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ARTICLE

Assessing the Convergence of Cropland Ecological Balance: A Panel Data Analysis of 13 Major Agricultural Countries

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ABSTRACT

This study investigates the convergence hypothesis and stochastic dynamics of agricultural land use and ecological balance across 13 major agricultural countries from 1992 to 2022. The study's concentrated samples are Russia, the United States, the Netherlands, Brazil, Germany, China, France, Spain, Italy, Canada, Belgium, Indonesia, and India. The research uncovers notable variations in ecological balance by utilizing a comprehensive set of advanced panel unit root tests (Panel CIPS, CADF, Panel-LM, Panel-KPSS, and Bahmani-Oskooee et al.'s Panel KPSS Unit Root Test). The findings highlight significant improvements in Canada, contrasting with declines in the Netherlands, France, Germany, and the United States. The results indicate convergence in ecological balance among these countries, suggesting that agricultural practices are progressively aligning with sustainability objectives. The considered countries can determine and enact joint and collective policy actions addressing cropland sustainability. However, the univariate outcome also shows that the cropland ecological balance of Germany, China, France, Indonesia, and India does contain a unit root and stationary which means the presence of the constant-mean. The univariate actions from the mentioned governments will not promote persistent impact. Therefore, joint actions determined by the countries considered are recommended for the

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mentioned countries. However, the rest of the countries also enact local policies. The insights gained are critical for informing global sustainability strategies and aiding policymakers in developing effective measures to enhance agricultural practices and mitigate environmental impacts. This research provides a data-driven foundation for optimizing agricultural sustainability and supports international efforts to achieve long-term ecological stability.

Keywords: Agricultural Land Use; Ecological Balance; Convergence Hypothesis; Stochastic Dynamics; Panel Unit Root Tests; Sustainable Development

1. Introduction

Environmental sustainability refers to practices that allow ecosystems to regenerate, ensuring that natural resources can meet both current and future needs. Essential aspects of this concept include sustainable resource management, pollution reduction, and biodiversity protection. These components are critical for long-term economic stability and social well-being [1]. Issues such as resource depletion, climate change, soil erosion, and water scarcity, driven by unsustainable practices, threaten not only the environment but also economic and social systems. Therefore, achieving environmental sustainability is a global priority [2].

One way to measure ecological sustainability is through the concept of biocapacity and ecological footprint. Biocapacity represents a region's biological capacity to regenerate resources, while the ecological footprint measures the demand placed on these resources by human activities [3]. Rees [4], Wackernagel [5], and Rees and Wackernagel [6] introduced the ecological footprint, which presents the pressure of anthropogenic activities on the environment. The ecological footprint comprises six sub-components: forest products, fishing grounds, cropland, built-land, carbon, and grassland footprint. The ecological footprint provides comprehensive knowledge of environmental degradation. However, biocapacity presents the ecosystem's regeneration and capacity, except for the carbon footprint. If a country's biocapacity exceeds its ecological footprint, it generates an ecological reserve, whereas an ecological deficit occurs when resource consumption outpaces regeneration, putting long-term sustainability at risk. Ecological balance is fundamental to environmental sustainability, defined by the harmonious interaction of living and non-living components within an ecosystem. Disruptions to this balance—through biodiversity loss, habitat destruction, or pollution—can severely impact ecosystem services like clean water, fertile soil, and climate regulation. Such disruptions can lead to ecological crises that directly affect human health and economic activities [7].

Agricultural lands are crucial in maintaining ecological balance, as they support food production and contribute to biodiversity preservation, carbon sequestration, soil erosion prevention, and water management [8]. However, unsustainable agricultural practices can result in soil degradation, water pollution, and biodiversity loss, exacerbating both local and global ecological challenges. Thus, the sustainable management of agricultural lands is key to preserving ecological balance and achieving environmental sustainability [9].

Regarding the importance of agricultural land to humans, joint actions and worldwide collaborations to improve fertile soils and mitigate environmental degradation in agricultural lands have been outstanding and critical initiatives. The convergence hypothesis has been one of the most outstanding and seminal research objectives within this objective. The Panel unit root methods are performed to test the convergence hypothesis for the related series. Assuming the series is stationary, the convergence hypothesis is verified. The convergence hypothesis suggests that environmental or economic indicators across different regions or countries will tend to converge over time [10]. If convergence is marked among members, it signifies that dissimilarities in environmental indicators will lessen over time. In another explanation, the country or region with high per capita environmental indicators loosens the evaluated environmental indicators. In contrast, the country or region with high per capita environmental indicators increases or maintains its series. Specifically, the agricultural land-ecological balance convergence hypothesis posits that countries' agricultural land use and ecological balance will eventually align, reaching a similar equilibrium. Studying this hypothesis can provide critical insights into how land use and ecological stability evolve across different nations.

Understanding the stochastic properties of the agricultural land-ecological balanced relationship is essential for predicting how this balance responds to any shocks induced by governmental interventions, such as the policies addressing the improvement in agricultural land properties and lessening the polluted agricultural-based methods. This approach allows policymakers to design and assess sustainability measures, helping to ensure that agricultural practices do not further compromise ecological balance [11,12].

In this study, we analyze the 13 countries with the largest agricultural land use—Russia, the United States, the Netherlands, Brazil, Germany, China, France, Spain, Italy, Canada, Belgium, Indonesia, and India. These nations play a critical role in global food security and ecological balance, and their agricultural practices have far-reaching environmental implications. **Figure 1** illustrates their ecological footprint, biocapacity, and ecological balance[13].

