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Research article



Assessing the impact of food trade centric on land, water, and food security in South Korea

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ABSTRACT

The observed and predicted changes in climate, as well as the growth in urban population, are creating severe stress on existing water resources in South Korea. By the importation of agricultural products from more water-rich countries through the virtual water concept, a country could save local water resources for other important uses. However, these imports from other countries could lead to certain vulnerabilities in the importing country derived from climate change. Therefore, through the application of the virtual water concept and the climate vulnerability index ((CVI) - measure of a country's vulnerability to indirect climate impacts), this study assessed the implication of virtual water imports and climate change through food trade, on the water, land and food security status of South Korea over the period of 2000–2017. The results showed that significant amounts of national water and land was saved through the importation of major upland crops. Virtual water imports increased significantly over time, rising from 16.2 Bm^3 in 2000 to 16.5, 17.4, and 20.7 Bm^3 in 2005, 2011, and 2017 respectively, with the USA, China, Australia, Brazil and Canada being the major exporters to South Korea. The study also revealed high CVI values for the oils and grains category of imported food, implying the high vulnerability of South Korea to climate change effects resulting from the import of these crops. The quantitative impacts and structural changes in virtual water trade, as well as the link between climate change, food security, international trade, and domestic water consumption could be evaluated for the sustainable management and allocation of resources. This study successfully identified and quantified the status of food trade and its environmental implications in the study area, providing insight into a better allocation of locally available resources.

1. Introduction

Food security and water scarcity are critical socioeconomic and environmental concerns that are inextricably intertwined. Food security necessitates that 'all people have physical, social, and economic access to adequate, safe, and healthy food that meets their nutrition requirements for an adequate standard of living at all times'(FAO, 2002). There are concerns about how the United Nations (UN) aim of "Zero Hunger by 2030″ will be met in the face of surging climate issues (Horn et al., 2022; UN, 2020). In some regions of the world today, there exists complications in food security due to elevated geopolitical risks and low domestic agricultural production brought about by inadequate arable land and water resources (Lee et al., 2019; Rastoin and Cheriet, 2010). Challenges with water resources are currently one of the serious global problems that have a detrimental impact on the sustainable development of many nations. The main contributors are natural disasters including floods and droughts, as well as rapid population growth, increased demand for food, depletion of aquifers, and climate change (Ekwueme and Agunwamba, 2020, 2021; Hirwa et al., 2022). Global freshwater needs are rising, and local water shortages are happening more frequently than ever (Da Silva et al., 2016). In Central Asia, more than 80% of people experience water stress, and around 50% experience water shortages (Porkka et al., 2012). In sub-Saharan Africa, there are predictions that the gap between freshwater availability, supply, and demand will increase even further (Dos Santos et al., 2017). In the Mediterranean region, climate change could increase the frequency of extreme climatic events, resulting in a 50% loss in agricultural productivity by the end of the century (Porter et al., 2014). Due to these

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challenges, several of these water-stressed regions cannot meet local food demands through domestic agricultural production; hence tend to food importation from other regions. Available studies suggests that through this trade, domestic water can be saved (Lezzaik et al., 2018; Odey et al., 2021; Oki et al., 2017). On a broader scale, the exporting of food from nations with higher water productivity may help to reduce global water use, hence contributing to global water savings (Konar et al., 2012). As a result, food trade is an integral factor of both food and water security in water-stressed regions.

In Korea, climate change predictions show a likely increase in the frequency and severity of droughts (Adelodun et al., 2022), making the sustainable management of water resources a local issue and in extension placing Korea at a high position amongst the Organization for Economic Co-operation and Development (OECD) countries in terms of water stress (OECD, 2018) (Fig. S1).

Agriculture constitutes the major percentage of water consumption in water-stressed regions (Hoekstra and Mekonnen, 2012b). Agricultural production accounted for about 61% of South Korea's water use in 2014, with an increase in groundwater exploitation. This increase was due to repeated, protracted droughts that have prompted groundwater exploitation in an effort to secure water sources (Lee and Kwon, 2016). This water stress, coupled with South Korea's relatively limited agricultural potential (due to land area) and its growing population, forces the country to rely largely on food imports (Yoo et al., 2016). This study thus focused on the impact of this food trade on the water, land and food security status of the country, applying the virtual water trade (VWT) and the water footprint (WF) concepts coined by Tony Allan in the early 90s and Arjen Hoekstra in the early 2000s respectively. These two concepts are closely related (Hoekstra and Mekonnen, 2012a). While the WF is a water efficiency metric that quantifies the amount of water used in the production of goods or services, the VWT is the trading of water incorporated in food products (Hoekstra and Hung, 2003). Water valuation for crops is becoming increasingly important for giving not just guidance in evaluating the biophysical and economic sustainability of agricultural water resources, but also critical information for policy makers, investors and agencies involved in water allocations (Zhuo et al., 2022). By forecasting future water demand for food supply and realistically assessing water shortage, the VWT concept can increase public awareness of water resources management (Lee et al., 2019; Oki and Kanae, 2004).

Following the introduction of the VWT and WF concepts, several studies have been conducted for a number of products at different spatiotemporal scales. For instance, Zhang et al. (2016) reported that China's virtual water trade in agricultural products had a surplus from 2001 to 2013 due to virtual water exports of 29.94 billion m^3/yr and imports of 155.55 billion m^3/yr. Considering the food supply challenge posed by increasing urban growth and climate change in sub-Saharan Africa, Akoto-Danso et al. (2019) determined the magnitude of virtual water flows in two major West African cities of Tamale and Ouagadougou. They revealed an importation of 514 and 2105 million m^3/yr of virtual water respectively, of all food commodities, with cereals contributing the most to the total virtual water inflows in both cities (Akoto-Danso et al., 2019). Harris et al. (2020) quantified the interstate trade in five key cereals and the associated trade in virtual water. They stated that in 2011–2012, trades of 54.0 km^3 of embedded blue water and 99.4 km^3 of embedded green water accounted for 40% of the total supply of cereal food in India (Harris et al., 2020). Hekmatnia et al. (2020) assessed the volume of virtual water exchange for crops in Iran from 2001 to 2018. According to the findings, Iran exported 90 billion m^3 and imported 280 billion m^3 of virtual water over this period (Hekmatnia et al., 2020). Park et al. (2020) analyzed the international virtual water trends with a focus on South Korea. They revealed that the country imported 72.2 billion m^3 of virtual water in 2018, which was 29 times more than the 2.5 billion m^3 it exported (Park et al., 2020). Nishad and Kumar (2022) investigated the implication of virtual water trade on water sustainability with India as a case study. They revealed that India was a major water exporter, exporting approximately 32 billion m^3 of water, or 1.6 percent of total available water, and contributing a 24 percent share of global virtual water export while virtual water import was minor (Nishad and Kumar, 2022). All of these studies have found evidence that importing food produced in regions with more abundant water is critical for the management of water resources, as the VWT relieves pressure on water-stressed regions (Graham et al., 2020; Hoekstra and Mekonnen, 2012b).

Food imports today are three times their value in 2000, indicating that the food system is becoming more global (European Commission, 2019). However, a strong reliance on food imports might threaten food security, even if it can result in domestic water and land savings in water-stressed areas (Lee et al., 2019). This is because increased food import might lead to vulnerability of the importing country to instabilities in trade partner (exporting) countries brought about by such factors as climate change (Yoo et al., 2016). By increasing the risk of interruptions to the stability of agricultural production, climate change increases the complexity of the complicated global system of food interdependency. As a result, net food importers, including highly advanced nations (like South Korea), are indirectly subjecting themselves to extreme-weather events occurring in other nations (Cottrell et al., 2019; Kummu et al., 2020). Therefore, it is important that we consider the implications of food trade on resource savings, putting into consideration the indirect impact of climate change.

