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# Assessing the Socio-Economic and Natural Factors Shaping Türkiye's Virtual Land Trade Balance

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**Abstract**

Agricultural trade not only facilitates the exchange of final products but also leads to the indirect transfer of arable land resources involved in their production processes across countries. These indirect flows are commonly referred to in the literature as virtual land flows or virtual land trade. An in-depth understanding of the factors influencing virtual land flows is crucial for both the management of these flows and the sustainable and efficient allocation of limited arable land resources on a global scale. The objective of this study is to identify the key determinants that influence virtual land flows in Türkiye's trade of plant-based agricultural products. To achieve this, the virtual land trade balance for Türkiye was computed by estimating the import and export volumes of virtual land from 1986 to 2019, based on crop, year, and country-specific yield values. Subsequently, the relationship between Türkiye's virtual land trade balance and macroeconomic and environmental variables—such as Gross Domestic Product (GDP), the real effective exchange rate, annual total precipitation, per capita arable land, and fertilizer usage—was investigated using the ARDL bounds testing approach. The findings of this study indicate that the most significant factors influencing Türkiye's virtual land flows are per capita arable land endowment and fertilizer usage. This result highlights the strong relationship between virtual land flows and variables related to productivity and natural resource endowment, while also emphasizing the importance of integrating sustainability considerations and environmental impacts into contemporary agricultural policy frameworks. Elucidating the dynamics of virtual land trade is a pivotal step toward ensuring the long-term sustainability of international agricultural trade, as well as the equitable and efficient allocation of arable land resources. Furthermore, it represents a fundamental strategy for global agricultural production, offering critical insights for shaping future agricultural policy and practice at the global level.

**Keywords:** virtual land trade; sustainable land management; land use efficiency; arable land resources; ARDL bounds testing; international trade and sustainability



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## 1. Introduction

The global distribution of arable land is highly heterogeneous, leading to substantial disparities in land endowments among countries and regions [1]. In addition to spatial inequality, significant temporal variations in the availability of these resources also exist. Due to economic, demographic, and environmental factors, arable land has increasingly become a scarce and declining resource worldwide [2]. Given the high dependency of agricultural production on arable land, agricultural trade has evolved from being a strategic choice to becoming a necessity—particularly for countries and regions where population density is high, but arable land resources are limited [3]. In this context, global agricultural trade acts as a bridge, linking countries with a surplus of arable land to those experiencing scarcity [4,5], thereby partially offsetting the global heterogeneity in land distribution. Consequently, agricultural trade not only promotes welfare gains for trading nations but also facilitates the efficient allocation of water and land resources across borders [6]. This mechanism primarily operates through the virtual land flows embedded in agricultural trade [7].

The concept of virtual land refers to the embedded arable land that is indirectly exchanged between trading countries through traded agricultural commodities [8]. The theoretical foundation of this concept lies in the observation that countries differ in the amount of land required to produce the same quantity of agricultural products, and that these differences create an opportunity for conserving and saving limited global arable land through trade [7]. Such conservation is only possible when trade flows are based on positive productivity differentials between countries [9].

The role of agricultural trade in conserving water and land resources has been extensively examined in the literature. Empirical studies indicate that when international trade flows originate from countries with higher production efficiency and are directed toward less efficient producers—or are reorganized accordingly—significant savings in global water and land resources can be achieved [10–12]. For instance, China's agricultural trade between 1986 and 2009 contributed to a global annual land saving of approximately 3.27 million hectares [4]. Similarly, global cereal trade alone results in an annual average land saving of about 50 million hectares—an area roughly equivalent to the size of Spain [7]. Moreover, the volume of arable land embedded in international trade has expanded significantly in parallel with the growth of agricultural trade, now encompassing nearly one-third of the world's total arable land area [5].

Global agricultural trade plays a particularly vital role in mitigating the adverse effects of land scarcity, especially in countries grappling with limited arable land resources [4]. Through international trade, local arable land is utilized not only to satisfy domestic consumption demands but also to meet cross-border consumption needs [12]. In this context, agricultural trade enables land-scarce countries to indirectly benefit from arable land resources located beyond their national borders, thereby significantly alleviating the pressure imposed on domestic land resources [8]. By meeting consumption demands through imports, countries effectively shift land-use demand from domestic to foreign land resources. However, such transboundary reallocations also generate cross-border environmental and ecological implications [13]. Although land resources remain physically situated within national boundaries, their functional use increasingly transcends domestic needs. As a result of growing consumption and trade activities, the utilization of local land resources increasingly transcends national borders, thereby necessitating a reconfiguration of land use and management strategies from an international perspective. Today, indirect land flows associated with global trade and consumption have become as significant as—or in many countries even more significant than—direct domestic land use. This paradigm shift underscores the urgent need to reconsider land-use policies through a virtual land perspective, particularly for countries facing arable land scarcity [5]. In this context, the systematic integration of virtual land flows into agricultural and trade policy frameworks is essential for ensuring sustainable food security and the effective, long-term management of limited arable land resources—especially in land-scarce nations.

A review of the existing literature reveals that virtual land flows in global agricultural trade are largely shaped by the economic development levels of countries, with flows predominantly directed from less developed to more developed nations [6,12,14,15]. This pattern points to an uneven distribution of environmental costs, which are disproportionately borne by developing countries [16]. Nevertheless, the observed structure of current trade flows also highlights the significant potential of virtual land trade to contribute to a more balanced, equitable, and sustainable global agricultural system—provided that such flows are appropriately managed. Realizing this potential requires not only identifying the spatial and temporal distributions of virtual land flows [2,4,7], but also systematically analyzing the key factors that influence these flows.

This study aims to identify the socio-economic and environmental factors influencing virtual land flows in Türkiye's crop trade. To this end, the volumes of virtual land exports and imports in crop trade between 1986 and 2019 were calculated based on yield data specific to year, crop type, and trading partner. Subsequently, the relationship between Türkiye's virtual land trade balance in crop products and selected macroeconomic and environmental variables was examined. Specifically, the study investigates how Gross Domestic Product (GDP), the Real Effective Exchange Rate (REER), total annual precipitation, arable land per capita, and fertilizer use relate to the virtual land trade balance, employing the Autoregressive Distributed Lag (ARDL) bounds testing approach.

Despite the decreasing share of agriculture in Türkiye's GDP, the country remains a major player in agricultural trade. However, existing research on indirect resource flows—particularly virtual flows—in Türkiye's agricultural trade remains scarce. This study addresses that gap and seeks to raise awareness among scholars and policymakers about the strategic relevance of virtual resource flows for shaping future agricultural and trade policies. Future studies that jointly examine virtual land and water flows, and extend the analysis to include livestock products, could offer a more comprehensive perspective.

Beyond its empirical focus, the study also aims to explore the extent to which virtual land flows align with or diverge from the predictions of the commodity trade model. In particular, it investigates whether traditional drivers such as relative income and price differentials remain dominant, or whether alternative dynamics—including economic growth, agricultural policy interventions, and sustainability considerations—are increasingly influencing the direction and magnitude of these flows. In this context, the study aims not only to reveal the determinants of virtual land trade but also to discuss how this phenomenon is positioned within the framework of the commodity trade model, while also reflecting the influence of contemporary economic dynamics and policy developments.

## 2. Materials and Methods

In the study, the driving factors of Türkiye's virtual land trade balance were examined through a foreign trade model developed within the context of socio-economic and environmental variables. The foreign trade balance is generally calculated based on net exports ($X - M$), which represents the difference between total exports (X) and total imports (M). However, in this study, the export-to-import ratio ($X/M$) was adopted [17–20] in calculating the virtual land trade balance. Calculating the trade balance based on ratio values has certain significant advantages, such as being insensitive to different measurement units and being interpretable in both nominal and real terms [17]. In this way, the difficulties related to logarithmic transformations of negative values encountered in calculations based on net exports are also eliminated. All statistical analyses in this study were conducted using EViews 12 software.

### 2.1. Theoretical Model Specification

The theoretical foundation of the trade balance model is based on the relationship between relative income and price levels across countries. The trade balance model, constructed through relative income and price variables, is expressed in the following equation:

$$X/M = f\{PH/PW, YH/YW\} \quad (1)$$

where X is virtual land exports, M is virtual land imports, PH is domestic price level (Türkiye), PW is world price level, YH is domestic income (Türkiye's GDP), and YW is world income (Global GDP).

In the study, the relative income level is incorporated into the model using the Gross Domestic Product (GDP) variable, while the relative price level is represented by the real effective exchange rate based on the Consumer Price Index (CPI).

