sustainability

MDPI

Article

Quantifying Resource Nexus: Virtual Water Flows, Water Stress Indices, and Unsustainable Import Fraction in South Korea's Grain Trade Landscape

Golden Odey [1], Bashir Adelodun [1,2,3], Qudus Adeyi [1], Akinsoji Adisa Hammed [1], Salau Rahmon Abiodun [1] and Kyung Sook Choi [1,3,*]

1 Department of Agricultural Civil Engineering, Kyungpook National University, Daegu 41566, Republic of Korea; goldenodey@knu.ac.kr (G.O.); adelodun.b@unilorin.edu.ng (B.A.); adeyi.qudus@knu.ac.kr (Q.A.); adisaakinsoji@gmail.com (A.A.H.); olanrewajusalau2790@gmail.com (S.R.A.)
2 Department of Agricultural and Biosystems Engineering, University of Ilorin, Ilorin 240103, Nigeria
3 Institute of Agricultural Science & Technology, Kyungpook National University, Daegu 41566, Republic of Korea
* Correspondence: ks.choi@knu.ac.kr; Tel.: +82-53-950-5731; Fax: +82-53-950-6752

Abstract: This study delves into the intricate dynamics of South Korea's grain production and trade, specifically scrutinizing water resource management and sustainability trends from 1991 to 2022. The primary objective was to assess the temporal evolution of South Korea's agricultural virtual water trade in maize, soybeans and wheat. Employing the virtual water flows assessment method, water stress index, and an unsustainable import fraction (UIF) analysis, this research aimed to uncover key patterns and dynamics within the agricultural grain trade landscape. Utilizing comprehensive datasets encompassing grain trade, as well as water and land footprint data, this study assessed the intricate interplay between agricultural production, trade, and resource utilization. Results showed a reduction in local production for soybeans and a slight increase in domestic wheat production over the study period. In addition, the study revealed an overall increase in the virtual water imports associated with grain crops, with maize exhibiting the steepest upward trend in comparison with the other grains (wheat and soybeans). Furthermore, the study demonstrated that the import of maize contributed the highest amount of water and land savings, implying that this grain crop had the most significant impact on conserving local water and land resources. Environmental impact assessments, including water stress indices and the unsustainable import fractions, contributed to a comprehensive understanding of grain trade sustainability with concrete result values and insights, highlighting the intricate interplay of international grain trade and local water resource conservation in South Korea. By scrutinizing the virtual land and water dimensions of grain trade, this research offers valuable insights for policymakers and researchers striving to navigate the nexus of agriculture, trade, and resource management. The findings hold significance in the context of ensuring food security, optimizing resource allocation, and fostering sustainable agricultural practices in a dynamically evolving global landscape.

Keywords: virtual water trade; land savings; water stress; food security; South Korea

Citation: Odey, G.; Adelodun, B.; Adeyi, Q.; Hammed, A.A.; Abiodun, S.R.; Choi, K.S. Quantifying Resource Nexus: Virtual Water Flows, Water Stress Indices, and Unsustainable Import Fraction in South Korea's Grain Trade Landscape. *Sustainability* **2024**, *16*, 2419. https://doi.org/10.3390/su16062419

Academic Editor: Ryo Kohsaka

Received: 6 February 2024
Revised: 6 March 2024
Accepted: 12 March 2024
Published: 14 March 2024

1. Introduction

In an era marked by burgeoning global populations, shifting climatic patterns, and the imperative for sustainable resource management, the intricate connections between international trade, agriculture, and environmental resources have come to the fore [1]. Among the crucial concepts that have emerged to address these complex interdependencies are virtual water trade, virtual land trade, and the broader dynamics of grain trade. As global trade expands, so does the flow of hidden resources embedded in agricultural products. Virtual water and virtual land, representing the water and land resources used in production, have become critical considerations in sustainable resource management [2]. More explicitly, virtual water trade, introduced by Professor Arjen Y. Hoekstra, captures the indirect movement of water within the production and trade of goods [3]. This concept provides a lens through which to examine the global distribution of water resources, as nations import and export water-intensive products. Complementing this, virtual land trade delves into the implicit transfer of land resources associated with the production and exchange of agricultural commodities [4]. These concepts are particularly relevant in the context of major grain-producing and consuming nations, such as South Korea, as they grapple with the dual challenge of meeting food security needs and addressing environmental sustainability.

The study of virtual water trade has progressed significantly over time, with a growing body of research focusing on its various dimensions and implications. It has gained attention due to its potential to address water scarcity, its economic implications, and its role in international trade. The concept has been the subject of scientific meetings, research articles, and reports, highlighting its significance in the context of water security, geopolitical dynamics, and economic aspects. Recent studies have documented the changes in trade and their impact on the virtual redistribution of freshwater resources, emphasizing the evolving nature of virtual water trade [5]. The concept has been discussed in the context of agricultural production, emphasizing its role in recognizing the importance of water and generating awareness about water footprints [6]. Furthermore, there is a growing focus on future evolution and analyses of virtual water trading, with studies exploring future consumptive virtual water trading in various sectors [7]. The evolution of the virtual water trade network has been a subject of interest, emphasizing the continued relevance and significance of this concept in the context of global trade and water management [8]. Virtual water trade can lead to land savings by enabling water-stressed regions to import water-intensive products rather than producing them domestically. This can free up land and water resources in the importing regions, leading to potential land savings [2]. Land savings through virtual water trade represent a dynamic approach to addressing the complex challenges posed by water scarcity and agricultural sustainability on a global scale. This concept revolves around the idea of importing water-intensive goods from regions where they can be produced more efficiently, thereby reducing the demand for land and water resources in water-scarce areas. At the core of the virtual water trade concept lies the recognition that not all water is used directly for consumption or irrigation. In fact, a substantial amount of water is embedded in the process of producing goods and services. By understanding and quantifying this virtual water content, regions can make informed decisions about resource management, allowing them to optimize their use of water and land. This becomes particularly pertinent in regions facing water scarcity, where traditional agricultural practices may strain available resources [9]. Virtual water trade thus emerges as a strategy for alleviating this strain, enabling regions to focus on their comparative advantages and import water-intensive products [10].

While the virtual water approach can enhance resource efficiency and alleviate the pressure on local ecosystems, a nuanced evaluation is essential, considering the potential trade-off between saving local resources and the resulting environmental consequences in both the exporting and importing regions. In fact, increasing attention is being directed towards potential water sustainability challenges resulting from the movement of water across various regions [11–14]. Therefore, striking a balance is crucial to ensure that virtual water trade contributes positively to both global and local environmental sustainability [14]. The quantification and evaluation of the sustainability of food production, consumption, and the trade of food commodities, along with their impact on the water resources of the source areas, are commonly achieved through the widely accepted approaches of virtual water and water footprint (WF) [9,11]. Since virtual water involves the conversion of agricultural products into the embedded water quantity within the products, it provides a measure for assessing sustainability by comparing the amount of water used to what is available [14]. Consequently, sustainability or scarcity-based indices can be derived by calculating virtual water volumes, offering a comprehensive method for gauging the environmental impact of food-related activities on water resources [15].

South Korea, with its limited water and arable land, relies heavily on food imports especially grains such as maize, wheat, and soybeans [16]. This dependence has significant implications for the country's virtual water and land trade, particularly in major grains. This study thus delves into the temporal evolution of South Korea's agricultural virtual water trade in maize, soybeans and wheat, analyzing trends and potential impacts. Specifically, this study (i) assesses the virtual water import change characteristics of the major grains over the period 1991 to 2017; (ii) determines the water and land savings due to grain imports over the study period; and (iii) examines the environmental impact of grain imports on South Korea from a water stress index and sustainability assessment perspective. By understanding these dynamics, we aim to provide insights for enhancing resource sustainability and food security in South Korea, with potential implications for other resource-scarce nations. Additionally, this study seeks to contribute valuable insights to the broader global discourse on sustainable agriculture, with implications for policy formulation geared towards enhancing the resilience and environmental consciousness of the agricultural sector (not just within South Korea), also offering lessons for other nations navigating similar challenges in the pursuit of a sustainable food future.

The organization of this research paper unfolds in the following manner. To begin, we will outline the materials and methods employed in this study. Subsequently, we will present the study's discoveries, followed by an examination of the implications for water conservation policy. Lastly, the article will be concluded by summarizing the key findings and proposing directions for future research.

2. Materials and Methods

In this study, we estimated virtual water flows to South Korea from export partners as a result of the trade in major grains of maize, soybeans, and wheat and assessed the environmental implication for South Korea for the periods 1991 to 2022. Trade and water use data for this study were collected from the Food and Agriculture Organization (FAO) [17] and the world bank [18] databases, respectively. Additionally, water footprint data for the analyzed grains were derived from Hoekstra [19], who quantified the virtual water flows between nations in relation to international crop trade, and Yoo et al. [20], who estimated the water footprint of upland crop cultivation in South Korea. The flowchart of the methodological procedures (Figure 1) and a detailed description are presented below.