Majority of existing WF research studies have concentrated on quantifying water use and global water flow. In recent times however, there is growing interest on the linkage of water use to climate change and national policy (Yoo et al., 2016). Whether green or blue water, understanding the link between water use and outside effects is important. In this study therefore, the implication of virtual water import and climate change through food trade, on the water, land and food security status of South Korea was assessed. Specifically, the study (i) analyzed the influence of VWT on water and land savings; (ii) identified South Korea's main trade sources through the quantification of the amount of virtual water from 2000 to 2017; (iii) evaluated South Korea's virtual water structure using degree centralities; and (iv) assessed the climate vulnerabilities associated with the trading partners and its impact on South Korea's food security using Climate Vulnerability Index (CVI). South Korea was selected as a case study due to the relatively limited research on virtual water (Park et al., 2020), and food security in the country. This study can aid in the development of effective policies that curb water stress and ensure sustainable resource management.

2. Materials and methods

2.1. The nexus system

This approach emphasizes the need to study the interconnections across different elements in order to avoid the prevalent practice of addressing each issue in isolation, which may result in the assertion of alleviating one problem while increasing others (Distefano et al., 2022; Rasul and Sharma, 2016). The term "Nexus" was originally used in 1983 under the Food-Energy Nexus Programme, and it was expanded to include water resources during the Bonn Nexus Conference in 2011 (Hoff, 2011). Due to rising global interconnectivity, increased resource scarcity, and failures of sector-specific management strategies, the nexus approach is becoming extremely relevant in today's world (Daher and Mohtar, 2015; Rasul, 2016).

Different studies have been undertaken in several topic areas, including resource management (Albrecht et al., 2018), environmental impact assessment (Conway et al., 2015), and decision support systems (Endo et al., 2017), employing the nexus concept and methodologies (Lee et al., 2020). The links between land-water-food are complex, and studying these interconnections from a nexus context has caught the interest of many researchers, notably over the last decade (Ren et al., 2021). For example, Chiarelli et al. (2018) examined the

land-water-food nexus of global rubber production and discovered that the increase in rubber plantations was at the expense of agricultural land for staple crop production. Under different regulatory policy scenarios, Pastor et al. (2019) evaluated the influence of climate change and socioeconomics on land use, water consumption, and food trade, and found that to satisfy future food demands, an increase in land use would be required. Ren et al. (2021) investigated the land-water-food-environment nexus using China's soybean import as a case study, discovering that China's cropland conversion resulted in increased crop production, water usage, and nitrogen application.

While many existing studies address the nexus pertaining to food trade in exporting regions, few studies have looked into the nexus-related implications of food trade on importing regions (Ren et al., 2021). In South Korea specifically, little or no information exists on the land-water-food nexus in the context of major upland crops. South Korea imports a huge amount of agricultural products each year (Yoo et al., 2016), implying a possible significant impact on domestic land and water resources. Therefore, it is crucial to look into the trade-offs associated with food imports from a land, water, and food nexus approach. Fig. 1 depicts a conceptual framework of the current study. We establish a land-water-food nexus that allows the quantification of linkages due to food trade. In summary, the main premise is as follows: i) water and land resources are used to produce agricultural products in exporting countries, which are sold to South Korea (importing country), via virtual water and land trade respectively; ii) the climatic implication of the food import on South Korea's food security via climate vulnerability index analysis.

2.2. Virtual water flows assessment

The concept behind the VWT is that when products are exchanged, so is virtual water. As a result, the VWT is determined based on exporters' water footprints (virtual water content) which reflect the total amount of water utilized for crop production, and the trade data (Lee et al., 2019). Accordingly, the VWT is calculated as the product of the amount of traded goods and the exporting country's corresponding water footprint (Hoekstra and Hung, 2005), stated as:

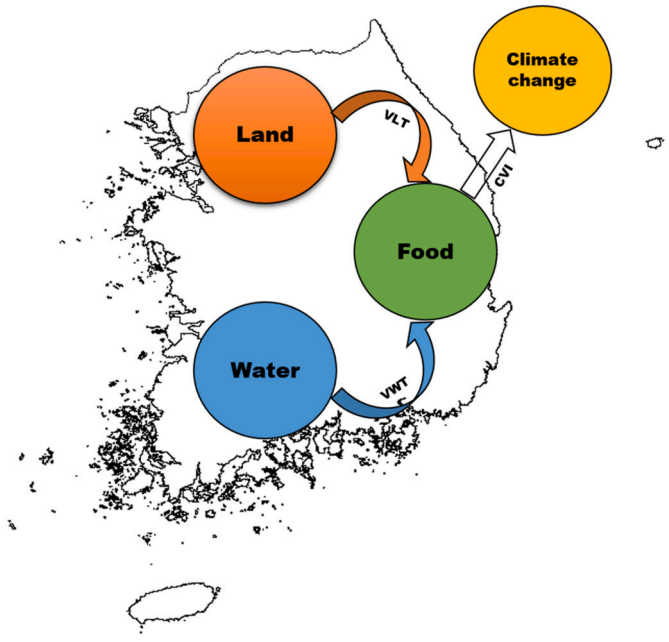


Fig. 1. Graphical representation of the connections in the Land–Water–Food (LWF) nexus in South Korea, and their indirect linkage with climate change. VLT represents virtual land trade, VWT represents virtual water trade, and CVI represents climate vulnerability index.

$$VWT\,[n_e, n_i, c, t] = QT\,[n_e, n_i, c, t] \times VWC\,[n_e, c] \quad (1)$$

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, n_e, 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.

The WF of a country is a factor of its climate, irrigation, and productivity. Hence, estimating the WF of all the countries involved in this study would require a lot of effort and was outside the scope of this study. Therefore, we considered the WF data for South Korea and her trade partners (exporting countries), available in studies by Yoo et al. (2014) and Mekonnen and Hoekstra (2011) respectively. Based on the water resources, the WF of a crop is classified as green or blue (Hoekstra and Chapagain, 2011; Lee et al., 2019). Green water is derived from rainfall and is contained in soils, and blue water is derived from surface and groundwater sources (Lillywhite, 2010). In addition, water savings related with a specific trade flow can be either green or blue water saving (or a combination of both) (Hoekstra, 2010).

The data on the international trade of fourteen major crops, divided into four categories, namely grains (barley, buckwheat, maize, millet, wheat, sorghum, soybeans), starch roots (potatoes, sweet potatoes), fruits (grapes, pears), and oils (groundnut, rapeseed, sesame seed) from 2000 to 2017, were acquired from the FAOSTAT database (https://www.fao.org/faostat/, last access: April 26, 2022) (Table 1).

The largest amount of imports were from the grains category, with an average value of 14.1 million tons/yr, imported by South Korea from 2000 to 2017, followed by oils (0.08 million tons/yr), fruits (0.03 million tons/yr), and starch roots (0.02 million tons/yr).

2.3. Water and land savings due to virtual water import

Through the importation of food, domestic water and land resources can be saved. Water and land saving refers to the amount of water and land required to produce the same amount of imported products domestically. This is determined by multiplying the amount of imported crop with the domestic WF and land footprint (LF) of the specific crop. The WF and LF of South Korea are presented in Table 2.

Since these crops are major upland (rainfed) crops in South Korea, WF data available represents only green water. However, the increasing importation of these crops over the years due to such factors as the frequent and prolonged droughts caused by rainfall variations is a strong

Table 1
South Korea's harvested area, production quantity, export and import quantities (2000–2017)*.

Category	Crop	Area (ha/yr)	Production (tons/yr)	Export (tons/yr)	Import (tons/yr)
Grains	Barley	48 554	132 953	47	64 704
	Buckwheat	2621	2487	17	2725
	Maize	15 987	75 114	263	8 806 842
	Millet	1460	1725	70	16 159
	Wheat	5767	19 359	86	3 922 655
	Sorghum	1627	2535	13	6192
	Soybeans	75 810	123 928	444	1 277 451
Starch roots	Potatoes	23 997	618 630	448	21 724
	Sweet potatoes	18 710	314 367	84	767
Fruits	Grapes	19 724	316 118	414	32 241
	Pears	18 270	347 110	19 923	52
Oils	Groundnut	4321	10 162	13	1307
	Rapeseed	1117	1271	2	4306
	Sesame seed	31 688	16 894	348	74 001
	Sum	269 653	1 982 652	22 172	14 231 126

* Average value from 2000 to 2017 retrieved from FAOSTAT (https://www.fao.org/faostat/).

Table 2
South Korea's water and land footprints of major upland crops.

