Article

Water-Energy-Food Nexus Approach to Assess Crop Trading in Saudi Arabia

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Abstract: Water scarcity is a global challenge, especially in arid regions, including Middle Eastern and North African countries. The distribution of water around the earth is not even. Trading water in the form of an embedded commodity, known as the water footprint (*WF*), from water-abundant regions to water-scarce regions, is a viable solution to water scarcity problems. Agricultural products account for approximately 85% of the earth's total *WF*, indicating that importing water-intense crops, such as cereal crops, can partially solve the local water scarcity problem. This study investigated water, energy, and food nexus dynamics for the trades of a few major crops, specifically considering Saudi Arabia. It analyzed the trade of crops and its impact on *WF*, energy, and carbon dioxide (CO_2) emission savings. The findings revealed that importing major cereal crops to Saudi Arabia could significantly reduce the local *WF*. The imports of wheat, maize, rice, and barley reduced approximately 24 billion m^3 per year of consumable *WF* (i.e., blue and green water footprint) in the global scale. Similarly, the trade of major crops had a significant impact on energy and CO_2 emission savings. The energy savings from the wheat, maize, and barley trades in Saudi Arabia was estimated to be approximately 9 billion kWh. It also saved about 7 million tons per year of CO_2 emissions. The trades of cereal crops in Saudi Arabia reduced water consumption, energy usage, and CO_2 emissions significantly.

Keywords: water footprint; agricultural product; energy footprint; carbon dioxide emission; water-energy-food nexus

1. Introduction

Freshwater is one of the critical global resources. Its availability for consumption is a global challenge [1,2], and this issue has been a concern for many years [3,4]. Day by day, the increase in the freshwater demand has imposed an elevated pressure on groundwater extraction. The exploitation of groundwater at a higher rate than the recharge may lead to the depletion of non-renewable groundwater aquifers. Groundwater withdrawals are expected to increase by half in developing countries and by one-fifth in developed countries by 2025 compared to 2011 demands [5].

Freshwater resources are not evenly distributed around the earth. Middle Eastern countries face higher water scarcity than many other countries due to the lack of renewable

water sources [5]. Saudi Arabia is the largest country without any rivers or natural lakes [6]. The country depends on renewable and non-renewable groundwater, seasonal rainfall, constructed dams, and freshwater trading (a partial solution for countries with water scarcity).

With the substantial increase in the global trade of goods and products, freshwater trading in the form of goods, such as agricultural and industrial products, has attracted attention within the water footprint (*WF*) concept as well as from water resources management [7]. The import of *WF* in products could relieve water scarcity pressure in water-scarce nations. The water requirements of products in arid regions are generally higher than the humid regions. Therefore, importing water-intensive products is a strategy to deal with water scarcity in arid regions [8]. The *WF* concept was introduced in 2003 by Hoekstra [8]. The amount of freshwater water used to produce a specific product is known as *WF* [7]. It is considered a freshwater sustainability indicator, as it indicates the flow of water embedded in products between regions and its consequences [9]. It is generally considered in the consumption of three types of water: green, blue, and grey. The green *WF* is the amount of rainwater consumed, which is stored as moisture in soil. The blue *WF* refers to ground and surface water consumption, and the grey *WF* deals with the amount of freshwater needed to assimilate the pollution caused by goods or products [7].

The consumptive water use means the surface or groundwater is no longer available after consumption: it may evaporate or be incorporated into a product [10]. Among the three types of *WF*, blue *WF* is the most valuable one. Its consumption has a higher opportunity cost than the other two types of *WF* as it comes from precious sources, such as groundwater and surface water resources [11]. On the other hand, the study of grey *WF* emphasizes the pollution caused by a specific product [7]. Blue and green *WFs* are considered consumptive *WF*, while grey *WF* is a polluted *WF* [11].