The concept of virtual land is relatively new in the literature, and its theoretical framework is yet to be fully established. As such, there is no widely accepted or standardized theoretical model currently available on the subject. Moreover, the virtual land concept largely builds upon the theoretical foundations of virtual water, which themselves remain underdeveloped [3], thereby further complicating the construction of a coherent theoretical framework for virtual land. Indeed, many studies in the literature do not directly address virtual land per se, but instead rely on theoretical approaches initially developed for virtual water trade [21–23]. However, due to the diversity of methodological approaches adopted in these studies—such as gravity models, input-output analysis, and panel regressions—there is a significant lack of theoretical consensus. In addition, there is still no agreement in the literature regarding the determinants of virtual land trade. Consequently, the absence of a well-defined theoretical model for virtual land flows and the lack of clarity about which variables influence these flows and in what direction make both the development of a theoretical framework and the selection of explanatory variables particularly challenging [22].

The concept of virtual water—introduced to the literature by Allan [24]—is considered an extension of the classical theory of comparative advantage. In a similar vein, Merret [25] underscores the close link between the virtual water concept and agricultural trade, arguing that the phenomenon cannot be examined independently of agricultural trade dynamics. Furthermore, most empirical studies have explored the issue within the context of countries' factor endowments [7,22,23]. Given these considerations, our study adopts a traditional trade balance model, which offers a theoretically coherent and analytically robust framework for two main reasons. First, virtual land trade is inherently connected to factor endowment theory. The trade of agricultural products entails not only the movement of final goods but also the implicit transfer of natural resources—such as land and water—used in the production process [7]. This dynamic reflects the logic of the Heckscher–Ohlin model, whereby countries are expected to export goods that utilize their relatively abundant factors of production and import goods that require relatively scarce ones. In this context, key variables in trade balance models—such as relative prices (real effective exchange rate) and income level (GDP)—are also meaningful and relevant in explaining virtual land flows [12,14,22]. Second, most empirical studies on virtual water and virtual land trade in the existing literature adopt methodological frameworks that closely align with classical international trade models [11,26,27].

For all these reasons, the adaptation of a traditional trade balance model to the context of virtual land trade in our study is not merely a technical choice, but also a deliberate effort to link the concept of virtual land to the foundational principles of classical international trade theory and to address the theoretical gap in the literature. This model enables a theoretically consistent examination of the socio-economic and environmental drivers of virtual land flows and contributes to establishing the theoretical coherence that is currently lacking in the field.

*2.2. Variable Selection and Rationale*

The concept of virtual land originates essentially from the notion of virtual water, and its theoretical framework has been largely shaped within the literature on virtual water. The term virtual water refers to the total amount of water embedded in agricultural products that is transferred between parties as a result of trade activities [28]. The concept was initially introduced as a global alternative solution to the water scarcity problem in the MENA region (Middle East and North Africa), where severe water shortages prevail and food demand is largely met through imports. In this context, the virtual water approach is grounded in the idea that local or regional water scarcity can be alleviated through the trade of agricultural products [3]. According to this approach, there are significant differences in water use efficiency across countries in agricultural production processes. Therefore, when agricultural trade flows occur in alignment with these differences in productivity, it becomes possible to conserve global water resources and achieve significant savings. These positive productivity differences are essentially based on countries' disparities in resource use efficiency and are closely linked to the agricultural production techniques and methods employed [9].

The virtual land concept, on the other hand, is a derived form of virtual water applied in the context of land resources. Accordingly, virtual land is defined as the productive land resources involved in the production processes of traded agricultural products, which are virtually transferred between trading partners [8]. When countries export or import goods, they also, in a sense, export or import the land resources used in the production of those goods. Thus, land, traditionally considered a fixed resource, becomes fluid through trade and virtually shifts between trading parties [7].

Virtual land flows in agricultural trade can be calculated based on countries' trade volume data [2]. Quantitative assessments of virtual land flows are critical for understanding land use profiles [12] and determining the level of dependency on transboundary land resources [7]. However, to manage these flows effectively and sustainably and to evaluate them within the scope of current agricultural production and trade policies, it is crucial to identify the factors that influence these flows. Yet, studies focusing on the determinants of virtual land trade [2,12,14,29] remain relatively limited compared to those examining the determinants of virtual water trade [21–23,30,31]. A limited number of studies [32–34] have jointly considered virtual water and land flows. More recent studies [6] have examined the determinants of virtual land trade in a broader context, encompassing both crop-based and livestock agricultural products. Their findings indicate that virtual land and water flows are significantly influenced by factors such as economic development, agricultural resource endowments, and trade policies. While this line of research underscores the importance of extending the scope of VLT analyses to include livestock products, the present study is deliberately restricted to crop-based trade. This focus is motivated by the structural differences in production systems and land-use intensity, which allow for more precise insights. Nevertheless, incorporating livestock-related flows into future VLT research is expected to provide valuable complementary evidence and contribute to a more comprehensive understanding of global virtual land dynamics.

A review of the existing literature on the determinants of virtual land flows shows that the availability of arable land is among the most widely agreed-upon explanatory variables. Empirical findings suggest that countries with abundant arable land tend to be virtual land exporters in global agricultural trade, while countries with limited land resources tend to be importers [4,7]. However, subsequent studies have indicated that relative rather than absolute endowments of land resources are more influential in determining virtual land flows [22,23]. Moreover, some studies show that there may not always be a linear relationship between a country's arable land endowment and its virtual land flows [14]. Indeed, despite having large arable land endowments, countries tend to increase their demand for transboundary land resources (i.e., virtual land imports) as income levels rise [35]. In this regard, GDP, a commonly used proxy for a country's level of economic development, is another frequently included variable in studies on the determinants of virtual water and land flows [12,14]. Empirical evidence shows that virtual water and land flows globally tend to move from less developed to more developed countries [16]. Regional-level studies also confirm that increases in economic development lead to increases in virtual land imports [6,12,14,15]. This trend is explained in the literature by the structural transformation accompanying rising economic development. In such a transformation, the industrial sector gains relative importance in the economy, while the agricultural sector's share in GDP diminishes [36]. At the same time, economic development leads to significant changes in dietary patterns. Rising income levels increase the demand for animal products such as meat and dairy, as well as high-value agricultural products like fruits and vegetables, thereby prompting a shift toward more diversified and resource-intensive diets [1].

Another variable thought to affect virtual land flows is the level of fertilizer use in agricultural production processes. Increases in fertilizer use enhance agricultural production and export capacity, thereby increasing virtual water and land exports [22]. Among environmental variables, precipitation is the most frequently studied. It is assumed that increased precipitation enhances agricultural production capacity, thereby increasing agricultural exports and indirectly boosting virtual water and land exports [23]. However, empirical findings on the role of precipitation are mixed. Some studies show that precipitation has no significant effect on virtual water and land flows [21,37].

For all these reasons, the independent variables in this study are classified into two main groups: socio-economic and environmental. Within the socio-economic group, gross domestic product (GDP), real effective exchange rate (REER), and total fertilizer use per hectare are selected as the primary explanatory variables. The environmental group includes arable land area per capita and annual precipitation.

The dependent variable of the study is defined as the ratio of Türkiye's total virtual land exports to total virtual land imports in the trade of crop-based agricultural products. This ratio reflects Türkiye's virtual land trade balance. In line with all the variables mentioned above, the conceptual framework of the study is presented in Figure 1.

The framework in Figure 1 illustrates the main channels through which socio-economic and natural factors influence VLT. Supply-side determinants include arable land per capita (ARL) as an indicator of resource availability, and fertilizer use (FRT) as an indicator of agricultural input intensity. Demand-side drivers are represented by gross domestic product (GDP), while external factors are captured by the real effective exchange rate (REER) and precipitation. The arrows indicate the independent influence pathways of each variable on VLT through resource availability, input intensity, demand, and external channels.