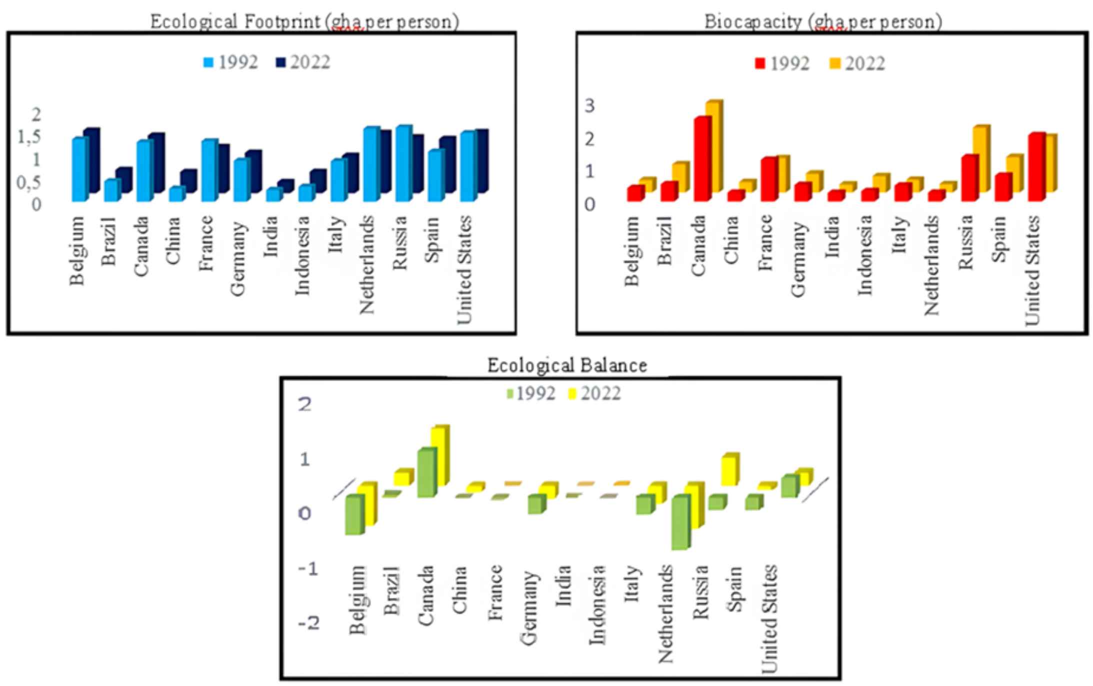

Figure 1. Ecological Footprint, Biocapacity, and Ecological Balance (1992 and 2022) .

Between 1992 and 2022, Canada saw the most significant improvement in ecological balance, while the Netherlands experienced the steepest decline—countries like France, Germany, Indonesia, Russia, Spain. Besides, the United States also showed reductions in ecological balance. However, Belgium, Brazil, China, India, and Italy made progress. Given their significant roles in agricultural production, these countries bear considerable responsibility for promoting environmental sustainability. A comparative analysis of their agricultural land use and ecological balance helps identify strategies for sustainable practices on both national and global levels [14].

Investigating how agricultural land use interacts with ecological balance across these countries delivers critical insights for fostering sustainable agricultural practices. Such analysis is paramount for evaluating the effectiveness of policy measures to reduce environmental harm while sustaining agricultural productivity. Moreover, studying the convergence hypothesis and stochastic properties of agricultural land-ecological balance proposes a framework for aligning agricultural practices with global sustainability goals.

This research fills an important gap by focusing on the relationship between agricultural land use and ecological balance across a unique group of major agricultural countries during the 1992–2022 period. To date, no study has explored this relationship among these particular nations, making this research original and relevant to discussions on agricultural and environmental policy.

Methodologically, this study employs advanced panel unit root tests—including the Panel CIPS, CADF, Panel-LM, Panel-KPSS, and Bahmani-Oskooee et al.'s [15]. Panel KPSS Unit Root Test—to accurately assess the stochastic properties of the agricultural land-ecological balance relationship. These methods are crucial for capturing long-term trends, structural shifts, and the resilience of ecosystems to shocks. By analyzing these trends, the study provides policymakers with vital information for crafting strategies that support sustainable agricultural production and ecological stability.

The results of this study will contribute to ongoing academic discussions on convergence theory and sustainable development, offering a data-driven basis for policy recommendations. As major agricultural players, the 13 countries studied have a disproportionate influence on both food security and environmental health. This research will provide actionable insights for optimizing agricultural practices to mitigate the environmental impacts of farming, particularly in the face of challenges such as climate change, soil degradation, and biodiversity loss.

In conclusion, this study not only addresses a critical gap in the literature but also applies rigorous econometric methods to generate valuable insights for national and international sustainability strategies. By enhancing our understanding of the relationship between agricultural land use and ecological balance, this research will play a crucial role in shaping policies that align agricultural practices with environmental sustainability in the 21st century.

2. Literature Review

Environmental quality is of great importance in terms of sustainable development goals. In this context, increasing environmental quality and reducing environmental degradation are considered very important. There are many studies in the literature examining environmental degradation. In these studies, it is determined that CO_2 emissions [16,17,18,19,20], ecological footprint [21,22,23], SO_2 [24,25,26], variables are generally used as environmental indicators. In these studies, it has been observed that economic growth, foreign direct investments, urbanization, renewable energy consumption, non-renewable energy consumption variables are generally used [27,28,29,30,31,32,33]. Among the studies in question, Bulut et al. [30] investigated the determinants of environmental degradation with the cointegration test axiom proposed by Tsong et al. [34]. In the study, it was understood that there is an inverted U relationship between renewable energy and environmental degradation variables. Environmental quality, which is considered important in terms of development goals and environmental sustainability, is tested in a limited number of studies [35,36,37]. Erdogan et al. [37] also revealed that non-renewable energy use, economic development and demand for air transportation reduce environmental quality. In the study investigating G-7 countries, it was concluded that renewable energy use and railway transportation increase environmental quality. The authors used panel data methods that take into account cross-sectional dependence. These studies have recently been tested with the load capacity curve hypothesis [23,38,39,40]. In the study on the validity of this hypothesis, Wu et al. [41] conducted research on E-7 countries (Turkey, Indonesia, India, Russia, Brazil, Mexico and China). Panel data techniques were used in the study conducted for the period 1996–2019. Empirical findings showed the validity of the Load Capacity Curve (LCC) hypothesis in E-7 countries. This result reveals that the relationship between economic growth and environmental quality is U-shaped. Essentially, this result supports the Environmental Kuznets Curve (EKC) hypothesis. On the other hand, the results show that environmental quality decreases in the event of economic policy uncertainty. It is important to reduce the use of renewable energy to increase environmental quality. In the study, it is considered important to increase the use of renewable energy, reduce trade openness and reduce policy uncertainty for sustainable environment and ecological balance in the context of sustainable development goals. Topal [42] investigated the validity of the LCC hypothesis in the Turkish economy. In the study conducted using data from the 1973–2022 sample period, the ARDL bounds test was used as an empirical method. Foreign direct investments, non-renewable energy consumption, economic growth and load capacity factor variables were used in the study. Empirical results revealed that the LCC hypothesis is not valid.