In terms of the trades, Saudi Arabia imported 164 different crops in 2012, totaling 16.5 million tons. Among these crops, barley (50%), wheat (14.3%), maize (11.7%), and rice (7.4%) were the four top contributors to imports [12]. The total of these four crops comprised around 83.4% of overall crop imports. Further, the *WF* import in Saudi Arabia was reported to be much higher than the *WF* export. The *WF* export of the country was only around 4% of the *WF* import [12].

Saudi Arabia encouraged self-sufficiency in wheat production in the 1970s by purchasing one ton of wheat at a price of approximately SAR 3500 (USD 933), albeit with a multitude of import prices in 1979 (SAR 967). The full self-sufficiency program's target was attained in the mid-1980s. By the early 1990s, the country became a wheat exporter to 30 countries [13]. Later on, the detrimental effects of groundwater depletion were realized. It is worth noting that most of the water demands in the agricultural sector in the GCC countries, including Saudi Arabia, were satisfied by non-renewable sources, which have led the groundwater tables to drop significantly [14]. It is worth noting that Saudi Arabia does not have any water body with a flowing surface. The seasonal rainwater is stored in the dams, which often recharge the shallow aquifers. This water is seasonally available for small-scale localized irrigation [15]. Considering the limited renewable water sources for agriculture, the effects of using the renewable water sources in Saudi Arabia are likely to be much lower in comparison to the non-renewable sources [15].

In 2007, Saudi Arabia imported 2% of total wheat consumption, while maize, rice, and barley imports were 91%, 100%, and 100%, respectively [16]. The self-sufficiency program on wheat was stopped in 2008 to reduce water-intensive wheat production that needed almost 100 m^3 of water to produce 1 ton of wheat [13]. Although the agricultural sector made marginal contributions (4.4%) to the Gross Domestic Product (GDP) in the country, this sector was the leading cause of groundwater depletion [16].

Due to the acceleration of global climate change, industrialized and emerging countries have agreed to reduce greenhouse gas (GHG) emissions [17]. This effort requires a significant reduction in energy consumption. Water and energy sources are vital resources for economic health and social development in countries including Saudi Arabia [18,19]. The inter-dependence between water and energy is known as the water-energy nexus [20].

Both water and energy are valuable resources inter-woven into each other [21]. Energy is required for water production and processing, and water is required for energy production and processing [22–24]. A similar concept, the water, energy, and food (WEF) nexus, helps understand the complicated interaction among the three critical resources.

The nexus study can help policymakers take decisions in the light of a better perspective on managing trade-offs and synergies in resources [25]. The WEF nexus is discussed in the literature, by many authors about different geographic locations. Radmehr, Ghorbani, and Ziaei [26] studied the WEF nexus in the Neishaboor basin in Iran using a nonlinear programming approach. The authors concluded that economic development relied on food production and energy used; however, overuse of energy and food production led to environmental problems. The proposed solution was an efficient irrigation mechanism to deal with water scarcity and environmental problems. Li et al. [27] studied the WEF nexus for northwest China using multi-objective programming, intuitionistic fuzzy, and nonlinear programming. The study considered the interaction and trade-offs between the resources for system sustainability. The author proposed a water-energy-food model under uncertainty for the coordinated management of WEF.

Consideration of the WEF nexus is required to avoid optimizing one sector at the cost of damaging the other sectors [28]. However, many policies do not consider the complex nexus among these sectors [16,29]. A noticeable example of isolated sector security is Saudi Arabia's self-sufficiency program. The program attained self-sufficiency in the 1990s and started to export wheat later on. However, the country realized that the self-sufficiency program cost invaluable groundwater depletion. Therefore, the country banned wheat production for two years (2016 and 2017) to avoid groundwater depletion [13].

