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The Impacts of Agricultural Energy Use and Cultivable Area on the Cropland Footprint in Light of the EKC Model: Evidence from the Top Ten Most Successful Countries in Agriculture

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ABSTRACT
This study examines the impact of agricultural production on environmental degradation. Specifically, it tests the agricultural energy use and arable land variables, along with the agricultural Environmental Kuznets Curve (EKC) hypothesis, in the ten most agriculturally successful countries: Australia, Canada, Mexico, Türkiye, United States, Argentina, Brazil, China, India, and Russia. Using annual data from 1992 to 2020, econometric analyses were conducted through Bootstrap ARDL (B-ARDL) and Bootstrap Toda-Yamamoto causality methods. The results only validate the agricultural EKC hypothesis in Türkiye among the countries in the sample. This finding highlights Türkiye's commitment to agricultural structural transformations. Recent developments and support in Türkiye's agricultural sector align with the study's findings. Policy recommendations focused on how these developments could threaten food security.

Keywords: Cropland, Agricultural energy use, Cultivable agricultural area, B-ARDL, Agricultural EKC

1. Introduction

Global climate change severely threatens the environment and food security caused by greenhouse gases. Agriculture is closely associated with greenhouse gas emissions and plays a vital role in environmental degradation as a sector particularly affected by climate change (Raihan et al. 2023). Climate change harms agricultural productivity and directly jeopardizes food security (Zhang et al. 2017). In addition, the agricultural sector is a major contributor to climate change, accounting for a large share of anthropogenic greenhouse gas emissions (Tigchelaar et al. 2018; Raihan & Tuspekova 2022). While the global population is expected to reach 9.1 billion by 2050, food production needs to increase by 70 percent to meet this increase. This will lead to a 30 percent increase in agricultural GHG emissions (Toor et al. 2020; Sapkota et al. 2021). Analyzing emissions from agriculture is critical for reducing GHG emissions and managing food security challenges. Various studies emphasize the importance of analyzing emissions from agricultural energy use and crop production in determining emission mitigation strategies (Zhang et al. 2017). These studies examine the agricultural sector's contribution to climate change and global warming and provide guidance on reducing emissions.

Agricultural production causes many environmental problems, from climate change to water pollution and biodiversity loss. Although agricultural activities have negative impacts on freshwater resources and soil, they also have important benefits, such as providing food, maintaining ecosystem services, and conserving biodiversity (Rega et al. 2019). Increasing population and urbanization put pressure on food production capacity by maintaining soil fertility, and increasing food demand worldwide leads to the expansion of agricultural areas and decreasing soil sustainability (Hafeez et al. 2020). In countries rich in biodiversity, the conservation of natural assets such as species diversity, vegetation, and forests is particularly important, as these areas are vital for the health of terrestrial ecosystems (Alvarado et al. 2021).

Intensive agricultural activities require extensive land use, resulting in a growing EFP and environmental degradation (Olanipekun et al. 2019). Agricultural processes involve energy-intensive activities, from fertilizer and pesticide production to irrigation, harvesting, and food processing. The intensive use of fossil fuels in these processes increases greenhouse gas emissions

and accelerates global warming (Liu et al. 2017). The top 10 countries in agriculture worldwide (Australia, Canada, Mexico, Türkiye, USA, Argentina, Brazil, China, India, Russia, Argentina, Brazil, China, India Russia) are major producers of agricultural products (Figure 1). These countries provide about 60 percent of the world wheat production between 2000 and 2020 (World Economic Forum 2022).

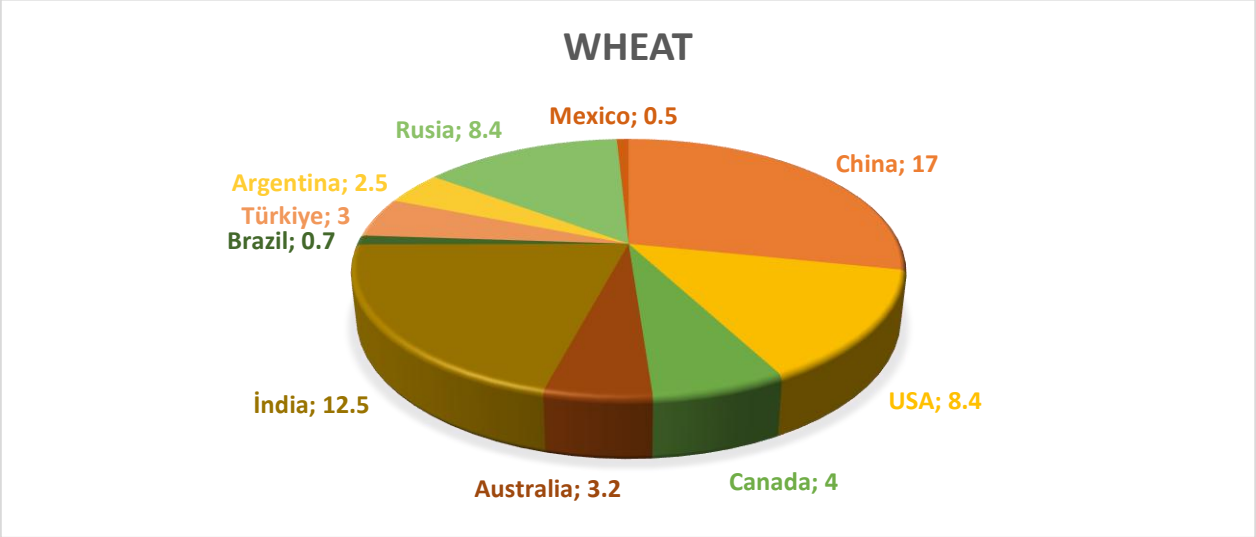


Figure 1- Wheat Production of the Top 10 Most Successful Countries in the World between 2000 and 2020
Source: (World Economic Forum 2022), (Note): Figure created by the authors

In 2020, world fruit production exceeded 887 million tonnes (Figure 2), with China, India, Brazil, Türkiye, and the United States alone accounting for about 450 million tonnes (World Population Review, 2024).