Category	Crop	Water footprint (m^3/t)[a]	Land footprint (ha/t)[b]
Grains	Barley	795.9	0.37
	Buckwheat	2683.1	1.05
	Maize	1039.7	0.21
	Millet	1060.2	0.85
	Wheat	1060.2	0.30
	Sorghum	2627.1	0.64
	Soybeans	3346.7	0.61
Starch roots	Potatoes	135.8	0.04
	Sweet potatoes	370.0	0.06
Fruits	Grapes	280.9	0.06
	Pears	400.3	0.05
Oils	Groundnuts	2383.4	0.43
	Rapeseed	4412.8	0.88
	Sesame seed	5556.5	1.88

[a] Water footprint data retrieved from Yoo, S. H., Lee, S. H., & Choi, J. Y. (2014).
[b] Land footprint calculated using average values of harvested area and production.

justification for the study. Available research has shown that changes in climate could cause a switch by local farmers from rainfed to irrigated farming (Peltonen-Sainio et al., 2016, 2021), thereby increasing the pressure on already stressed water resources. Therefore, the transfer of these crops from more water abundant countries would amongst causing "green water saving", reduce the possibility of employing irrigation sources in their production domestically. The LF indicates the amount of land required to produce 1 ton of crops, calculated based on the crop production and cultivated area data obtained from FAOSTAT (Table 1). The water and land savings were calculated as:

$$\mathrm{VWC}\,[\mathrm{ni}, \mathrm{c}] = \mathrm{CWR}\,[\mathrm{ni}, \mathrm{c}] \,/\, \mathrm{P}\,[\mathrm{ni}, \mathrm{c}] \tag{2}$$

$$\mathrm{LF}\,[\mathrm{ni}, \mathrm{c}] = \mathrm{Area}\,[\mathrm{ni}, \mathrm{c}] \,/\, \mathrm{P}\,[\mathrm{ni}, \mathrm{c}] \tag{3}$$

$$\mathrm{WS}\,[\mathrm{ni}, \mathrm{c}] = \mathrm{QI}\,[\mathrm{ni}, \mathrm{c}] \times \mathrm{VWC}\,[\mathrm{ni}, \mathrm{c}] \tag{4}$$

$$\mathrm{LS}\,[\mathrm{ni}, \mathrm{c}] = \mathrm{QI}\,[\mathrm{ni}, \mathrm{c}] \times \mathrm{LF}\,[\mathrm{ni}, \mathrm{c}] \tag{5}$$

where VWC [n_i, 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 [n_i, c] is the land footprint of crop c in the importing country n_i measured in hectares per ton (ha/t), and "Area" represents the cultivated area measured in hectares (ha). WS [n_i, c] and LS [n_i, c] represents water and land savings of crop c in the importing country n_i measured in cubic meters (m^3) and hectares (ha) respectively, and QI represents amount of imported crop c in the importing country n_i.

2.4. Virtual water trade structure analysis

The VWT structure is crucial for assessing the quantity of import and export to determine whether a trade system is sustainable or vulnerable. In this study, we analyzed the VWT structure using degree centrality. A country's degree shows the number of direct trade links the country possesses (Sun et al., 2022). Depending on the trade direction, the degree centrality is divided into in- and out-degree centralities. The in-degree value indicates how many countries country i imports goods from, and the value of the out-degree indicates how many countries country i exports goods to. However, this study focused on the in-degree centrality because South Korea is a major importer of primary (agricultural) products. Just like the study by Lee et al. (2019), the in-degree centrality is further expressed in terms of non-scaled in-degree centrality (NSInDC), which is based on the number of trade links, and scaled in-degree centrality (SInDC), which is based on the volume of links. This is expressed mathematically as:

$$\mathrm{NSInDCi} = \sum_{\mathrm{j}}^{\mathrm{N}} \mathrm{Link_ij} \tag{6}$$

$$\mathrm{SInDCi} = \sum_{\mathrm{j}}^{\mathrm{N}} \mathrm{Flow_ij} \tag{7}$$

The non-scaled in-degree centrality of country i is represented as NSInDCi, while the number of links between the ith and jth countries is $\mathrm{Link_{ij}}$. The scaled in-degree centrality of country i is represented as SInDCi, while $\mathrm{Flow_{ij}}$ is the virtual water trade volume between the ith and jth countries. N represents the total number of countries that traded with South Korea. The realized values of NSInDCi and SInDCi were converted into a 0–1 scale to enable comparison over time (Golbeck, 2015). Through the VWT structure analysis, we can provide context for South Korea's current position as a net food importer globally.

2.5. Climate vulnerabilities associated with food trade

The climate vulnerability assessment sought to analyze the implication of international food trade on South Korea's food security status. We employed the food import and trade data retrieved from FAOSTAT to create a Climate Vulnerability Index (CVI), which is a measure of a country's vulnerability to indirect climate impacts (Horn et al., 2022). Vulnerability is a function of exposure, sensitivity and adaptive capacity (Raghavan Sathyan et al., 2018). In this study, we calculated the CVI using the formula as applied by Parry et al. (2007) and Horn et al. (2022) as follows:

$$\mathrm{CVI} = (\mathrm{E} \times \mathrm{S}) - \mathrm{A} \tag{8}$$

where E represents exposure, S is sensitivity, and A is adaptive capacity.

2.5.1. Exposure

The term 'exposure' refers to the nature and extent to which a system is exposed to significant climatic changes (Cárcamo et al., 2014). A country's reliance on climate-vulnerable countries determines how exposed its food system is to climate change. This is determined as:

$$\mathrm{E} = \mathrm{D_o} + \mathrm{D_r} + \mathrm{D_i} \tag{9}$$

where D_o represents dominance, D_r is direct trade, and D_i is diversity.

The number of trading partners accounting for 75% imports for each food category is referred to as dominance. Each food sub-category received a score between 1 and 10, with 1 representing one partner accounting for 75% of all imports and 10 representing at least 10 partners. The relationship between South Korea and its actual import partners is referred to as direct trade. Each food sub-category was scored between 1 and 10, with 1 denoting one partner as the product's source and direct exporter to South Korea and 10 denoting ten partners. In this study, we assumed that all South Korea's trade partners were the primary producers (source) of the agricultural products hence direct exporters. Diversity is based on the identified source partners and represents the ability of a food sub-category to be produced in different climatic zones (Beck et al., 2005). These climatic zones include temperate, tropical, continental, polar and dry, and each food sub-category was scored between 1 and 5, with 1 indicating production in one climate zone and 5 indicating production in all five. Each food subcategory's three D_o, D_i, and D_r scores were added up to provide a total exposure value that ranged from 3 to 26, with 3 being the lowest possible score because direct trade, diversity and dominance each required a minimum score of 1 for each exposure dimension (Horn et al., 2022).

2.5.2. Sensitivity

The extent to which a system is affected by exposure is referred to as

sensitivity (Islam et al., 2022). In this study, we employed the climate risk index (CRI) to identify the extent to which South Korea's trade partner countries have been affected by extreme weather events. The CRI measures the impacts of extreme weather occurrences in terms of fatalities and economic losses, and assigns a sensitivity value. CRI scores from 2000 to 2019 in 180 countries were used. This was adapted from Munich RE's NatCatSERVICE on losses caused by natural disasters such as floods and droughts (Eckstein et al., 2021). For the determination of the CRI, country weighted average ranking in four indicators including number of deaths, number of deaths per 100 000 inhabitants, sum of losses in US$ in purchasing power parity (PPP), as well as losses per unit of gross domestic product (GDP) were calculated (Eckstein et al., 2021). The equation is as follows:

$$CRI = (F.1/6) + (I.1/3) + (A.1/6) + (L.1/3) \quad (10)$$

where F is death toll, I is deaths per 100 000 inhabitants, A is absolute losses in PPP, and L is losses per GDP unit.

Based on the relative score given to each country, we calculated the average CRI score in relation to South Korea's trade partner countries, and used it as the sensitivity value for each sub-category.