Despite the national interest, no study presented the findings of the current practices in terms of the WEF nexus in Saudi Arabia. This study investigated the trades of major cereal crops in Saudi Arabia and their impact on water footprint, energy, and carbon dioxide (CO_2) emission savings. The water and energy savings as well as the reduction of CO_2 emissions associated with the trades of major cereal crops were estimated. The scopes of improving the performance from these trades were highlighted. It is worth noting that grey *WF* requires wastewater treatment and transport. Grey *WF* savings is likely to be much lower than blue *WF* savings because of its insignificant contribution to the agricultural sector in Saudi Arabia [30]. As such, grey water footprint savings is not included in this study.

## 2. Materials and Methods

2.1. Data

This sub-section summarizes the data used for this study including (i) crop production and imports; (ii) types and quantities of water used in the agriculture sector; and (iii) energy requirements for water extraction. The data used in this study were obtained for nine years (i.e., 2011 to 2019) from different sources (Table 1). The crop exports of Saudi Arabia were negligible compared to imports (exports are 4.2% of imports) and production [12]. The irrigation system energy requirements depend on the type of irrigation. In Saudi Arabia, the irrigation system consists of groundwater pumping (i.e., blue *WF*) and treated wastewater (i.e., grey *WF*) [31]. Irrigation by treated wastewater comprised approximately 3% of total irrigation water [32]. The energy required for groundwater pumping depends on the aquifer's depth, water transition length, and type. In Saudi Arabia, the energy requirements for groundwater pumping and wastewater treatment were reported to be 0.764 Kwh/m^3 and 0.4 Kwh/m^3, respectively [33]. The global average energy requirement for groundwater pumping has been estimated to be 0.0285 kWh/m^3 [16].

Table 1. Data description.

Number	Data	Description/Value	Source
1	Wheat, barley, rice, maize	Import and production data	[34]
2	*WF*	*WF* data	[35]
3	Groundwater pumping energy requirement	0.764 Kwh/m^3	[33]
4	Wastewater treatment energy requirement	0.4 Kwh/m^3	[33]
5	Shipment Energy Intensity (SEI) for crop transportation (for an average ship speed of 20 knots)	0.015 Kwh/ton-km	International Maritime Organization (IMO) [36]
6	Emission intensity of energy production	0.73 Kg-CO$_2$/Kwh	[37]

2.2. Method

The analysis starts from crop trades and *WF* savings from trading (Figure 1). The *WF* of imports is based on a hypothetical *WF* estimation. It indicates the quantity of *WF* consumed if these crops were produced inside Saudi Arabia. On the other hand, the actual *WF* of imports will be calculated based on the *WF* of crops in the regions where these crops were cultivated. In this study, long-term global averages of the *WF* from recent years were used [35]. If the water requirement of crops in exporting countries is less than in importing countries, water trade can improve water efficiency [38]. This notion leads to the water-saving concept. The water-saving by water trade between two countries is estimated by multiplying the volume of the traded crops by the difference between *WF* per unit of the crops of the importing and exporting countries [11].
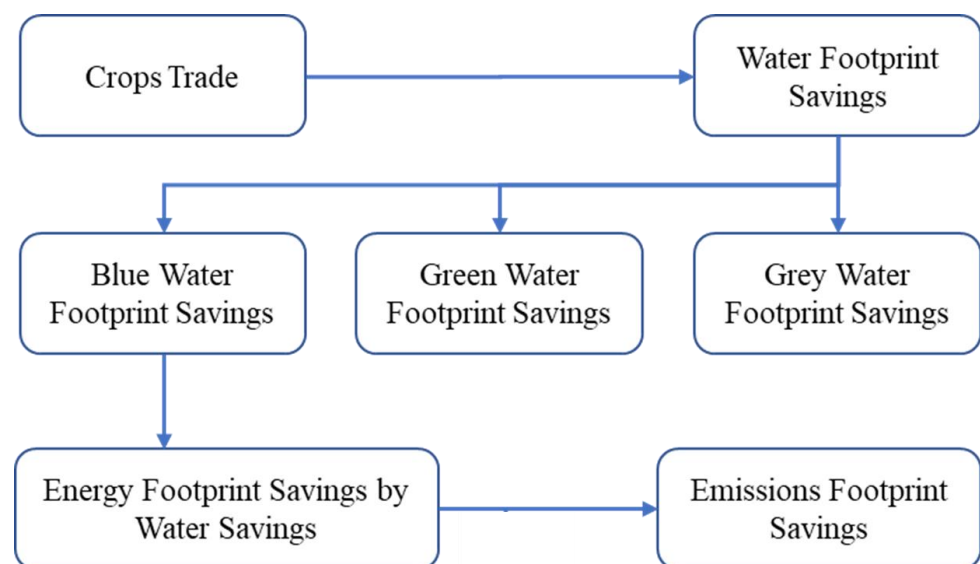
Figure 1. Methodology to estimate water and emission footprint savings through crop trading.