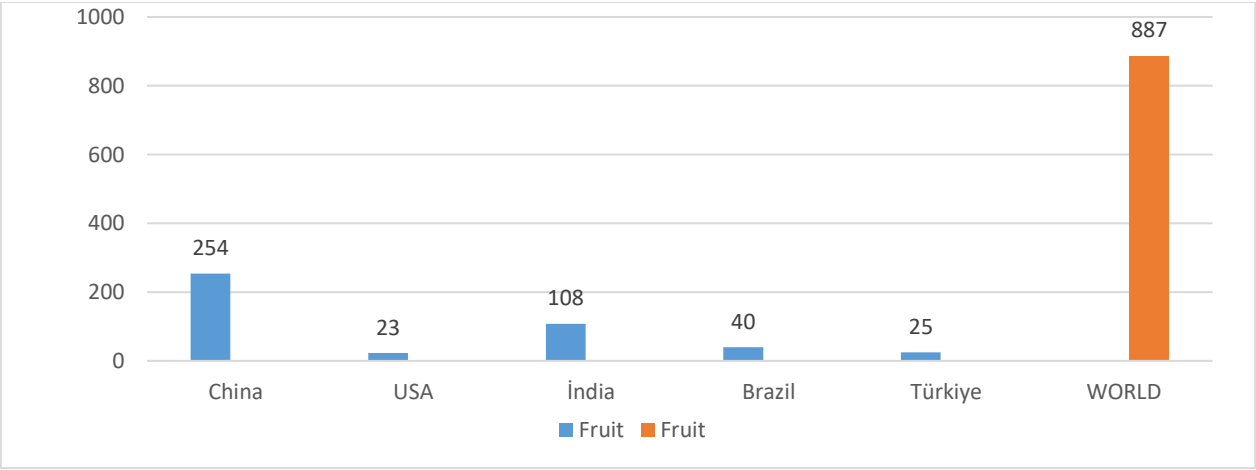


Figure-2 Share of the Amount of Fruit Produced by China, Brazil, India, Türkiye, and the USA in 2020 in the Total Amount of Fruit (Million Tons) Source: (World Population Review 2024), (Note): The graph shows worldwide data on the right and country-based data on the left. The figure was created by the authors

From 2000 to 2020, agricultural energy use varied significantly across countries, reflecting agricultural expansion, mechanization, and efficiency trends. In Australia, energy use rose from 69,582 thousand tonnes of oil equivalent in 2000 to 78,735 thousand tonnes in 2020, marking a 13% increase. This steady rise likely indicates greater mechanization and an expansion of agricultural activities. Canada saw a slight increase, from 181,516 thousand tonnes in 2000 to 185,269 thousand tonnes in 2020 (a 2% rise), suggesting stable agricultural practices and possible improvements in energy efficiency. Mexico's energy use increased by around 7%, from 95,274 thousand tonnes in 2000 to 102,031 thousand tonnes in 2020, reflecting gradual growth in agricultural activities to meet domestic and export demand. In Türkiye, energy use surged from 57,840 thousand tonnes in 2000 to 107,572 thousand tonnes in 2020, an 86% increase. This substantial growth indicates agricultural expansion or a shift toward more energy-intensive practices. The United States saw a slight decrease in agricultural energy use, dropping from 1,546,276 thousand tonnes in 2000 to 1,457,978 thousand tonnes in 2020, a 6% reduction. This decrease could be attributed to improvements in energy efficiency and a move toward more sustainable agricultural practices (OECD FAO 2023).

Argentina's energy use grew from 42,583 thousand tonnes in 2000 to 51,361 thousand tonnes in 2020, a 21% increase, reflecting its expanding role as a global agricultural exporter, particularly in commodities like soybeans and corn. Brazil showed a 45% increase, with energy use rising from 153,865 thousand tonnes in 2000 to 223,282 thousand tonnes in 2020, likely driven by its growth as an agricultural powerhouse, especially in livestock and biofuel production. China and India exhibited the most dramatic increases, with China's energy use nearly tripling from 781,192 thousand tonnes in 2000 to 2,179,869 thousand tonnes in 2020 (a 179% increase). This growth reflects modernization and intensification in agriculture to support China's large population. India's agricultural energy use more than doubled, rising from 290,033 thousand tonnes in 2000 to 596,270 thousand tonnes in 2020, a 106% increase, likely driven by expanding agricultural production and increased mechanization. In Russia, energy use rose by 22%, from 417,887 thousand tonnes in 2000 to 509,439 thousand tonnes in 2020, possibly due to renewed agricultural productivity and a focus on food security (OECD 2023).

While developed countries like the United States and Canada leaned toward stable or declining energy use, suggesting efficiency gains and sustainable practices, emerging economies such as China, India, Türkiye, and Brazil demonstrated substantial increases. This growth was likely driven by expanding agricultural demands, modernization, and the need to support growing populations and export markets.

As As a result of agricultural activities, almost one-fifth of annual CO2 emissions originate from the agricultural sector, making it the second largest CO2 producer (Raihan et al. 2023). It is emphasized that agricultural wastes should be systematically and sustainably managed, recycled, and transformed into value-added products to reduce environmental impacts (Srivastava et al. 2023). Countries commit to reducing CO2 emissions while maintaining economic development (Ridzuan et al. 2020). In this context, the Environmental Kuznets Hypothesis sheds light on the relationship between economic growth and environmental quality. Economic growth pollutes the environment, but it suggests that at some point in economic development, environmental damage can be reduced with increasing country income (Apergis 2016; Aydin et al. 2023).

Although there is no consensus on the various factors causing the increase in CO_2 emissions, the EKC provides a framework for the development and detailed examination of the basic EKC model by integrating the potential determinants of these emissions into the growth-environment relationship (Pata 2018). Studies show that factors such as globalization, the quality of institutional structures, technological innovation, urbanization, and the use of renewable energy play an important role in the analysis of the relationship between economic development and environmental degradation. This research tests how the cultivable agricultural areas and agricultural energy use of the top 10 countries that are pioneers in the agricultural sector in the world affect the changes in environmental quality with the help of the EKC model. It is expected to contribute to the literature in various aspects. (i) First of all, the model discussed in this study is an innovation in the literature. (ii) It is aimed to develop policy recommendations on how factors such as cultivable agricultural areas and agricultural energy consumption can be evaluated together with economic growth. (iii) While existing literature mostly focuses on CO2 and EFP, this study directly considered soil and water pollution, which are vital for a sustainable environment. Due to the subject of the study and the variables taken into account, cropland was used as an indicator of environmental pollution to obtain effective results. (iv) The studies reviewed in the literature are conducted either on a single-country basis or for specific groups of countries. Our study, however, originates from considering the top 10 most successful countries in agriculture, which account for most agricultural activities worldwide. Motivated by this, the aim is to identify the impact of these countries, which play a significant role in global agriculture, on the environment caused by agricultural activities and to develop policy recommendations. (v) Another issue that makes our study different from other studies is the analysis method. B-ARDL (Augmented-ARDL) used in econometrics technique has two main differences. First, in addition to the hypothesis in the traditional ARDL bounds test, two additional hypotheses are put forward, and three test statistics are calculated. Second, it derives the critical values of three different test statistics by bootstrapping. This increases the reliability of the study's empirical findings.

The literature on the subject is given in detail under the subheadings in Table 1. At this point, according to the authors' perspectives, the indicators they use in their studies, factors such as the time interval of the data sets and the econometric method they apply in their studies, almost all dimensions of the relationship between agriculture and the environment are presented. Under these headings, the changes caused by agricultural activities, energy used in agriculture, and economic growth on the "Environmental Quality" are comprehensively discussed.