In addition, the research on specific ecosytem or sectors have been recently upsurging topics. Within this scope, the agricultural sector has an important place for environmental sustainability. Demonstrating the relationship between agricultural land and ecological balance with strong evidence can provide important clues for policy makers. Agricultural sustainability, which is of vital importance especially in the context of the present and future of humanity, needs to be determined. There are few studies on environmental sustainability in the context of agricultural land use. It has been determined that the ecological footprint variable has recently been used in the literature in terms of ecological balance measured by biocapacity minus ecological footprint and presenting the sustainability of the ecosystem [43,44,45]. In this context, Çelik et al. [46] investigated the validity of environmental sustainability by examining the stationarity of the ecological footprint. Ecological footprint data belonging to the Economic Community of Central African States and the Economic Community of West African States were used in the study. In the study examining the period 1961–2017, Bahmani-Oskooee et al. [15] panel unit root test was used. Empirical results show that the relevant variable does not contain a unit root process in both country groups. In other words, the ecological footprint converges in the analyzed countries. These results pave the way for sustainable development in the relevant countries. However, the broad framework of the ecological footprint may cause some subheadings to be overlooked. Agricultural sustainability is one of the most important subfields. In this context, studies on agricultural yield and agricultural land are addressed in terms of the union of agriculture and ecological balance. It is important to estimate how this balance responds to external shocks such as climate change or resource depletion. However, it is seen that there are limited studies on agricultural sustainability. In this context, it is determined that the relationships between agricultural variables and technology, energy and environment are mostly addressed [47].

Detection of convergence in agricultural activities (agricultural yield, agricultural land use, etc.) shows that agricultural practices provide ecological balance and are in harmony with sustainability goals. In this context, it has been determined that agricultural productivity is used in the literature. Chivu et al. [48] also examined regional agricultural productivity convergence in development regions in Romania in the 2001–2017 sample period. The study concluded that agriculture has a major impact on the regional development process. On the other hand, the importance of continuing and increasing reforms in the field of agriculture was emphasized, and the importance of agriculture for both environmental performance and sustainability of economic growth was revealed. Andrei et al. [49] investigated the importance of agricultural productivity for EU countries. The study emphasized the importance of environmental sustainability and agricultural productivity and revealed the importance of differences in geographical and natural conditions. It was also stated that regional differences due to population and economic development affect agricultural productivity. According to Oncioiu [50] and Constantin [51], the largest deviations occur in land productivity. The differences observed in capital and labor productivity are less important in terms of agricultural productivity and environmental sustainability [52,53].

Mollavelioğlu et al. [54], who investigated agricultural sustainability in Turkey and 16 EU countries, examined the period 1995–2005. The authors, who investigated agricultural sustainability with the Malmquist Index Method and Data Envelopment Analysis methods, determined agricultural land, number of tractors, chemical fertilizer, pesticide and labor as input variables. Agricultural added value, food safety and greenhouse gas emission variables were determined as output variables. As a result of the study, it was found that the agricultural sustainability gap between Turkey and the EU widened against Turkey in the relevant period. On the other hand, the importance of technology in ensuring agricultural sustainability was emphasized in the study. Mıhcı and Mollavelioğlu [55] investigated agricultural sustainability in 23 OECD countries, including Turkey. The study used the Data Envelopment Method and used data from the years 1990, 1995, 2000 and 2005. In the study using data similar to Mollavelioğlu et al. [54] it was found that agricultural sustainability was valid in Belgium, Denmark, the Netherlands and Slovakia. It was concluded that agricultural sustainability was not valid in Turkey.

Bartolini et al. [56], who conducted a similar study for 21 EU countries, investigated the environmental efficiency of the agricultural sector. Mollavelioğlu et al. [54] reached similar findings in the study where the period 1992–2011 was investigated. The results revealed the importance of technology in ensuring agricultural sustainability. The importance of technology in agricultural sustainability has begun to be emphasized in recent studies. In this context, Şenol [57] also evaluated agricultural sustainability in Turkey from a descriptive perspective. The study emphasized that technology is important in terms of agricultural sustainability. The study emphasized the importance of the public in the development of technology in Turkey and emphasized the encouragement of the young population. Domagala [58] investigated the economic efficiency of agricultural sectors in 26 EU countries in his study. In the study where 2019 was used as the sample period, agricultural land, employment, chemical fertilizer and energy consumption were used as input variables. The output variable was determined as agricultural production value. In the study where data envelopment analysis was used, the validity of agricultural sustainability was concluded in Italy, Greece, Cyprus, the Netherlands and Portugal in 2019. Bezner conducted the study by Pishgar-Komleh et al. [59], who examined the 2008–2017 sample period for 27 EU countries, using window slack-based measurement data envelopment analysis. In the study where cultivated agricultural area, labor, input costs (specific costs), fixed costs (overhead costs) and depreciation costs were used as input variables, agricultural greenhouse gas emissions and gross plant and animal production were used as output variables. The analysis findings showed that agricultural sustainability is not valid in Slovakia, Latvia and Estonia. On the other hand, evidence for the validity of agricultural sustainability was found in the Netherlands, Belgium, Italy, Malta, Spain, Luxembourg, Greece, Cyprus and Ireland.

