiştir. Veriler TÜİK ve diğer resmi kaynaklardan elde edilmiştir.

*Materyal ve yöntem:* Çalışmada değişkenler arasındaki uzun dönem ilişkileri incelemek amacıyla ARDL modeli ve Johansen eşbütünleşme analizi kullanılmış, serilerin durağanlığı birim kök testleri ile değerlendirilmiştir.

*Temel sonuçlar:* Bulgular, orman alanlarının genişlemesinin uzun dönemde sera gazı emisyonlarını azalttığını ve çevresel sürdürülebilirliğe katkı sağladığını göstermektedir. Buna karşılık sanayi üretimi, enerji tüketimi ve kişi başına GSYİH emisyonları artıran ve istatistiksel olarak anlamlı pozitif etkilere sahip faktörlerdir.

*Araştırma vurguları:* Türkiye'nin emisyon azaltım hedeflerine ulaşabilmesi için orman yönetimi politikalarının güçlendirilmesi ve enerji tüketimi ile sanayi üretiminin çevresel sürdürülebilirlik ilkeleriyle uyumlu hale getirilmesi gerekmektedir.

**Anahtar kelimeler:** Sera Gazı Emisyonları, Orman Alanları, Enerji Tüketimi, Sanayileşme, Türkiye



## Introduction

Global warming and climate change represent some of the most pressing environmental and socio-economic challenges of the 21<sup>st</sup> century. Greenhouse gas (GHG) emissions, particularly carbon dioxide (CO<sub>2</sub>), play a dominant role in this process, necessitating urgent action to mitigate their impacts (IPCC, 2023). Forests, as critical carbon sinks, sequester CO<sub>2</sub> released into the atmosphere through photosynthesis, thereby playing a vital role in combating climate change (Pan et al., 2011).

Türkiye, despite its considerable forest cover accounting for approximately 30% of its total land area, has witnessed a significant increase in GHG emissions due to industrialization, economic growth, and rising

energy consumption. Between 1990 and 2021, the country's CO<sub>2</sub> emissions increased from 170 million tons to over 530 million tons (World Bank, 2021). This dramatic rise underscores the environmental pressures exerted by industrial production and energy consumption (IEA, 2021).

While industrial production is recognized as the engine of economic growth in developing countries, it also intensifies environmental degradation, particularly through energy-intensive activities (Grossman & Krueger, 1995; Sims et al., 2014). The increasing population further exacerbates these pressures by amplifying demand for energy and industrial output, leading to higher emissions (Ehrlich & Holdren, 1971).



Figure 1. Graphs of variables

Figure 1 shows the long-term trends in various variables for Türkiye over the period 1990-2021. These graphs reveal the changes over time in the key variables analyzed in this

study, such as greenhouse gas emissions, gross domestic product per capita, industrialization, energy consumption, forest areas and population.

It is noteworthy that greenhouse gas emissions are constantly increasing. This can be attributed to the fossil fuel-based nature of energy consumption and the intensity of industrialization. As emphasized in the literature (Wang & Su, 2020; Stern & Stern, 2020), the fact that energy consumption is based on carbon-intensive resources is one of the most important causes of greenhouse gas emissions. This trend once again highlights the importance of energy efficiency and renewable energy sources for Türkiye's climate policies.

The industrialization graph shows an increasing trend as a significant engine of economic growth. However, when the environmental impacts of this increase are considered, the need for sustainable industrial policies becomes evident. In particular, technological investments to reduce carbon emissions in energy-intensive sectors should be encouraged. These arguments are consistent with the literature on the environmental pressures of industrialization highlighted by Stern and Stern (2020).

Forest areas have shown a gradual increase in the period under review. This confirms the critical role of forests as carbon sinks in offsetting environmental degradation. However, the adequacy of this increase may be limited given the emissions caused by industrialization and energy consumption. As highlighted in Magazzino et al. (2024), supporting forest areas with sustainable management practices is critical in enhancing this positive impact.

GDP per capita indicates that Türkiye's economy has been following a continuous upward growth trend. However, the environmental consequences of this growth, particularly in the context of the Environmental Kuznets Curve (EKC) hypothesis, must be carefully managed. According to the EKC hypothesis, while economic growth initially leads to increased environmental degradation, beyond a certain income threshold, this trend may reverse (Grossman & Krueger, 1995). How close Türkiye is to reaching this turning point depends largely on the effectiveness and implementation of sustainable development policies.

Population growth, especially when considered together with the increase in energy consumption and industrial production, stands out as an important factor that increases environmental pressures. The fact that increasing population increases energy demand and this demand is met by fossil fuel-based energy production supports the strong relationship between energy consumption and emissions, which is also emphasized in the literature.

Finally, the continuous increase observed in the energy consumption graph reflects Türkiye's dependence on fossil fuels in energy production. This makes it a necessity to accelerate the transition to renewable energy and implement policies to increase energy efficiency. In the literature, the impact of such policies in reducing GHG emissions is often emphasized (Wang & Su, 2020; Magazzino, 2016).