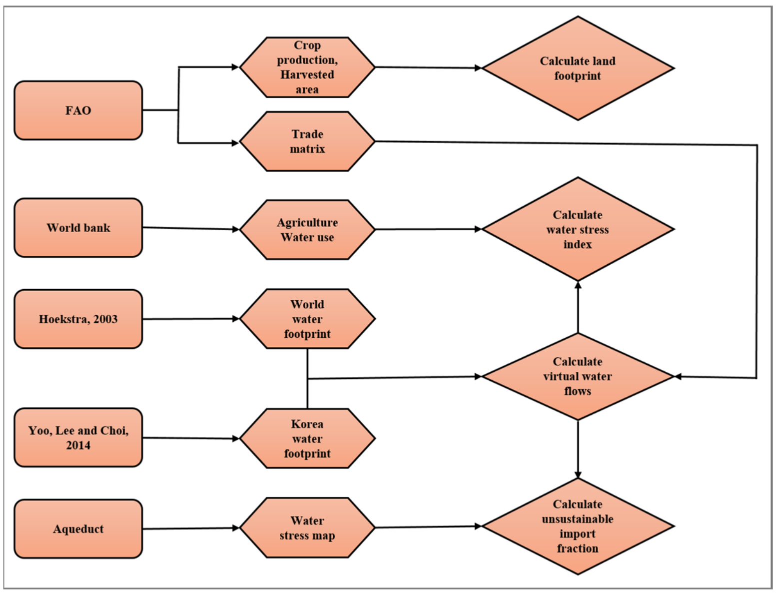


Figure 1. Methodology flow chart.

2.1. Virtual Water Flows within Grain Trade

The idea underlying virtual water flows is that the exchange of products involves the transfer of virtual water. Consequently, the determination of virtual water trade relies on the water footprints of exporters, representing the virtual water content, which indicate the overall volume of water used in crop production along with trade data [9,21]. Thus, the calculation of virtual water trade involves multiplying the quantity of traded goods by the exporting country's associated water footprint [22]. This is stated mathematically as follows:

$$VWT_{[ne,\, ni,\, c,\, t]} = QT_{[ne,\, ni,\, c,\, t]} \times VWC_{[ne,\, c]} \tag{1}$$

where VWT refers to the virtual water trade that occurred in year t as a result of trade in crop c from the exporting country, ne, to the importing country, n_i; QT refers to the amount of crop trade to the importing country, n_i, from the exporting country, n_e, in year t, due to trade in crop c; VWC is the virtual water content (WF) of crop c in the exporting country, n_e.

2.2. Conservation of Water and Land Resources through Virtual Water Importation

Calculating water and land savings resulting from the importation of virtual water involves a comprehensive assessment of the embedded water in traded goods. Land savings are closely linked to water savings in this context, as water-intensive agricultural practices often entail significant land use. Analyzing virtual water flows allows for understanding how importing goods rather than producing them locally can lead to a reduction in the demand for both water and land resources in regions facing scarcity. The calculation requires multiplying the quantity of an imported crop by both the domestic water footprint (WF) and the land footprint (LF) associated with that particular crop. The water and land savings were calculated as follows:

$$VWC_{[ni,\, c]} = \frac{CWR_{[ni,\, c]}}{P_{[ni,\, c]}} \tag{2}$$

$$LF_{[ni,\, c]} = \frac{Area_{[ni,\, c]}}{P_{[ni,\, c]}} \tag{3}$$

$$WS_{[ni,\, c]} = QI_{[ni,\, c]} \times VWC_{[ni,\, c]} \tag{4}$$

$$LS_{[ni,\, c]} = QI_{[ni,\, c]} \times LF_{[ni,\, c]} \tag{5}$$

where $VWC_{[ni,\, c]}$ represents the virtual water content (WF) of crop c in the importing country n_i measured in cubic meters per ton (m^3/t), CWR represents the crop water requirement measured in cubic meters (m^3), and P is the production measured in tons (t). $LF_{[ni,\, c]}$ is the land footprint of crop c in the importing country n_i, measured in hectares per ton (ha/t); "Area" represents the cultivated area measured in hectares (ha). $WS_{[ni,\, c]}$ and $LS_{[ni,\, c]}$ represent the water and land savings of crop c in the importing country n_i, measured in cubic meters (m^3) and hectares (ha), respectively; QI represents amount of imported crop c in the importing country n_i.

2.3. Water Stress Index and Assumed Water Stress Index

The water stress index (WSI) is a measure of the pressure on water resources in a specific area. It indicates the ratio of water consumed that deprives other users in the same watershed of water [23]. Water stress occurs when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use. The assumed water stress index (AWSI) on the other hand, is a hypothetical measure used to assess the potential impact of increased water consumption on a particular area [24]. This study presented the water stress index and the assumed water stress index as tools to assess the influence of virtual water imports on South Korea's water resources.

$$\text{Water stress index (WSI)} = \frac{WU}{W_a} \tag{6}$$

$$\text{Assumed water stress index (AWSI)} = \frac{\text{WU} + \text{VW}_{\text{import}}}{\text{W}_{\text{a}}} \tag{7}$$

where WU indicates the total water consumption for local grain production; VW_{import} refers to the virtual water import from external sources; and W_a represents the available water resources. To facilitate the analysis of the regulation and utilization of water resources in South Korea's agricultural sector, this study adopted the total water consumption of the agricultural sector as the available water. The water stress index is categorized into four tiers: no stress ($WSI < 0.2$), moderate stress (0.2–0.4), severe stress (0.4–1.0), and extreme water shortage ($WSI > 1.0$) [24,25].

2.4. Evaluation of Virtual Water Import Sustainability

The evaluation of the sustainability of grain imports relies on analyzing the proportion of virtual water imported from countries facing water stress in relation to the overall virtual water import of a nation (South Korea in this context). This analysis is known as the unsustainable import fraction (UIF). It is crucial to emphasize that the calculation of the UIF only takes into account the utilization of blue virtual water. The UIF specifically denotes the portion of virtual water sourced from water-stressed nations, indicating the extent of unsustainable imports in this context [14]. It is depicted as

$$\text{UIF} = \frac{\text{VWT}_{\text{ws}}}{\text{VWT}_{\text{tot}}} \tag{8}$$

where VWT_{ws} represents the amount of blue virtual water imported from a water-stressed country, and VWT_{tot} is the total blue virtual water import. The data used to identify water stressed trade partner countries were obtained from *Aqueduct data platform* run by the World Resources Institute (WRI), a renowned environmental research organization [26]. We assume import unsustainability if the percentage of UIF is high (and vice versa).

3. Results

3.1. Local Production Water Footprint and Virtual Water Import Change Characteristics

Figure 2 shows the changing trends in local production water footprint for maize, soybeans, and wheat over the study period. The local production water footprint refers to the total volume of water used in cultivating and producing these grains within South Korea. Soybean recorded a negative trend between 1991 and 2022, implying a reduction in the production water footprint over this period. However, maize production showed a relatively stable trend, with soybean production characterized by significant variations over the years. On the other hand, the wheat production water footprint showed a slight increase, evidenced by the positive trend recorded.

The virtual water import change characteristics for the three grains are shown in Figure 3. The figure explains the trends associated with alterations over time in the volume of virtual water imports by South Korea. The trend analysis reveals an overall increase in the virtual water content associated with these crops. Maize exhibits the steepest upward trend, indicating a significant rise in the volume of embedded water in imported maize products. Following closely is wheat, showing a noticeable but less steep increase in virtual water import. Soybean, while also displaying an upward trend, records a comparatively more gradual rise in virtual water content over the analyzed period. These trends suggest a consistent growth in the water footprint associated with the importation of these key grain crops.