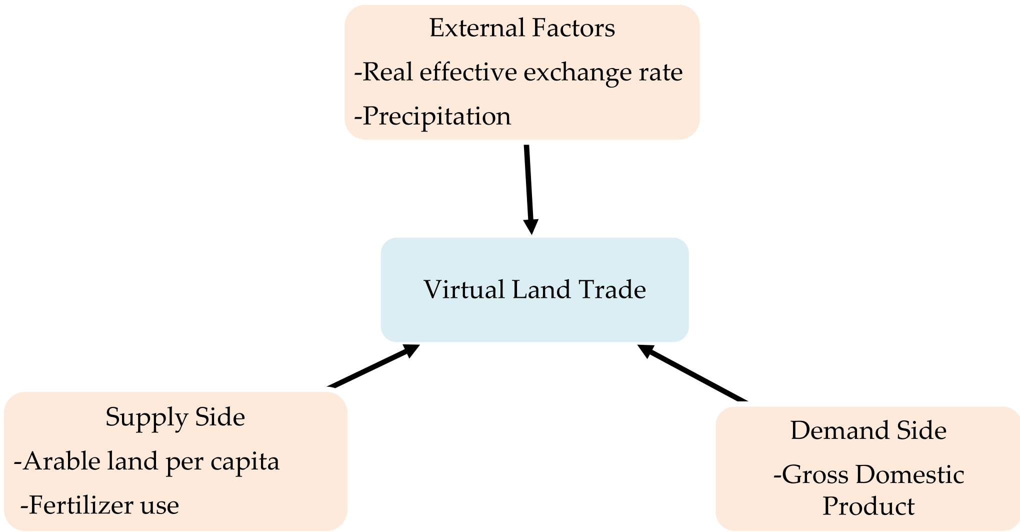


**Figure 1.** Conceptual framework of virtual land trade (VLT).

### 2.3. Data Summary

The variables included in the model, along with their descriptions, are presented in Table 1, while their descriptive statistics are provided in Table 2.

**Table 1.** Details of the study variables.

| Variables | Symbol | Unit | Source |
|---|---|---|---|
| Virtual land trade balance | VLT | ha | FAOSTAT |
| Türkiye GDP/World GDP | GDP | dollars | World Bank |
| Real effective exchange rate | REX | - | Federal Reserve Bank |
| Total fertilizer use per hectare of arable land | FRT | kg | World Bank |
| Arable land per capita | ARL | ha | FAOSTAT |
| Total annual precipitation | YGS | mm | Türkiye State Meteorological Service |

**Table 2.** Descriptive statistics of the variables.

| | LNVLT | LNREX | LNGDP | LNFRT | LNARL | LNYGS |
|---|---|---|---|---|---|---|
| Mean | −0.306887 | 4.500884 | −4.487273 | 4.461156 | 1.059003 | 6.434646 |
| Median | −0.465173 | 4.499706 | −4.517966 | 4.468356 | 1.027678 | 6.455871 |
| Maximum | 1.425132 | 4.779526 | −4.194023 | 4.925319 | 0.715453 | 6.676832 |
| Minimum | −1.221096 | 4.211636 | −4.704256 | 4.111094 | 1.450119 | 6.200712 |
| Std, Dev, | 0.674537 | 0.155984 | 0.158094 | 0.211886 | 0.229709 | 0.113251 |

Source: Author's computation.

Figure 2 presents the annual differences between the growth rates of Türkiye's virtual land exports and imports during the period 1987–2019. The use of the export-to-import (X/M) ratio as the dependent variable may involve certain limitations, as ratio variables do not always reflect changes in absolute trade volumes and may appear artificially stable if exports and imports increase at similar rates. However, as illustrated in Figure 2, the growth rates of exports and imports differ significantly in most years within the dataset, and do not exhibit a synchronized pattern. This suggests that the X/M ratio serves as a meaningful indicator that reflects not only proportional, but also structural changes in trade dynamics. Accordingly, the methodological concern noted above appears to have limited relevance in the specific context of our dataset.

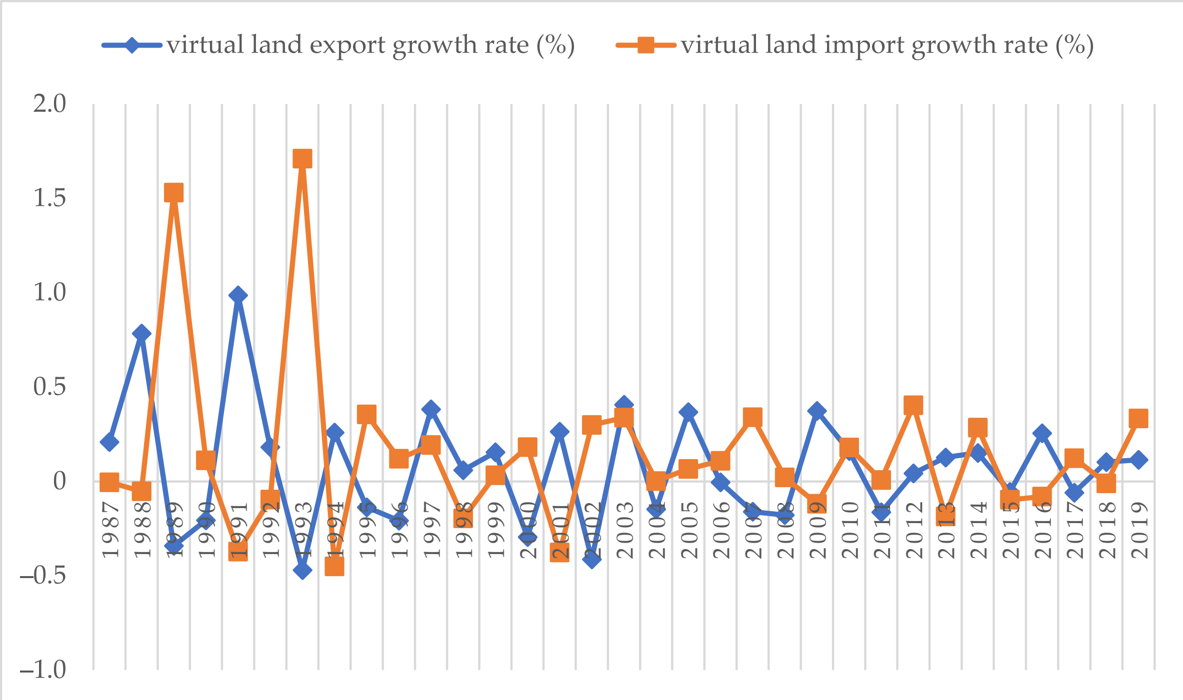


**Figure 2.** Annual differences between export and import growth rates in Türkiye's virtual land trade (1987–2019).

## *2.4. Econometric Methodology: ARDL Bounds Testing Approach*

This study aims to examine the determinants of virtual land flows in Türkiye's crop trade. To this end, the relationship between the virtual land trade balance and key macroeconomic and agro-environmental variables—including Gross Domestic Product (GDP), Real Effective Exchange Rate (REER), arable land per capita, total fertilizer use per hectare, and annual total precipitation—is analyzed using the Autoregressive Distributed Lag (ARDL) bounds testing approach [38].

The Autoregressive Distributed Lag (ARDL) model is considered a highly effective approach for analyzing both short- and long-run relationships among variables. One of its principal advantages is that it does not require all variables to be integrated of the same order. The method is applicable when the variables are integrated of order I (0), I (1), or a combination of both. However, a fundamental prerequisite for applying the ARDL approach is that none of the variables included in the model should be integrated of order I (2) [39].

Therefore, prior to the ARDL bounds testing approach, Augmented Dickey–Fuller (ADF) [40] and Phillips–Perron (PP) [41] unit root tests were performed to determine the stationarity status of the variables included in the model

### Model Specification

The relationship between the virtual land trade balance (VLT) and its socio-economic and natural determinants is formally represented by the following equation:

$$VLT_t = f\,(REX_t, GDP_t, FRT_t, ARL_t, YGS_t) \quad (2)$$

where VLT is virtual land trade balance (ratio of exports to imports), REX is real effective exchange rate, GDP is gross domestic product, FRT is total fertilizer use per hectare of arable land (kg), ARL is arable land per capita (ha/person), and YGS is annual total precipitation (mm).

After applying the logarithmic transformation, the research model is reformulated as presented in Equation (3):

$$\mathrm{lnVLT_t} = \beta_0 + \beta_1\,\mathrm{lnREX_t} + \beta_2\,\mathrm{lnGDP_t} + \beta_3\,\mathrm{lnFRT_t} + \beta_4\,\mathrm{lnARL_t} + \beta_5\,\mathrm{lnYGS_t} + \mu_t \quad (3)$$

where $\beta_0$ is the constant term, $\beta_1, \ldots, \beta_5$ are the coefficients to be estimated, and $\mu t$ is the error term.