Overall, the graphs show how fragile the balance between Türkiye's economic growth, industrialization and energy consumption growth and environmental sustainability is. These findings support the importance of the policy recommendations presented in this study and suggest that forest management, energy efficiency and industrial policies should be addressed in an integrated manner to achieve sustainable development goals.

This study aims to analyze the interplay between Türkiye's GHG emissions and factors such as forest areas, industrial production, energy consumption, economic growth, and population dynamics over the period 1990-2021. A particular focus is placed on the carbon absorption capacity of forests, evaluating their potential to offset emissions arising from carbon-intensive activities. The study also investigates the extent to which forest management policies can align with Türkiye's sustainable development goals, particularly under the Paris Climate Agreement (UNFCCC, 2021).

This study contributes to existing literature in several original ways. First, while many previous studies have explored the EKC hypothesis or the environmental impacts of industrialization and energy consumption separately, this study integrates forest area expansion directly into the EKC framework in the context of Türkiye, providing a more

comprehensive approach to understanding carbon dynamics. Second, by employing both ARDL and Johansen cointegration techniques, the study ensures methodological robustness and captures both short- and long-run dynamics, offering nuanced insights that are often missing in single-method analyses. Third, the study uses updated time series data (1990-2021), which enables the evaluation of Türkiye's climate commitments, especially after the Paris Agreement. The empirical results, particularly the mitigating role of forests and the strong emission-enhancing effects of industrialization and energy use, offer concrete evidence for the formulation of integrated policy strategies. These findings contribute to both national and international policy discussions by emphasizing the need for afforestation, renewable energy adoption, and environmentally responsible industrial development as complementary components of climate policy.

#### *Literature Review*

Forests play a strategic role in the global carbon cycle by serving as carbon sinks and mitigating GHG emissions. Pan et al. (2011) emphasized the critical importance of forests in reducing atmospheric CO<sub>2</sub> levels through sequestration. Similarly, Keenan et al. (2015) highlighted a positive relationship between forest area expansion and global carbon balance, emphasizing the necessity of sustainable management practices.

Le Quéré et al. (2018) extended this discussion by emphasizing that while forest expansion boosts carbon sequestration, these efforts must be supported by robust reforestation and forest conservation policies. These studies underscore the role of forests as a strategic asset in achieving climate goals, particularly in countries like Türkiye, where rapid industrialization poses significant environmental challenges.

Industrial production and energy consumption are major drivers of GHG emissions globally. Wang and Su (2020) confirmed the EKC hypothesis of Grossman and Krueger (1995) in developed economies while noting complexities in its applicability to developing countries like Türkiye.

Türkiye's industrial production index has shown consistent growth since 1990,

correlating with a steady increase in energy consumption and emissions (TurkStat, 2022). Sims et al. (2014) observed that energy-intensive sectors contribute disproportionately to carbon emissions, highlighting the need for integrated industrial and environmental policies.

Recent studies on the carbon sink function of forest areas empirically demonstrate the potential of these natural assets in reducing GHG emissions. For example, in an analysis specific to Brazil, it has been shown that an increase in forest cover reduces CO<sub>2</sub> emissions in a statistically significant way and it has been emphasized that this effect is particularly pronounced in the long run (Raihan & Tuspekova, 2022). Similarly, presenting a conceptual review on Türkiye, Inanç and Ayaz (2018) revealed the role of forest ecosystems in both environmental sustainability and combating climate change. These findings overlap with the results obtained in our study and strengthen the environmental stabilizing effect of forests.

Energy consumption and industrialization have been among the main determinants of greenhouse gas emissions in many studies. In particular, the impact of high carbon-intensive sectors such as coal-based electricity generation, steel and cement industries on emissions has been demonstrated in detail with panel quantile regression method in the case of Eastern European and Central Asian countries (Lobanov et al., 2025). This study also shows that land use change becomes more significant in terms of environmental impacts, especially in the upper emission distributions. These findings are important for analyzing industry and energy-based environmental pressures in the Turkish context.

Some studies on the environmental impacts of economic growth emphasize that the impact of growth on emissions varies according to contextual and sectoral differences. Magazzino et al. (2024), in their analysis covering 50 countries, provide empirical support for the EKC hypothesis by stating that income growth initially increases environmental degradation, but this effect may reverse after a certain income threshold. This approach is directly related to the

environmental transformation process tested for Türkiye in our study.

The environmental impacts of land use change and agricultural production is another dimension that attracts attention in the literature. Spatial analyses of crop production in China have revealed that factors specific to agricultural practice, such as irrigation intensity and monoculture practices, increase carbon emission intensity (Wu et al., 2024). The study by Mahdavian et al. (2024) in Iran showed that land use reductions have negative impacts on food security and agricultural production, which also affect CH<sub>4</sub> emissions. Such results suggest that the management of land-based resources needs to be reconsidered not only in terms of agricultural policies, but also in terms of climate policies.