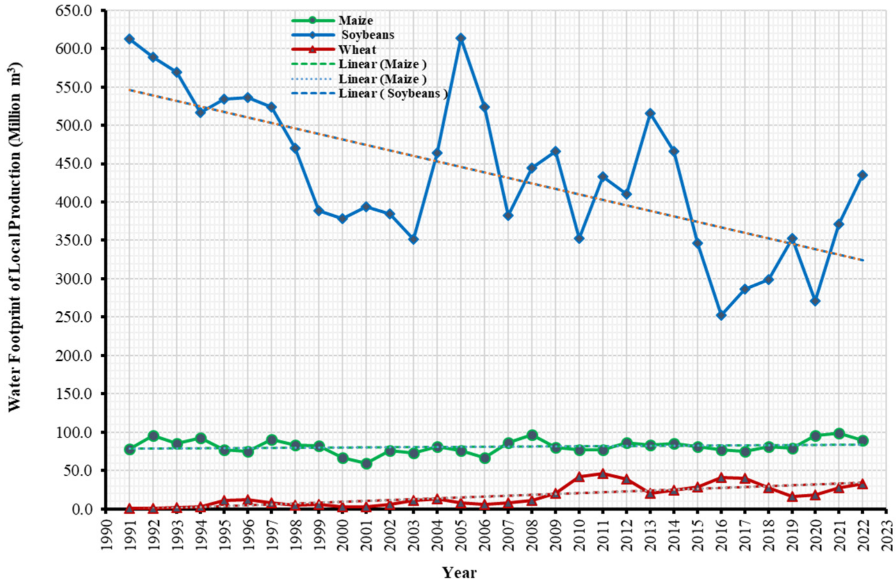


Figure 2. Change trend of local production water footprint for three major grains in South Korea during 1991–2022.

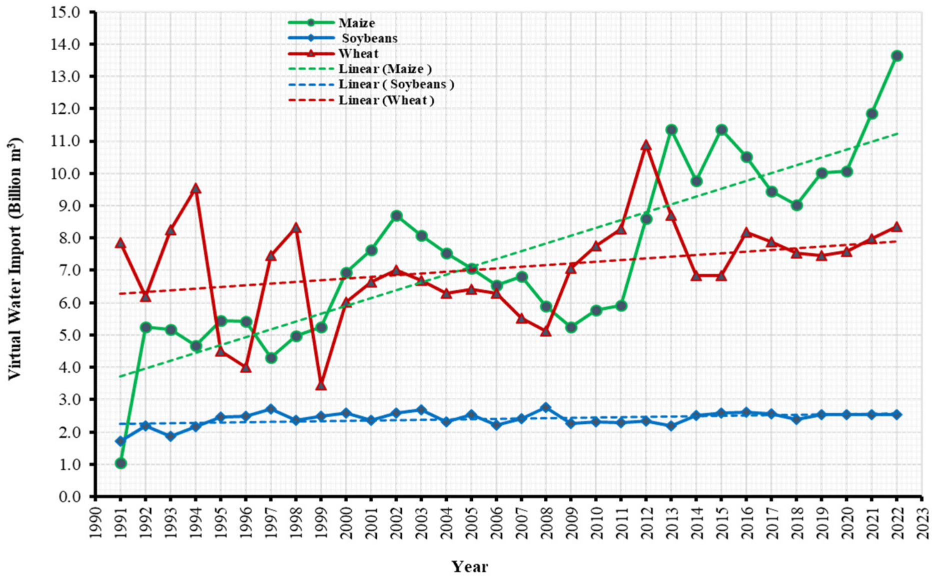
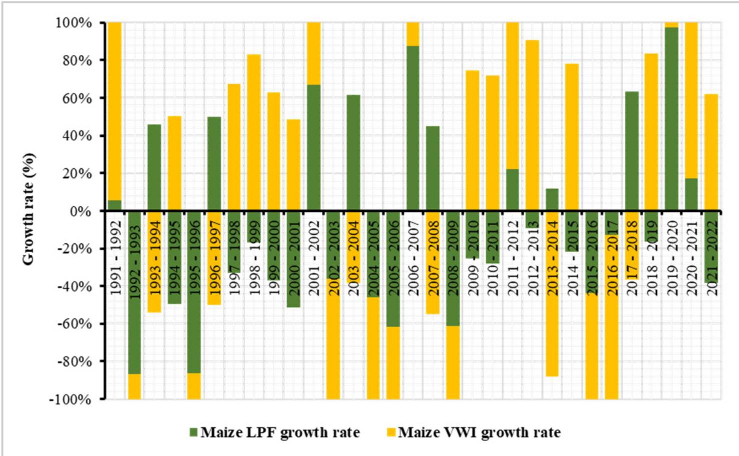
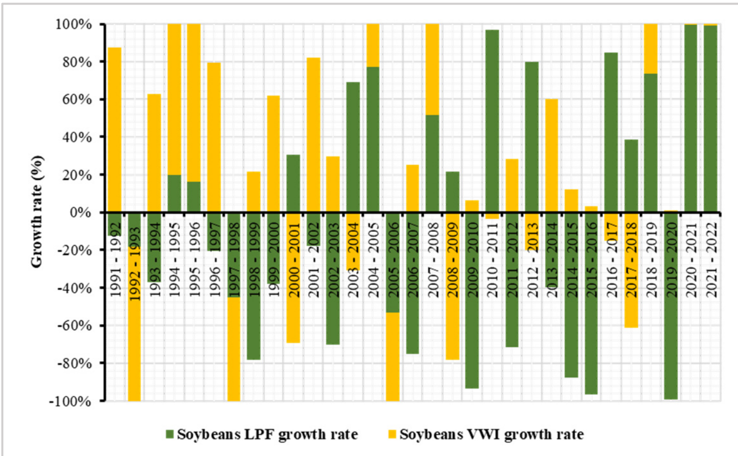


Figure 3. Virtual water import change characteristics of three major grains in South Korea during 1991–2022.

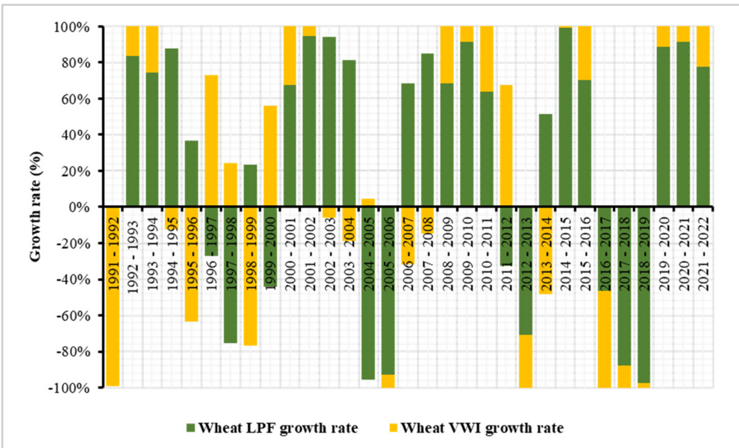
Figure 4 illustrates the growth trends of local production water footprint and virtual water imports for maize, soybean, and wheat from 1991 to 2022. Maize and soybean exhibited similar patterns, with virtual water imports growing at higher percentages than local production water footprints, indicating significant increases in imported water content relative to local water use. Conversely, local water usage for maize and soybean cultivation decreased or remained stable over time. However, wheat showed contrasting dynamics, with the local production water footprint growing more positively compared to virtual water imports, suggesting an increase in water usage for local production while the virtual water content of imported wheat decreased. These findings highlight varying trends in water usage between local production and virtual water imports for the three grains over the study period.



(**a**)



(**b**)



(**c**)

Figure 4. Growth rate of local production water footprint (LPF) to virtual water import (VWI) for (**a**) maize, (**b**) soybeans and (**c**) wheat grains during 1991–2022.

3.2. Water and Land Savings Due to Grain Imports

Virtual water trade is considered a potential method of solving local water shortage and unequal water distribution, as it allows water-scarce regions to rely on the water resources of other regions through trade [27]. For example, a study on the international trade of some grain products highlighted the savings and losses of scarce virtual water in international trade, emphasizing the significance of virtual water saving in global trade [28]. Figure 5 and Table A1 show the water savings due to the import of maize, soybean and wheat in South Korea over the period 1991 to 2022. The results indicate that the import of maize contributed the highest amount of water savings with an average value of 9.1 Bm^3, followed by soybeans and wheat, with average values of 4.3 Bm^3 and 4.2 Bm^3, respectively. The overall trend for water savings due to the combined import of all grains showed a positive trajectory over the specified period. This suggests that on the whole, South Korea experienced increasing water savings as a result of importing these specific grains, with maize imports having the most significant impact on conserving local water resources. The observed trend underscores the potential benefits of relying on international trade in grains as a strategy to alleviate local water scarcity concerns and optimize water resource management.