In recent studies on agricultural sustainability, it is seen that time series and panel data methods are used. Ozturk [60] also examined agricultural sustainability with data from Sub-Saharan African countries for the period 1980–2013. The study focused on the relationship between agricultural sustainability and food-energy-water resources. In the study using panel data methods, empirical results revealed that agricultural sustainability is a prerequisite for reducing food-energy-water poverty. Bekun et al. [61] investigated the validity of agricultural sustainability in the Nigerian economy. In the study examining the period 1981–2016, traditional unit root tests and traditional cointegration tests were used. The study findings revealed the importance of agricultural credits in terms of agricultural sustainability. Direk et al. [62] investigated the validity of agricultural sustainability in Turkey for the period 2000–2018. The study utilized time series methods that take structural breaks into account. The study emphasized the importance of structural reforms in the field of agriculture. In addition, attention was drawn to the importance of agricultural subsidies. Karadavut et al. [63] examined the validity of agricultural sustainability in Turkey in the period 1995–2020. In the study, which utilized the ARDL bounds test, it was concluded that water resources and economic stability have a serious role in agricultural sustainability. Zhang et al. [64] investigated the validity of agricultural sustainability and environmental sustainability by examining agricultural performance in regions belonging to China. Multi-criteria comprehensive assessment method and convergence analysis were used in the study. In the study conducted in the 1990–2015 sample period, it was concluded that sustainable agricultural development was valid in urban environments and economically developed areas in accordance with the market rationality of regional division. On the other hand, the importance of creating policies that encourage large-scale and industrial farming in remote areas is emphasized in the study. Yeni and Teoman [65] investigate agricultural sustainability in Turkey by comparing it with EU countries. The Malmquist index method was used in the study where the period 2008–2019 was investigated. The analysis results show that total factor productivity increased by 1.4% and 1% in the relevant period in Turkey and EU average, respectively. The results show the existence of convergence between the EU and Turkey in the context of agricultural sustainability in the period 2008–2019.

When studies on agricultural sustainability are examined, it is determined that the relationship with the environment is frequently addressed. In addition, it has been seen that agricultural variables are used in the literature along with variables such as technology, energy, and economic growth. However, no study has been found in the literature examining agricultural sustainability within the scope of convergence theories with current panel unit root tests. On the other hand, the fact that the countries used in this study are the 13 largest agricultural countries and that no study with this feature has been found in the literature constitutes another gap in the literature. When the power of the empirical methods used in the study and the variables used are evaluated, it is evaluated that it will contribute to the literature in terms of both agricultural sustainability and environmental sustainability.

3. Data and Methodology

The study aims to investigate the convergence hypothesis and the stochastic properties of the cropland-ecological balance belonging to the top 13 cropland-producer countries. Cropland-ecological balance is achieved from the biocapacity of the cropland and the cropland footprint under the initiatives on the supply and demand side of the cropland. Because of the availability of data on all considered countries, the data covers the period from 1992 to 2022. The biocapacity of the cropland and cropland footprint are achieved from the Global Footprint Network's [13] data stream. Within this scope, various panel unit root tests allowing for consideration of sharp one and two structural breaks, smooth and multiple structural breaks, and ignoring structural breaks are performed. In reference to the study's objective, the cross-sectional dependence tests are first employed to find whether the cross-sectional dependence is verified. The convergence hypothesis is the second path of the econometric steps in the study, which uses panel unit root tests. Thirdly, univariate unit root tests provided by some employed panel unit roots in the study are evaluated.

Moreover, performing some panel unit root tests provides a univariate finding, which is used to investigate whether the police on the cropland will have a permanent impact on the cropland's sustainability or not. Besides, the presence of the cross-section dependence becomes a pivotal factor in determining the study's performing panel unit root tests. Within this context, Breusch and Pagan LM [66], Pesaran scaled LM [67], and Bias-corrected scaled LM [68], cross-section dependence tests are performed, and the null hypothesis of the tests disclose the absence of the cross-section dependence. If the null hypothesis is rejected, some factors involving spatial impact and unobservable common factors lead to cross-section interactions among the panel sample. In another explanation, any shocks occurred in one cross-section units promote spillover effect on the rest of the cross-section units in the panel sample. Within this scope, the panel unit root tests are classified into the first and second-generation panel unit root tests, considering whether the test allows for considering cross-section dependence or not. The first-generation panel unit root test ignores the cross-section dependence. However, the second-generation panel unit root tests allow for considering the cross-section dependence. In the case of verifying the cross-section dependence in the panel sample, the biased and inconsistent result can be achieved by using the first-generation panel methods. Therefore, the second-generation panel unit root tests are executed in the study as a result of the cross-section dependence tests. The theoretical frameworks of the performing panel unit root tests are presented as follows:

The Covariate-augmented Dickey-Fuller (CADF) introduced by Pesaran [69] and the (CIPS) panel unit root tests proposed by lm et al. [70] are some of the most popular second-generation panel methods allowing for cross-sectional dependence. In the CADF unit root tests, the cross-section averages of lagged levels and the individual series' first differences are used to enhance the standard ADF unit root test to overcome the cross-section dependence issue. The CADF panel unit root test is also applicable. It promotes reliable and consistent results in the cases n > T and T > n and works well in small samples. It is also used to determine the stochastic properties of the series on the whole panel and cross-sectional units. The null hypothesis of the CADF and CIPS panel unit root tests shows that the series contains a unit root and it is not stationary, and the series' stationarity possessions can be detected by comparing the CIPS and CADF statistics values with the critical values by Pesaran [69]. Assuming the absolute value of the CIPS and CADF statistics is lower than the critical values, the null hypothesis is not rejected, which means that the series involves a unit root. Regarding the mentioned information on the CADF unit root test, the CADF test statistics is achieved by using the following:

$$\Delta b_{it} = \alpha_i + h_{it} + y_i b_{i,t-1} + c_i b_{t-1} + \sum_{j=0}^{p} d_{ij} \Delta b_{t-j} + \sum_{j=0}^{p} \beta_{ij} \Delta b_{i,t-j} + \epsilon_{it} \quad (1)$$

In equation 1, $b_{i,t-1}$ and ϵ_{it} represent the lag period and the standard error term. In addition, α_i and t show the constant terms and a trend, respectivelly. However, a cross-sectionally lm-Pesaran-Shin (CIPS) test can be performed to analyze the findings of the CADF test for the whole panel, as follows:

$$CIPS_{ist} = (1/N) \sum_{i=1}^{N} CADF_i \quad (2)$$

In addition to the cross-sectional dependence in investigating the series' stochastic properties, the form, numbers, endogen, and exogen of the structural breaks in the panel data generation process are pivotal. If only unit root tests ignore the structural breaks, it may promote biased and inconsistent results, which leads to mistakenly rejecting the null hypothesis of the tests. The study also performed unit root tests, allowing for cross-sectional dependence and structural breaks. The accuracy of the content on the validity of the convergence hypothesis. In addition, the knowledge of the stochastic properties of the series for each cross-section unit tightly relies on the result of the unit root tests. Within this scope, the Panel LM unit root tests introduced by Lee and Tieslau [71], the Panel KPSS unit root tests, and the Bahmani-Oskooee et al. [15] panel Fourier unit root tests are employed. The panel LM unit root test is introduced by lm et al. [70,72], based on the univariate LM test statistics, while the panel LM unit root test provides more statistical power. Regarding the panel LM unit root test processes, achieving t-test statistics of the univariate LM unit root test is the first step, and the related univariate LM unit root test's equation is presented as follows:

$$\Delta b_{it} = \gamma_i' \Delta a_{it} + \theta_i \tilde{s}_{i,t-1} + \sum_{j=1}^{pi} p_{ij} \Delta \tilde{s}_{i,t-j} + \varepsilon_{it} \quad (3)$$