The energy savings associated with the *WF* were investigated. The green *WF* does not require any energy for applying in the crop field. The blue *WF* requires pumping from groundwater aquifers and transporting water to an irrigation area, and the grey *WF* requires wastewater treatment and transport. The grey *WF* savings are likely to be much lower than the blue WF savings because of its insignificant contribution to the agricultural sector to date. As such, grey water energy footprint savings is not considered in this study. The details of the methods are summarized below:

Step 1: *WF* savings
The total hypothetical *WF* of crops is calculated as follows:

$$HWF_n = \sum_{i}^{m} WFL_i \times W_i \tag{1}$$

where HWF_n is the total hypothetical WF of all types (n = 1, 2, 3; 1. Blue, 2. Green, and 3. Grey) in million m^3 (Mm^3) for m types of crops; WFL_i is the hypothetical *WF* of crop i in the local area (i.e., Saudi Arabia) in (m^3/ton), and W_i is the gross weight of imported crop *i* in million ton (MT). The total actual *WF* of crops for global average is calculated as follows:

$$AWF_n = \sum_{i}^{m} WFG_i \times W_i \tag{2}$$

where AWF_n is the total actual *WF* of all types in Mm^3, WFG_i is the global average of *WF* (m^3/ton), and W_i is the gross weight of imported crop *i* in MT. The total *WF* savings from crop trade is calculated as follows:

$$WFS_n = \sum_{i}^{m}(WFL_i - WFG_i)W_i \tag{3}$$

where WFS_n is the total *WF* savings of *WF* type *n* (Mm^3) by *WF* trade.
Step 2: Energy footprint savings
The energy requirements for water extraction in the case of local production is calculated as follows:

$$EC_n = \sum_{j}^{l} WF_n \times P_j \times EI_j \tag{4}$$

where EC_n is the energy consumption (in kWh) for water extraction and processing for *WF* type (n). The *WF* is shown as WF_n, and the energy intensity for irrigation is shown as EI_j, where j indicates the type of irrigation water collected from underground aquifers and wastewater treatment plants. The percentage of irrigation by groundwater or wastewater is shown as P_j (j = groundwater or wastewater). EI_j indicates energy intensity (kWh/m^3) for irrigation type j. The total energy requirement for water extraction and processing is calculated as follows.

$$EE = \sum_{i}^{n} WFS_n \times EC_n \tag{5}$$

where *EE* is the total energy consumption for three WFS_n in kWh.
The energy requirement for transportation of imported crops from outside Saudi Arabia is calculated as follows:

$$ET = SEI \times D \times W \tag{6}$$

where *SEI* is shipment energy intensity (Kwh/ton-km), *D* is distance (km), and *W* is the weight (ton) of the crops. The distance (*D*) is approximated as the average distance from four major grain exporters (i.e., Germany, Canada, Poland, and Lithuania) to Saudi Arabia. The total energy savings (Kwh) from crop trades can be calculated as follows:

$$ES = EE - ET \tag{7}$$

Step 3: Emission footprint savings
The emission savings through energy savings can be estimated as:

$$EFS = EFI \times ES \tag{8}$$

where *EFS* is the emission footprint savings in Kg-CO$_2$, *EFI* is emission footprint intensity (Kg-CO$_2$/Kwh).