2.5.3. Adaptive capacity

The ability of a system to adapt to climate change, mitigate possible damage, capitalize on opportunities, or cope with the implications is referred to as adaptive capacity (Islam et al., 2022). In other words, a system is said to be adaptive if it can adjust to climate change due to access to such resources as finance, technology, education and community (Benzie et al., 2019). We employed the Fragile State Index (FSI), developed by Fund for Peace (FFP, 2021), to assess the adaptive capacity of South Korea's trade partner countries. The FSI is a yearly ranking of 178 countries based on the various influences that affect their levels of fragility. It is based on the Conflict Assessment System Tool (CAST), which employs both qualitative and quantitative indicators, and publicly available data, to produce quantifiable findings (FFP, 2021). Several papers were evaluated, and by using highly specialized search criteria, scores were assigned to each country based on 12 important political, social, economic and cohesion indicators (Fig. 2). The political indicators include.

i. State Legitimacy: this takes into account how representative and transparent the government is, as well as how well-connected it is to its people.
ii. Public Services: this describes the existence of fundamental public services that benefit the populace, e.g. transport, electricity, health, education, security.
ii. Human Rights and Rule of Law: this examines the connection between the government and its citizens in terms of fundamental human rights and freedoms being recognized and upheld.

The social indicators include.

i. Demographic Pressures: this examines pressures on the state resulting from the population or the environment.
ii. Refugees and Internally Displaced Persons (IDPs): this assesses the burden placed on nations as a result of significant communities being compelled to relocate due to social, political, environmental, or other factors, including displacement within countries, in addition to refugee flows into other countries.
ii. External Intervention: this takes into account how foreign players affect a state's ability to function, notably in the areas of security and economy.

The economic indicators include.

i. Economic Decline: this takes into account factors associated with a country's economic downturn, e.g. unemployment rates, poverty levels, productivity, etc.
ii. Uneven Economic Development: this measures economic disparity regardless of an economy's actual performance.
ii. Human Flight and Brain Drain: this takes into account the economic implications of mass migration (of mostly skilled workforce) and the potential negative effects on a nation's growth.

The cohesion indicators include.

i. Security Apparatus: this considers a state's security threats as well as major criminal elements in domestic security.
ii. Factionalized Elites: this takes into account the division of state institutions along ethnic, racial, or religious lines, as well as politicking and conflicts among ruling elites.
ii. Group Grievances: this focuses on societal divisions, particularly based on social or political factors, and their impact on access to public services, as well as involvement in the political process.

Further information on these twelve important indicators can be found in FFP (2021).

To arrive at the final scores for the FSI, the data streams including quantitative, qualitative, and expert validation were triangulated and critically reviewed to address any biases (FFP, 2021). Each of the 178 countries was assigned an FSI score, and the countries were then ranked, with a higher score indicating a less fragile country.

Based on the relative score assigned to each country, we calculated the average FSI score in relation to South Korea's trade partner countries, and used it as the adaptive capacity score for each sub-category.

To make the vulnerability indices comparable, this study standardized the indicators (exposure, sensitivity and adaptive capacity) to a common scale (Kim et al., 2016; Tessema and Simane, 2019). The scale of the indicators was normalized from 0 to 1 using the formula:

$$Z_{ij} = \frac{X_{ij} - X_i^{MIN}}{X_i^{MAX} - X_i^{MIN}} \quad (11)$$

where Z_{ij} is the normalized value of the variable i (exposure, sensitivity, or adaptive capacity) of item j; X_{ij} is the non-normalized value of variable i of item j; X_i^{MAX} and X_i^{MIN} are the maximum and minimum values respectively, of the variable i across all the sub-categories.

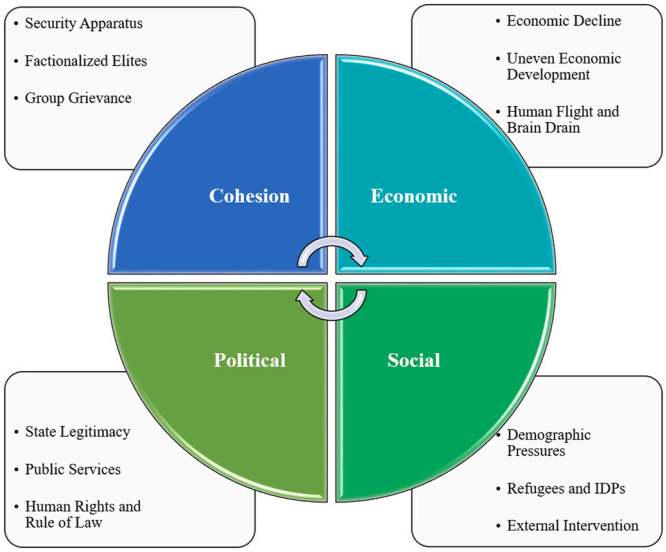


Fig. 2. Description of Fragile State Index (FSI) score indicators.

3. Results

3.1. Influence of VWT on water and land savings

One of the key progressive implications of VWT between geographical areas is the determination of water/land savings. The results revealed that food imports could improve domestic water and land management in South Korea. As shown in Table 3, between the periods 2000 to 2017, majority of the water savings came from the importation of grain products. Specifically, maize, soybeans and wheat in the grains category, contributed about 9156.20, 4273.81, and 4158.71 Mm^3/yr respectively. In the starch roots category, potatoes and sweet potatoes contributed about 2.94 and 0.27 Mm^3/yr respectively. Furthermore, grapes from the fruits category contributed about 8.98 Mm^3/yr, and sesame seed, rapeseed and groundnuts from the oils category contributed 409.27, 19.00 and 3.07 Mm^3/yr respectively. In terms of land savings, majority of the contributions were also from the grains category, with the most contributions from maize (1849.34 thousand ha/yr), wheat (1176.77 thousand ha/yr) and soybeans (779.03 thousand ha/yr).

According to the World-Bank (2021), South Korea's internal water resources (IWR) are estimated at about 64.9 billion m^3/yr. With a total water savings of 18.1 billion m^3/yr, this represents about 27.9% of the country's IWR, implying a significant contribution of the food imports to reducing pressure on local water resources thus saving water. In addition, an estimated 4.0 million ha (total land savings) of land could be saved from crop importation. South Korea's agricultural land is currently estimated at 1.65 million ha, and has been on the decline since the late 90s (World-Bank, 2021). Results reveal that the trade in agricultural products can thus provide significant benefits in terms of land resources. Generally, these results showed a positive effect of food trade on the country's water and land savings.

3.2. Characteristics of South Korea's VWT from 2000 to 2017

3.2.1. Virtual water imports in South Korea

In South Korea, all of the crops used in this study have virtual water content. This implies that these crops can be grown locally. It was therefore assumed that these crops were necessarily imported to meet domestic demand (Odey et al., 2022). The annual total amount of green and blue water import from 2000 to 2017 reached 17.2 and 1.1 billion m^3 respectively, as shown in Table 4.

The grains category (specifically maize, wheat and soybeans), was the largest contributor in terms of virtual water imports. Maize imports contributed the highest volume of green water (7.3 billion m^3/yr), followed by wheat (6.7 billion m^3/yr) and soybeans (2.4 billion m^3/yr) annually. In addition, the largest amount of annual blue water contribution was realized from the trade of maize (0.57 billion m^3/yr), followed by wheat (0.43 billion m^3/yr) and soybeans (0.09 billion m^3/yr). Generally, the largest volume of virtual water imports was due to the trade of grains. The annual volume of virtual water imports based on grain trade from 2000 to 2017 was estimated at 17.7 billion m^3/yr, making up approximately 96% of the total virtual water imports. This is understandable, since food demand in South Korea is heavily reliant on imported grains (Yoo et al., 2016). The other crop categories including starch roots, fruits, and oils made up 0.02%, 0.04%, and 3.60% respectively of the total virtual water imports. In addition, based on a yearly scale (shown in Fig. S2), the virtual water import for all crop categories showed positive trends, indicating an overall increase in South Korea's virtual water trade throughout the study period. Furthermore, as shown in Fig. 3, the green water footprint was much larger than the blue water footprint in majority of the crops. This was due to the prevalence of rain-fed agriculture in main exporting countries such as Australia and Canada.

Table 4
The amounts of virtual water from South Korea's crop importation (2000–2017).