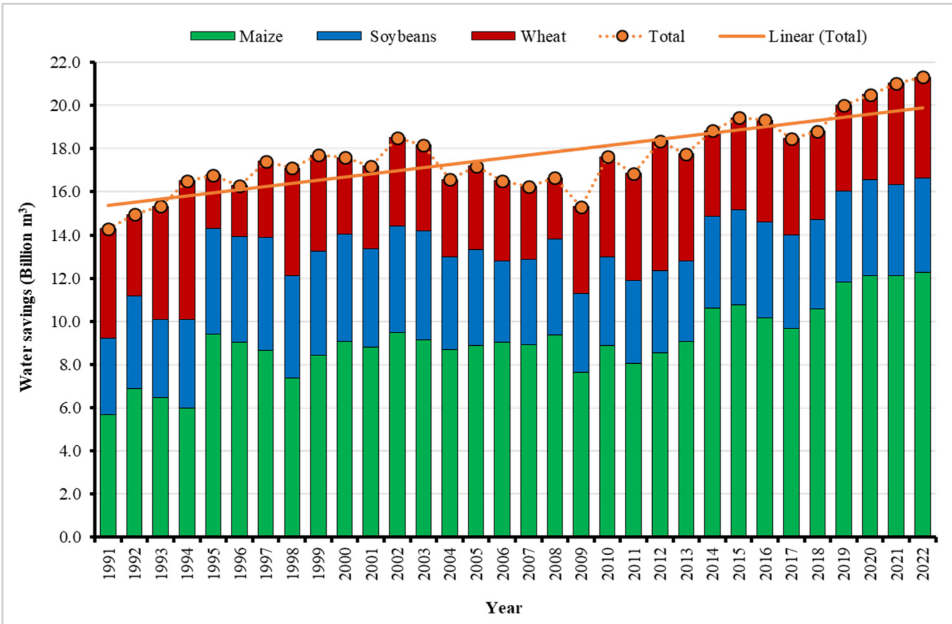


Figure 5. Grain's net imported water savings between 1991 and 2022.

The impact of grain imports on land use and potential land savings is crucial, especially in regions with limited land resources or competing land use priorities [29]. Our analysis from 1991 to 2022, as illustrated in Figure 6 and summarized in Table A2, highlights the utilization of land for local production of soybeans, maize, and wheat, alongside corresponding land savings resulting from imports. Soybean cultivation required the highest average land use, covering approximately 81,157 hectares, followed by maize and wheat production. Conversely, maize imports contributed to the highest average land savings, amounting to 2.0 million hectares over the study period. Wheat imports followed with average land savings of 1.2 million hectares, while soybean imports resulted in average land savings of 0.8 million hectares. These findings underscore the importance of grain importation in optimizing land use efficiency, with maize imports yielding the most substantial savings in local land resources.

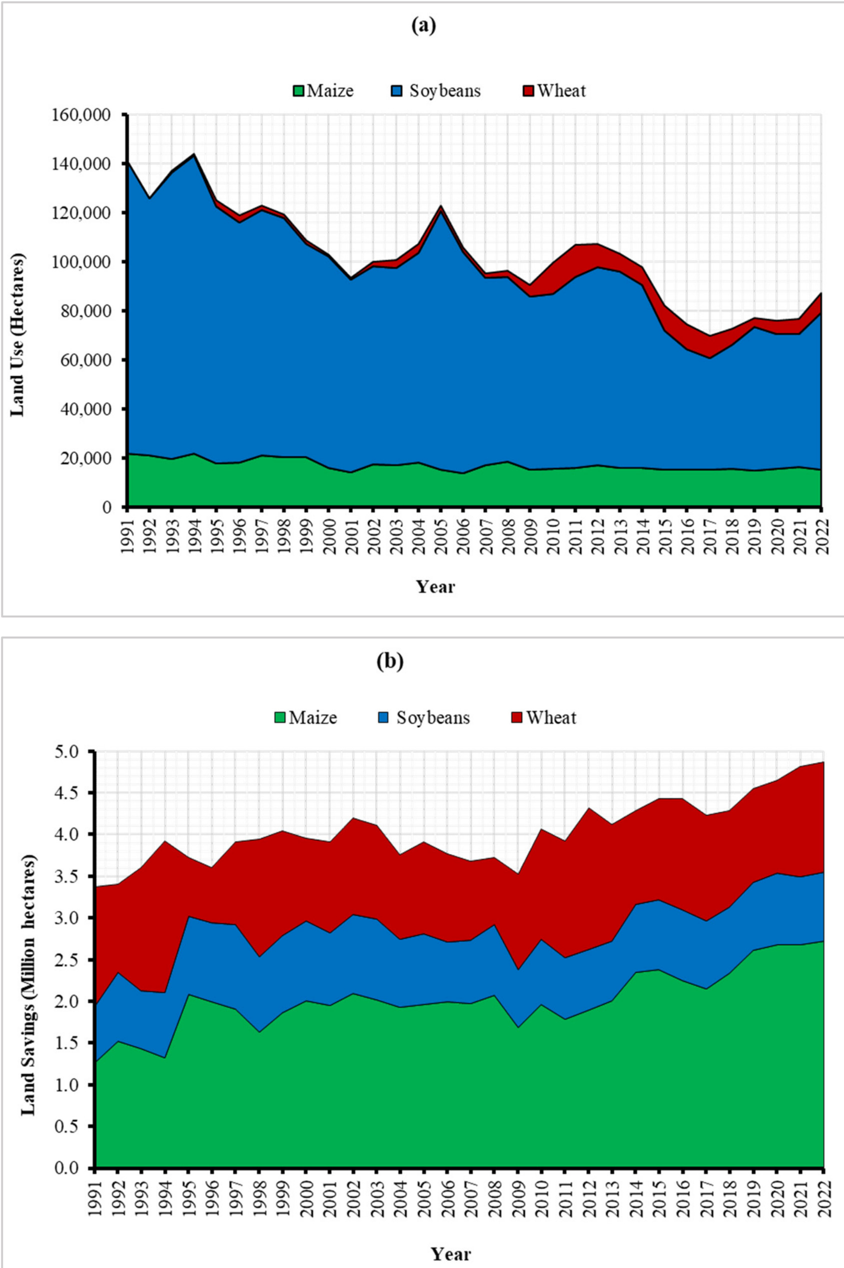


Figure 6. Grain's (**a**) local production land use and (**b**) net import land savings between 1991 and 2022.

3.3. Environmental Impact of Grain Imports

3.3.1. Impact of Domestic Water Consumption and Virtual Water Flows

Our analysis of domestic water consumption and virtual water flows focused on assessing the impact of major grains trade on South Korea's agricultural water resources (Figure 7 and Table A3). The water stress index, a measure of the pressure on local water resources, consistently remained low, always below 0.2 and ranging from 0.02 to 0.05. These values indicate that the utilization of local water resources for producing these grains imposed minimal stress on the country's agricultural water resources. However, this local grain production is insufficient to meet domestic consumption needs [30], hence the necessity of virtual water imports. In contrast, the assumed water stress index, which considers the scenario without the influence of external water resources (virtual water), ranged from "severe stress" to "extreme water stress" throughout the study period, with values spanning between 0.70 and 1.36. This suggests that without the contribution of virtual water, local water resources alone cannot fulfill the country's demand for water in cultivating these grains. This is also evident by the percentage reduction in stress on local water resources through the virtual water inflow from the trade of these grains, which ranged between 88.49% and 96.64%. These results affirm that the importation of virtual water through grain trade significantly alleviates stress on local water resources, bridging the gap between domestic production and consumption needs. The findings emphasize the interdependence of global trade and water resources, highlighting the role of virtual water flows in ensuring water sustainability in the context of grain production and consumption.