Table 1- Literature

Author(s)	*Countries*	*Period*	*Methods*	*Results*
Agriculture and Environmental Quality				
Ramzan et al. (2024)	China	1990Q1-2019Q4	QARDL	Lowers CO_2 and EFP
Bekun (2024)	South Africa	1975-2020	ARDL	Increases CO_2
Alam et al. (2023)	India	1990Q1-2018Q4	BARDL	Increases CO_2
Raihan (2023)	Vietnam	1984-2020	ARDL-VECM	Lowers CO_2
Karimi Alavijeh et al. (2023)	15 Developing Countries	2004- 2020	Quantile Regression	Increases CO_2
Selvanathan et al. (2023)	24 OECD countries	1990–2018	Sys-GMM	Increases CO_2
Shah et al. (2023)	Four ASEAN Countries	1990-2019	CCEMG-AMG	Increases CO_2
Raihan et al. (2022)	Malesia	1990-2019	ARDL	Increases CO_2
Pata (2021)	BRIC	1990-2016	FADL	Increases CO_2
Yurtkuran (2021)	Türkiye	1970-2017	ARDL	Increases CO_2
Aydoğan & Vardar (2020)	E-7	1990-2014	Granger Causality	Lowers CO_2
Energy Used in Agriculture and Environmental Quality				
Perone (2024)	27 OECD Countries	1965-2017	ARDL	Lowers CO_2
Raihan (2023)	Vietnam	1984-2020	ARDL-VECM	Increases CO_2
Saidmamatov et al. (2023)	five countries of Central Asia	1992-2020	ARDL	Increases CO_2
Saray et al. (2022)	Iran	2017-2019	WEFNI-MILP-LP	Increases CO_2
Phiri et al. (2021)	Zambia	1975-2014	ARDL	Increases CO_2
Chandio et al. (2020)	China	1990-2016	ARDL	Lowers CO_2
Ridzuan et al. (2020)	Malesia	1978-2016	ARDL	Lowers CO_2
Pakrooh et al. (2020)	Iran	2001-2016	Theil index and the Kaya factors	Mixed Result
Li et al. (2016)	European Union	1995-2009	Shapley/Sun index	Lowers CO_2
Economic Growth and Environmental Quality				
Nguyen (2024)	Southeast Asian countries	1990-2019	ARDL	Lowers CO_2
Alakbarov et al. (2024)	G-20	1992- 2014	ARDL	Increases CO_2
Ahmad et al. (2023)	G-11	2000- 2018	CS-ARDL	Lowers EFP
Farooq et al. (2023)	6 Gulf Cooperation Council Countries	1996–2019	FMOLS	Increases CO_2
Shafiq et al. (2021)	Pakistan	1985-2018	DARDL	Increases CO_2
Rahman &Vu (2020)	Australia, Canada	1960–2015	ARDL	Increases CO_2
Ozcan et al. (2020)	OECD	2000-2014	PVAR-GMM	Increases CO_2 and EFP
Testing Agricultural Land, Energy Consumption Used in Agriculture and Economic Growth with the EKC Hypothesis				
Trofimov (2024)	143 Countries	1990-2019	GMM	EKC Valid
Selvanathan et al. (2023)	24 OECD countries	1990–2018	Sys-GMM	EKC Valid
Koshta et al. (2021)	Selected Emerging Economies	1990-2014	DOLS-FMOLS	EKC Valid
Ridzuan et al. (2020)	Malesia	1978-2016	ARDL	EKC Valid
Gokmenoglu &Taspinar (2018)	Pakistan	1971–2014	FMOLS	EKC Valid

A comprehensive review of the existing literature highlights the complex relationship between arable land, energy use in agriculture, economic growth, and environmental quality. Agricultural land and energy use have dual roles as contributors to CO_2 emissions and potential mitigators through their sequestration capabilities. However, there are important gaps in the literature that deserve further investigation. First, most studies primarily focus on CO_2 emissions as a single indicator of environmental impact, ignoring other critical aspects such as soil degradation and water pollution. For example, Alam et al. (2023) and Karimi Alavijeh et al. (2023) analyze agricultural CO_2 emissions but neglect the broader environmental impacts of land-use changes. This study addresses this gap by including arable land footprint as a more holistic measure of environmental impact, reflecting the nuanced effects of agricultural practices on soil and ecosystem health. Second, the geographic scope of existing research is often limited to homogeneous country groups such as OECD or BRIC countries, and few studies examine diverse economic and agricultural contexts. Selvanathan et al. (2023) and Pata (2021) primarily investigate developed or rapidly industrializing countries and do not make detailed comparisons across different development stages. This study aims to provide a unique perspective on the role of agricultural practices in different economic contexts by examining the ten most successful agricultural countries in the world and to fill a critical gap in comparative analysis. Third, while the Environmental Kuznets Curve (EKC) hypothesis has been extensively tested in the industrial and energy sectors, its application in agriculture has not been sufficiently studied. Studies such as Ridzuan et al. (2020) and Yurtkuran (2021) validate the EKC in specific sectors but provide limited insights into its relationship with agricultural energy use and land dynamics. This study pioneers the application of the EKC model to agriculture, testing its validity in ten agriculturally important countries and highlighting the need for specific agricultural sustainability policies.

Methodologically, existing studies mostly rely on traditional econometric models such as ARDL and VECM, which often fail to capture the complexities of long-term dynamics in heterogeneous datasets. For example, Shah et al. (2023) and Alam et al. (2023) use these traditional approaches to provide limited insights into causality and cointegration in various cases. By using advanced techniques such as Bootstrap ARDL and Bootstrap Toda-Yamamoto causality tests, this study provides a more robust and reliable framework for analyzing agricultural impacts. It aims to establish a methodological benchmark for future research. Finally, this study contributes to the literature by providing concrete, agriculture-specific policy recommendations such as the adoption of renewable energy technologies, promotion of sustainable farming practices, and strategic land use planning; addresses gaps in the literature, and provides a detailed understanding of the interaction between agricultural energy use, land dynamics, and environmental sustainability. The findings from the study aim not only to enrich the theoretical discourse but also to provide practical implications for policymakers who aim to balance economic growth with environmental protection.

2. Model and Data

In this study, which investigates the functioning of the environmental Kuznets curve for the 10 most successful countries in agriculture (Argentina, Australia, Brazil, Canada, China, India, Mexico, Russia, Türkiye, US), the relationships between variables are modeled as shown in Equation 1.

$$lcropf_t = \beta_0 + \beta_1 lgdp_t - \beta_2 lgdp_t^2 + \beta_3 lagren_t + \beta_4 lfarmland_t + u_t \quad (1)$$

In Equation 1, $lcropf_t$ is the cropland footprint, $lgdp_t$and $lgdp_t^2$ is the gross domestic product per capita and its square, $lagren_t$ and $lfarmland_t$ represent total energy used in agriculture and the total cultivable area, respectively. The indis "t" indicates that the variables are time series and the period analyzed is 1992-2020. u_t is the error term of the model. Data on variables were obtained from the OECD. Stat, Global Footprint Network, and Word Bank database. The β is in the model are the coefficients of the constant and other variables. In particular, while the expected sign of the coefficient β_1 is positive, the expected sign of the coefficient β_2 is negative. In countries where this is the case, the "EKC " is valid.