Category	Crop	Water imports (million m^3/yr)	
		Green water	Blue water
Grains	Barley	93.6	3.3
	Buckwheat	5.5	0.2
	Maize	7377.7	574.5
	Millet	27.0	0.7
	Wheat	6703.0	427.7
	Sorghum	11.5	0.3
	Soybeans	2363.4	88.7
Starch roots	Potatoes	1.1	2.0
	Sweet potatoes	0.2	0.0
Fruits	Grapes	6.7	1.0
	Pears	0.0	0.0
Oils	Groundnuts	1.8	0.1
	Rapeseed	11.4	0.0
	Sesame seed	617.7	30.0

3.2.2. Virtual water exports to South Korea

The amount of virtual water exported to South Korea from each trade partner country from 2000 to 2017 is illustrated in Fig. 4a and b. Based on barley trade, 83% of the green water exported to South Korea was from Australia. The remaining 17% was from other exporters including India, Ukraine, Canada, China, the USA and others. In terms of blue water, India was the dominant exporter, with 86% of the total blue water traded. Based on Buckwheat, China exported 92% of the total green water to South Korea. Blue water exports in terms of buckwheat were majorly from the United States of America (USA) and China with 59% and 39% respectively. Based on the trade of maize, the USA (29%), Brazil (27%), and China (21%) were the major green water exporters. However, majority of the blue water exports in terms of maize were from

Table 3
South Korea's annual water and land savings from crop importation (2000–2017).

Category	Crop	Water savings (million m^3/yr)			Land savings (thousand ha/yr)		
		Import	Export	Net saving	Import	Export	Net saving
Grains	Barley	51.5	0.04	51.46	23.9	0.02	23.88
	Buckwheat	7.3	0.05	7.25	2.9	0.02	2.88
	Maize	9156.5	0.30	9156.20	1849.4	0.06	1849.34
	Millet	17.1	0.07	17.03	13.7	0.06	13.64
	Wheat	4158.8	0.09	4158.71	1176.8	0.03	1176.77
	Sorghum	16.3	0.03	16.27	4.0	0.00	4.00
	Soybeans	4275.3	1.49	4273.81	779.3	0.27	779.03
Starch roots	Potatoes	3.0	0.06	2.94	0.9	0.02	0.88
	Sweet potatoes	0.3	0.03	0.27	0.1	0.00	0.10
Fruits	Grapes	9.1	0.12	8.98	1.9	0.03	1.87
	Pears	0.0	7.98	−7.98	0.0	1.00	−1.00
Oils	Groundnuts	3.1	0.03	3.07	0.6	0.00	0.60
	Rapeseed	19.0	0.00	19	3.8	0.00	3.80
	Sesame seed	411.2	1.93	409.27	139.1	0.65	138.45

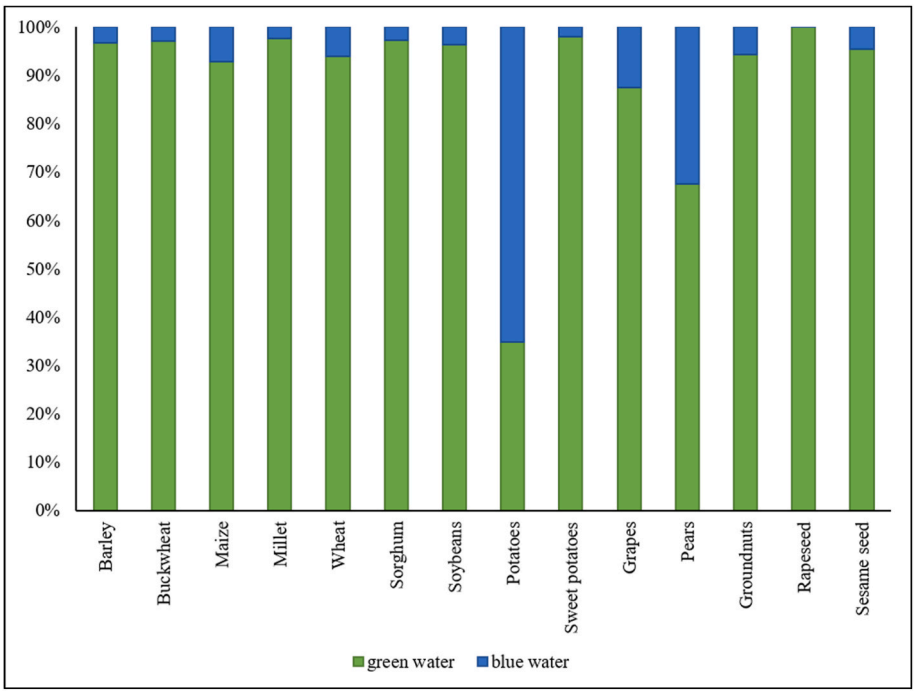


Fig. 3. The total amounts (in percentage) of virtual water imported by South Korea from 2000 to 2017.

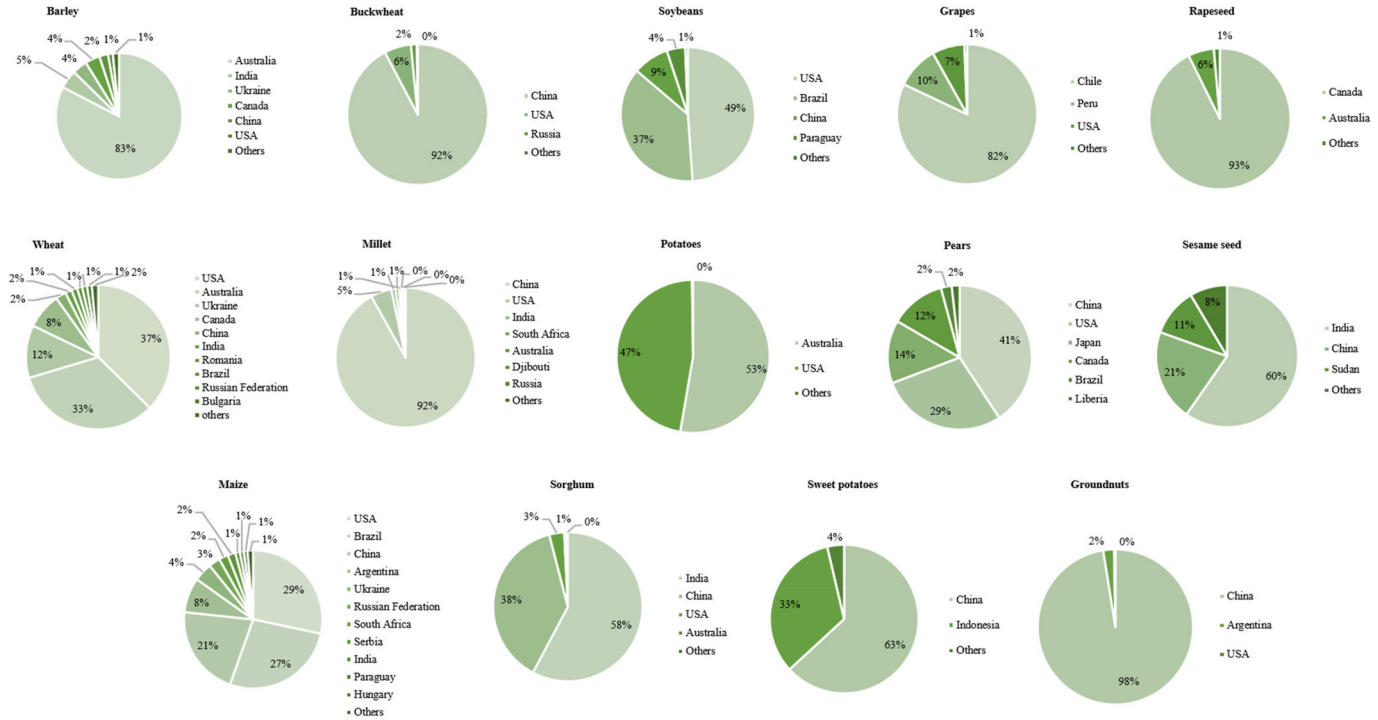


Fig. 4a. Quantities of green water export from the trade partners to Korea from 2000 to 2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the USA with a contribution of 44%. In terms of millet trade, 92% of the green and blue water respectively, was from China, making the Asian nation the main trade partner of South Korea, based on the trade of millet. The USA and Australia were the major exporters of green water based on wheat trade, with 37% and 33% respectively. In terms of blue water exports to South Korea, India (42%), the USA (29%), and China (21%) were major contributors, based on the trade of wheat. Based on the trade of Sorghum, the major exporters of green water were India and China with 58% and 38% respectively. In terms of sorghum blue water exports however, China was the major contributor with 58%, followed closely by India with 34% of the blue water exports to South Korea. The major green water exporters based on the trade of soybeans were the USA (49%) and Brazil (37%), who happen to be major world exporters of the crop. In terms of blue water exports for soybeans, the USA and China were the major contributors with 77% and 23% respectively. Based on the trade of potatoes, major green water exporters to South