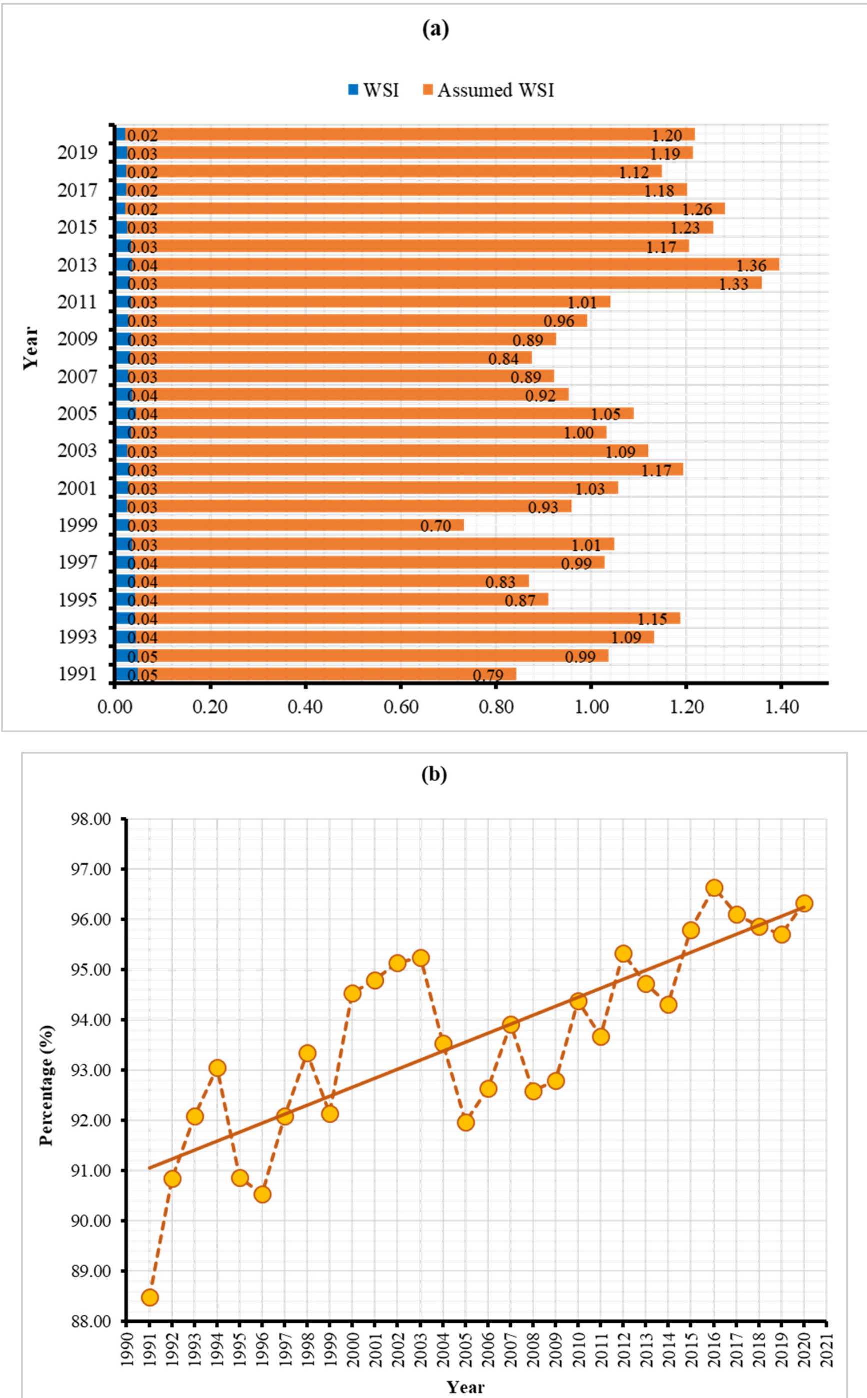


Figure 7. Grain (**a**) water stress index and assumed water stress index; and (**b**) percentage stress reduction through trade between 1991 and 2020.

3.3.2. Import Sustainability of Grain Trade

The importation of virtual water from a region facing water stress can strain the resources of the exporting area. Additionally, the importing region may encounter an imbalance between supply and demand, stemming from unsustainable imports influenced by water shortages in the exporting region [14]. The concept of the "unsustainable import fraction" (UIF) was introduced, representing the proportion of total blue water resources imported from water-stressed countries. The findings reveal that particularly in the early years between 1991 and 2012, there was a high unsustainable virtual water import fraction for all grains, ranging from 0.64 to 0.99. This implies that a significant portion, between 64% and 99%, of the total blue water resources was being imported from water-stressed countries during this period (as shown in Table 1). However, there was a notable shift from 2013 to 2022, where the UIF values for maize grain decreased, fluctuating between 0.21 and 0.48. In contrast, soybeans and wheat grains maintained relatively high UIF values throughout this period, ranging from 0.76 to 0.99.

Table 1. Unsustainable import fractions of major grains between 1991 and 2022.

Unsustainable Import Fraction (UIF)						
	Maize		**Soybeans**		**Wheat**	
Year	**% of Exporters Facing Water Stress**	**UIF**	**% of Exporters Facing Water Stress**	**UIF**	**% of Exporters Facing Water Stress**	**UIF**
1991	44	0.99	67	1	45	0.96
1992	83	0.99	25	0.99	40	0.98
1993	71	0.99	40	0.99	60	0.95
1994	50	0.99	40	0.99	36	0.93
1995	50	0.99	43	0.99	75	0.99
1996	63	0.98	33	0.99	57	0.99
1997	51	0.98	37	0.99	41	0.89
1998	38	0.98	40	0.99	25	0.80
1999	55	0.98	40	0.99	35	0.64
2000	63	0.99	29	0.99	50	0.98
2001	36	0.97	29	0.99	57	0.99
2002	43	0.97	40	0.99	57	0.98
2003	57	0.99	40	0.99	50	0.99
2004	58	0.99	43	0.99	71	0.99
2005	50	0.99	29	0.99	67	0.94
2006	50	0.99	40	0.99	40	0.96
2007	40	0.99	40	0.99	67	0.99
2008	64	0.99	29	0.99	57	0.95
2009	33	0.96	29	0.99	50	0.75
2010	44	0.98	40	0.99	21	0.83
2011	44	0.99	29	0.99	17	0.95
2012	40	0.68	22	0.99	56	0.99
2013	47	0.21	27	0.98	42	0.98
2014	47	0.41	29	0.99	42	0.96
2015	33	0.32	29	0.98	31	0.87
2016	38	0.32	22	0.98	33	0.76
2017	41	0.35	29	0.99	42	0.86
2018	33	0.48	29	0.99	57	0.83
2019	38	0.38	28	0.99	41	0.86
2020	37	0.37	27	0.99	41	0.84
2021	39	0.36	27	0.99	34	0.91
2022	41	0.35	27	0.99	27	0.99

The table also discusses the percentage of trade partners exporting scarce blue water resources to South Korea over the study period. Notably, in 1992, 83% of maize trade partners were water-stressed, supplying 99% of the total blue water resources to South Korea. For soybeans and wheat, the highest percentages were recorded in 1991 and 1995, with values of 67% and 75%, supplying 100% and 99% of the total blue water, respectively. These findings highlight the dependence on water-stressed regions for blue water resources and the variations in unsustainable import fractions over time for the different grain types.

4. Discussion

The analysis of the water footprint and virtual water imports for maize, soybeans, and wheat over the period from 1991 to 2022 reveals complex trends and implications for water sustainability, land use efficiency, and the environmental impact of grain imports. South Korea's grain trade policy, which is characterized by domestic production incentives, import regulations, and international trade agreements, significantly influences the country's agricultural landscape [31,32]. These elements collectively shape the country's agricultural landscape by influencing production decisions, trade flows, and market dynamics. Domestic production incentives, such as subsidies and support programs, aim to stimulate agricultural productivity and ensure food security by incentivizing farmers to produce certain crops (e.g., soybeans) [33]. Import regulations, including tariffs and tariff rate quotas, are designed to protect domestic producers while managing the flow of imported grains into the country. Additionally, participation in international trade agreements, such as bilateral or multilateral trade deals, influences South Korea's access to global grain markets and shapes its trade relationships with other countries. Together, these policy measures play a pivotal role in determining the structure and dynamics of South Korea's grain trade, ultimately shaping the country's agricultural sector and food security strategy.

The observed reduction in the local production water footprint for soybeans is noteworthy as it underscores the potential effectiveness of domestic policies aiming to improve water management practices. However, wheat demonstrates a slight increase in its production water footprint, with maize water footprint being relatively stable. This divergence suggests varying water management strategies for different crops within the country. The positive trend in wheat's water footprint implies an increased demand for water resources in domestic wheat production, highlighting potential challenges in sustainable water usage. The examination of virtual water imports further emphasizes the global dimension of South Korea's grain trade. The overall upward trajectory in the virtual water content associated with maize, soybeans, and wheat imports signifies the increasing reliance on external water resources from imported grains. This interconnectedness highlights South Korea's dependence on the global market for meeting its agricultural water needs, thus underscoring the importance of strategic trade policies in optimizing water resource management.

The growth rates of local production water footprints and virtual water imports provide additional insights into changing dynamics. Maize and soybeans display scenarios where the percentage growth in virtual water imports surpasses the reduction in local production water footprints. This dynamic suggests a strategic shift towards importing grains with higher virtual water content, potentially driven by factors such as cost-effectiveness or resource optimization. Wheat, however, presents a different scenario, with local production water footprints outpacing the growth in virtual water imports, indicating increased water usage in domestic wheat cultivation.

The examination of water savings due to grain trade in South Korea presents a compelling narrative about the strategic use of international trade as a tool for optimizing water resource management. This aspect of the analysis delves into the dual impact of grain imports, shedding light on not only the economic and dietary benefits but also the significant environmental advantage in terms of water conservation. The positive trajectory observed in water savings, particularly driven by the importation of maize, highlights the effectiveness of global trade in addressing local water scarcity concerns [30]. Maize, with its substantial contribution to water savings, emerges as a key player in this narrative. The average water savings of 9.1 Bm^3 associated with maize imports signify a considerable reduction in the domestic water footprint. This reduction is not merely a statistical figure but a tangible reflection of the utilization of global resources in order to meet local needs more efficiently. The increasing water savings over the study period suggest an evolving strategy in leveraging international trade to achieve greater resilience in the face of water scarcity. The benefits extend beyond mere self-sufficiency, signaling a proactive approach in adapting to changing climate patterns and local resource constraints. The agricultural sector, often a major consumer of water resources, appears to be navigating towards a more sustainable path thanks to the strategic importation of water-intensive grains.