The main objective of our study is to analyze the effects of agricultural energy use and arable land on the cropland footprint from an environmental sustainability perspective and to test whether this relationship has an inverted U-shaped structure. The EKC model is a widely used and accepted tool in analyzing such relationships. Especially in examining the dynamics between economic growth and environmental pressures, the EKC hypothesis closely overlaps with the framework of our study in that it predicts that environmental impacts will decrease at certain income levels. Other econometric models that can be alternatives to the EKC model are not fully suitable for the purpose and assumptions of our study. Although fixed-random effect models, among the alternative models, are suitable for analyzing the general relationship, they cannot directly test a specific inverted-U-shaped relationship. Such models do not consider the nonlinear structure that forms the basis of EKC and cannot provide sufficient depth for testing the hypothesis. Dynamic models are generally used to address the problem of endogeneity. However, in our study, the main priority was to test the short- and long-term inverted-U relationship rather than determining causality between variables. In addition, GMM requires large sample sizes and may create efficiency problems in smaller data sets, such as the top 10 countries selected in our study. Since spatial dependency is not the focus of our study, spatial econometric models will not contribute to our research questions. The reason for choosing the EKC model in this study is both its conformity to the nature of the theoretical framework and the advantages of its assumptions in addressing our research questions. Alternative models are insufficient to achieve the main objectives of our analysis. However, alternative methods can be evaluated in future studies to test larger data sets or different assumptions.

3. Methodology

In order to estimate the relationships in Equation 1, the analysis follows a four-stage process. Firstly, the existence of significant long-run (cointegration) relationships in the showed model is investigated using the Bootstrap ARDL (B-ARDL) method suggested by Mc-Nown, Sam and Goh (2018) and Sam, Mc-Nown and Goh (2019). Second, the long-run and short-run coefficients and the error correction model are estimated in a cointegration relationship. Third, the Granger causality test based on the error correction model tests the existence of causal relationships from the independent variables in Equation 1 to the dependent variable. Lastly, in countries with no cointegration relationship, causality relationships from independent variables to dependent variables is investigated with the help of the bootstrap Toda-Yamamoto causality test developed by Hacker and Hatemi-j (2012). Appendix 2 describes these techniques step by step. There are also explanations as to why these techniques are used.

4. Findings and Discussions

In this part of the study, the findings of the analyses obtained for each country using the techniques in the methodology section are presented. Firstly, Table 2 presents the B-ARDL test results for 10 countries. Türkiye is the only country where the cointegration relationship is significant, according to the B-ARDL analysis. No significant cointegration relationship is found in other countries. Only in Türkiye, *lgdp, lgdp2, lagren and lfarmland* together significantly affect *lcropf* in the long run.

Table 2- Bootstrap ARDL Cointegration Test Results

Country	*B-ARDL*	$F_{overall}$	$F_{overall_cv\ (\%5)}$	*t*	*t_cv (%5)*	F_{ind}	$F_{ind_cv\ (\%5)}$	*Case*	*Results*
Argentina	B-ARDL (2,2,2,2,2)	1.734	5.520	-1.186	-3.370	1.468	4.990	3	No Cointegration
Australia	B-ARDL (2,3,1,1,1)	6.523*	6.230	-5.467*	-3.170	4.181	5.640	5	Degenerate Case 2
Brazil	B-ARDL (2,1,1,3,1)	4.343	6.850	-4.473*	-2.870	2.055	4.470	5	No Cointegration
Canada	B-ARDL (2,1,1,2,1)	8.846*	5.460	-6.032*	-3.820	3.384	4.270	3	Degenerate Case 2
China	B-ARDL (2,2,2,2,2)	5.897	7.990	-4.643*	-2.170	6.109*	4.140	5	No Cointegration
India	B-ARDL (2,2,2,2,2)	2.050	6.310	-1.630	-1.880	2.502	7.220	5	No Cointegration
Mexico	B-ARDL (2,1,1,1,1)	2.874	5.220	-0.974	-2.500	3.377	3.650	5	No Cointegration
Russia	B-ARDL (2,1,1,2,1)	3.392	5.960	-3.904	-4.440	2.137	4.750	3	No Cointegration
Türkiye	**B-ARDL (2,2,2,1,1)**	**12.510***	**9.160**	**-6.200***	**-4.200**	**8.652***	**4.850**	**3**	**Cointegration**
US	B-ARDL (2,1,2,2,1)	5.509	6.990	-3.261	-3.350	4.555	5.420	3	No Cointegration

*; Indicates that the significance of the test statistic is greater than the 5% bootstrap critical value.
Notes: The optimal lags values are determined by BIC. Critical values are determined by 2000 Bootstrap samples. Case 5 model is estimated if a significant deterministic trend is significant in the dependent variables. If the trend is not significant and only the constant is significant, the Case 3 model is estimated.

Table 3 presents the long and short run coefficients and error correction coefficient estimates. The estimation results show that the independent variables have a significant effect on *lcropf* in the long run. The significance of lgdp and lgdp2 indicates the validity of the "agricultural environmental kuznet curve" in Türkiye. The threshold value for Türkiye is calculated as= $-\frac{10.833}{2\,(-0.580)}$ =9,34. When the anti-logarithm of this value is taken, the point where GDP per capita in Türkiye reaches 11384,415 dollars is determined as the threshold value.

Also, increases in *lagren* and *lfarmland* variables decrease the agricultural footprint by 0.419% and 0.383%, respectively, in the long run. When the short-run coefficients are analyzed, it is observed that *lgdp* is positive and *lgdp2* is negative and significant in the short run. The other two variables have no significant effect on the agricultural footprint in the short run. The fact that the error correction coefficient is -0.874 and significant indicates that the short-run shocks are eliminated and the series are balanced again in the long-run.

Table 3- Long and short-run estimates for Türkiye[1]

Long-run coefficients		
Variable	**Coef.**	**Prob.**
lgdp_tur	10.833*	0.000
lgdp2_tur	-0.580*	0.000
lagren_tur	-0.419**	0.012
lfarmland_tur	-0.383**	0.039
Short-run coefficients and error correction model		
Variable	**Coef.**	**Prob.**
Δlcropf_tur (-1)	-0.717*	0.000
Δlgdp_tur	13.697***	0.063
Δlgdp_tur(-1)	11.881***	0.089
Δlgdp2_tur	-0.755***	0.066
Δlgdp2_tur(-1)	-0.651***	0.089
Δlagren_tur	0.191	0.461
Δlfarmland_tur	0.122	0.799
C	-0.011	0.299
ect(-1)	-0.874**	0.043

*,**,*** respectively indicate significance at 1%, 5% and 10%.