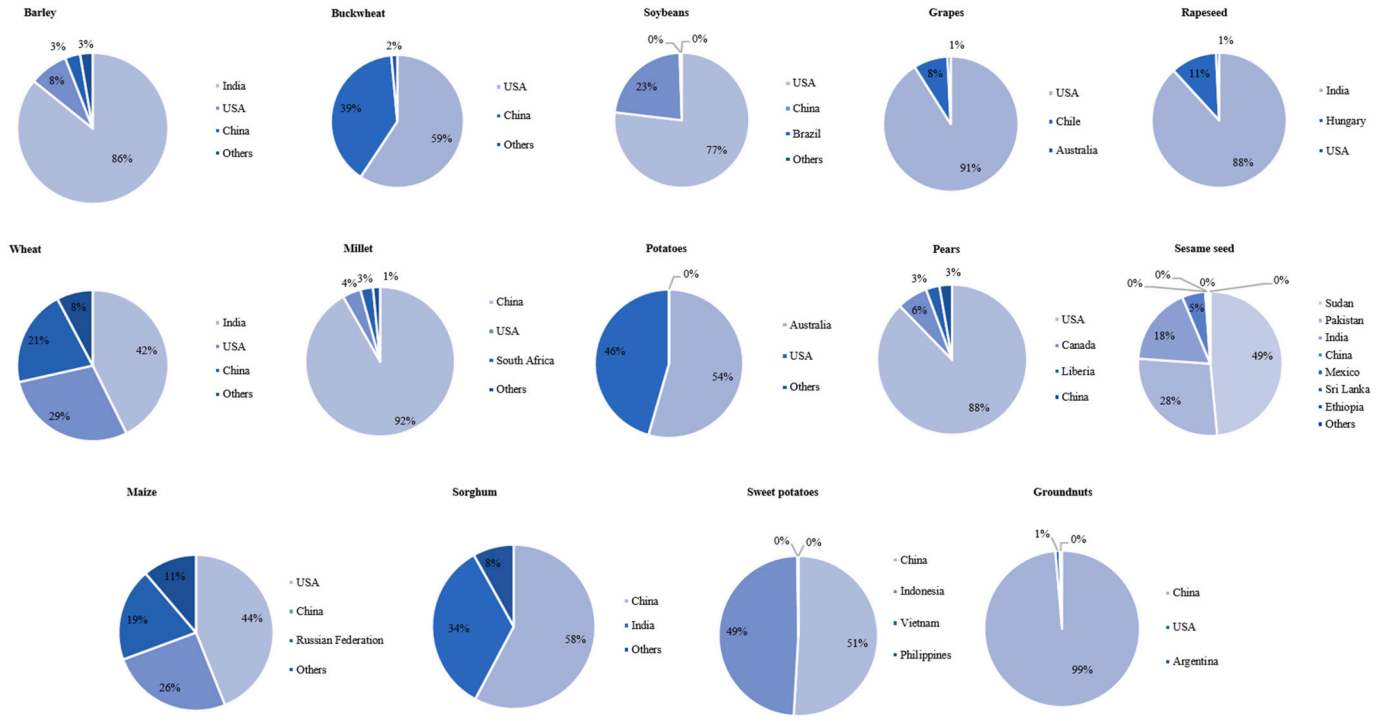


Fig. 4b. Quantities of blue water export from the trade partners to Korea from 2000 to 2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Korea were Australia and the USA with a contribution of 53% and 47% respectively. Similarly, Australia and the USA were the major blue water exporters to South Korea with contributions of 54% and 46% respectively. In terms of sweet potato trade, major green water exports came from China (63%) and Indonesia (33%). The two Asian nations were also the major blue water exporters to South Korea, with 51% and 49% respectively. Based on the trade of grapes, 82% of the green water exports were from Chile, while 91% of the blue water exports came from the USA. In terms of the trade in Pears, China and the USA were major green water exporters with contributions of 41% and 29% respectively. Blue water exports based on pear trade were however, mainly from the USA, with a contribution of 88%. Green and blue water exports based on the trade of groundnuts were mainly from China with 98% and 99% contributions respectively. In terms of rapeseed trade, 93% of the exported green water was from Canada, while 88% of the blue water exported was from India. Based on the trade of sesame seed, the major exporter of green water was India with 60%, followed closely by China with 21%. In terms of blue water exports, Sudan and Pakistan were major exporters to South Korea, with 49% and 28% contributions respectively, based on sesame seed trade.

3.3. *Understanding the dynamics in South Korea's VWT structure*

Fig. 5 shows the changes in VWT from 2000 to 2017. There were increases in the volume and connectivity of VWT throughout the study period. The volume of virtual water imported into South Korea increased from 16.2 Bm^3/yr in 2000, to 16.5, 17.4 and 20.7 Bm^3/yr in 2005, 2011 and 2017 respectively. In addition, the VWT structure reflected a dispersed network, indicating an increase in trade connectivity. Though the VWT distribution increased, the study showed a high dependency on the USA, China, Australia, Brazil and Canada. In 2000, VWT was dominated by the USA, China and Australia; in 2005, it was dominated by China, the USA and Australia; in 2011, it was dominated by the USA, Australia and Canada; and in 2017, it was dominated by the USA, Brazil and Australia (Fig. 5). A study by Sun et al. (2022) had also reported large but concentrated import trade volumes in countries such as South Korea and Japan, implying that these countries imported a large proportion of their total agricultural products from a single or few countries. The consequence of this would be a severe negative impact on South Korea's food security, if any of these important trade partners decided to cut import links.

The VWT structure is indicative of the vulnerable expansion or reduction of a trade network. That is, a country's level of trade reliance can be ascertained through its VWT structure. Accordingly, Lee et al. (2019) revealed that changes in VWT are more structure related, hence the structure of VWT must be considered alongside the volume of virtual water (Lee et al., 2019). Through the degree centrality analysis of NSInDC and SInDC from 2000 to 2017, we determined the sustainability of South Korea's trade system. The NSInDC and SInDC patterns of South Korea are presented in Fig. 6. The realized values were converted into a 0–1 scale to enable comparison over time.

Between 2000 and 2017, South Korea's agricultural trade partners for the analyzed products and the virtual water trade volume increased. However, for the trade periods 2000 and 2005, the country had a small NSInDC and a large SInDC, implying an intensive connectivity with a few exporters. Conversely, the NSInDC and SInDC increased significantly for the periods 2011 and 2017, implying a more distributed structure of the virtual water trade network. Generally, South Korea showed an expanded connectivity over time, indicating a rise in number of connections (exporters), as well as volume of virtual water traded (imports).