In another study analyzing the combined environmental impacts of urbanization, energy use and tourism, it was shown that these variables increase CO<sub>2</sub> emissions, but renewable energy and forested areas play an offsetting role (Raihan & Tuspekova, 2022). Considering Türkiye's industrialization and urbanization process, analyzing these multidimensional impacts together necessitates a more holistic design of environmental policies. Magazzino et al. (2024) utilized non-parametric analysis to examine the drivers of GHG emissions across 50 countries, emphasizing the interplay between forest density, land use, and emissions. Magazzino et al. (2023a) explored the nexus between agricultural land use, urbanization, and GHG emissions, revealing how sustainable practices can mitigate emissions in different socio-economic contexts. Magazzino (2016) analyzed the association among GDP, CO<sub>2</sub> emissions, and energy use in the South Caucasus and Türkiye, highlighting the regional complexities of energy-driven emissions.

In the Turkish context, Karaca and Demirtaş (2020) analyzed the role of forests as carbon sinks, noting a 5% increase in forest area between 1990 and 2018. Their study revealed that while forest expansion contributes positively to offsetting GHG emissions, industrial production and energy consumption often counteract these gains. Erdoğan et al. (2021) stressed that stronger integration of forest policies into Türkiye's

climate commitments is essential to achieving emission reduction targets under the Paris Agreement.

Despite these contributions, research gaps remain. Dietz and Rosa (1997) emphasized the need to integrate socio-economic factors into environmental analyses. This study addresses this gap by examining the interrelations between Türkiye's forest assets, economic activities, and GHG emissions using a novel econometric approach.

The findings presented here aim to expand the current understanding of the environmental impacts of industrial production and energy consumption, providing actionable recommendations for sustainable forest management and climate policy alignment.

In summary, this study integrates descriptive insights, theoretical grounding, and rigorous econometric techniques to analyze the factors influencing GHG emissions in Türkiye. The findings are expected to provide significant implications for sustainable development policies, particularly in balancing industrial growth with environmental conservation.

## Material and Methods

This study analyzes the association between GHG emissions and various explanatory variables, including forest area, industrial production, energy consumption, GDP, and population, for Türkiye during the period 1990-2021. The data were obtained from the Turkish Statistical Institute (TurkStat) and the World Bank.

The dependent variable in the model is GHG emissions, specifically carbon dioxide (CO<sub>2</sub>) emissions measured in metric tons. To account for potential non-linearities and scale differences, the natural logarithm of CO<sub>2</sub> emissions was taken. This transformation is common in econometric studies as it allows for the interpretation of coefficients as elasticities, thereby simplifying the analysis of proportional changes (Gujarati, 2021).

The independent variables include forest area, measured in hectares, which represents the extent of Türkiye's forest cover. The forest area data was continuous and available for the entire period under consideration. The industrial production index represented

industrial production, adjusted for seasonality and calendar effects, with 2015 as the base year. This variable was included as it captures the contribution of industrial activities to environmental pressures, a well-documented phenomenon in the literature (Wooldridge, 2020). The energy consumption variable reflects annual primary energy consumption measured in terajoules. Like the CO<sub>2</sub> emissions data, the logarithm of energy consumption was taken to normalize its distribution and address scale differences.

The GDP variable represents Türkiye's annual gross domestic product, measured in constant prices. This variable was also logarithmically transformed to analyse the proportional effects of economic growth on GHG emissions. Lastly, population data, obtained from TurkStat, were included as a key macroeconomic factor influencing energy demand and industrial activities. However, due to stationarity concerns identified during unit root testing, the population variable was excluded from the final model.

The selection of variables in the estimated model is grounded in the theoretical framework of the EKC and supported by extensive empirical literature. Forest area is included due to its well-established role as a carbon sink, capable of absorbing CO<sub>2</sub> and reducing overall GHG emissions (Pan et al., 2011; Keenan et al., 2015). Within the EKC framework, economic growth-measured by GDP per capita-plays a pivotal role by capturing the potentially non-linear linkage between income levels and environmental degradation (Grossman & Krueger, 1995). In parallel, industrial production constitutes a

major source of greenhouse gas emissions, particularly in developing countries where production processes are highly energy-intensive and largely dependent on fossil fuel use (Sims et al., 2014; Stern & Stern, 2020). Energy consumption is included to capture the environmental impact of energy use, which has been widely associated with rising emissions in both BRICS and OECD countries (Wang & Su, 2020; Magazzino, 2016). These variables collectively allow for a comprehensive analysis of the economic and environmental dynamics that influence Türkiye's GHG emissions trajectory.

The descriptive analysis which is shown in Table 1, reveals significant variability across the variables, reflecting the diverse economic and environmental dynamics in Türkiye during the studied period. For instance, the standard deviation of GDP (2.7374) indicates substantial fluctuations in economic activity over the years, while the relatively low standard deviation of forestry (0.0428) suggests more stability in forest area coverage. The CO<sub>2</sub> emissions variable has a mean value of 5.86, reflecting a steady rise in emissions as Türkiye's economy and industrial activities expanded. Such descriptive insights provide a foundation for understanding the relationships explored in the econometric analysis.