To identify the short- and long-run relationships, the model has been re-specified in the unrestricted error correction model form as presented in Equation (4):

$$\begin{aligned}\mathrm{InVLT_t} &= \beta_0 + \textstyle\sum_{i=1}^{j} \beta_{1i}\Delta \mathrm{InVLT_{t-i}} + \sum_{i=0}^{k} \beta_{2i}\Delta \ln(\mathrm{REX})_{t-i} + \sum_{i=0}^{l} \beta_{3i}\Delta \ln(\mathrm{GDP})_{t-i} + \\ &\textstyle\sum_{i=0}^{m} \beta_{4i}\Delta \ln(\mathrm{ARL})_{t-i} + \sum_{i=0}^{n} \beta_{5i}\Delta \ln(\mathrm{FRT})_{t-i} + \sum_{i=0}^{p} \beta_{6i}\Delta \ln(\mathrm{YGS})_{t-i} + \mu_t\end{aligned} \quad (4)$$

In the context of the ARDL bounds testing approach, the F-test is applied to assess the existence of a cointegration relationship among the variables. Unlike conventional tests, the F-statistic exhibits a non-standard distribution that depends on the integration order of the variables—whether they are stationary at level (I (0)) or at first difference (I (1))—as well as on whether a constant or trend is included in the model and the number of regressors.

If the computed F-statistic is greater than the upper bound critical value, the null hypothesis of no cointegration is rejected, indicating the existence of a long-run relationship among the variables [32]. If the F-statistic is lower than the lower bound critical value, the null hypothesis cannot be rejected. When the F-statistic falls between the lower and upper bound critical values, the result is inconclusive, and no definitive inference can be made regarding the existence of a cointegration relationship.

The short-term equality and error correction model (ECM) for the ARDL model is as follows:

$$\begin{aligned}\Delta \mathrm{InVLT_t} &= \beta_0 + \beta_1 \mathrm{ECT_{t-i}} \textstyle\sum_{i=1}^{J} \beta_{2i}\Delta \mathrm{InVLT_{t-i}} + \sum_{i=0}^{k} \beta_{3i}\Delta \ln(\mathrm{REX})_{t-i} + \\ &\textstyle\sum_{i=0}^{l} \beta_{4i}\Delta \ln(\mathrm{GDP})_{t-i} + \sum_{i=0}^{m} \beta_{5i}\Delta \ln(\mathrm{ARL})_{t-i} + \sum_{i=0}^{n} \beta_{6i}\Delta \ln(\mathrm{FRT})_{t-i} + \\ &\textstyle\sum_{i=0}^{p} \beta_{7i}\Delta \ln(\mathrm{YGS})_{t-i} + \mu_t\end{aligned} \quad (5)$$

where $\mathrm{ECT_{t-i}}$ is the error correction term.

The coefficient of the error correction term (ECT) indicates the speed at which short-term deviations converge to the long-run equilibrium. A negative and statistically significant coefficient of the error correction term confirms the existence of a long-term relationship among the variables and shows that the system returns to the equilibrium state following any shock.

## 3. Results

### *3.1. Unit Root Tests*

Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests were conducted to determine the integration order of the variables included in the model. The results of the unit root tests for the variables are presented in Tables 3 and 4.

According to the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests, the variables LNVLT, LNREX, LNGDP, LNARL, and LNFRT are integrated of order one, I (1). The variable LNYGS, on the other hand, is stationary at level according to both tests and is thus classified as I (0). The unit root test results applied to the first differences in all series indicate that they are stationary at first differences, I (0), and that none of them contain a unit root at this stage. The fact that none of the series are stationary at the second difference, I (2), and that the variables exhibit different orders of integration, I (0) and I (1), suggests the possibility of a cointegration relationship among them. Therefore, the ARDL bounds testing approach, which allows for the analysis of cointegration relationships among variables with different orders of integration, was selected for this study.

**Table 3.** Augmented Dickey–Fuller (ADF) unit root test results.

| | Level | | | | | |
|---|---|---|---|---|---|---|
| **Variables** | **LNVLT** | **LNREX** | **LNGDP** | **LNARL** | **LNFRT** | **LNYGS** |
| Intercept | −2.6521 * | −1.8054 | −0.2578 | 0.8661 | 2.0317 | −5.6295 *** |
| | (0.0932) | (0.3714) | (0.9208) | (0.9937) | (0.9998) | (0.0000) |
| Trend and Intercept | −5.2519 *** | −1.7126 | −2.1180 | −2.1767 | −4.6696 *** | −5.5388 *** |
| | (0.0008) | (0.7229) | (0.5173) | (0.4862) | (0.0037) | (0.0004) |
| | First Difference | | | | | |
| | d (LNVLT) | d (LNREX) | d (LNGDP) | d (LNARL) | d (LNFRT) | d (LNYGS) |
| Intercept | −8.0771 *** | −6.4908 *** | −6.3142 *** | −5.6991 *** | −7.3859 *** | −8.1685 *** |
| | (0.0000) | (0.0000) | (0.0000) | (0.0000) | (0.0000) | (0.0000) |
| Trend and Intercept | −7.9777 *** | −6.6834 *** | −6.369 *** | −5.6734 *** | −5.3608 *** | −8.0330 *** |
| | (0.0000) | (0.0000) | (0.0000) | (0.0003) | (0.0009) | (0.0000) |

Source: Authors' computation. Note: The symbols *, and *** denote stationarity at the 10%, and 1% significance levels, respectively. Values presented in parentheses represent the corresponding *p*-values. Lag lengths were determined based on the Schwarz Information Criterion (SIC).

**Table 4.** Phillips–Perron (PP) unit root test results.

| | Level | | | | | |
|---|---|---|---|---|---|---|
| **Variables** | **LNVLT** | **LNREX** | **LNGDP** | **LNARL** | **LNFRT** | **LNYGS** |
| Intercept | −2.5032 | −1.8047 | −0.1690 | 1.5530 | −1.7636 | −5.7763 *** |
| | (0.1239) | (0.3718) | (0.9330) | (0.9991) | (0.3912) | (0.0000) |
| Trend and Intercept | −5.2519 *** | −1.7126 | −2.0991 | −2.1389 | −4.6376 *** | −5.6715 *** |
| | (0.0008) | (0.7229) | (0.5273) | (0.5062) | (0.0040) | (0.0003) |
| | First Difference | | | | | |
| | d (LNVLT) | d (LNREX) | d (LNGDP) | d (LNARL) | d (LNFRT) | d (LNYGS) |
| Intercept | −20.3108 *** | −6.4821 *** | −6.2946 *** | −5.7947 *** | −13.7646 *** | −18.8528 *** |
| | (0.0001) | (0.0000) | (0.0000) | (0.0000) | (0.0000) | (0.0001) |
| Trend and Intercept | −25.0290 *** | −7.1929 *** | −6.5554 *** | −6.2332 *** | −17.1186 *** | −16.8842 *** |
| | (0.0000) | (0.0000) | (0.0000) | (0.0001) | (0.0000) | (0.0000) |

Source: Authors' computation. Note: The symbols *** denotes stationarity at the 1% significance levels, respectively. Probability values are provided in parentheses. Lag lengths were determined based on the Schwarz Information Criterion (SIC).

### 3.2. ARDL Bounds Test

The results of the ARDL bounds test are presented in Table 5. In Table 5, the parameter k denotes the number of independent variables included in the ARDL model. In this study, instead of the critical values calculated by Pesaran et al. [38], the critical values provided by Narayan [39], which are specifically designed for studies with small sample sizes, were used.

**Table 5.** ARDL bounds test results.

| **k** | **F-Statistics** | **1%** | | **5%** | | **10%** | |
|---|---|---|---|---|---|---|---|
| | | **I (0)** | **I (1)** | **I (0)** | **I (1)** | **I (0)** | **I (1)** |
| 5 | 11.61330 | 4.537 | 6.370 | 3.125 | 4.608 | 2.578 | 3.858 |

Source: Authors' computation.

According to Table 5, the calculated F-statistic value (11.61) is substantially higher than the upper critical values at all significance levels (1%, 5%, and 10%). Therefore, the null hypothesis of no cointegration is rejected. This result indicates the presence of a long-run cointegration relationship between the dependent and independent variables.

The long-run coefficients of the variables were estimated employing the ARDL (2, 0, 2, 2, 0, 3) model specification. The statistical significance of the estimated coefficients, evidenced by probability values below 0.05 ($p < 0.05$), confirms their relevance. Interpretations regarding the direction and magnitude of the relationships between the dependent variable and explanatory variables are drawn based on these coefficients. The estimated long-run coefficients along with their associated probability values for the ARDL (2, 0, 2, 2, 0, 3) model are presented in Table 6.