In the equation 3, Δb_{it} and Δa_{it} present the first differenced values of and, respectively while $\Delta \tilde{s}_{i,t-j}$ the augmentation terms to correct for serial correlation impled by Amsler and Lee [73]. Besides, $\Delta \tilde{s}_{i,t-j}$ is the detrended value of b_{it} with the interrelated coefficient $\theta_i = 1 - \emptyset_i$ The validity of a unit root in b_{it} for i meaning each cross section units implies $\theta_i = 0$. Then, the t-test obtained from equation 3 for $\theta_i = 0$ is employed to compute the univariate LM test statistics for the ith time series, and the achieved statistics are posed as LM_i^T. In addition, the second path of the Panel LM unit root test is computing the panel LM test statistics by averaging the univariate LM unit root t-test statistics, and the related equation on the second path is disclosed as follows:

$$\bar{L}MNT = \frac{1}{N} \sum_{i=1}^{N} LM_i^T \quad (4)$$

Moreoever, normalization yields the following Standard finding:

$$\Gamma_{LM} = \frac{\sqrt{N\left(\overline{LM}_{NT} - E\left(LM_i^T\right)\right)}}{\sqrt{V\left(LM_i^T\right)}} \rightarrow N(0,1) \quad (5)$$

In equation 5, $V(LM_i^T)$ and $E(LM_i^T)$ display variance of the and the expected value and their critical values is presented in lm et al.'s [74] research.

The panel LM and KPSS unit root tests allow for considering sharp and limited structural breaks, whereas the structural breaks may be unknown, smooth, multiple, and sharp, which have impacted the result of the unit root tests. In order to provide comprehensive evidence on the presence of the convergence hypothesis and the stochastic properties for each cross-section unit, Bahmani-Oskooee et al. 's [15] panel unit root test is also performed in the study. Bahmani-Oskooee et al. [15] developed the unit root test depending on Carrion-i-Silvestre et al.'s [75] panel unit root test. The following model where is implied as level stationary is presented as follows:

$$b_t = \vartheta + \sum_{l=1}^{v+1} \vartheta_l DU_{l,t} + \sum_{k=1}^{n} \omega_{1,k} + \sin\left(\frac{2\pi pt}{T}\right) + \cos\left(\frac{2\pi pt}{T}\right) + \epsilon_{i,t} \quad (6)$$

In Equation (6), DU discloses the dummy variable and v donates the optimal number of breaks; T and t show the sample size and t, respectively. Besides, ϑ means the intercept. Dummy variable is employed in the model to capture the sharp breaks and values for dummy variables is measured under the two circumstance as presented as follows:

$$DU_{i,k,t} = \begin{cases} 1 & \text{if } t > TB_i^l \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

TB_i^l shown in Model 7 means the break's kth date for the ith unit and Model 6 posing the Fourier form is performed to capture the smooth structural changes.

Bahmani-Oskooee et al. [15] use the Equation (8) to test the null hypothesis, disclosing the series is stationary with different forms such as sharp or smooth, multiple and unknown structural breaks.

$$V(\lambda) = \frac{\left(\sum_{i=1}^{N} LM(\lambda_i) - N\bar{\mu}_{LM}\right)^{0.5}}{\sigma_{LM}} \quad (8)$$

$\bar{\mu}_{LM}$ and σ_{LM} in equation 8 disclose the mean and standard deviation, respectively; equation 9 below is performed to LM statistics.

$$LM(\lambda_i) = \widetilde{\varphi_i} T^{-2} \sum_{t=1}^{T} \widetilde{M}_{i,t}^{2} \quad (9)$$

In Equation 9, $\widetilde{\varphi_i}$ represents a consistent estimate of the long-run variance of $\epsilon_{i,t}$ shown in equation 6 while $\widetilde{M}_{i,t}^{2}$ indicates the partial sum process analyzed by OLS in eqaution 6.

When processing Bahmani-Oskooee et al.'s [15] panel unit root test, the two defined paths are considered. The first path notices the optimum structural breaks fixed at a maximum of 5 and frequency. Equation 6 is estimated under the suggestion of Bai and Perron [76] and saves the sum of squared residual (hereafter, SSR). The optimal frequency minimizing the SSR is specified, and the optimal frequency is labeled as. Later, Equation (6) is reestimated by considering and the optimum structural breaks with locations and numbers are highlighted. In the second, the validity of nonlinear structural posing Equation (7) is investigated with the help of the proposition of Becker et al. [77] on F-test statistics [15,78].

$$F(k^*) = \frac{(SSR_{ur} - SSR_r(k^*))/2}{\frac{SSR_r(k^*)}{T-q}} \quad (10)$$

In equation 10, the abbreviations ur and r mean unrestricted and restricted, and $SSR_r(k^*)$ and $SSR_r(k^*)$ display the SSR obtained from equation 7 with or without a nonlinear feature.

4. Empricial Results

In the study, investigation for the cross-section dependence of the series is the first step of the econometric examinations. The cross-section dependence result is pivotal to determining which first and second-generation panel unit root methods are applicable to test the convergence hypothesis. In terms of cross-section dependence, panel unit root techniques are classified into the first, ignoring cross-section dependence, and the second generation, allowing for considering cross-section dependence, panel unit root tests. The first-generation panel unit root tests promote biased results and size distortions if the cross-dependence is verified among the series. The cross-section dependence is induced by various factors involving spatial impact, unobservable common factors, and externalities.

The environmental-related series tends to be cross-sectional among the countries because the countries are located in a single environment called the Earth. Within this scope, Breusch and Pagan LM [66], Pesaran scaled LM [67], and Bias-corrected scaled LM cross-section [68] dependence tests are executed. The results of the cross-sectional dependence tests are shown in **Table 1**. According to **Table 1**, the null hypothesis of all tests is rejected, and the cross-section dependence is verified; in another explanation, the cropland ecological balance is intersectional in the considered countries. The second-generation panel unit root tests should be applied to test the convergence hypothesis of the cropland ecological balance.