In conclusion, using data for Türkiye from 1990-2021, this study analyses the relationship between forest area expansion and greenhouse gas emissions, industrial production, economic growth and energy consumption (Eq. 1). The model used to quantify this:

$$Co2_t = \alpha_0 + \alpha_1 forestry_t + \alpha_2 industrialization_t + \alpha_3 GDP_t + \alpha_4 energy_t + \alpha_5 population_t + u_t \quad (1)$$

Table 1. Descriptive statistics

Variables	Obs.	Min	Max	Mean	Std Dev
CO <sub>2</sub>	32	5.3915	6.3358	5.8559	0.2969
Forestry	32	9.9134	10.048	9.9618	0.0428
Industrialization	32	3.4499	4.9127	4.0967	0.4579
GDP	32	1.9789	11.365	8.1537	2.7374
Energy	32	6.8454	7.4325	7.1407	0.1782
Population	32	18.249	17.811	18.044	0.1307

According to EKC hypothesis, as income levels increase initially, environmental degradation worsens due to the reliance on

resource-intensive industrial processes and fossil fuel-based energy consumption. However, after reaching a certain income

threshold, the demand for cleaner environments grows, leading to investments in sustainable technologies, stricter environmental regulations, and reduced emissions (Grossman & Krueger, 1995).

The EKC hypothesis has been extensively tested in literature, particularly for developing countries, where economic growth often coincides with increased environmental pressures. However, the hypothesis has been critiqued for its oversimplification of complex socio-economic dynamics. For instance, the EKC does not fully account for the role of land use changes, such as deforestation or forest expansion, in mediating the relationship between economic growth and environmental outcomes. By incorporating forestry variables into the EKC framework, this study extends the traditional model, highlighting the mitigating role of forest areas in offsetting emissions caused by industrial production and energy consumption. This approach aligns with recent studies that emphasize the interconnectedness of land use, economic activity, and environmental sustainability (Pan et al., 2011; Le Quéré et al., 2018).

The econometric framework of the study is based on the autoregressive distributed lag (ARDL) approach, which enables the analysis of both short-run adjustments and long-run equilibrium relationships among the variables. Originally developed by Pesaran et al. (2001), the ARDL methodology is particularly appropriate for time series analyses in which the variables exhibit mixed orders of integration, provided that they are integrated of order zero or one [ $I(0)$  or  $I(1)$ ], but not of order two [ $I(2)$ ]. This feature distinguishes ARDL from conventional cointegration techniques that impose stricter requirements regarding the integration properties of the variables. In addition, the ARDL approach is well suited for empirical studies with relatively limited sample sizes and allows for the joint estimation of long-term coefficients and short-term dynamics through its associated error correction mechanism.

Before estimating the model, the stochastic characteristics of the series were assessed through the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests. The findings show that most variables attain

stationarity after first differencing, indicating an order of integration of  $I(1)$  and thereby satisfying the requirements of the ARDL methodology. By contrast, the population series was found to be stationary only at the second difference, classifying it as an  $I(2)$  process. As the ARDL framework does not permit the inclusion of variables integrated beyond the first order, the population variable was excluded from the final model specification.

The dependent variable, CO<sub>2</sub> emissions, was logarithmically transformed to stabilize variance and account for potential non-linearities. Similarly, the logarithms of GDP and energy consumption were taken to normalize the data distribution and reduce scale differences. The industrial production index, as a base year-adjusted measure, was included without transformation, since it already captured proportional changes. Forest area data were used in their original form due to their relatively stable distribution over the study period.

The presence of a long-run relationship among the variables was examined using the ARDL bounds testing approach. This technique is particularly suitable for small samples and allows for cointegration analysis without requiring all variables to be integrated at the same order. Cointegration is assessed by comparing the computed F-statistic with the corresponding critical bounds; values exceeding the upper bound indicate the existence of a long-run equilibrium relationship.

To reinforce the robustness of the long-run findings, the Johansen cointegration test was additionally employed as a complementary procedure. While the ARDL framework provides flexibility in model specification, the Johansen approach enables the identification of cointegrating relationships within a multivariate system, thereby offering an effective cross-validation of the results.

Model adequacy and reliability were further evaluated through a set of standard diagnostic tests addressing serial correlation, heteroscedasticity, normality of residuals, and functional form misspecification. The absence of econometric violations confirms the statistical soundness of the estimated model.

All estimations and diagnostic procedures were carried out using EViews 12 software.

**Results**

Economic data are often not distributed in a general average. By their very nature, these data progress along a trend. This situation causes the data to move away from stationarity. In order to ensure that the data set used in the study is subjected to a sound

forecasting process, the degree of stationarity of the series should be determined first. The series in the data set are tested with the most widely used ADF and PP unit root tests. Optimal lag values were determined according to Schwarz information criterion for ADF and Newey West Bandwith for PP (Bektaş & Baykuş, 2020). Table 2 shows the unit root results.