**Table 6.** Long-run coefficients.

| Variable | Coefficient | Standard Error | t-Statistics | *p*-Value |
|---|---|---|---|---|
| REX | −0.573776 | 0.229651 | −2.498471 | 0.0237 |
| GDP | −3.101086 | 0.914933 | −3.389414 | 0.0037 |
| FRT | 3.280867 | 0.566879 | 5.787594 | 0.0000 |
| ARL | 2.487782 | 0.607732 | 4.093553 | 0.0008 |
| YGS | −1.642159 | 0.530064 | −3.098037 | 0.0069 |

Source: Authors' computation.

According to Table 6, the estimated long-run coefficient values for all variables included in the model are statistically significant ($p < 0.05$). In terms of the direction of the relationships, a negative association is observed between the virtual land trade balance and the real effective exchange rate, GDP, and precipitation variables. Conversely, a positive relationship exists between the virtual land trade balance and both arable land per capita and fertilizer use per hectare of arable land.

The analysis results indicate that the factors exerting the greatest influence on virtual land flows in Türkiye's crop trade are, respectively, fertilizer use and per capita arable land endowment. A 1% change in fertilizer use leads to a 3.28% improvement in the virtual land trade balance, while this effect is 2.49% for the per capita arable land variable.

The variables of GDP, the real effective exchange rate (REER), and precipitation exhibit a negative impact on the virtual land trade balance. Specifically, a 1% increase in GDP is associated with a 3.1% deterioration, a 1% increase in REER leads to a 0.57% deterioration, and a 1% change in total annual precipitation results in a 1.64% deterioration in the virtual land trade balance.

Based on the long-run coefficients of the explanatory variables, the average virtual land trade ratio (VLT = −0.3069), and the mean annual virtual land import volume (4,295,167 hectares), the estimated impacts of key socio-economic and environmental factors on Türkiye's virtual land trade balance in crop-based agricultural trade were calculated in terms of land area. A 1% increase in fertilizer use (FRT) is associated with an estimated decrease of approximately 4.32 million hectares in virtual land imports, while the corresponding reduction for per capita arable land (ARL) is about 3.28 million hectares. Conversely, a 1% increase in Gross Domestic Product (GDP) leads to an estimated rise of 4.08 million hectares in virtual land demand, and for the real effective exchange rate (REX), this figure is approximately 751,000 hectares. Finally, a 1% increase in annual precipitation (YGS) is estimated to increase virtual land imports by around 2.16 million hectares.

The results of the error correction model (ECM) are presented in Table 7. According to Table 7, the coefficient of the error correction term (ECT) is negative (−1.81) and statistically significant ($p < 0.05$). A coefficient value between 0 and −1 indicates that short-term shocks converge unidirectionally toward the long-term equilibrium. In contrast, a coefficient greater than zero or less than −2 suggests divergence from equilibrium. When the coefficient of the error correction term falls between −1 and −2, as observed in this study, it implies that short-term shocks do not follow a monotonic path but instead adjust through dampened oscillations around the long-term equilibrium curve [42,43].

**Table 7.** Short-run coefficients.

| Short Run | Coefficient | t-Statistics | *p*-Value |
|---|---|---|---|
| d (vlt (−1)) | 0.297375 | 2.921579 | 0.0100 |
| d (gdp) | −4.479891 | −4.474698 | 0.0004 |
| d (gdp (−1)) | 5.145674 | 4.967889 | 0.0001 |
| d (frt) | 2.187875 | 6.205118 | 0.0000 |
| d (frt (−1)) | −2.221698 | −5.794320 | 0.0000 |
| d (ygs) | −0.851956 | −2.321939 | 0.0338 |
| d (ygs (−1)) | 2.562893 | 7.292331 | 0.0000 |
| d (ygs (−2)) | 0.945085 | 2.818764 | 0.0124 |
| ECT * | −1.806957 | −9.563198 | 0.0000 |

Source: Authors' computation. Note: * indicates statistical significance at the 1% significance level.

The diagnostic test results for the model are presented in Table 8. The Breusch-Godfrey Serial Correlation LM Test was conducted to assess the presence of autocorrelation in the model. To identify potential heteroskedasticity, the Breusch-Pagan-Godfrey test was applied. The Ramsey RESET test was used to detect any model specification errors. Lastly, the Jarque–Bera normality test was carried out to examine whether the residuals follow a normal distribution. As can be seen in Table 8, the *p*-values for all diagnostic tests exceed the 0.05 significance level ($p > 0.05$), indicating that the model does not suffer from autocorrelation, heteroskedasticity, or specification errors. Furthermore, the results of the Jarque–Bera test confirm that the error terms are normally distributed.

**Table 8.** Diagnostic test results.

| Test | F-Statistics | *p*-Value | Decision |
|---|---|---|---|
| Breusch-Godfrey Serial Correlation LM Test | 2.090076 | 0.1606 | No Autocorrelation |
| Breusch-Pagan-Godfrey Test for Heteroskedasticity | 1.913681 | 0.1069 | Homoskedasticity |
| Ramsey Reset Test for Omitted Variable Bias | 2.090076 | 0.1606 | No Specification Bias |
| Jarque–Bera Normality Test | 4.099397 | 0.128774 | Normal Distribution |

Source: Authors' computation.

To test the stability of the constructed ARDL model, the CUSUM and CUSUMQ tests were applied. These tests examine the stability of the regression coefficients and detect possible structural breaks in the model. The results of the CUSUM and CUSUMQ tests are presented in Figure 3. As can be seen from Figure 3, the test statistics remain within the 5% significance boundaries, indicating that the constructed model maintains a stable structure throughout the sample period.

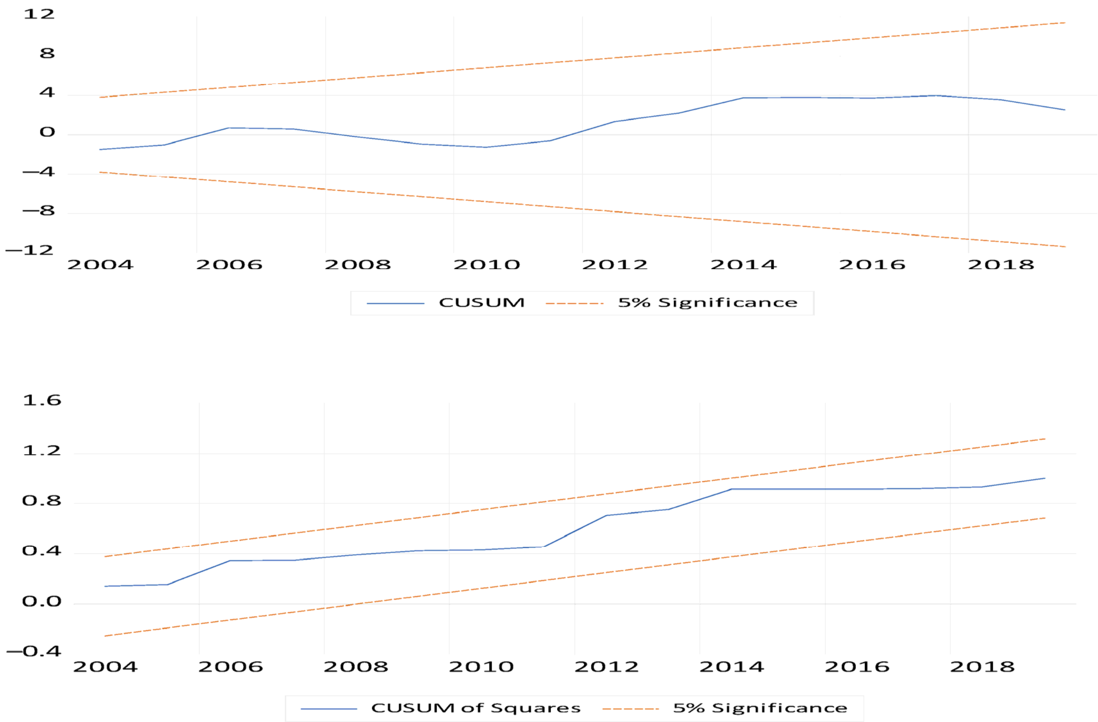


**Figure 3.** Plot of CUSUM and CUSUM of squares for parameter stability test.

## 4. Discussion

This study investigates the socio-economic and environmental variables influencing Türkiye's virtual land trade balance in crop-based agricultural products using annual time series data from 1986 to 2019 and the ARDL bounds testing approach. According to the findings, fertilizer use and per capita arable land area variables exhibit strong positive effects on the virtual land trade balance. In contrast, macroeconomic variables such as economic growth (GDP) and the real effective exchange rate (REER) negatively affect the virtual land trade balance by increasing virtual land imports. Furthermore, due to Türkiye's semi-arid climate conditions and the agricultural sector's dependence on irrigation, the precipitation variable also has a negative impact on the virtual land trade balance. These factors collectively reflect the current situation associated with the structural problems in Türkiye's agricultural sector, including high input dependency and limited productivity gains, thereby shaping the country's agricultural trade patterns. Within this general framework, a detailed examination of the effects of each variable on the virtual land trade balance is presented below.