As can be seen from the B-ARDL results, there is a cointegration relationship only in Türkiye. Therefore, Granger causality analysis based on the error correction model is applied only for Türkiye. When the findings in Table 4 are reviewed, it is seen that there is a short-run causality relationship from *lgdp* and $lgdp^2$ to *lcropf*. In the short run, there is no causality from either lagren or lfarmland to lcropf. In the long run, there is causality between the three variables and lcropf. The existence of a causality relationship indicates that there are dynamic relationships between these variables in Türkiye.

[1] Descriptive statistics of the model assumptions are presented in Appendix 1.

Table 4- The results of Granger Causality Based on ECM for Türkiye

Causality Periods:	*Short-run*					*Long-run*
Dependent Variable	*Δlcropf*	*Δlgdp*	*Δlgdp2*	*Δlagren*	*Δlfarmland*	*ect(-1)*
Δlcropf	-	11.718* (0.002)	11.389* (0.003)	0.588 (0.442)	0.107 (0.747)	5.080 (0.0362)

*; indicates causality at 5% significance level. Values in parentheses are probability values

Under the assumption that there may be a causality relationship in other 9 countries even if there is no cointegration relationship, it was decided to test causality relationships with the bootstrap Toda-Yamamoto causality test developed by Hacker and Hatemi- j (2012). Table 5 shows the Bootstrap Toda-Yamamoto causality findings for the other 9 countries. As a result of the analysis, there is no significant causality relationship in each of the 9 countries because the calculated test statistic values are smaller than the bootstrap critical values.

Table 5- Bootstrap Toda-Yamamoto Causality Test Results for Other Countries

Causality / Country	*Argentina [1+1]*[a]	*Australia [1+1]*	*Brazil [1+1]*	*Canada [1+1]*	*China [3+1]*	*India [1+1]*	*Mexico [1+1]*	*Russia [3+1]*	*US [1+1]*
lgdp ⇏ lcropf	0.063 (4.776)[b]	0.215 (4.684)	0.396 (4.696)	0.090 (4.481)	1.597 (15.645)	1.475 (4.643)	1.848 (4.580)	4.184 (20.380)	0.359 (4.459)
lgdp2 ⇏ lcropf	0.069 (4.757)	0.223 (4.611)	0.375 (4.527)	0.081 (4.451)	1.658 (15.606)	1.464 (4.634)	1.859 (4.504)	4.460 (20.628)	0.369 (4.334)
lagren ⇏ lcropf	0.093 (4.490)	0.163 (4.419)	0.232 (4.387)	0.834 (4.474)	4.846 (15.792)	1.327 (4.481)	1.490 (4.348)	1.664 (19.343)	0.369 (4.401)
lfarmland ⇏ lcropf	2.883 (4.567)	0.965 (4.712)	1.375 (4.415)	0.001 (4.379)	5.512 (14.620)	0.261 (4.492)	0.241 (4.492)	2.441 (19.110)	1.140 (4.427)

[$p+d_{max}$], (%5 Bootstrap Critical Values), bootstrap sample: 10000, Hatemi-J Information Criterion (HJC) used

Agricultural EKC studies are very limited in the literature. When these studies are analyzed, it is seen that the puzzle of agriculture - growth and pollution is not clearly solved. In addition to the theoretical background of the EKC models estimated in the existing literature, the accuracy of the estimation methods is also debated. While the period intervals analyzed and sample choices cause differences in the results, the econometric estimation methods' sensitivities also cause differences. Bootstrap-based analyses are preferred in this study to overcome these problems. In addition, it aims to ensure the significance of the study group with a sample of 10 countries in the best position in agriculture. Jebli and Youssef (2015) showed that agricultural EKC is not valid in their study, which is specific to Tunisia. Another study that reached a similar conclusion is the study conducted by Liu et al. (2017) for 4 selected ASEAN (Indonesia, Malaysia, the Philippines, Thailand) countries. Empirical analyses conducted with data for 1970-2013 showed that the EKC hypothesis, included in agricultural value added, is invalid. Liu et al. (2021) tested the EKC hypothesis for selected provinces of China based on annual data for 1978-2017. The evidence showed that the EKC in Hubei province was N-shaped, which was unexpected, and that the classical EKC could not be verified. These results are in line with the findings obtained in the study. EKC could not be verified in the countries included in the sample except Türkiye.

The findings obtained for Türkiye are similar to those reported by Selcuk et al. (2021), Trofimov (2024), and Selvanathan et al. (2023). The coefficients of agricultural energy use and cultivable land variables are statistically significant and negative. We can state that changes in agricultural energy use and cultivable land in Türkiye reduce the cropland footprint. This finding is in line with Ramzan et al. (2024), Raihan (2023), Aydoğan and Vardar (2020), Perone (2024), and Ridzuan et al. (2020). This result for Türkiye allowed us to analyze the causality relationship between the variables using Granger Causality Based on ECM. As a result of the analysis, it was determined that there is a causality between GDP and GDP2 and the cropland footprint. Bootstrap Toda-Yamamoto Causality tests for the countries where the cointegration relationship was not found showed that there is no causality relationship between the variables in these countries.

The study findings for Türkiye reveal that agricultural practices and processes in Türkiye reduce the cropland footprint. Two different situations can justify this situation. The positive reflections of environmental practices in the agricultural sector in Türkiye include the decrease in land use and energy use with the shrinkage of the agricultural sector. The share of the agriculture sector in GDP in Türkiye has been on a downward trend over the years. In 2020, the share of the agricultural sector in GDP was 7.0%, while in 2021 and 2022, these shares decreased to 6.1% and 5.8%, respectively (TurkStat 2022). On the other hand, when the per capita agricultural area data in Türkiye are analyzed, we see that the amount of agricultural area has decreased despite the increase in population. As of 1990-2018, despite the 45.2% increase in Türkiye's population, the per capita agricultural area decreased by 39.3% in the same period. From 0.76 hectares (ha) in 1990, the total amount of agricultural land per capita decreased to 0.45 ha in 2021. As of 2022, when the total cultivable area (23,845 thousand ha) is taken into account, there is 0.28 ha per capita (TurkStat, Ministry of Agriculture and Forestry, 2023). Despite these declines, Türkiye's agricultural area per capita is above world (0.18 ha) and EU (0.22) averages (Word Bank Indicators, 2023). The picture of agricultural energy use in Türkiye is not positive. Inflation in energy inputs can be seen by comparing the figures for 2022 with 2015. There were price increases of 632% for coal, 531% for electricity, and 435% for diesel fuel (Ağır et al. 2023). This situation has led to a decrease in agricultural energy use along with agricultural land use. The finding that cultivable land and agricultural energy use reduce the cropland footprint for Türkiye is a possible conclusion when looking at the overall picture. On the other hand, it is also a fact that there have been positive developments in Türkiye with the good agriculture and organic agriculture practices that have been implemented recently. In particular, the strategic planning of support for the agricultural sector in Türkiye within the framework