Moreover, the findings herein underscore the interconnectedness of global food systems and the role of trade in optimizing resource allocation. By importing grains from external sources, South Korea not only ensures food security but also effectively 'imports' water in an embedded form. This strategy aligns with the concept of virtual water trade, where nations can capitalize on the water resources embedded in traded goods to address imbalances in local water availability [22]. The importance of water savings through grain trade becomes particularly pronounced in the context of climate change and unpredictable weather patterns. As countries face heightened challenges related to water scarcity and droughts, the ability to import grains with lower water requirements becomes a crucial adaptation strategy. It allows nations to mitigate the impact of climate-induced variations in water availability on their food production systems [34].

The analysis of land use and savings due to grain trade in South Korea sheds light on a crucial aspect of the country's agricultural dynamics. Understanding how different grains impact local land resources and the potential savings resulting from international trade provides valuable insights into the sustainability and efficiency of South Korea's agricultural practices. Firstly, the examination of local production land use highlights significant variations among the different grain crops. Soybeans exhibited the highest average land use, covering a substantial area over time, suggesting that in terms of land efficiency, soybean cultivation consumed more land compared to maize and wheat production. The reasons behind this variation could be influenced by factors such as crop yield per hectare, agricultural practices, and the suitability of land for different crops [35].

The notion of land savings due to grain imports introduces a compelling dimension to the discussion. The data indicate that maize imports contribute significantly to land savings, followed by wheat and soybeans. This implies that through international trade, South Korea not only meets its grain consumption needs but also conserves local land resources that would otherwise be required for domestic grain cultivation. The land savings resulting from grain imports become particularly relevant in a country like South Korea, where land resources are limited [36] and there are competing priorities for land use. The concept of land savings due to grain trade becomes crucial when viewed in the broader context of sustainable resource management. The trade-off between domestic land use for agriculture and the environmental and societal benefits of preserving land for other purposes, such as conservation or urban development, is a critical consideration. By strategically relying on grain imports, South Korea can potentially optimize land use, ensuring the efficient allocation of limited land resources to meet diverse societal needs.

Furthermore, the analysis suggests that maize imports contribute the most substantial land savings. Maize, being a staple grain in many parts of the world, could be more efficiently produced in regions with favorable agro-climatic conditions, leading to higher yields per unit of land. This aligns with the principle of comparative advantage in international trade, where countries focus on producing goods for which they have a relative efficiency [37,38], thereby optimizing global resource use. The observed trends in land use and savings due to grain trade also have implications for environmental sustainability. Preserving natural ecosystems and biodiversity is critical for maintaining ecological balance, and the efficient use of agricultural land contributes to this goal. The land savings resulting from grain imports provide an avenue for South Korea to minimize the ecological footprint of its agricultural activities.

Delving deeper into the environmental impacts of South Korea's grain trade, the examination of water stress indices and the unsustainable import fraction provides critical insights into the sustainability of the country's agricultural practices. These metrics offer a lens through which we can assess the broader implications of South Korea's reliance on external water resources embedded in imported grains. The water stress indices, as revealed in the analysis, shed light on the immediate impact of grain production on South Korea's local water resources. The consistently low water stress index throughout the study period implies that, at a surface level, the cultivation of maize, soybeans, and wheat did not impose significant pressure on the country's agricultural water resources. However, crucial nuance emerges when considering the assumed water stress index, which factors out the influence of external water resources (virtual water). The scenario depicted by the assumed water stress index is one of stark contrast, ranging from "severe stress" to "extreme water stress" throughout the study period. This stark divergence underscores the critical role played by virtual water imports in bridging the gap between local production and consumption needs. It implies that South Korea's local water resources alone are insufficient to meet the demands of grain cultivation. The significant percentage stress reduction on local water resources through the virtual water inflow further highlights the indispensable contribution of imported virtual water in ensuring water sustainability.

Moving beyond these indices, the concept of the unsustainable import fraction (UIF) adds a layer of complexity to the discussion. The UIF represents the proportion of total blue water resources imported from water-stressed countries. During the early years from 1991 to 2012, South Korea exhibited a high UIF for all grains, ranging from 0.68 to 0.99. This implies that a substantial portion of the country's total blue water resources during this period were being imported from regions facing water stress. This high UIF raises concerns about the potential strain on the water resources of exporting regions and poses questions about the sustainability of such practices. Importing a significant fraction of water from regions already grappling with water stress can contribute to environmental degradation and exacerbate existing water stress in those areas. It also points to potential vulnerabilities in South Korea's supply chain, highlighting the importance of adopting sustainable sourcing practices in global grain trade. Notably, there is a noteworthy shift in UIF values from 2013 to 2022, particularly in the case of maize. The decrease in UIF values for maize during this period suggests a potential improvement in the sustainability of maize imports. This shift may be indicative of changes in trade dynamics, adoption of more sustainable sourcing practices, or a diversification of import sources [9]. However, it is crucial to juxtapose this improvement with the relatively high UIF values for soybeans and wheat during the same period, signaling ongoing challenges in achieving sustainability across all grain types. The analysis also considers the percentage of trade partners exporting scarce blue water resources to South Korea over the study period. The high percentages, especially in the early years, underscore the dependence on water-stressed regions for blue water resources. This dependence, while facilitating South Korea's grain production and trade, highlights the need for a conscientious approach to water resource management and the adoption of sustainable practices in international trade relationships.

5. Limitations of the Study

To begin with, it is essential to highlight that this research has certain constraints as it did not rely on direct field measurements of water footprint data but instead utilized pre-existing data from prior studies. Consequently, the calculations related to virtual water trade and water–land savings in the context of grain trade in this investigation were derived from a historical database, introducing the possibility of slight inaccuracies in the data. Secondly, the estimation of land savings was predicated on the hypothetical assumption of a singular cropping system for each analyzed grain crop, resulting in a land savings value that at times exceeded the available agricultural land area in South Korea (currently estimated at 1.55 million hectares [39]). Nevertheless, the outcomes suggest that grain imports could positively influence water and land savings in the country. Furthermore, due to data limitations, this study focused solely on the aspects of water and land resources. Future research should explore additional factors such as national policies and scientific technology's influence on water and land conservation in agriculture and greenhouse gas emissions associated with transportation and production to provide a more comprehensive understanding of South Korea's grain trade sustainability.

6. Conclusions

This comprehensive analysis of South Korea's grain production and trade dynamics offers valuable insights into the intricate relationship between local resource management and global trade dynamics. The observed reduction in local production for soybean signifies a notable shift, yet it is crucial to consider that this reduction may be influenced by the concurrent increase in grain imports over the same period. The strategic reliance on virtual water imports emerges as a key driver in addressing domestic water scarcity concerns and improving overall resource management. Particularly noteworthy is the positive trajectory in water savings, particularly influenced by maize imports, highlighting the pivotal role of international grain trade in conserving local water resources. To enhance resilience in the face of potential uncertainties, it is recommended to further diversify sources of grain imports and establish collaborations with nations that prioritize sustainable water practices. This strategic approach can contribute significantly to stabilizing South Korea's grain imports and ensuring a more robust and sustainable water resource management system.

Considerations regarding land efficiency further underscore the complexities in agricultural practices, with substantial land savings resulting from grain imports showcasing the potential of international trade to alleviate land use pressures domestically. However, a cautious approach is recommended, recognizing the interconnected nature of water and land resource utilization. Emphasizing sustainable farming practices, precision agriculture techniques, and the adoption of crop varieties that demonstrate high yields while minimizing land requirements remains critical for achieving long-term environmental sustainability.

Environmental impact assessments, including water stress indices and the unsustainable import fraction, underscore the overall sustainability of grain trade practices. While a low water stress index during grain production implies minimal immediate burden on local water resources, potential vulnerability without virtual water highlights the importance of continued reliance on global trade. To address evolving challenges, it is recommended that continuous monitoring and adaptive strategies are implemented. Regular assessments of water stress indices, import fractions, and sustainability practices will provide crucial feedback for evidence-based policy making.

Conclusively, a tailored and adaptive approach to resource management, trade policies, and sustainable practices is essential for ensuring a resilient and sustainable future for South Korea's agricultural sector. By building on the progress achieved in water efficiency, diversifying grain sources, and embracing sustainable agricultural practices, the nation can navigate the challenges posed by water scarcity and land limitations. Continuous collaboration with the scientific community and a commitment to ongoing research will further refine strategies and ensure that South Korea's agricultural landscape remains robust and sustainable.