Before delving into the empirical findings, it would be beneficial to provide a brief overview of the theoretical framework of virtual land trade in order to better understand the significance and implications of the results obtained. The theoretical scope and framework of the virtual land concept are largely built upon the conceptual foundations of the virtual water literature [4,5,8]. Nevertheless, virtual land trade also exhibits certain features that distinguish it from virtual water trade. While the virtual water approach primarily focuses on differences in water use efficiency, virtual land trade emphasizes both land endowment and the role of agricultural input use [2,7]. In this regard, virtual land trade should not be regarded merely as a theoretical extension of the virtual water concept but also as an independent subject of inquiry in the context of the efficient allocation and sustainable management of arable land resources. Accordingly, the present study contributes to filling the existing gap in the literature while making the land dimension of agricultural trade more visible.

Consistent with this theoretical framework, our empirical findings reveal that the most influential factors on Türkiye's virtual land trade balance in the trade of crop-based agricultural products are fertilizer use (3.28) and per capita arable land availability (2.49). Increases in fertilizer use per hectare enhance agricultural production capacity, thereby contributing positively to the virtual land trade balance. Although the existing literature links fertilizer use to improvements in agricultural productivity [44,45], and suggests that boosting production and export capacity through such inputs may help reduce pressure on limited arable land resources [22], the assumption that fertilizer use alone serves as a proxy for agricultural efficiency remains debatable.

One of the main limitations of the virtual land framework lies in its association of productivity solely with high input use [3]. When land requirement is considered the sole parameter, empirical evidence suggests that intensive farming practices aiming for high yields emerge as the most viable option to meet growing food demand [46]. However, while intensive agricultural practices—characterized by high input use and monoculture—may improve competitiveness in exports in the short term, they pose serious environmental and ecological challenges in the long term, including biodiversity loss, soil degradation, eutrophication [47], and increased greenhouse gas emissions [48,49].

When the fertilizer use variable is examined within the context of Türkiye, it becomes clear that, in addition to environmental sustainability, the economic dimension must also be considered. Domestic production is insufficient to meet the country's fertilizer demand, and the raw materials required for production are largely imported. Consequently, high fertilizer use contributes not only to rising production costs and a loss of competitiveness in global markets but also to increased dependency on imports [50].

From an economic perspective, it is expected that countries' trade structures align with their factor endowments [23]. In global cereal trade, empirical evidence indicates that net exporters of virtual land tend to have abundant arable land resources, while net importers are characterized by more limited land availability [7]. Nevertheless, findings also demonstrate that trade structures are determined not by absolute, but by relative factor endowments [22]. Our findings align with this view, showing that the per capita arable land variable (as a proxy for relative endowment) has a significant and positive effect (2.49) on Türkiye's virtual land trade balance.

According to the analysis results, the GDP variable has a statistically significant and negative effect ($-3.1$) on the virtual land trade balance. This is consistent with findings in the literature, which argue that rising levels of economic development increase countries' food imports and, consequently, their demand for cross-border land resources [3,35]. Economic development also brings about changes in consumption and dietary patterns. Rising income levels promote a shift towards richer, more protein-intensive diets, increasing demand for land-intensive products such as meat, dairy, and fresh fruits and vegetables [51].

The finding related to the GDP variable also indicates a growing decoupling between economic growth and the agricultural sector in Türkiye, pointing to a broader structural transformation process. In this context, the country's economic development has been largely driven by the industrial and service sectors, while agriculture has remained in a secondary position. According to World Bank [52] data, agriculture's share in GDP declined from 16.6% in 1986 to 6.4% in 2019. However, this transformation has not been accompanied by productivity gains or technological advancement in agriculture. Agricultural production in Türkiye is still predominantly carried out by small-scale family farms, operating within a fragmented land structure and relying on labor-intensive methods, which significantly limits the adoption of technology and improvements in productivity [53]. As a result, the sector has struggled to meet the growing food demand of the population, while changes in trade patterns have positioned Türkiye as a net virtual land importer. While imports of staple agricultural commodities have increased, the country has maintained a trade surplus in processed food products [54,55]. These structural challenges have contributed to the marginalization of agriculture within Türkiye's growth process, which in turn explains the long-run negative effect of GDP on virtual land trade through both production and trade channels.

The estimated coefficient of –3.1 for the GDP variable indicates that as economic growth increases, the export/import ratio decreases, consequently leading to a rise in virtual land imports. This finding can be better understood through horizontal comparisons with other empirical studies. For instance, Ni et al. [56], employing an extended gravity model for China's agricultural trade between 2000 and 2019, estimated the GDP elasticity at 3.1. Although the –3.1 coefficient estimated for Türkiye appears to differ in sign from these positive values, this discrepancy arises from modeling choices: while these studies use net virtual land imports as the dependent variable, the present study employs the ratio of total virtual land exports to virtual land imports as the dependent variable. Within this context, the direction and magnitude of economic growth's pull effect on virtual land imports are consistent. These elasticity values suggest that the magnitude of economic growth's influence on virtual land imports is similar in both Türkiye and China, reflecting a comparable pull effect despite methodological differences.

In the context of virtual water trade, elasticity coefficients for GDP also exhibit considerable variation across countries. For example, Tamea et al. [21], in a multiple regression analysis covering Tunisia during 1981–2010, reported GDP coefficients ranging from 0.001 to 0.05 for staple crops (wheat, barley, potatoes) and from –5 to 0.10 for export-oriented products (dates, olive oil, tomatoes). In the Mediterranean context, Fracasso et al. [22], using gravity model analysis with 2004 data, found per capita GDP coefficients of 0.38 and 0.64 under two alternative specifications. The variation in GDP coefficients across the literature essentially stems from differences in methodological approaches, product coverage, country samples, and the time periods under consideration. Compared to these relatively low elasticity values, the coefficient estimated for Türkiye (–3.1) indicates a stronger pull effect of economic growth on virtual land imports. This suggests that in Türkiye, where agricultural productivity growth lags behind rising domestic demand, economic growth more markedly intensifies dependence on transboundary arable land resources, reflecting a structural disequilibrium and an acute contradiction between lagging agricultural productivity and domestic demand growth.

Our findings indicate that the real effective exchange rate (REER) has a statistically significant and negative impact (−0.57) on the virtual land trade balance. An appreciation of the domestic currency through an increase in REER tends to increase virtual land imports while reducing exports. In the case of Türkiye, the high dependence of its agricultural production and trade structure on imported inputs [50] necessitates the consideration of both direct and indirect effects of REER fluctuations. Ensuring a balanced virtual land trade structure is inherently linked to the establishment of long-term economic stability. One of the key indicators of such stability is, without doubt, the relative value of the domestic currency against the currencies of major trading partners.

The negative relationship between precipitation and the virtual land trade balance, while initially counterintuitive, becomes clearer when considering Türkiye's climatic and agricultural conditions. The country's semi-arid climate and significant regional variations in precipitation necessitate the use of irrigation in agricultural production. According to 2023 data, 77% of Türkiye's total water consumption is allocated to irrigation [57]. Since the 1990s, government-supported irrigation infrastructure has played a vital role in boosting agricultural productivity, particularly for export-oriented crops like fresh fruits and vegetables, as well as for import-substituting crops such as cotton and maize [58]. In recent years, the reliance on blue water (surface and groundwater) has increased, while the use of green water (precipitation and soil moisture) has declined [59,60]. This shift indicates that productivity gains in agriculture are more dependent on irrigation systems and water management practices than on natural rainfall patterns

Furthermore, Türkiye's agricultural trade structure contributes to this dynamic. The country experiences a persistent trade deficit in primary agricultural commodities while maintaining a trade surplus in processed agricultural products. From 1980 to 2024, Türkiye recorded a deficit of approximately 145 billion USD in raw agricultural materials but a surplus of 189 billion USD in processed food products [55]. This pattern suggests that increased precipitation alone does not translate into improved virtual land trade balances, especially in a trade structure dominated by the import of raw inputs and the export of value-added goods.