of the Basin-Based Support Model is an important practice. There is a crop pattern map application for 21 products that are of strategic importance and important in terms of production (BAT Agriculture Sector Report 2023). These supports are provided within the framework of sustainable and good agricultural practices, and food safety and environmental sustainability are also taken into consideration. This practice supports SDG-2, SDG-8, and SDG-13, the development goals set by the United Nations. Türkiye is taking steps in line with the Paris Climate Agreement and the European Green Deal. The 2019-2023 Strategic Plan of the Ministry of Agriculture and Forestry is designed in line with these goals. Good agricultural practices have been implemented by prioritizing food security and sustainable agriculture. Good agricultural practices are practices that do not include practices harmful to human health and prioritize environmentalism and welfare. These practices are also forms of agricultural production subject to inspection. Good agricultural practices have been implemented in 63 provinces for products such as olives, pistachios, citrus fruits, hazelnuts, and potatoes, whose production creates added value. Although the share of organic agriculture in total agricultural areas is not at the desired level, efforts are being made to expand production in organic agriculture areas (BAT Agriculture Sector Report, 2023). In addition to all these practices, there are also efforts to promote the use of renewable energy in agricultural energy use. One of the most important steps in this sense is the efforts to popularize SES. In Türkiye, which has a high solar potential, SES accounts for 4.87% of total energy production (EMRA 2022). Along with SES, the use of other renewable energy sources in agricultural energy use is also important for sustainable agriculture.

As a result of the findings of the study, various policy recommendations can be made regarding the agricultural sector in Türkiye and its impact on environmental quality. First of all, it is positive that the cropland footprint, which is one of the elements of EFP, the most important environmental quality indicator, is decreasing in Türkiye. However, one of the sources of this decrease is the shrinking agricultural sector in Türkiye, which jeopardizes food security. Therefore, structural steps to protect food security and prioritize environmental quality are inevitable for the country. At this point, producers should be supported by environmental incentives, and R&D activities that will increase productivity should be supported. In order to expand existing good agriculture and organic agriculture practices, it is important to increase the shares allocated from both central and local government budgets and channel them to the right places. Good and organic practices are important in solving the chronic problems regarding the use and efficiency of existing resources. In particular, crop planning, crop selection in accordance with climatic conditions and soil structure, and effective input use will be important practices in terms of food safety as well as environmental planning. One of the impact channels of agricultural processes on environmental quality is agricultural energy use. In the agricultural sector, where non-renewable energy is generally used intensively, this situation will pose significant problems in the near future in terms of environmental sustainability. In this sense, there have been recent breakthroughs in agri-photovoltaic systems developed in Türkiye. With this system, which enables energy production as well as agricultural activities on the same land, it is possible to reduce possible risks to agricultural processes. As stated by Ağır et al. (2023), who discusses the subject of agriculture-photovoltaic (AgriPV) in detail, pilot applications have already started in Türkiye despite the lack of official legislation. The advantages of Agri-FV applications in irrigation and, therefore, in energy demand compared to other systems are discussed in detail in the study. In Türkiye, where fossil fuel and electricity costs are increasing rapidly, this situation is also reflected in agricultural product prices. Increasing costs discourage producers from production and create negative pressure on food security. In this sense, the Agri-PV model will prepare the environment for minimizing these risks. Completing the legislative processes in Türkiye and increasing and sustaining incentives for Agri-Finance practices will be a structural step. Instead of reducing the cropland footprint by shrinking agricultural production and the sector, it would be most desirable to continue production effectively and efficiently without interruption and to protect the environment at this point. In order to eliminate food security risks, these policy recommendations should be taken into consideration by those concerned.

5. Conclusions

Agricultural production is an indispensable process for sustaining human life. Accessibility to food is a factor that makes agricultural production compulsory. The most important input of agricultural production is cultivable land. The expansion of cultivable land also necessitates the use of more agricultural energy. Energy use is mandatory in almost all stages of agricultural production. From soil cultivation to fertilization, from spraying to harvesting and transportation, all stages require energy use. Food security necessitates agricultural production, and a growing population requires more agricultural output. This paves the way for increased energy use in agriculture. These integrated relationships also determine the size of the cropland footprint. This study was written to reveal these relationships. The EKC model examines the relationship between cropland footprint, agricultural energy use, and cultivable land in the 10 most successful agricultural countries. This is one of the unique aspects of the study. To the best of the author's knowledge, no study tests the EKC model with cropland footprint, cultivable land, and agricultural energy use in the world's ten most successful agricultural countries. The agricultural EKC analyzed with the explanatory variables will contribute to the gap in the literature in this sense. The period of the study covers 1992-2020. A fourth-stage econometric procedure was followed in the study. Bootstrap ARDL (B-ARDL) technique was used to examine the cointegration relationship between variables on a country basis. In the second stage, causality research was conducted using the Granger Causality Based on ECM and Bootstrap Toda-Yamamoto Causality tests.

When the empirical findings are analyzed, it is observed that the cointegration relationship between the variables is found only in Türkiye. There is no cointegration relationship for the other countries in the sample. The coefficient estimates of the cointegration relationship indicate that the Agricultural EKC hypothesis is confirmed for Türkiye. Based on the results and conclusions of the study, political steps need to be taken to guide the implementation of sustainable agricultural practices that

reduce environmental impacts in Türkiye and other countries. Policymakers should be encouraged to progress in organic management and systems that can reduce environmental pollution and are compatible with sustainable environmental goals. In particular, renewable energy transformation should be increased in agricultural infrastructure investments to achieve sustainable agriculture. Fossil fuels used during the production phase in the agricultural sector are the main causes of air pollution. In this case, renewable energy transformation is indispensable in the energy used in agriculture. At this point, positive discrimination towards the agricultural sector in public incentive mechanisms can be made a policy. These steps are also important in terms of ensuring food security and sustainability. Considering the population and infrastructure potentials of the countries in the study's sample group, both renewable transformation and ensuring food security are indispensable elements for the countries' future. The study findings show that economic growth in Türkiye is compatible with improving environmental outcomes in agriculture. Türkiye must promote sustainable agricultural practices such as crop rotation, soil conservation plowing and precision agriculture to maintain and further develop this trend. These methods support the EKC dynamics between economic growth and reduced environmental impacts by reducing resource consumption and energy use. Considering that the EKC trend in Türkiye may be due to the diversified agricultural sector, policies should also focus on providing resources and training to small and medium-sized farms. Providing access to sustainable agricultural technologies, knowledge-sharing platforms, and financial support can help small farms adopt environmentally friendly practices. The policy recommendations based on the study findings will guide all countries and politicians.