Author Contributions: Conceptualization, G.O.; methodology, G.O., B.A. and Q.A.; software, G.O., B.A., A.A.H. and S.R.A.; validation, G.O., B.A. and K.S.C.; formal analysis, G.O., B.A. and Q.A; investigation, G.O., B.A., A.A.H. and S.R.A.; resources, G.O. and K.S.C.; data curation, G.O., B.A., Q.A., A.A.H. and S.R.A.; writing—original draft preparation, G.O., B.A., Q.A., A.A.H. and S.R.A.; writing—review and editing, G.O., B.A., Q.A., A.A.H., S.R.A. and K.S.C.; visualization, G.O., B.A., Q.A., A.A.H., S.R.A. and K.S.C.; project administration, K.S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Grain net import water savings from 1991 to 2017.

Water Savings (m^3)				
Year	**Maize**	**Soybeans**	**Wheat**	**Total**
1991	5,693,922,248.50	3,521,990,105.90	5,077,995,411.60	14,293,907,766.00
1992	6,874,746,967.70	4,315,372,194.70	3,759,791,500.80	14,949,910,663.20
1993	6,453,510,433.30	3,641,192,866.50	5,236,154,987.40	15,330,858,287.20
1994	5,976,925,469.40	4,111,039,426.20	6,421,126,744.80	16,509,091,640.40
1995	9,393,865,209.30	4,911,971,670.20	2,482,754,095.80	16,788,590,975.30
1996	9,023,318,208.70	4,918,370,560.60	2,356,800,215.40	16,298,488,984.70
1997	8,642,637,252.20	5,248,027,204.00	3,525,662,233.80	17,416,326,690.00
1998	7,393,798,478.10	4,728,923,913.70	4,977,769,404.60	17,100,491,796.40
1999	8,437,396,313.40	4,822,992,957.30	4,440,726,154.80	17,701,115,425.50
2000	9,060,471,888.20	4,994,038,979.06	3,529,742,943.60	17,584,253,810.86
2001	8,818,559,690.70	4,535,494,693.80	3,847,184,847.00	17,201,239,231.50
2002	9,474,269,369.10	4,936,258,672.10	4,093,802,209.80	18,504,330,251.00
2003	9,131,021,771.40	5,047,938,051.10	3,990,204,766.80	18,169,164,589.30
2004	8,703,341,176.40	4,295,459,329.70	3,571,420,465.80	16,570,220,971.90
2005	8,872,024,183.80	4,451,783,686.70	3,864,010,221.00	17,187,818,091.50
2006	9,013,839,263.80	3,771,325,949.30	3,736,225,375.20	16,521,390,588.30
2007	8,919,616,451.30	3,966,398,398.90	3,370,074,703.20	16,256,089,553.40
2008	9,379,128,501.50	4,432,707,496.70	2,843,780,821.20	16,655,616,819.40
2009	7,625,491,464.30	3,650,413,025.00	4,034,142,635.40	15,310,047,124.70
2010	8,880,043,389.90	4,102,672,676.20	4,648,326,037.20	17,631,042,103.30
2011	8,066,676,722.60	3,840,535,705.30	4,952,550,427.20	16,859,762,855.10
2012	8,546,525,304.80	3,814,582,046.80	5,995,595,331.00	18,356,702,682.60
2013	9,068,973,515.10	3,736,861,632.70	4,962,629,748.60	17,768,464,896.40
2014	10,626,995,863.10	4,226,489,063.55	3,977,044,154.33	18,830,529,080.98
2015	10,760,506,339.35	4,404,990,595.84	4,263,952,181.11	19,429,449,116.30
2016	10,178,566,578.22	4,441,529,766.04	4,702,417,112.54	19,322,513,456.80
2017	9,690,478,207.17	4,304,931,528.18	4,475,275,666.15	18,470,685,401.49
2018	10,569,941,233.91	4,149,225,172.80	4,096,561,274.28	18,815,727,680.99
2019	11,818,142,463.97	4,229,892,155.45	3,971,461,862.07	20,019,496,481.49
2020	12,127,034,973.85	4,444,905,917.00	3,932,354,232.86	20,504,295,123.71
2021	12,116,193,533.29	4,239,179,984.22	4,688,302,245.86	21,043,675,763.37
2022	12,278,795,179.44	4,360,002,212.95	4,671,078,194.25	21,309,875,586.64

Table A2. Grain local production land use and net import land savings from 1991 to 2017.

	Land Use (ha)			Land Savings (ha)		
Year	**Maize**	**Soybeans**	**Wheat**	**Maize**	**Soybeans**	**Wheat**
1991	21,874.00	119,066.00	178.00	1,259,596.15	673,521.28	1,436,897.40
1992	20,937.00	104,647.00	164.00	1,520,815.43	825,242.24	1,063,891.20
1993	19,622.00	116,825.00	547.00	1,427,630.47	696,316.80	1,481,651.10
1994	21,667.00	121,729.00	582.00	1,322,201.46	786,167.04	1,816,957.20
1995	17,541.00	105,035.00	2,312.00	2,078,088.87	939,331.84	702,533.70
1996	17,908.00	97,989.00	2,787.00	1,996,117.33	940,555.52	666,893.10
1997	21,097.00	99,862.00	1,838.00	1,911,903.98	1,003,596.80	997,640.70
1998	20,140.00	97,682.00	1,372.00	1,635,638.79	904,327.04	1,408,536.90
1999	20,134.00	87,026.00	1,533.00	1,866,501.06	922,316.16	1,256,572.20
2000	15,808.00	86,176.00	919.00	2,004,336.38	955,025.83	998,795.40
2001	14,208.00	78,415.00	915.00	1,950,821.13	867,336.96	1,088,620.50
2002	17,344.00	80,804.00	1,808.00	2,095,875.69	943,976.32	1,158,404.70
2003	16,966.00	80,447.00	3,281.00	2,019,943.26	965,333.12	1,129,090.20
2004	18,218.00	85,270.00	3,792.00	1,925,332.76	821,434.24	1,010,588.70

Table A2. *Cont.*

	Land Use (ha)			Land Savings (ha)		
Year	**Maize**	**Soybeans**	**Wheat**	**Maize**	**Soybeans**	**Wheat**
2005	15,176.00	105,421.00	2,395.00	1,962,648.42	851,328.64	1,093,381.50
2006	13,661.00	90,248.00	1,738.00	1,994,020.42	721,202.56	1,057,222.80
2007	16,981.00	76,267.00	1,928.00	1,973,176.67	758,506.88	953,614.80
2008	18,366.00	75,242.00	2,549.00	2,074,828.85	847,680.64	804,691.80
2009	15,326.00	70,265.00	5,067.00	1,686,893.37	698,080.00	1,141,523.10
2010	15,528.00	71,422.00	12,548.00	1,964,422.41	784,567.04	1,315,315.80
2011	15,823.00	77,849.00	13,044.00	1,784,491.34	734,437.76	1,401,400.80
2012	17,001.00	80,842.00	9,467.00	1,890,642.32	729,474.56	1,696,546.50
2013	15,905.00	80,031.00	7,373.00	2,006,217.09	714,611.84	1,404,252.90
2014	15,839.00	74,652.00	7,180.00	2,350,879.15	808,244.84	1,125,366.20
2015	15,356.00	56,666.00	10,076.00	2,380,414.02	842,380.25	1,206,551.27
2016	15,183.00	49,014.00	10,440.00	2,251,678.67	849,367.75	1,330,621.71
2017	15,074.00	45,556.00	9,283.00	2,143,704.90	823,245.64	1,266,348.52
2018	15,472.00	50,638.00	6,600.00	2,338,257.65	793,469.42	1,159,185.42
2019	14,840.00	58,537.00	3,736.00	2,614,381.81	808,895.62	1,123,786.61
2020	15,633.00	55,008.00	5,224.00	2,682,714.29	850,013.38	1,112,720.50
2021	16,145.00	54,444.00	6,224.00	2,680,315.97	810,671.76	1,326,627.69
2022	15,296.00	63,956.00	8,118.00	2,716,286.32	833,776.98	1,321,753.88

Table A3. Water stress index, assumed water stress index, and percentage stress reduction through trade between 1991 and 2020 for major grains.