The estimated short-run error correction coefficient offers important insights into Türkiye's agricultural trade dynamics, highlighting that shocks such as exchange rate volatility, abrupt input price changes, or unexpected climatic events do not fade away instantly or in a linear manner. Instead, the system exhibits a strong immediate response to such disturbances, followed by a gradual adjustment process toward restoring long-term equilibrium. This cyclical pattern reflects the structural realities of Türkiye's agricultural sector, characterized by macroeconomic instability and significant policy influence. In particular, the sector's reliance on imported inputs—including fertilizers, animal feed, and energy—renders production costs highly vulnerable to external shocks, especially fluctuations in exchange rates, thereby contributing to short-term trade imbalances that are slowly corrected over time [50]. Despite these vulnerabilities, the relatively rapid return to equilibrium suggests a notable degree of resilience and adaptability within the sector. Türkiye's prominent role in exporting fresh fruits, vegetables, and processed agricultural products, alongside fulfilling domestic food needs, underscores the significance of this resilience [61]. Overall, this finding transcends a mere statistical observation and sheds light on the adjustment mechanisms shaped by the sector's structural characteristics and policy framework, offering valuable implications for policymakers aiming to enhance the agricultural sector's responsiveness to economic and external shocks.

## 5. Conclusions and Policy Implications

The findings of this study provide important insights for policymakers in Türkiye's agricultural sector. The positive and significant effects of arable land per capita and fertilizer use per hectare on virtual land trade indicate that agricultural production capacity is largely determined by land availability and input utilization. However, fertilizer use alone cannot serve as a comprehensive indicator of productivity. Therefore, policies should aim to simultaneously support production increases while mitigating negative environmental externalities, for example, through the promotion of conservation agriculture, incentives for organic and biological fertilizers, and farmer training programs.

The results further highlight the necessity of preserving arable land both quantitatively and qualitatively. Agricultural land conversion to non-agricultural uses such as urbanization, industrial development, and infrastructure should be minimized. At the same time, sustainable land management practices are required to prevent soil degradation caused by over-irrigation, excessive chemical input use, and monoculture practices, thereby maintaining soil health and ecological balance.

The negative impact of GDP growth on the virtual land trade balance suggests that rising domestic demand increases import dependency. To address this, it is essential to strengthen domestic production capacity in strategic crops through investments in irrigation infrastructure, the development of climate-resilient varieties, and technological innovations. Agricultural policies should also prioritize value-added exports over raw material imports. Similarly, the adverse effect of real effective exchange rate appreciation highlights the sector's vulnerability to macroeconomic fluctuations and high import dependency, emphasizing the need for policies that reduce reliance on imported inputs and expand export support programs.

Finally, the unexpected negative effect of precipitation indicates that Turkish agriculture relies more heavily on irrigation than on rainfall. Modern irrigation projects should therefore be implemented in coordination with land consolidation policies to address the fragmented and small-scale nature of agricultural land. Collectively, these findings underscore the critical need to integrate resource efficiency and environmental sustainability into agricultural policy design, thereby enhancing Türkiye's capacity to achieve a more balanced, resilient, and sustainable position in global virtual land trade.

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## References

1. Ali, T.; Huang, J.; Wang, J.; Xie, W. Global footprints of water and land resources through China's food trade. *Glob. Food Secur.* **2017**, *12*, 139–145. [CrossRef]
2. Qiang, W.; Niu, S.; Liu, A.; Kastner, T.; Bie, Q.; Wang, X.; Cheng, S. Trends in global virtual land trade in relation to agricultural products. *Land Use Policy* **2020**, *92*, 104439. [CrossRef]
3. Yang, H.; Zehnder, A. "Virtual Water": An unfolding concept in integrated water resources management. *Water Resour. Res.* **2007**, *43*, W12301. [CrossRef]
4. Qiang, W.; Liu, A.; Cheng, S.; Kastner, T.; Xie, G. Agricultural trade and virtual land use: The case of China's crop trade. *Land Use Policy* **2013**, *33*, 141–150. [CrossRef]
5. Chen, G.Q.; Han, M.Y. Virtual land use change in China 2002–2010: Internal transition and trade imbalance. *Land Use Policy* **2015**, *47*, 55–65. [CrossRef]
6. Zhou, M.; Wang, J.; Ji, H. Virtual land and water flows and driving factors related to livestock products trade in China. *Land* **2023**, *12*, 1493. [CrossRef]
7. Zhang, J.; Zhao, N.; Liu, X.; Liu, Y. Global virtual-land flow and saving through international cereal trade. *J. Geogr. Sci.* **2016**, *26*, 619–639. [CrossRef]
8. Würtenberger, L.; Koellner, T.; Binder, C.R. Virtual land use and agricultural trade: Estimating environmental and socio-economic impacts. *Ecol. Econ.* **2006**, *57*, 679–697. [CrossRef]
9. Yang, H.; Wang, L.; Abbaspour, K.C.; Zehnder, A.J. Virtual water trade: An assessment of water use efficiency in the international food trade. *Hydrol. Earth Syst. Sci.* **2006**, *10*, 443–454. [CrossRef]
10. Fader, M.; Gerten, D.; Thammer, M.; Heinke, J.; Lotze-Campen, H.; Lucht, W.; Cramer, W. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1641–1660. [CrossRef]

11. Dalin, C.; Konar, M.; Hanasaki, N.; Rinaldo, A.; Rodriguez-Iturbe, I. Evolution of the global virtual water trade network. *Proc. Natl. Acad. Sci. USA* **2021**, *109*, 5989–5994. [CrossRef]
12. Wang, J.; Wang, S.; Zhou, C. Quantifying embodied cultivated land-use change and its socioeconomic driving forces in China. *Appl. Geogr.* **2021**, *137*, 102601. [CrossRef]
13. Meyfroidt, P.; Lambin, E.F.; Erb, K.H.; Hertel, T.W. Globalization of land use: Distant drivers of land change and geographic displacement of land use. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 438–444. [CrossRef]
14. Fan, X.; Liu, H.; Wang, M. Study on the agricultural land transfer embodied in ınter-provincial trade in China. *Land* **2022**, *11*, 656. [CrossRef]
15. Tian, X.; Bruckner, M.; Geng, Y.; Bleischwitz, R. Trends and driving forces of China's virtual land consumption and trade. *Land Use Policy* **2019**, *89*, 104194. [CrossRef]
16. Chen, W.; Kang, J.N.; Han, M.S. Global environmental inequality: Evidence from embodied land and virtual water trade. *Sci. Total Environ.* **2021**, *783*, 146992. [CrossRef]
17. Bahmani-Oskooee, M. Is there a long-run relation between the trade balance and the real effective exchange rate of LDCs? *Econ. Lett.* **1991**, *36*, 403–407. [CrossRef]
18. Bahmani-Oskooee, M.; Brooks, T.J. Bilateral j-curve between the US and her trading partners. *Weltwirtschaftliches Arch.* **1999**, *H. 1*, 156–165. [CrossRef]
19. Lal, A.K.; Lowinger, T.C. The j-curve: Evidence from East Asia. *J. Econ. Integr.* **2002**, *17*, 397–415. [CrossRef]
20. Onafowora, O. Exchange rate and trade balance in East Asia: Is there a j-curve? *Econ. Bull.* **2003**, *5*, 1–13.
21. Tamea, S.; Carr, J.A.; Laio, F.; Ridolfi, L. Drivers of the virtual water trade. *Water Resour. Res.* **2014**, *50*, 17–28. [CrossRef]
22. Fracasso, A.; Sartori, M.; Schiavo, S. Determinants of virtual water flow in the Mediterranean. *Sci. Total Environ.* **2016**, *543*, 1054–1062. [CrossRef]
23. Chouchane, H.; Krol, M.S.; Hoekstra, A.Y. Virtual water trade patterns in relation to environmental and socioeconomic factors: A case study for Tunisia. *Sci. Total Environ.* **2018**, *613*, 287–297. [CrossRef]
24. Allan, J.A. Virtual water-the water, food, and trade nexus useful concept or misleading metaphor? *Water Int.* **2003**, *28*, 106–113. [CrossRef]
25. Merrett, S. Virtual water and the Kyoto consensus: A water forum contribution. *Water Int.* **2003**, *28*, 540–542. [CrossRef]
26. Ramirez-Vallejo, J.; Rogers, P. Virtual water flows and trade liberalization. *Water Sci. Technol.* **2004**, *49*, 25–32. [CrossRef] [PubMed]
27. Zhao, D.; Hubacek, K.; Feng, K.; Sun, L.; Liu, J. Explaining virtual water trade: A spatial-temporal analysis of the comparative advantage of land, labor and water in China. *Water Res.* **2019**, *153*, 304–314. [CrossRef]
28. Allan, T. Productive efficiency and allocative efficiency: Why better water management may not solve the problem. *Agric. Water Manag.* **1999**, *40*, 71–75. [CrossRef]
29. Wang, J.; Wang, S.; Zhou, C.; Sun, D. Uncovering the patterns and driving forces of virtual forestland flows in China. *J. Clean. Prod.* **2022**, *339*, 130598. [CrossRef]
30. Alamri, Y.; Reed, M.; Saghaian, S. Determinants of virtual water trade of cereal crops in Saudi Arabia. *Iraqi J. Agric. Sci.* **2020**, *51*, 1118–1127. [CrossRef]
31. Xia, W.; Chen, X.; Song, C.; Pérez-Carrera, A. Driving factors of virtual water in international grain trade: A study for belt and road countries. *Agric. Water Manag.* **2022**, *262*, 107441. [CrossRef]
32. Chen, B.; Han, M.Y.; Peng, K.; Zhou, S.L.; Shao, L.; Wu, X.F.; Wei, W.D.; Liu, S.Y.; Li, Z.; Li, J.S.; et al. Global land-water nexus: Agricultural land and freshwater use embodied in worldwide supply chains. *Sci. Total Environ.* **2018**, *613*, 931–943. [CrossRef] [PubMed]
33. Taherzadeh, O.; Caro, D. Drivers of water and land use embodied in international soybean trade. *J. Clean. Prod.* **2019**, *223*, 83–93. [CrossRef]
34. Cai, B.; Hubacek, K.; Feng, K.; Zhang, W.; Wang, F.; Liu, Y. Tension of agricultural land and water use in China's trade: Tele-connections, hidden drivers and potential solutions. *Environ. Sci. Technol.* **2020**, *54*, 5365–5375. [CrossRef]
35. Weinzettel, J.; Hertwich, E.G.; Peters, G.P.; Steen-Olsen, K.; Galli, A. Affluence drives the global displacement of land use. *Glob. Environ. Chang.* **2013**, *23*, 433–438. [CrossRef]
36. Ashktorab, N.; Zibaei, M. Future virtual water flows under climate and population change scenarios: Focusing on its determinants. *J. Water Clim. Chang.* **2022**, *13*, 96–112. [CrossRef]
37. Duarte, R.; Pinilla, V.; Serrano, A. Long term drivers of global virtual water trade: A trade gravity approach for 1965–2010. *Ecol. Econ.* **2019**, *156*, 318–326. [CrossRef]
38. Pesaran, M.H.; Shin, Y.; Smith, R.J. Bounds testing approaches to the analysis of level relationships. *J. Appl. Econom.* **2001**, *16*, 289–326. [CrossRef]
39. Narayan, P.K. The saving and investment nexus for China: Evidence from cointegration tests. *Appl. Econ.* **2005**, *37*, 1979–1990. [CrossRef]