Table 2. Augmented Dickey–Fuller Unit Root Test Result

I(0)			I(1)		
Variables	t-stat	p-value	Variables	t-stat	p-value
CO <sub>2</sub>	-0.2215	0.9255	CO <sub>2</sub>	-5.5193	0.0001
Forestry	0.8996	0.9942	Forestry	-4.9304	0.0004
Industrialization	0.4443	0.9817	Industrialization	-5.0376	0.0003
GDP	-2.3457	0.2471	GDP	-6.6987	0.0001
Energy	-0.9120	0.7708	Energy	-6.7522	0.0000
Population	-2.4295	0.1425	Population	-3.0179	0.1441

Table 3. Phillips–Perron Unit Root Test Result

I(0)			I(1)		
Variables	t-stat	p-value	Variables	t-stat	p-value
CO <sub>2</sub>	0.1826	0.9670	CO <sub>2</sub>	-7.2958	0.0000
Forestry	3.1547	1.0000	Forestry	-6.6120	0.0000
Industrialization	1.4518	0.9988	Industrialization	-5.3766	0.0001
GDP	-1.7438	0.1749	GDP	-4.8456	0.0005
Energy	-0.7378	0.8224	Energy	-6.7942	0.0000
Population	-2.5233	0.3155	Population	-2.8990	0.1769

The results of the ADF (Table 2) and Phillips-Perron (Table 3) unit root tests provide important insights into the stationarity levels of the series in the dataset. In the ADF test, the CO<sub>2</sub>, forestry, industrialization, energy, GDP and population series are non-stationary at level (I(0)) since the p-values for these series are above the 5% significance level. These findings suggest that the relevant series are non-stationary at their levels and must be differenced to be analyzed. When the first differences of the series were tested for stationarity, CO<sub>2</sub>, forestry, industrialization, GDP, and energy series became stationary at the 1% significance level. This indicates that these series can be classified as I(1), meaning that their first differences are stationary. However, the population series did not show stationarity even at its first difference. This finding suggests that the population series can be classified as I(2), meaning that the second difference must be taken to achieve

stationarity. Similarly, the Phillips-Perron test results align with the ADF test results.

From an econometric modelling perspective, the fact that the population series is I(2) prevents this variable from being directly included in the ARDL model. ARDL models are designed to include only I(0) and I(1) series. Since the population series must be differenced twice, it cannot be integrated into the ARDL model. Therefore, the population variable will be excluded from the model. On the other hand, the I(1) series (CO<sub>2</sub>, forestry, industrialization, and energy) can be used in the ARDL model, and their cointegration relationships can be tested. Given that these series are stationary at their first difference, long-term cointegration relationships can be examined.

Cointegration relationships between the series can be examined through tests such as those proposed by Engle and Granger (1987), Johansen (1988), and Johansen and Juselius (1990). However, these methods have certain

limitations. In the Engle and Granger method, if there are more than two variables, the presence of more than one cointegrating relationship can occur, making this method less preferred. In the Johansen and Johansen-Juselius methods, all variables must be stationary at their level values or stationary when differenced by the same order (Koçak, 2014). The ARDL bounds testing approach, developed and introduced to the literature by Pesaran et al. (2001), overcomes these limitations. The ARDL bounds test has several advantages over other cointegration tests. The first advantage is that the test can be applied regardless of whether the variables are stationary at I(0) or I(1). However, if any of

the series is I(2), the ARDL method cannot be applied. Thus, in this method, the requirement to determine the integration order of the series is eliminated. For this reason, the population variable, which is stationary at I(2), has been excluded from the equation. The second advantage is the ability to use the unrestricted error correction model (UECM) in this method, which generally yields better results than other tests. The third advantage is that it can provide reliable results in small and limited samples (Şahin & Gökdemir, 2016; Pamuk & Bektaş, 2014). To apply the ARDL bounds test, the UECM equation is used (Eq. 2).

$$\begin{aligned} \Delta CO_{2t} = & a_0 + a_{1t} + \sum_{i=1}^m a_{2i} \Delta CO_{2t-i} + \sum_{i=0}^m a_{3i} \Delta forestry_{t-i} + \sum_{i=0}^m a_{4i} \Delta industrilization_{t-i} \\ & + \sum_{i=0}^m a_{5i} \Delta GDP_{t-i} + \sum_{i=0}^m a_{6i} \Delta energy_{t-i} + a_7 CO_{2t-1} + a_8 forestry_{t-1} \\ & + a_9 industrilization_{t-1} + a_{10} GDP_{t-1} + a_{11} energy_{t-1} + \varepsilon_t \end{aligned} \quad (2)$$

In the UECM model, “m” represents the number of lags, while “t” denotes the trend variables. Within the ARDL bounds testing framework, the null hypothesis assumes the absence of a long-run relationship among the variables, which is tested by imposing joint restrictions on the lagged level terms in the model. The decision regarding cointegration is based on the comparison of the estimated F-statistic with the critical bounds reported by Pesaran et al. (2001). When the F-statistic exceeds the upper critical bound, the null hypothesis is rejected, indicating the presence

of a long-run equilibrium relationship; when it falls below the lower bound, cointegration is not supported.

If the calculated statistic lies between the lower and upper bounds, the test remains inconclusive. Upon confirmation of cointegration, the analysis proceeds with the estimation of the UECM. The error correction term captures the speed at which short-run deviations from the long-run equilibrium are corrected, reflecting the adjustment process following an exogenous shock (Narayan & Narayan, 2004; Alper, 2017).