Appendix 1. Descriptive test statistics for Türkiye

Tests	***Test stat.***	***Prob.***
Breusch-Godfrey Serial Correlation LM Test	0.496	0.7803
Heteroskedasticity Test: Breusch-Pagan-Godfrey	8.363	0.7561
Ramsey RESET Test	1.879824	0.1905
CUSUM Test	CUSUMQ Test	
Stable (%5)	Stable (%5)	

Appendix 2. Detailed Methodology

Step 1. Bootstrapping the autoregressive distributed lag test for cointegration

This study examines the cointegration relationship for the model in Equation 1 with the help of Mc-Nown et al. (2018) and Sam et al. (2019) B-ARDL test. The B-ARDL test is based on the ARDL bounds test developed by Pesaran, Shin, and Smith (2001). In this test developed by Pesaran et al. (2001), long-run (cointegration) relationships between variables can be analyzed even if the variables are stationary[2] at different levels. Pesaran et al. (2001) investigate the cointegration relationship between variables using the test equation in Equation 2. Test equation of the ARDL (p, q1, q2, q3, q4)[3] model: the "p" value indicates the lag length of the dependent variable, and the "q" values indicate the lag lengths of the independent variables. In the ARDL model, in addition to the lags of the independent variables, the lagged values of the dependent variable are also included as independent variables in the equation.

$$\Delta lcropf_t = \alpha_0 + \alpha_1 lcropf_{t-1} + \alpha_2 lgdp_{t-1} + \alpha_3 lgdp_t^2 + \alpha_4 lagren_{t-1} + \alpha_5 lfarmaland_{t-1} + \sum_{i=1}^{p} \varphi_i \Delta lcropf_{t-i} + \sum_{i=1}^{q_1} \gamma_i \Delta lgdp_{t-i} + \sum_{i=1}^{q_2} \delta_i \Delta lgdp_{t-i}^2 + \sum_{i=1}^{q_3} \partial_i \Delta lagren_{t-i} + \sum_{i=1}^{q_4} \Theta_i \Delta lfarmland_{t-i} + \varepsilon_t \quad (2)$$

In Equation 2, $\alpha_0$is the constant term coefficient, α_1, α_2, α_3, α_4, α_5 are the coefficients of the first lags of all variables used in the analysis. φ_i, γ_i, δ_i, ∂_i, Θ_i are the coefficients of lagged values of $lcropef, lgdp, lgdp^2, lagren\ and\ lfarmland$, respectively. Pesaran et al. (2001), after estimating this model with optimal lags, apply a constraint test to the relevant coefficients in the hypothesis in order to test the hypothesis H_{0A}: $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = 0$ (no cointegration) and obtain the F statistic

[2] In this paper, the stationarity (unit root) tests applied to the variables are not included in order not to exceed the word count. According to the unit root test findings, some variables are I(1) and some are I(0). The stationarity findings can be provided by the author(s) upon request. Mc-Nown et al. (2018) state that the dependent variable can be I(0) or I(1).

[3] The model's optimal lags are determined using the Bayesian information criterion (BIC).

value. They compare these values with the I(0) lower bound and I(1) upper bound critical values in their studies. If the calculated F statistic value is greater than the upper bound critical values, the null hypothesis is rejected and it is concluded that there is a significant cointegration relationship.

Mc-Nown et al. (2018) and Sam et al. (2019) have augmented ARDL test in their studies. B-ARDL (Augmented-ARDL) has two main differences. The first is that in addition to the hypothesis in the traditional ARDL bounds test, two additional hypotheses are proposed, and a total of three test statistics are calculated. Secondly, it derives the critical values of three different test statistic values with bootstrap. Considering Equation 2, the new hypotheses tested are as follows;

H_{0B}: $\alpha_1 = 0$, and H_{0C}: $\alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = 0$

The test statistic obtained with the restriction test to test the null hypothesis H0A, which indicates the joint significance of the first lags of all variables, is called $F_{overall}$. The test statistic obtained with the help of the constraint test to test the H_{0C} hypothesis, which indicates that only the first lags of the explanatory variables are significant together, is represented as F_{ind}. Hypothesis H_{0B} is also tested by the *t*-test and shows the significance of the first lag of the dependent variable. If all three $F_{overall}$, F_{ind}, and *t* statistic values are greater than the bootstrap critical values calculated together, a significant cointegration relationship is detected in the model. If any of the three hypotheses cannot be rejected, it means that there is no cointegration relationship[4],[5].

Step 2. Estimation of short and long run coefficients and error correction model

The long run coefficients of $lgdp, lgdp^2, lagren, and\ lfarmland\ on\ lcropef$ are calculated as; $\frac{-\alpha_2}{\alpha_1}, \frac{-\alpha_3}{\alpha_1}, \frac{-\alpha_4}{\alpha_1}$, and $\frac{-\alpha_5}{\alpha_1}$ respectively. These coefficients are given in Equation 2. The fact that the long run coefficient of *lgdp* is positive and the coefficient of $lgdp^2$ is negative reveals the validity of the inverted U hypothesis. Here, it is important to calculate after which threshold value the value of the effect of lgdp turns negative. For this, Song, Zheng, & Tong (2008) and Stern (2004) suggest that the threshold value can be calculated by the formula= $-\frac{lgdptur\ coeeff.}{2\ lgdptur^2 coeff.}$.

The short-run coefficients and the coefficient of the error correction term can be estimated using Equation 3. ECT_{t-} in Equation 3 is referred to as the error correction term. The error correction coefficient "Φ" expected to be significant between 0 and -1. In some studies, it is also observed to be in the range of -1 and -2 (Alam & Quazi, 2003). This coefficient shows the adjustment period in rebalancing after a shock to the long-run equilibrium relationship.

$$\Delta lcropf_t = \sum_{i=1}^{q_1} \varphi_i \Delta lcropf_{t-i} + \sum_{i=1}^{q_2} \gamma_i \Delta lgdp_{t-i} + \sum_{i=1}^{q_3} \delta_i lgdp_{t-i}^2 + \sum_{i=1}^{q_4} \partial_i \Delta lagren_{t-i} + \sum_{i=1}^{q} \Theta_i \Delta lfarmland_{t-i} + \Phi ECT_{t-1} + \varepsilon_t \quad (3)$$

Step 3. Granger causality test based on error correction model

If there is a cointegration relationship between variables, short and long-run causality relationships can be investigated with the Granger causality test based on the error correction model (Hasballa,2014; Gülmez et al. 2020). Short-run causality is detected by applying a restriction test separately to the short-run coefficients in Equation 3 (H_0: γ_i=0, $\delta_i = 0$, $\partial_i = 0$, $\Theta_i = 0$). Long-run causality can also be tested by applying the restriction test to the error correction coefficient (H_0: $\Phi = 0$).