40. Dickey, D.A.; Fuller, W.A. Distribution of the estimators for autoregressive time series with a unit root. *J. Am. Stat. Assoc.* **1979**, *74*, 427–431.
41. Perron, P. Trends and random walks in macroeconomic time series: Further evidence from a new approach. *J. Econ. Dyn. Control* **1988**, *12*, 297–332. [CrossRef]
42. Alam, I.; Quazi, R. Determinants of capital flight: An econometric case study of Bangladesh. *Int. Rev. Appl. Econ.* **2003**, *17*, 85–103. [CrossRef]
43. Narayan, P.K.; Smyth, R. What determines migration flows from low-ıncome to high-ıncome countries? an empirical ınvestigation of Fiji–Us migration 1972–2001. *Contemp. Econ. Policy* **2006**, *24*, 332–342. [CrossRef]
44. Upekshani, H.A.N.; Dharmakeerthi, R.S.; Weerasinghe, P.; Dandeniya, W.S. Fertilizer usage and land productivity in intensively cultivated vegetable farming systems in Sri Lanka: An analysis based on a questionnaire survey. *Trop. Agric. Res.* **2018**, *30*, 44–55. [CrossRef]
45. Martey, E.; Kuwornu, J.K.; Adjebeng-Danquah, J. Estimating the effect of mineral fertilizer use on land productivity and income: Evidence from Ghana. *Land Use Policy* **2019**, *85*, 463–475. [CrossRef]
46. Kastner, T.; Nonhebel, S. Changes in land requirements for food in the Philippines: A historical analysis. *Land Use Policy* **2010**, *27*, 853–863. [CrossRef]
47. Matson, P.A.; Parton, W.J.; Power, A.G.; Swift, M.J. Agricultural intensification and ecosystem properties. *Science* **1997**, *277*, 504–509. [CrossRef] [PubMed]
48. Huang, W.; Jiang, L. Efficiency performance of fertilizer use in arable agricultural production in China. *China Agric. Econ. Rev.* **2019**, *11*, 52–69. [CrossRef]
49. Krasilnikov, P.; Taboada, M.A.; Amanullah. Fertilizer use, soil health and agricultural sustainability. *Agriculture* **2022**, *12*, 462. [CrossRef]
50. Turkish Union of Chambers of Agriculture. *Agricultural Report of Türkiye, 2015–2018*; Turkish Union of Chambers of Agriculture: Ankara, Turkey, 2019.
51. Kastner, T.; Chaudhary, A.; Gingrich, S.; Marques, A.; Persson, U.M.; Bidoglio, G.; Le Provost, G.; Schwarzmüller, F. Global agricultural trade and land system sustainability: ımplications for ecosystem carbon storage, biodiversity, and human nutrition. *One Earth* **2021**, *4*, 1425–1443. [CrossRef]
52. World Bank. World Development Indicators. 2023. Available online: https://databank.worldbank.org/source/world-development-indicators (accessed on 20 August 2025).
53. FAO. The State of Food and Agriculture 2022: Leveraging Automation in Agriculture for Transforming Agrifood Systems. Food and Agriculture Organization of the United Nations. 2022. Available online: https://www.fao.org/3/cb9479en/cb9479en.pdf (accessed on 20 August 2025).
54. Ministry of Trade of the Republic of Türkiye. *General Agriculture Sector Report*; Ministry of Trade of the Republic of Türkiye: Ankara, Turkey, 2023. Available online: https://ticaret.gov.tr/data/5b8700a513b8761450e18d81/Genel%20Tar%C4%B1m%20Sekt%C3%B6r%C3%BC%20Raporu.pdf (accessed on 22 August 2025).
55. Dinçer, B. *Structural Trends and Comparative Advantages in Türkiye's Agricultural Foreign Trade*; Ankara University Press: Ankara, Turkey, 2025.
56. Ni, G.; Teng, M.; Su, B.; Chen, Z. Impact of political relationships on virtual land flow from China's food trade. *Socio. Econ. Plan. Sci.* **2024**, *96*, 102085. [CrossRef]
57. State Hydraulic Works. 2023 Annual Activity Report. 2023. Available online: https://cdniys.tarimorman.gov.tr/api/File/GetFile/425/Sayfa/759/1107/DosyaGaleri/dsi_2023_yili_faaliyet_raporu.pdf (accessed on 22 August 2025).
58. Cakmak, E.H.; Dudu, H.; Saracoglu, D.S.; Diao, X.; Roe, T.L.; Tsur, Y. Macro-Micro Feedback Links of Irrigation Water Management in Türkiye. World Bank Policy Research Working Paper WPS4781. 2008. Available online: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/698961468108847250 (accessed on 3 September 2025).
59. Akbostancı, E.; Tunç, G.; Türüt-Aşık, S. Virtual water flows of Türkiye's agricultural products: A gravity approach. *J. Clean. Prod.* **2023**, *420*, 138453. [CrossRef]
60. Demir, M.S.; Muratoglu, A.; Kartal, V.; Nas, H. Temporal analysis of agricultural water footprint dynamics in Türkiye: Climate change impacts and adaptation. *J. Environ. Manag.* **2025**, *390*, 126310. [CrossRef] [PubMed]
61. Ministry of Agriculture and Forestry. Agricultural Foreign Trade Strategy Document (2021–2025). 2021. Available online: https://www.tarimorman.gov.tr/TAGEM/Belgeler/yayin/TARIMSAL%20DI%C5%9E%20T%C4%B0CARET%20SPB%202021-2025.pdf (accessed on 22 August 2025).