Table 1. Results of CSD tests.

Variables	Breusch-Pagan LM	Pesaran Scaled LM	Bias-Corrected Scaled LM
lnGLC	475.6020***	31.83364***	31.61697***

Note: *,**, and *** are significance level at the 10%,5%, and 1% level, respectively.

Following testing the cross-section dependence, the convergence of the cropland ecological balance is investigated by the second-generation panel unit root tests. In addition to the effect of the cross-section dependence on the power of the test result, the validity of the structural breaks and the structural breaks' forms, endogenous and exogenous, and the number of structural breaks in the series generation highly matter for the reliability of the unit root test results. In order to reach more comprehensive and accurate evidence on the convergence of the cropland ecological balance, three kinds of panel unit root tests in the second-generation approaches are performed, and the classification is conducted in terms of the panel unit root tests' allowing or ignoring the structural breaks. The first group of the applied panel unit root tests, ignoring the structural breaks, involves CIPS and CADF panel unit root tests. The null hypothesis of these panel unit root tests indicates that the panel involves a unit root. Suppose the test statistics' absolute values are lower than the absolute values of the critical values. In that case, the null hypothesis can not be rejected, which reveals the findings that verify the absence of the convergence hypothesis and the validity of the divergence hypothesis. The CIPS and CADF panel unit root test results are documented in Panel A and Panel B Table 2, respectively. The null hypothesis of the CIPS panel unit root tests is accepted, which means that the panel involves a unit root. The difference in the cropland ecological balance among the countries is not mitigated, and the cropland ecological balance is diverged. However, the convergence hypothesis is verified by the CADF panel unit root tests.

Table 2. The Finding of the Panel Unit Root Tests.

Panel A: The Result of CIPS Unit Root Test				
CIPS t-stat	**CV 1%**	**CV 5%**	**CV 10%**	**P-Value**
–1.80058	–2.50	–2.28	–2.17	>=0.10
Panel B: The Result of CADF Unit Root Test				
CADF t-bar	**CV 1%**	**CV 5%**	**CV 10%**	**P-Value**
–2.542***	–2.030	–2.110	–2.260	0.000
Panel C: The Result of Panel-LM Unit Root Test				
	Statistics	**P-value**		
Panel LM	-9.163***	0.000		
Panel CA-LM Transformed	-2.291**	0.011		
Panel D: The Result of Panel-KPSS Unit Root Test				
	Statistics	**CV 1%**	**CV 5%**	**CV 10%**
Stationarity test with structural breaks (homogeneous):	4.441	13.563	9.688	7.474
Stationarity test with structural breaks (heterogeneous):	7.524	12.121	9.512	8.295
Panel E: Bahmani-Oskooee et al.'s [15] Panel KPSS Unit Root Test				
	PANKPSS	**CV 1%**	**CV 5%**	**CV 10%**
homogeneous panel_KPSS stat	2.3853	5.2518	3.9334	3.0739
heterogeneous panel_KPSS stat	1.0394	8.6618	5.9831	4.7920

Note: *,**, and *** are significance level at the 10%,5%, and 1% level, respectively.

Regarding the theoretical framework of the convergence hypothesis, differences in the series among the panel sample decrease over time. Each series in the panel possesses a different movement pattern, which is induced by the presence of the stochastic pattern of each series. In addition to implementing joint actions, examining the univariate stationary analysis provides an essential insight into whether individual efforts can be applicable to enhance the cropland ecological balance. Although Time-series unit root tests disclose the stochastic pattern of the series of each country, CADF, Panel KPSS, and the Panel KPSS of Bahmani-Oskooee unit root tests also promote the univariate unit root tests of cross-sectional units. Like following the interpretation steps in examining the convergence hypothesis, the finding of the CADF unit roots of cross-sectional units is first considered. Later, the outcome of Panel Lm, Panel KPSS, and the Panel KPSS of Bahmani-Oskooee unit root tests of cross-sectional units are evaluated, respectively.

The finding of CADF unit roots is displayed in the second and third columns of **Table 3**. As a result of the CADF univariate unit root tests, it is found that the cropland ecological balance of France and Canada does not possess a unit root. They are stationary because the mentioned countries' CADF test statistics are higher than the 5% level of significance of the critical values in the absolute forms. Meanwhile, the null hypothesis can not be rejected for the rest of the cross-sectional units.

At the same time, 11 out of 13 countries' series will be persistently influenced by ant shocks caused by countries' efforts. As for the Panel KPSS test results allowing for considering multiple sharp structural breaks shown in **Table 3**, the null hypothesis can not rejected for 11 out of 13 countries, and only the cropland ecological balance of Brazil and India does not have a constant-mean and mean-reverting patterns. Brazil and Indian governments can implement local policies that will negatively impact the cropland ecological balance.

Following the first-group of panel unit root tests, which ignore structural breaks, the Panel-LM and Panel KPSS panel unit root tests are executed to verify whether the cropland balance is converged. The Panel-LM and KPSS panel unit root tests are utilized as the second kind of panel unit root tests, allowing for sharp structural breaks and considering the cross-section dependence. The Panel-LM and KPSS unit root test findings are displayed in Panel C and D in **Table 2**, respectively. The Panel LM, which provides the result based on the first-generation approach, and the Panel CA-LM transformed, which promotes the result based on the second-generation approach, can be evaluated by performing Panel-LM unit root tests. The null hypotheses of the Panel LM unit root tests indicate that the panel involves a unit root. If the p-values of the Panel LM and Panel CA-LM transformed do not exceed the significance of 5%, the null hypothesis can not confirmed. The outcomes of the tests are documented in Panel C in **Table 2.** The results of Panel LM and Panel CA-LM confirm the validity of the alternative hypothesis, which means that the cropland ecological balance is converged across the panel sample. However, the Panel KPSS unit root test null hypothesis means the panel is stationary. If the test statistic does not exceed the critical values, the null hypothesis is accepted, which approves the convergence hypothesis. When comparing the test statistics with a 5 % significance level, it is concluded that the null hypothesis can be accepted, and the evidence reveals that the difference in the cropland ecological balance lessens over time among the panel samples. The convergence hypothesis holds for the considered countries. The Panel KPSS introduced by Bahmani-Oskooee et al. [15] is the last panel unit root test applied in the study in Panel E in **Table 2**, and it is regarded as the third version of the panel unit root tests, allowing for considering multiple sharp and smooth structural breaks. Like the Panel KPSS unit root tests, the Panel KPSS of Bahmani-Oskooee directly investigates the convergence hypothesis because the null hypothesis reveals the presence of the panel stationary. The test statistics of homogeneous and heterogeneous panel KPSS stat do not exceed the critical values of a 5% significance level. Hence, the null hypothesis is valid for the considered countries, which claim supportive evidence of the presence of the convergence hypothesis.