3. Results and Discussion

The production and import of four major cereal crops in the recent years are presented in Figure 2. The wheat production was the highest in 2011 but gradually decreased until

2015. By 2015, Saudi Arabia banned wheat production for two years (2016 and 2017). Wheat production started again in 2018 on a limited scale to support the small-scale growers. On the other hand, wheat imports fluctuated between 2 to 4 million tons (MT)/year (Figure 2). Maize imports have been gradually increasing since 2011. However, the production is relatively constant and much lower than the imports. Barley and rice are mostly imported, and the local production of these crops is negligible.
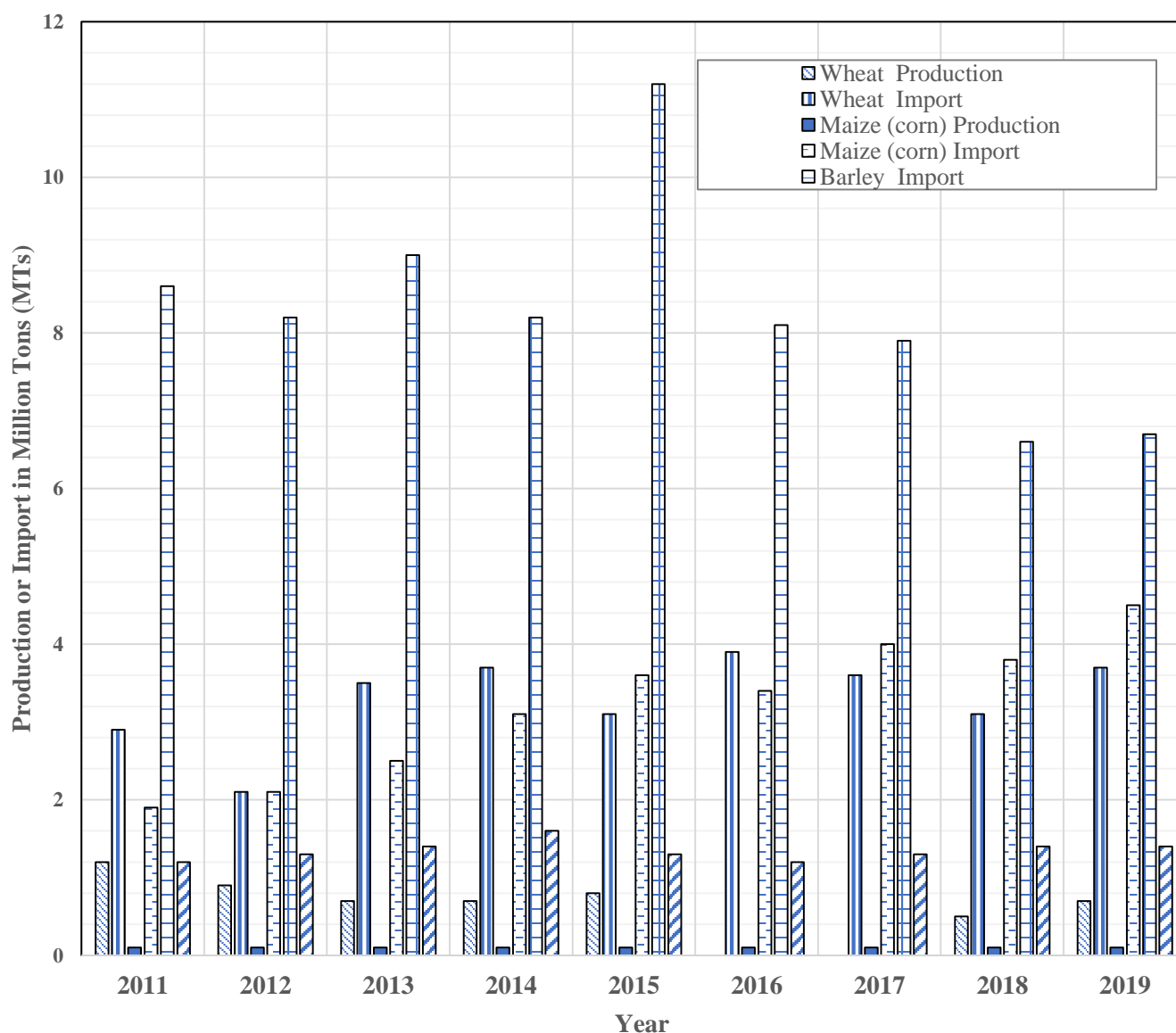