While this trade structure can be resilient to global changes, it also revealed the increase in the dependence of South Korea on virtual water imports. This was evident by the large increase in the volume of virtual water imported. To ascertain the level of dependence on virtual water, we also evaluated the virtual water imported per capita (VWIcap) as illustrated in Fig. 7. Results showed that the virtual water import per capita (VWIcap) increased significantly between 2000 and 2017. In other words, South Korea's dependence on virtual water import increased from 341.4 m^3/capita/yr in 2000 to 405.5 m^3/capita/yr in 2017. This confirms that the country is strongly dependent on virtual water imports, even with the increase in the trade connectivity and

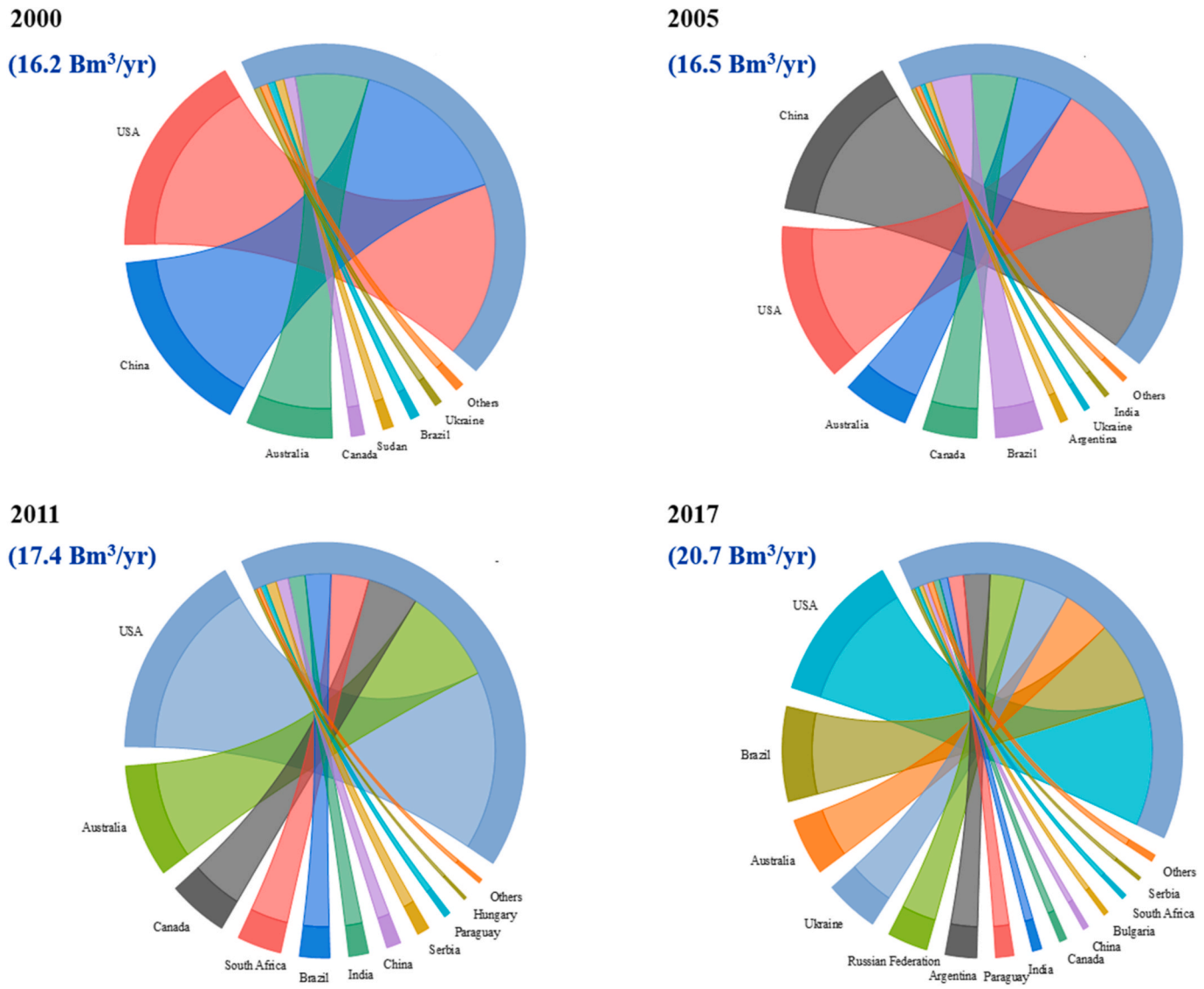
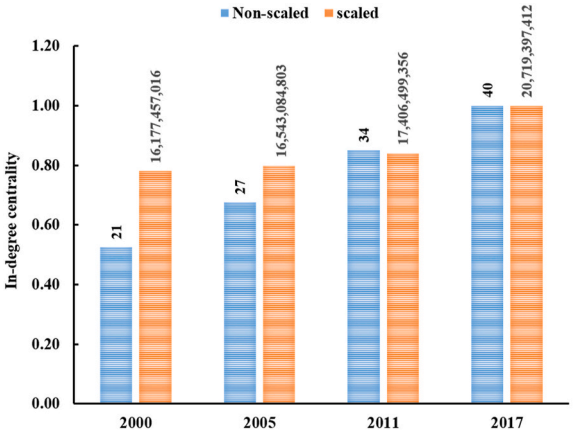


Fig. 5. South Korea's virtual water import in 2000, 2005, 2011, and 2017. Countries that exported less than 100 Mm^3/yr are represented as "others".



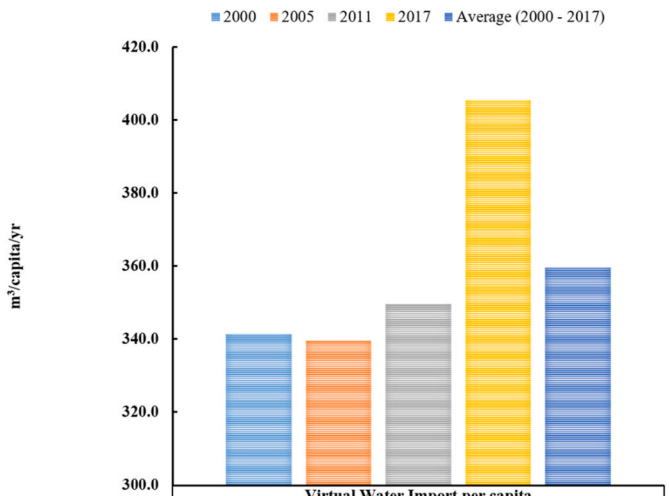
Year	Non-scaled	scaled
2000	0.53	0.78
2005	0.68	0.80
2011	0.85	0.84
2017	1.00	1.00

Fig. 6. Non-scaled and scaled in-degree centralities of South Korea in 2000, 2005, 2011, and 2017.

volume. The increase in dependence is most likely due to factors such as population growth, fast industrialization, and urbanization which have increased food demand while decreasing arable land (Yoo et al., 2016).

3.4. Climate vulnerabilities associated with food trade

Table 5 shows the overall Climate Vulnerability Index (CVI) values



	Virtual Water Import per capita
2000	341.4
2005	339.7
2011	349.6
2017	405.5
Average (2000 - 2017)	359.7

Fig. 7. Virtual water import per capita in South Korea (2000–2017).

Table 5
Climate Vulnerability Index (CVI) values for the 4 categories and 14 sub-categories of food imports to South Korea in 2017.

Category	CVI	Crop	CVI		
Grains	−0.26	Barley	−0.83		
		Buckwheat	−0.53		
		Maize	0.07	**Climate Vulnerability Classification**	
		Millet	−0.12	High	0.31–1.00
		Wheat	0.49	Medium	−0.41–0.30
		Sorghum	−0.67	Low	−1–−0.40
		Soybeans	−0.23		
Starch roots	−0.66	Potatoes	−1		
		Sweet potatoes	−0.32		
Fruits	−0.77	Grapes	−0.6		
		Pears	−0.93		
Oils	−0.22	Groundnuts	−0.47		
		Rapeseed	−0.61		
		Sesame seed	0.43		

for the 4 categories and 14 sub-categories of food imports to South Korea in 2017. The CVI values are a representation of the level of exposure, sensitivity, adaptive capacity and susceptibility of the trade network to climate change. The CVI scale is ranged from (-1) to (−0.4) as not vulnerable; (−0.41) to (0.3) as vulnerable; and (0.31) to (1) as very vulnerable (Suryanto and Rahman, 2019). Results revealed that the wheat crop with a CVI value of 0.49 was the most susceptible to climate change, followed by sesame seed with a CVI score of 0.43. Potatoes with a CVI value of −1.00 was the least susceptible to climate effects. At the category level however, oils and grains were the most susceptible to climate changes with CVI values of −0.22 and −0.26 respectively. The results are in agreement with Horn et al. (2022), who posited that staple crops are more vulnerable to the effects of indirect climate change. Also, Yoo et al. (2016) have reported vulnerabilities to climate-related instabilities in the global grain markets due to an increase in the importation of such grains as maize, wheat and soybeans.