Step 4. Bootstrap toda-yamamoto causality test

Under the assumption that there may be a causality relationship in other 9 countries even if there is no cointegration relationship, it was decided to test causality relationships with the bootstrap Toda-Yamamoto causality test developed by Hacker and Hatemi-j (2012). The causality test developed by Toda and Yamamoto (1995) is based on the Granger (1969) causality test. Both of these tests use Vector Autoregressive (VAR) models developed by Sims (1980). However, while the traditional Granger (1969) causality test requires the series must be stationary, the Toda-Yamamto causality test allows the variables to be stationary at different levels. In the Toda-Yamamoto causality test, the "d_{max}" value, which is the maximum degree of integration and obtained by unit root tests, is added to the VAR(p) [6] model as an additional lag. Moreover, it is not important whether there is a

[4] If $F_{overall}$ and *t* statistics are significant and F_{ind} is insignificant, "degenerate case 1" is determined, and if $F_{overall}$ and F_{ind} test statics are significant and *t* is insignificant, "degenerate case 2" is determined. In these cases, there is no cointegration relationship.

[5] For detailed explanations please see: Mc-Nown et al. (2018) and Sam et al. (2019)

[6] It is the optimal number of lags and is determined using the Hatemi-j Information Criterion (HJC).

cointegration relationship between the variables prior to this test. Hacker and Hatemi- j (2012) derive the critical values of the test using the bootstrap method. Thus, they eliminate the problem of non-normal distribution. The VAR($p+d_{max}$) model is presented in Equation 4.

$$\begin{bmatrix} lcropf_t \\ lgdp_t \\ lgdp_t^2 \\ lagren_t \\ lfarmland_t \end{bmatrix} = \begin{bmatrix} \psi_0^{lcropf} \\ \psi_0^{lgdp} \\ \psi_0^{lgdp^2} \\ \psi_0^{lagren} \\ \psi_0^{lfarmalnd} \end{bmatrix} + \begin{bmatrix} \psi_{11,1} & \psi_{12,1} & \psi_{13,1} & \psi_{14,1} & \psi_{15,1} \\ \psi_{21,1} & \psi_{22,1} & \psi_{23,1} & \psi_{24,1} & \psi_{25,1} \\ \psi_{31,1} & \psi_{32,1} & \psi_{33,1} & \psi_{34,1} & \psi_{35,1} \\ \psi_{41,1} & \psi_{42,1} & \psi_{43,1} & \psi_{44,1} & \psi_{45,1} \\ \psi_{51,1} & \psi_{52,1} & \psi_{53,1} & \psi_{54,1} & \psi_{55,1} \end{bmatrix} \begin{bmatrix} lcropf_{t-1} \\ lgdp_{t-1} \\ lgdp_{t-1}^2 \\ lagren_t \\ lfarmland_t \end{bmatrix} + \cdots +$$

$$\begin{bmatrix} \psi_{11,p+d_{max}} & \psi_{12,p+d_{max}} & \psi_{13,p+d_{max}} & \psi_{14,p+d_{max}} & \psi_{15,p+d_{max}} \\ \psi_{21,p+d_{max}} & \psi_{22,p+d_{max}} & \psi_{23,p+d_{max}} & \psi_{24,p+d_{max}} & \psi_{25,p+d_{max}} \\ \psi_{31,p+d_{max}} & \psi_{32,p+d_{max}} & \psi_{33,p+d_{max}} & \psi_{34,p+d_{max}} & \psi_{35,p+d_{max}} \\ \psi_{41,p+d_{max}} & \psi_{42,p+d_{max}} & \psi_{43,p+d_{max}} & \psi_{44,p+d_{max}} & \psi_{45,p+d_{max}} \\ \psi_{51,p+d_{max}} & \psi_{52,p+d_{max}} & \psi_{53,p+d_{max}} & \psi_{54,p+d_{max}} & \psi_{55,p+d_{max}} \end{bmatrix} \begin{bmatrix} lcropf_{t-p+d_{max}} \\ lgdp_{t-p+d_{max}} \\ lgdp_{t-p+d_{max}}^2 \\ lagren_{t-p+d_{max}} \\ lfarmland_{t-p+d_{max}} \end{bmatrix} + \begin{bmatrix} u_{1t} \\ u_{2t} \\ u_{3t} \\ u_{4t} \\ u_{5t} \end{bmatrix} \quad (4)$$

The's in Equation 4 indicate the coefficient matrices. The following hypotheses can be tested by applying the following restrictions to the coefficients in this equation;

H_0: $\psi_{12,1}= \psi_{12,2}=\ldots= \psi_{12,p}=0$ (lgdp is not the Granger cause of lcropf)
H_0: $\psi_{13,1}= \psi_{13,2}=\ldots= \psi_{13,p}=0$ ($lgdp^2$ is not the Granger cause of lcropf)
H_0: $\psi_{14,1}= \psi_{14,2}=\ldots= \psi_{14,p}=0$ (lagren is not the Granger cause of lcropf)
H_0: $\psi_{15,1}= \psi_{15,2}=\ldots= \psi_{15,p}=0$ (lfarmland is not the Granger cause of lcropf)

In addition to these hypotheses, it is also possible to test hypotheses that test other relationships. However, since the research question of the study is to determine the variables affecting the cropland footprint, only the hypotheses mentioned above are reported. The Wald F test statistic values obtained with the restriction test are compared with the bootstrap critical values as suggested in Hacker and Hatemi-j (2012) and a decision on the existence of causality is taken. If the calculated test statistic value is greater than the critical values, the hypotheses above are rejected, and causality occurs.

Abbreviations

Agro-photovoltaic: (AgriPV)
Association of Southeast Asian Nations: (ASEAN)
Augmented Mean Group: (AMG)
Autoregressive Distributed Lag: (ARDL)
Banks Association of Türkiye: (BAT)
Bootstrapping the Autoregressive Distributed Lag: (BARDL)
Carbon Footprint: (CO2)
Common Correlated Effect Mean Group: (CCEMG)
Dynamic Ordinary Least Squares: (DOLS)
Ecological Footprint: (EFP)
Energy Markets Regulatory Authority: (EMRA)
Environmental Cuznets Curve: (EKC)
Fully Modified Ordinary Least Squares: (FMOLS)
Generalized Method of Moments: (GMM)
Kantil Autoregressive Distributed Lag: (QARDL)
Linear Programming: (LP)
Mixed Integer Linear Programming: (MILP)
Panel Vector Autoregressive Regression (PVAR)
Solar Energy Systems: (SES)
System generalized method of Moments: (Sys-GMM)
Water-Energy-Food Nexus Index: (WEFNI)
Vector Error Correction Model (VECM)

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