Table 4. General results of ARDL model

Selected Model: ARDL (1, 0, 0, 1, 0)			
R-square	0.996231	Akaike info criterion	-5.221914
Adj. R-sq	0.993080	Schwarz info criterion	-4.032446
Log L	98.10679	Hannan – Quinn criter.	-4.858282
F-stat	162.4430	Durbin-Watson stat	1.978509
Prob (F)	0.000684		

In Table 4, the general equation of the ARDL model has been estimated. The optimal model is determined as ARDL (1, 0, 0, 1, 0). Additionally, the presence or absence of a long-term relationship between the variables has been analyzed according to this model. When examining the probability value of the

F-statistic of the general equation, it is understood that the model is statistically significant at the 1% significance level. The results of the bounds test and the long-term coefficient estimates are presented in Tables 5 and 6.

Table 5. Bound test results

Model	k	m	F	Signif.	I(0)	I(1)
(1,0,0,1,0)	4	4	8.606441*	1% 5% 10%	3.29 2.56 2.2	3.09 3.49 3.09

Note: k denotes the number of explanatory variables, m refers to the maximum lag length, and \* indicates statistical significance at the 1% level

The bounds testing results indicate that the estimated F-statistic exceeds the relevant critical values associated with both the lower and upper bounds. This outcome provides clear evidence of a stable long-run equilibrium relationship among the variables included in the model. The confirmation of

cointegration implies that the variables move together over time and converge toward a common long-term path. Following the identification of this long-run relationship, the analysis proceeds with the interpretation of the estimated long-run coefficients, which are reported in Table 6.

Table 6: Long-run relationships

Variables	Coefficient	Probability
<i>Forestry</i>	-1.984852	0.0162**
<i>Industrialization</i>	0.007691	0.0001***
<i>GDP</i>	0.020004	0.0318**
<i>Energy</i>	0.309341	0.0363**
<i>constant</i>	21.42002	0.1106

Note: \* for 10% significance level, \*\* for 5% significance level, \*\*\* for 1% significance level

The long-term coefficients of the ARDL model in Table 6 reveal the long-term relationships between the variables used in the model and their environmental impacts. The coefficient obtained for the forestry variable is -1.98, which is statistically significant at the 5% significance level. This result indicates that an increase in forest areas has a mitigating effect on environmental degradation. The negative sign of the coefficient can be associated with the expansion of forest areas through sustainable management and environmental protection activities, contributing to the preservation of ecological balance.

The industrialization variable has a positive coefficient and is found to be statistically significant at the 1% significance level. This result indicates that industrialization has a long-term, detrimental effect on environmental degradation. Industrialization is a factor that increases environmental burden, particularly through energy consumption and industrial production processes that exert pressure on natural resources.

The GDP variable also has a positive and significant coefficient. This suggests that

economic growth could have an adverse effect on environmental degradation. The relationship between economic growth and environmental pressures indicates that in developing countries, economic growth may threaten environmental sustainability.

Lastly, the energy variable has a positive coefficient and is statistically significant at the 5% level. This result indicates that energy consumption has a strong, positive effect on environmental degradation. In other words, increased energy consumption exacerbates environmental pressures and degradation. Energy production based on fossil fuel usage is linked to carbon emissions and other environmental harms.

Overall, these findings suggest that economic growth, industrialization, and energy consumption all have exacerbating effects on environmental degradation. However, forestry activities seem to play a counterbalancing role, mitigating environmental degradation.

Table 7. Johansen cointegration test

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob.
None	0.576846	76.71913	76.97277	0.0423
At most 1	0.439450	50.91854	54.07904	0.0630
At most 2	0.365203	33.55343	35.19275	0.0544
At most 3	0.310269	19.91993	20.26184	0.0357
At most 4	0.253637	8.776310	9.164546	0.0492

The Johansen cointegration test results in Table 7 show that there is a long-run equilibrium relationship between the variables in the model. This implies that the variables move together in the long run and exhibit a relationship consistent with the economic theoretical framework. The presence of cointegration confirms that the variables tend to converge towards an equilibrium over time and that this model

provides a reliable basis for long-run analysis. While these results support the long-run results found in the ARDL method, they are also critical for the development of long-run policy recommendations. Moreover, the cointegration relationship supports a structure in which short-run deviations can be handled by error correction models (ECM) and increases the methodological power of the study.

Table 8. Short-run error correction model

Variables	Coefficient	t-stat	Probability
CointEq(-1)	-0.562345	-7.899158	0.0000
<i>R-square</i>	0.796500	<i>Akaike info criterion</i>	-4.558588
<i>Adj. R-sq</i>	0.632586	<i>Schwarz info criterion</i>	-4.466072
<i>Log L</i>	72.65811	<i>Hannan – Quinn criter.</i>	-4.528430
<i>F-stat</i>	8.606441	<i>Durbin-Watson stat</i>	1.977651
<i>Prob (F)</i>	0.000000		

Table 8 presents the estimation values for the short-term error correction model. The error correction model shows how much of any shock or adverse situation that occurs in the short term will be corrected in the next period. For the model to be considered working correctly, the error correction coefficient must be negative, between zero and one, and statistically significant. As seen in Table 8, the error correction coefficient (CointEq(-1)) is statistically significant, negative, and falls between zero and one. This indicates that the error correction model is

functioning properly. According to the results in Table 8, any imbalance or deviation resulting from a shock can be corrected by 0.56 units in the next period, implying that equilibrium will be restored in the long term. After the ARDL estimates are made, several diagnostic (specification) tests must be performed to verify that the model works correctly and without error, and that there are no structural problems. The results of these specification tests are shown in Table 9.