South Korea's reliance on countries with a wide range of possible climate risks due to their different geographic, socio-economic and political dynamics raises concerns about the vulnerabilities of the country's food system. The low CVI values identified for crops like barley, buckwheat, sorghum, potatoes, grapes, pears, groundnuts and rapeseed are owing to the trade partners' low exposure and sensitivity values, and their high adaptive ability. On the other hand, crops with medium to high CVI values as also presented in the table are representative of trade partners' high exposure and sensitivity, with limited adaptive capacity (Table 5). Concisely, a system is considered vulnerable if it is exposed to, and sensitive to the impacts of climate change with low adaptation potential and vice versa (Mearns and Norton, 2009; Niemeijer, 2002). The impact of climate change will continue to vary between regions, with local crops cultivated in specific climate conditions particularly affected (Hoegh-Guldberg et al., 2018). For example, if countries such as the USA, China and Australia, who are South Korea's main trade partners experience decreasing crop production or yield quality reduction due to challenges in climate, South Korea's options for obtaining the traded agricultural products would decrease, leaving the country exposed. More diversification of significant trade partners, particularly nations with varied present and expected future climates, should thus be explored.

4. Discussion

In terms of resource management and food security, the trade in virtual water is a crucial issue for both exporting and importing countries. During the period 2000 to 2017, South Korea saved a substantial amount of green water in the course of the VWT of important upland crops. Even though these crops are locally produced using green water, the prevalence of recurrent drought events have negatively influenced their local production, forcing the country to rely heavily on imports from other countries. Due to the country's increasingly limited water supply, there are also fears of possible conflicts over competing uses at the agricultural, domestic and industrial sectors. Since agriculture is the main consumer of water resources, the scarcity of green water would increase the pressure on available blue water resources as farmers try to switch. Yoo et al. (2016) suggested that in order to mitigate the local climate challenges for a more stable domestic production, more blue water would need to be appropriated to crop production rather than green. Water scarcity issues could also be addressed through the establishment of adequate agricultural policies (Tamea et al., 2016), especially as it concerns water use efficiency and resource allocation. Peng et al. (2021) also discovered that countries experiencing water scarcity could employ virtual water imports as a coping technique to address food security concerns while conserving limited domestic water resources. The increased importation of these crops that would otherwise have been produced locally, would most likely reduce the pressure on available water resources, while also improving the food security status of the country. Consequently, the major virtual water exporters to South Korea during the study period were Australia, China, the USA, and India for grains; China, Australia, and the USA for starch roots; the USA, Chile, and China for fruits; and China, India, Sudan, and Canada for oils.

As the VWT concept entails, if crops are transferred from nations with high water productivity to those with low water productivity, there is reallocation of water resources and global savings in freshwater use. However, other factors influence VWT aside from freshwater availability for crop production. In fact, the VWT concept is still under serious scrutiny (Wichelns, 2010). This is because, while VWT may help to connect water management to food security, food trade may be influenced by the availability or scarcity of other critical resources such as land, labor, and capital (Biewald et al., 2014). Many other studies have also reported the significant influence of such factors as population, geographical distance, price of goods and Gross Domestic Product (GDP), on VWT (Duarte et al., 2019; Tuninetti et al., 2017). This makes it difficult to apply the virtual water concept to trade policies, especially from an economic perspective. We therefore suggest that South Korean policy makers should consider the economic and environmental implications of international trade through a possible linkage of the VWT concept with resource management policies. Even though the VWT concept lacks a clear conceptual framework, the global increase in water demand makes the management and implementation of water resource

policies more difficult (Tian et al., 2018). Global VWT assessment, considering the entire socio-ecological system, could thus serve as a long-term solution for places suffering from significant water stress (Graham et al., 2020). Through this assessment, the South Korean government could implement or strengthen existing strategies regarding international trade and domestic water resource consumption in the major sectors of the country, especially in agriculture.

This study also revealed the complexities of estimating the vulnerability of international food trade to climate change. It demonstrated that there were hidden links between food trade and climate change, thus offering a foundation for considering South Korea's management options in relation to food security. Because of the country's erratic climate and growing population, there is a need for the government to provide climate mitigation and adaptation assistance to its main trade partners. In addition, based on the CVI values, an alert system for food insecurity could be established (Gomez-Zavaglia et al., 2020), especially for grain crops that make up a bulk of the country's import. Even though the import of virtual water through food trade might enable the sustainability of water, land and food security, the climate change implication must be assessed, as carried out in this study. However, there is a need for improvement of the CVI methodology in future assessments for either a specific crop category or South Korea's entire network of exporters. As also opined by Horn et al. (2022), more detailed understanding of the food system's vulnerabilities to changes in climate is required to design policies that can aid in meeting the SDG2 targets (Horn et al., 2022).

Through the assessment of South Korea's international food trade, this study has highlighted a land-water-food nexus framework. The analysis revealed that although international trade might save a significant quantity of land and water, such trade actions have certain climatic consequences. Specifically, the importation of grain products will yield more land and water savings, but at the same time, produce the highest vulnerability due to climate change. Therefore, it is crucial that a nexus viewpoint be established when creating comprehensive policies for the country's sustainable growth.

5. Limitations of the study

Firstly, it should be emphasized that this study has certain limitations because it was not based on actual field measurements of WF data but on the use of already existing data from previous studies. By extension, VWT and water – land savings by food trade, as well as CVI in this study were calculated based on a historical database thus, some errors in data may occur. Secondly, the land savings estimate was based on the hypothetical assumption of a single cropping system for each crop analyzed in this study, hence resulting in a land savings value that was larger than the available agricultural land area. Nonetheless, the findings indicated that food imports could have a favourable influence on water and land savings in the country, and could be effective in the provision of detailed information as it concerns VWT, climate change and food security.

6. Conclusions

Agriculture is South Korea's largest consumer of water, and the country's fast growing population increases both food demand and pressure on water resources. Virtual water imports have been critical in mitigating global and national water scarcity. This study was therefore carried out to quantify the prospect of saving land and water in South Korea through trade in important agricultural products, as well as to assess the climatic implications. The study period was from 2000 to 2017, and the fourteen crops investigated in this research were chosen based on their relative importance in the country. Over the period 2000 to 2017, significant amounts of national water and land was saved through the importation of major upland crops. Virtual water imports increased significantly over time, rising from 16.2 Bm^3 in 2000 to 16.5, 17.4, and 20.7 Bm^3 in 2005, 2011, and 2017 respectively, with the USA, China, Australia, Brazil and Canada being the major exporters to South Korea. The study also revealed that South Korea was a significant importer of virtual water over time, based on the values of both virtual water import and virtual water import per capita. In terms of climate vulnerability due to food trade, high CVI values were recorded for the oils and grains category of imported food, implying the high vulnerability of South Korea to climate change effects resulting from the import of these crops.

The difficulties in achieving the sustainable development goals (SDGs) necessitate an integrated strategy that identifies policy priorities and tools to enhance economic and social wellbeing without jeopardizing natural resources. By quantifying the land and water flows linked with food trade, we highlighted potential threats to food security due to climate change. Therefore, more focus must be placed on building effective trade strategies to meet the primary food needs of the country. In addition, a quantitative assessment of future climate consequences (especially with respect to trade partners) would shed new light on how indirect environmental changes could impair the country's food security. Lastly, the government must establish policies that link climate change, food security, international trade, and domestic water consumption. This would aid the effective management of corresponding risks, as well as place the country on the right path to achieving the Agenda 2030 SDG2 of the United Nations.

Credit author statement

Golden Odey conceived and designed the research, analyzed the data, and wrote the paper; **Bashir Adelodun** analyzed the data and wrote the paper; **Seulgi Lee** contributed analysis tools and data sourcing; **Khalid Adeola Adeyemi** contributed analysis tools; **Kyung Sook Choi** provided funding and analyzed the data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.117319.

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