Table 3. The Result for Univariate Panel Unit Root Test.

Panel A: CADF Unit Root Test			**Panel B: KPSS Unit Root Test**		
Country	**CADF t-stat**	**p-Values**	**KPSS test**	**Breaks Dates**	**Critical Values 5%**
Russia	–1.65248	>=0.10	0.351	2008–2016	0.656
United States	2.35070	>=0.10	0.087	1996–2003	0.710
Netherlands	–3.04035	<0.10	0.168	1995	0.449
Brazil	–1.74065	>=0.10	0.596	2003–2014	0.280
Germany	–2.76096	>=0.10	0.168	1995–2005	0.470
China	–0.15586	>=0.10	0.056	2003–2011	0.346
France	–4.64724	<0.01	0.268	-	0.571
Spain	0.33393	>=0.10	0.214	2017	0.429
Italy	–1.00195	>=0.10	0.051	2001–2007	0.322
Canada	–4.12934	<0.01	0.104	2013	0.495
Belgium	–3.25750	<0.10	0.129	2008	0.421

Table3. *Cont.*

Panel A: CADF Unit Root Test			Panel B: KPSS Unit Root Test		
Country	**CADF t-stat**	**p-Values**	**KPSS test**	**Breaks Dates**	**Critical Values 5%**
Indonesia	–0.85340	>=0.10	0.286	2003	0.382
India	–2.85242	>=0.10	0.634	2014	0.513

The final part of the empirical investigation evaluates the univariate result of Bahmani-Oskooee et al.'s [15] panel unit root test for each cross-sectional unit. The evidence from this analysis is reported in Table 4. Before examining whether any shocks will have a persistent influence on each cross-sectional unit's series, the significance of the Fourier function is to be detected. When reviewing the comparison between F-test statistics values and the critical values of the F-test at a 5 % significance level, the Fourier function is statistically significant for all considered countries except Italy. As for Italy, the result of the unit root tests ignoring multiple smooth structural breaks and the structural breaks should be regarded as providing the policy recommendations. In the case of the remaining countries, the numerous smooth structural breaks matter for the series data generation process. As a consequence of the Bahmani-Oskooee et al.'s [15] panel unit root test, it is indicated that the null hypothesis holds for Germany, China, France, Indonesia, and India at a 5% significance level, while the null hypothesis is not verified for the rest of the countries. Regarding the null hypothesis verified countries, their series possess a constant mean, mean-reverting pattern and do not involve a unit root. Therefore, their mean values and variance tend to move around their series' long-term trend paths. Any attempt will not induce the series to deviate from the series' long-term trend paths, and the policies do not temporarily impact the cropland ecological balance. Therefore, these countries should concentrate on joint actions. As for the series belonging to 6 out of 12 countries, they can implement their determined policies to enhance the cropland ecological balance in addition to the joint actions.

Table 4. The Result Univariate Panel Unit Root Test of Bahmani-Oskooee.

Panel A: The Result Univariate Panel Unit Root Test of Bahmani-Oskooee et al.'s [15]						
Country	**KPSS**	**95%CV**	**Breaking Dates**	**OF**	**F-Test**	**95%CV**
Russia	0.1105	0.0928	2001–2011	3	9.9994	3.2947
United States	0.1741	0.0724	1996	1	23.5475	3.5330
Netherlands	0.1979	0.0657	1996–2000	1	6.5166	4.8833
Brazil	0.0888	0.0879	2003–2008	2	52.1866	3.3808
Germany	0.0350	0.0470	1995–2012	1	24.5115	3.5242
China	0.1540	0.1641	2007–2014	4	12.4161	3.1668
France	0.0742	0.0847	2009	1	8.0874	3.2009
Spain	0.3690	0.1692	2009	3	3.8230	3.3937
Italy	0.0545	0.1000	2001–2007	5	1.4076	3.2873
Canada	0.3444	0.2520	2013	2	3.2955	3.3497
Belgium	0.1261	0.0874	2001	2	9.3756	3.3174
Indonesia	0.1471	0.1534	2007	2	7.5816	3.4203
India	0.0514	0.1946	2010–2013	5	4.4417	3.4774

OF means optimal frequency and CV presents critical values.

5. General Assessment on the Importance of the Sustainable Agriculture Ecosystem

In this section, some assessments and evaluations are disclosed before the conclusion. Famine and starvation are among the most mentioned cussedly oracles in the holy books and ancient documents. Regarding economic thoughts, some outstanding authors, such as Malthus and D. Ricardo, have also pointed out that, if necessary, measures are not taken, humanity will inevitably face hunger, famine, and economic collapse. However, the cursed prophecy has been out of the matter for a long time, with the help of technological improvement and advances in agriculture, improvement in worldwide transportation, and the world population has reached a massive number. However, extensive use of fertile soils, polluted wastes, deforestation, and environmentally hazardous substances have nowadays harmed the natural assets' capacity, threatening the global food supply chain. Environmental degradation, such as floods, droughts, extreme cold and heat weather, melting glaciers driven by global warming, and climate change, are significant menaces to sustainable agriculture and livestock. A substantial portion of society, primarily developing and least developing countries, has encountered severe famine and starvation, and the developed countries have encountered a food supply crisis because of extreme weather conditions. Moreover, the prediction of the global population and the severe effects of various environmental degradation on the planet will accelerate the problems associated with famine and starvation. Therefore, the future generation will encounter an unbearable catastrophe if accurate and reliable solutions and policies cannot be detected and implemented.