Table 9. Specification Tests

Tests	Probability
Serial Correlation LM test (Breusch–Godfrey)	0.9319
Heteroscedasticity test (Breusch–Pagan–Godfrey)	0.7248
Jarque–Bera Normality test	0.4994
Ramsey Reset Test	0.6581

The diagnostic test results reported in Table 9 indicate that the estimated model satisfies the standard econometric assumptions. The Breusch-Godfrey LM test

yields a high p-value, suggesting the absence of serial correlation in the residuals. Similarly, the Breusch-Pagan-Godfrey test does not provide evidence of heteroscedasticity,

implying that the variance of the error terms remains constant across observations.

In addition, the Jarque-Bera test results support the assumption of normally distributed residuals, which is essential for the reliability of inference based on parametric estimators. The Ramsey RESET test further

confirms that the model is correctly specified, with no indication of omitted variables or functional form misspecification. Overall, the diagnostic outcomes confirm that the model is econometrically well behaved and that the estimated coefficients can be interpreted with confidence.

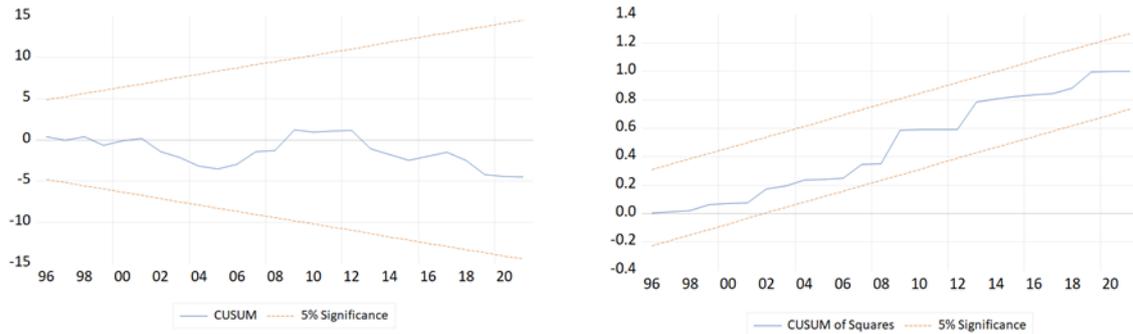


Figure 2. Cusum and Cusum of square results

Figure 2 presents the results of the CUSUM and CUSUM of Squares stability tests. In both cases, the test statistics remain within the 5% critical bounds throughout the sample period, indicating parameter stability and the absence of structural breaks. These results confirm that the estimated coefficients are stable over time and that the model does not exhibit time-varying instability, thereby supporting the robustness and reliability of the empirical findings.

### Discussion and Conclusion

This study examines the relationship between Türkiye's greenhouse gas emissions and variables such as forest areas, industrial production, energy consumption and economic growth over the period 1990-2021. The results of the analysis show that the expansion of forest areas contributes to environmental sustainability, offsetting environmental degradation as carbon sinks. However, industrialization, energy consumption and economic growth are found to have increasing effects on greenhouse gas emissions. These findings point to policy priorities that need to be considered in line with Türkiye's sustainable development goals.

The contribution of forest areas to environmental sustainability is widely emphasized in literature. In studies such as Pan et al. (2011) and Keenan et al. (2015), the

role of forest expansion in stabilizing GHG emissions is clearly stated. Similarly, in this study, the expansion of forest areas shows an offsetting effect in reducing GHG emissions. However, as stated in Magazzino et al. (2024), it is clear that sustainable forestry policies and afforestation practices should support this positive effect. Although the increase in forest assets in Türkiye has been partly realized through natural expansion, the contribution of sustainably planned forestry activities and policies to this process can be increased. The findings of the study suggest that the environmental pressures of industrialization and energy consumption may limit the positive impact of forest expansion efforts.

Industrialization and energy consumption are among the most important findings of the study, clearly demonstrating the negative impacts on environmental sustainability. The GHG emission-enhancing effects of industrial production are particularly associated with production processes in energy-intensive sectors. This finding is in line with other studies in the literature, such as Stern and Stern (2020), and highlights the impacts of industrialization on environmental sustainability in developing countries. Similarly, Magazzino et al. (2023) assessed the impacts of industrialization, land use and urbanization on GHG emissions and argued that these impacts can be mitigated through

sustainable policies. In the context of Türkiye, the findings of this study reveal the necessity of policies that ensure energy efficiency in industrial production processes and promote environmentally friendly technologies.