Year	WSI	Assumed WSI	Stress Reduction through Trade (%)
1991	0.05	0.79	88.49
1992	0.05	0.99	90.86
1993	0.04	1.09	92.09
1994	0.04	1.15	93.06
1995	0.04	0.87	90.87
1996	0.04	0.83	90.53
1997	0.04	0.99	92.09
1998	0.03	1.01	93.35
1999	0.03	0.70	92.14
2000	0.03	0.93	94.54
2001	0.03	1.03	94.79
2002	0.03	1.17	95.14
2003	0.03	1.09	95.25
2004	0.03	1.00	93.53
2005	0.04	1.05	91.98
2006	0.04	0.92	92.64
2007	0.03	0.89	93.92
2008	0.03	0.84	92.58
2009	0.03	0.89	92.79
2010	0.03	0.96	94.38
2011	0.03	1.01	93.68
2012	0.03	1.33	95.32
2013	0.04	1.36	94.73
2014	0.03	1.17	94.31
2015	0.03	1.23	95.80
2016	0.02	1.26	96.64
2017	0.02	1.18	96.11
2018	0.02	1.12	95.87
2019	0.03	1.19	95.72
2020	0.02	1.20	96.33

References

1. Ortiz, A.M.D.; Outhwaite, C.L.; Dalin, C.; Newbold, T. A review of the interactions between biodiversity, agriculture, climate change, and international trade: Research and policy priorities. *One Earth* **2021**, *4*, 88–101. [CrossRef]
2. 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]
3. Hoekstra, A.Y.; Hung, P.Q. Virtual water trade. In Proceedings of the International Expert Meeting on Virtual Water Trade, Delft, The Netherlands, 12 December 2003; pp. 1–244.
4. 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]
5. Carr, J.A.; D'Odorico, P.; Laio, F.; Ridolfi, L. Recent history and geography of virtual water trade. *PLoS ONE* **2013**, *8*, e55825. [CrossRef]
6. Mubako, S.T.; Lant, C.L. Agricultural virtual water trade and water footprint of US states. *Ann. Assoc. Am. Geogr.* **2013**, *103*, 385–396. [CrossRef]
7. Graham, N.T.; Iyer, G.; Wise, M.; Hejazi, M.; Wild, T.B. Future evolution of virtual water trading in the United States electricity sector. *Environ. Res. Lett.* **2021**, *16*, 124010. [CrossRef]
8. Dalin, C.; Konar, M.; Hanasaki, N.; Rinaldo, A.; Rodriguez-Iturbe, I. Evolution of the global virtual water trade network. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 5989–5994. [CrossRef]
9. Odey, G.; Adelodun, B.; Lee, S.; Adeyemi, K.A.; Choi, K.S. Assessing the impact of food trade centric on land, water, and food security in South Korea. *J. Environ. Manag.* **2023**, *332*, 117319. [CrossRef] [PubMed]
10. Antonelli, M.; Tamea, S. Food-water security and virtual water trade in the Middle East and North Africa. *Int. J. Water Resour. Dev.* **2015**, *31*, 326–342. [CrossRef]
11. Hoekstra, A.Y.; Mekonnen, M.M. The water footprint of humanity. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 3232–3237. [CrossRef]
12. Islam, M.S.; Oki, T.; Kanae, S.; Hanasaki, N.; Agata, Y.; Yoshimura, K. A grid-based assessment of global water scarcity including virtual water trading. *Water Resour. Manag.* **2007**, *21*, 19–33. [CrossRef]
13. Qu, S.; Liang, S.; Konar, M.; Zhu, Z.; Chiu, A.S.; Jia, X.; Xu, M. Virtual water scarcity risk to the global trade system. *Environ. Sci. Technol.* **2018**, *52*, 673–683. [CrossRef] [PubMed]
14. Rathore, L.S.; Aziz, D.; Demeke, B.W.; Mekonnen, M.M. Sustainability assessment of virtual water flows through cereal and milled grain trade among US counties. *Environ. Res. Infrastruct. Sustain.* **2023**, *3*, 25001. [CrossRef]
15. Mekonnen, M.M.; Hoekstra, A.Y. Blue water footprint linked to national consumption and international trade is unsustainable. *Nat. Food* **2020**, *1*, 792–800. [CrossRef] [PubMed]
16. Lee, S.H.; Yoo, S.H.; Choi, J.Y.; Shin, A. Evaluation of the dependency and intensity of the virtual water trade in Korea. *Irrig. Drain.* **2016**, *65*, 48–56. [CrossRef]
17. FAO. Crops and Livestock Products. Available online: http://www.fao.org/faostat/en/#data/QCL (accessed on 7 December 2023).
18. World-Bank. Renewable Internal Freshwater Resources, Total (Billion Cubic Meters)—Korea, Rep. Available online: https://data.worldbank.org/indicator/ (accessed on 12 December 2023).
19. Hoekstra, A.Y. Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade. In Proceedings of the International Expert Meeting on Virtual Water Trade 12, Delft, The Netherlands, 12 December 2003; pp. 25–47.
20. Yoo, S.-H.; Lee, S.-H.; Choi, J.-Y. Estimation of water footprint for upland crop production in Korea. *J. Korean Soc. Agric. Eng.* **2014**, *56*, 65–74.
21. Lee, S.-H.; Mohtar, R.H.; Yoo, S.-H. Assessment of food trade impacts on water, food, and land security in the MENA region. *J Hydrol. Earth Syst. Sci.* **2019**, *23*, 557–572. [CrossRef]
22. Hoekstra, A.Y.; Hung, P.Q. Globalisation of water resources: International virtual water flows in relation to crop trade. *Glob. Environ. Chang.* **2005**, *15*, 45–56. [CrossRef]
23. Hanafiah, M.M.; Ghazali, N.F.; Harun, S.N.; Abdulaali, H.S.; AbdulHasan, M.J.; Kamarudin, M.K.A. Assessing water scarcity in Malaysia: A case study of rice production. *Desalination Water Treat.* **2019**, *149*, 274–287. [CrossRef]
24. Huang, H.; Jiang, S.; Gao, X.; Zhao, Y.; Lin, L.; Wang, J.; Han, X. The Temporal Evolution of Physical Water Consumption and Virtual Water Flow in Beijing, China. *Sustainability* **2022**, *14*, 9596. [CrossRef]
25. Deng, J.; Li, C.; Wang, L.; Yu, S.; Zhang, X.; Wang, Z. The impact of water scarcity on Chinese inter-provincial virtual water trade. *Sustain. Prod. Consum.* **2021**, *28*, 1699–1707. [CrossRef]
26. WRI. Baseline Water Stress. Available online: https://www.wri.org/applications/aqueduct/country-rankings/ (accessed on 22 December 2023).
27. Xu, Y.; Tian, Q.; Yu, Y.; Li, M.; Li, C. Water-saving efficiency and inequality of virtual water trade in China. *Water* **2021**, *13*, 2994. [CrossRef]
28. Wu, H.; Jin, R.; Liu, A.; Jiang, S.; Chai, L. Savings and losses of scarce virtual water in the international trade of wheat, maize, and rice. *Int. J. Environ. Res. Public Health* **2022**, *19*, 4119. [CrossRef] [PubMed]
29. Kim, H.-J. The Improvements of Land Suitability Assessment for Sustainable Land Use Management through Multi-Criteria Analysis in Korea: Focused on Assessment System 2. *Int. J. Urban Sci.* **2010**, *14*, 16–32. [CrossRef]

30. Odey, G.; Adelodun, B.; Lee, S.; Adeyemi, K.A.; Cho, G.; Choi, K.S. Environmental and Socioeconomic Determinants of Virtual Water Trade of Grain Products: An Empirical Analysis of South Korea Using Decomposition and Decoupling Model. *Agronomy* **2022**, *12*, 3105. [CrossRef]
31. Eun-Mee, J. The development and characteristics of the environment-friendly agricultural policy in Korea. *Korean J. Org. Agric.* **2006**, *14*, 117–137.
32. Hopkinson, J. *Overview of US-South Korea Agricultural Trade*; Congressional Research Service: Washington, DC, USA, 2018.
33. USDA. South Korea: Grain and Feed Update. Available online: https://fas.usda.gov/data/south-korea-grain-and-feed-update-23 (accessed on 5 March 2024).
34. Konar, M.; Hussein, Z.; Hanasaki, N.; Mauzerall, D.L.; Rodriguez-Iturbe, I. Virtual water trade flows and savings under climate change. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 3219–3234. [CrossRef]
35. Olesen, J.E.; Bindi, M. Consequences of climate change for European agricultural productivity, land use and policy. *Eur. J. Agron.* **2002**, *16*, 239–262. [CrossRef]
36. Choi, Y.-J.; Oh, B.-C.; Acquah, M.A.; Kim, D.-M.; Kim, S.-Y. Optimal operation of a hybrid power system as an island microgrid in south-korea. *Sustainability* **2021**, *13*, 5022. [CrossRef]
37. Dellink, R. The consequences of a more resource efficient and circular economy for international trade patterns: A modelling assessment. 2020. Available online: https://www.oecd-ilibrary.org/environment/the-consequences-of-a-more-resource-efficient-and-circular-economy-for-international-trade-patterns_fa01b672-en (accessed on 5 February 2024).
38. 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]
39. Statista. Area of Farmland in South Korea in 2021, by Type (in 1000 Hectares). Available online: https://www.statista.com/statistics/1249737/south-korea-farmland-area-by-type/ (accessed on 12 December 2023).