6. Conclusion

It is crucial to base sustainable agricultural practices and global supply chain strategies on solid scientific evidence and comprehensive analyses. While numerous reports and policy frameworks provide fundamental guidance, the integration of scientific methodologies ensures actionable and effective measures. Researchers have extensively analysed key food-related indicators, such as fishing, grassland, and cropland, using advanced econometric techniques to understand their dynamics and resilience. In ecological economics, studies on sustainable agriculture and livestock have garnered significant attention due to the critical role these sectors play in mitigating risks to the global food supply. Disruptions in agricultural systems can ripple through economic structures, highlighting the importance of examining the stochastic properties of agricultural and livestock data. Such rigorous analyses provide policymakers with the necessary evidence to design interventions that enhance resilience, support ecological balance, and align with long-term sustainability goals.

The evidence derived from the stochastic properties of the series provides critical insights into the effectiveness of joint actions and local policies. The convergence hypothesis and the persistence of the series are central to understanding the dynamics of these properties. The convergence hypothesis assesses whether joint, international actions and collaborations can be effectively implemented to align practices among countries. Simultaneously, the persistence of the series indicates whether any shocks have a permanent impact, highlighting the degree to which policy success depends on the series' response to external influences.

Panel unit root tests are instrumental in evaluating the convergence hypothesis, with the verification of stationarity within the panel sample signifying convergence. This suggests that disparities across countries diminish over time, allowing for coordinated and harmonized policy actions. On the other hand, univariate unit root findings from specific panel unit root tests and time-series analyses provide deeper insights into whether the series responds persistently to shocks introduced by policies. If stationarity is confirmed, the series follows a mean-reverting pattern, implying a stable long-term trajectory where shocks cannot permanently alter the series.

To enhance policy effectiveness, country-specific recommendations should complement joint actions. For instance:

Canada should continue leveraging its improvements in ecological balance by focusing on policies that reinforce sustainable practices in cropland management.

The Netherlands, France, Germany, and the United States must prioritize reversing declining trends by adopting stricter measures against soil degradation and promoting regenerative agricultural methods.

Emerging agricultural powers like China, India, and Indonesia should integrate advanced sustainable technologies to mitigate ecological footprints without compromising productivity.

Belgium, Brazil, Italy, and Spain, having shown progress, could serve as regional models for sustainable practices by sharing best practices with neighboring countries.

These tailored recommendations, grounded in the stochastic dynamics and convergence analysis, provide a balanced approach to addressing country-specific challenges while fostering global collaboration for ecological stability.

Another essential initiative concerning the global supply chain is employing a comprehensive indicator, and the study focuses on the cropland because the cropland footprint is the most bio-productive of the land-use types involving the area of land required to grow all crop products, including livestock feed, fish meal, oil crops, and rubber. In the study, the cropland ecological footprint donating the anthropogenic pressure or degradation on the cropland and the cropland biocapacity representing the reproductive and capacity of the cropland is simultaneously executed, and the cropland ecological balance (calculated by cropland biocapacity- cropland ecological footprint) is employed. With the help of using cropland ecological balance, the study provides evidence on the supply and demand side of the cropland and plays a vital role in sustainable cropland production. The top 13 cropland-producer countries are concentrated in the study because of the objectives of revealing comprehensive and extensive evidence of global cropland sustainability. In addition, various types of panel unit root tests allowing for cross-sectional dependence are performed, and the classification of the panel unit root tests is based on the tests' assumption of the structural breaks. Three kinds of panel unit root methods are employed: the first group methods, ignoring the structural breaks, are the CIPS and CADF panel unit root tests; the second group methods, allowing for sharp and limited structural breaks, are Panel LM, Panel CA-LM, Panel KPSS; the third group methods, allowing for multiple, smooth and unknown structural breaks, is Bahmani-Oskooee et al.'s [15] Panel KPSS Unit Root Tests.

The study discloses that the convergence hypothesis holds for the countries considered when interpreting the evidence from the panel unit root tests. This finding implies that cropland sustainability in a country with adequate levels is impaired, while cropland sustainability in a country with deficient levels improves over time. The countries in the study should consider and evaluate collaborative actions and policies to enrich the cropland biocapacity and mitigate cropland degradations. In addition, the univariate result for each cross-section unit is varied through the panel unit root tests. For example, the CADF unit root tests show that all countries' series except France and Canada possess a persistent response against the policy's shocks, while the cropland ecological balance of Brazil and India have a constant mean and mean-reverting patterns inducing the non-persistence response according to the Panel KPSS unit root tests. Bahmani-Oskooeal's et al.'s [15] panel unit root test presents that the governments of Germany, China, France, Indonesia, and India can not achieve perminant results because their series can not deviated from their long-run paths. After all, the policies will not persistently impact the cropland ecological balance. Therefore, the study discloses that most of the countries have an applicable situation where collaborative and local policies can be implemented to enrich cropland sustainability. When viewing the literature concerning the stochastic properties of environmental-related indicators, many studies also reveal the convergence hypothesis and mixed university stationary results [15,46,49].

One of the most required policy actions for mitigating cropland degradation and improving cropland capacity is using green, least polluted, energy-efficient, and advanced agriculture methods. The accessibility of funds, such as long-term and low-interest-based loans for small and medium farmers, plays a vital role in applying these methods for cropland production. The local governments and all considered countries can create and facilitate the funds for the producers. However, subsidies, tax exemption, and encouragement of young and women's enterprises are also other essential policy recommendations for sustaining and improving cropland production. Mainstream biodiversity conservation and protection ecosystem functions, strengthening the enabling environment and reforming the institutional framework, and preventing and protecting against shocks: enhancing resilience is underlined policy action for strength cropland productions. Intelligence water and land management, controlling and implementing strict norms and laws against toxic pesticides are also promoted actions for lessening cropland degradation. Finally, increasing awareness and promotion for reducing losses, encouraging reuse and recycling, and promoting sustainable consumption are among the most required actions.

All in all, the study has been operated under some limitations, and further research will expand and enrich the literature by considering the study's limitations. For example, the study sample can include regional and country development levels. Besides, the determinants of the cropland-related indicators, such as the cropland ecological footprint, the cropland ecological balance and the cropland Load capacity factor, are underlined further research topics. Some seminal hypotheses in the literature, such as the Pollution Haven, EKC hypothesis, and the LCC hypothesis, can be investigated.

Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest

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