The effect of economic growth on greenhouse gas emissions, together with the findings of this study, is associated with the EKC hypothesis in literature. According to the EKC hypothesis, while economic growth increases environmental degradation in the initial stages, once a certain level of income is reached, the demand for environmental quality increases and emissions begin to decline (Grossman & Krueger, 1995). However, in developing countries such as Türkiye, managing the impacts of economic growth on environmental sustainability is complicated by increases in industrialization and energy consumption. In this context, Wang and Su (2020) emphasized that the relationship between economic growth and energy consumption should be supported by sustainable energy policies.

Energy consumption stands out as the strongest determinant of environmental degradation in this study. The increase in fossil fuel-based energy consumption significantly increases greenhouse gas emissions in Türkiye. This finding is in line with studies by Wang and Su (2020) and confirms that reducing the environmental impacts of energy consumption is critical. Magazzino (2016) revealed the strong impact of energy consumption on GHG emissions in the case of South Caucasus and Türkiye and emphasized that increasing renewable energy sources is an effective strategy to reduce GHG emissions. Promoting renewable energy sources and developing energy efficiency policies in Türkiye, in line with the results of this study, provides a critical roadmap for achieving sustainable development goals.

The policy implications derived from the empirical findings underscore the critical role of forest resources in Türkiye's climate mitigation strategy. In addition to protecting existing forest assets, expanding afforestation and reforestation efforts should be prioritized as proactive climate actions. Forests must not only be valued for their carbon sequestration potential, but also for their broader ecosystem services-ranging from biodiversity

conservation to water regulation-which together strengthen the resilience of ecological systems under pressure from economic growth.

Given the statistically significant mitigating effect of forest areas on GHG emissions, it is essential that forestry policies are integrated into Türkiye's broader climate strategy, particularly within the framework of its commitments under the Paris Agreement. Beyond national targets, regional policy differentiation is necessary: the ecological capacity, industrial concentration, and forest structure of each region vary significantly, requiring place-based approaches to forest governance and emission management.

Moreover, the findings that industrialization, energy consumption, and GDP growth increase GHG emissions suggest an urgent need for structural transformation in the energy and production sectors. Aligning industrial policies with environmental objectives, strengthening energy efficiency regulations, and encouraging green innovation will be necessary to decouple economic growth from environmental degradation. In particular, renewable energy policies should be expanded to include large-scale deployment of low-carbon technologies such as wind and solar, supported by green financing mechanisms and public-private partnerships.

The empirical confirmation of an Environmental Kuznets Curve (EKC) dynamic also implies that Türkiye has not yet reached the income threshold where environmental improvements naturally emerge. This indicates that environmental policy cannot rely solely on income-driven transformations, but must be supported by deliberate, forward-looking interventions. Policies targeting emission reduction, forest preservation, and clean energy deployment must therefore be coordinated across institutional levels and sectors.

This study offers evidence-based insights for designing integrated environmental and development strategies. Protecting and expanding forest resources, decarbonizing energy systems, and mainstreaming sustainability across industrial planning are imperative for achieving long-term climate targets. The policy agenda should be grounded

not only in national goals but also in the spatial and structural realities of Türkiye's diverse regions.

In conclusion, protecting and expanding forest resources is critical to Türkiye's efforts to reduce GHG emissions. Forestry policies play a balancing role against environmental pressures such as industrial production and energy consumption. However, the success of these policies depends on the implementation of sustainable industrial and energy policies in line with sustainable development goals. For Türkiye to fulfil its GHG emission reduction commitments under the Paris Climate Agreement, forest management policies will need to be strengthened, and energy consumption will need to be made more sustainable. This study provides important findings for sustainable forest management and environmental sustainability policies in Türkiye and makes a significant contribution to the literature.

The contributions of this study to the literature can be evaluated under three main headings. First, the study makes a theoretical contribution by relating the EKC hypothesis to the forest area and energy consumption variables in the Turkish context. Second, it offers a methodologically original approach by analyzing short and long run relationships by using ARDL and Johansen cointegration tests together. Third, it distinguishes the study from other studies in the literature by providing policy recommendations for Türkiye's commitments under the Paris Climate Agreement. These findings provide guidance to national and international policymakers in line with sustainable development goals.

The study has some limitations. Since the data set is based on annual data, short-term fluctuations and seasonal effects could not be considered. Analyses using more frequent data (e.g. quarterly) may provide more precise results. Moreover, the study focuses only on macroeconomic factors; micro-level influences such as local-level forest policies, technological developments and energy efficiency policies are not considered. Future studies can develop more specific policy recommendations by focusing on forest resources, industrial structures and energy consumption patterns in different regions of

Türkiye. In addition, assessing forests in terms of other ecosystem services, such as biodiversity and water cycle, can provide a more holistic approach to climate change mitigation policies. Finally, addressing the long-term environmental impacts of energy policies together with the utilization rate of renewable energy sources and energy efficiency policies stands out as a critical research area in terms of sustainable development goals.

### **Ethics Committee Approval**

N/A

### **Peer-review**

Externally peer-reviewed.

### **Author Contributions**

Conceptualization: S.Ş.; Material and Methodology: S.Ş.; Visualization: S.Ş.; Writing-Original Draft: S.Ş.; Writing-review & Editing: S.Ş. All authors have read and agreed to the published version of the manuscript.

### **Conflict of Interest**

The authors declare that they have no conflict of interest.

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