Figure 2. Major crop production and import for Saudi Arabia (source of data: International Grains Council, [34]).

The *WF* of four main crops in Saudi Arabia and global averages are provided in Figure 3. The local *WF* of rice is not available. The *WF* of crops in Saudi Arabia has a higher value for the blue *WF* and a lower value for the green *WF* due to lower annual rainfall. The hypothetical blue *WFs* of three major crops (i.e., wheat, maize, and barley) were higher than the green and grey *WFs*. Thus, importing these major crops can save groundwater extractions from aquifers.
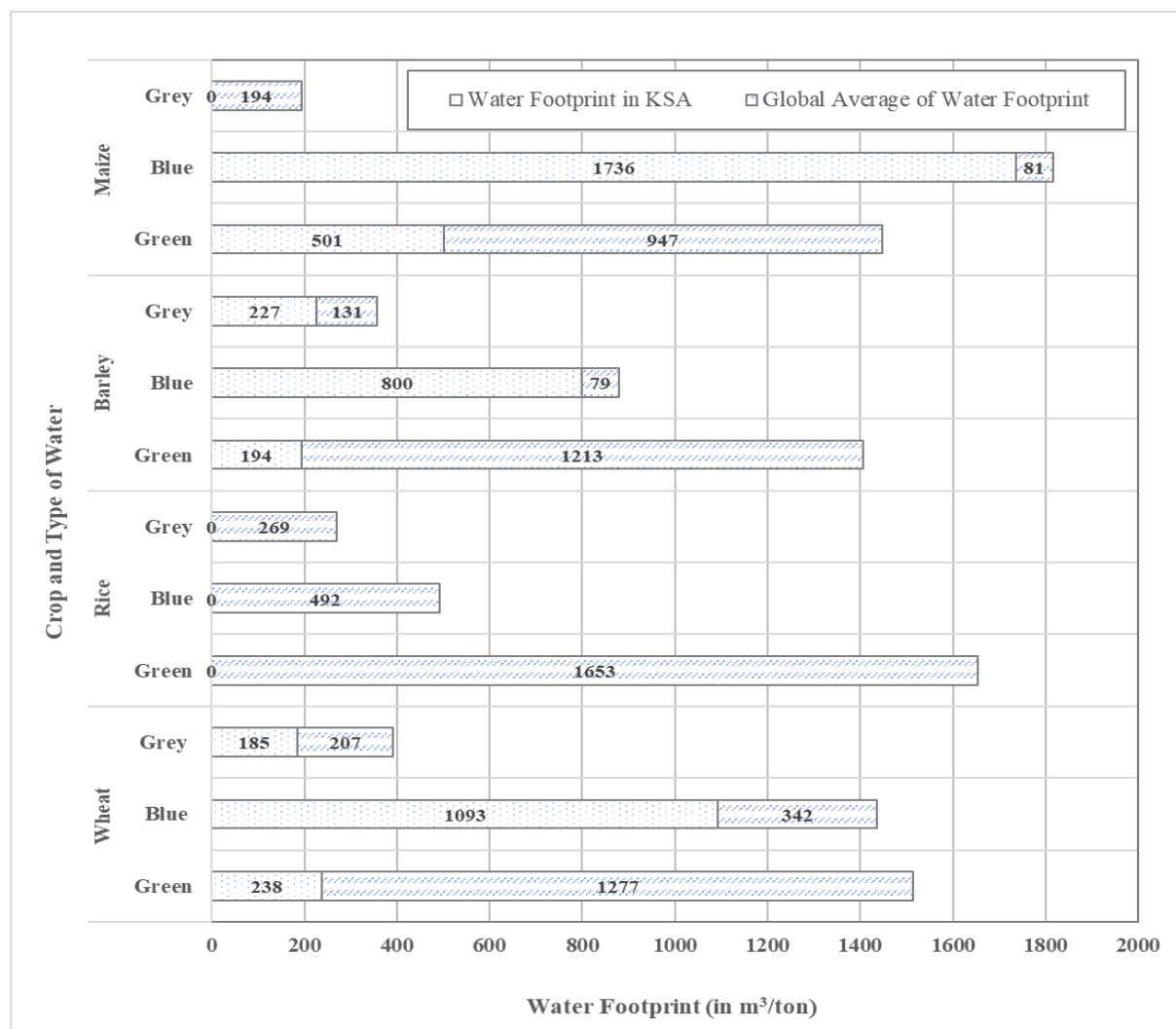
Figure 3. *WF* of Saudi Arabia and global average of *WF* (Hoekstra and Mekonnen 2010).

The total hypothetical *WF* for four major crops is calculated (Table 2). The wheat *WF* was highest in 2011 and experienced a continuous decrease until 2015. The wheat *WF* of production was very low during 2016 and 2017. The hypothetical *WF* of imported and produced major crops is calculated for between 2011 and 2020 (Table 2). The wheat import hypothetical *WFs* primarily rely on the blue type. The green and grey *WFs* comprise a relatively small portion of the total *WF*. The local *WF* rates are not available for rice, and the global averages are adopted, so the green *WF* is the dominant type in this case. The barley and maize import *WFs* are also mostly the blue *WF*. However, the maize does not have a grey *WF*. Analysis of a hypothetical *WF* indicated that they mostly consumed groundwater if the imported products were produced locally. Among the four major crops, only wheat and maize are produced locally to a considerable extent. The local production of wheat *WFs* varied significantly over the years. The *WFs* of wheat approached to zero during 2016 and 2017. On the other hand, the *WFs* of maize were stable over the years.

The green and blue *WFs* are consumable as these are not available after use. The consumable *WFs* for production and imports were calculated. The total consumable *WF* was lower in 2012 (19,852 Mm^3) and 2018 (23,080 Mm^3) compared to the years before and after these years, respectively (Figure 4). There was a significant rise in total consumable *WF* in 2015 (27,387 Mm^3), attributed to the increased import of barley. The total consumable *WF* of the selected crops was dominated by imports (Figure 4).

Table 2. Hypothetical *WFs* for imports and production, in a million m³ (Mm³).

Crop	Type of *WF*	2011	2012	2013	2014	2015	2016	2017	2018	2019
Import										
Wheat (Durum)	Green	691.3	500.6	834.3	882.0	739.0	929.7	858.2	739.0	882.0
	Blue	3170.3	2295.7	3826.2	4044.8	3388.9	4263.5	3935.5	3388.9	4044.8
	Grey	535.9	388.1	646.8	683.8	572.9	720.8	665.3	572.9	683.8
Rice	Green	1983.6	2148.9	2314.2	2644.8	2148.9	1983.6	2148.9	2314.2	2314.2
	Blue	590.1	639.3	688.4	786.8	639.3	590.1	639.3	688.4	688.4
	Grey	322.9	349.9	376.8	430.6	349.9	322.9	349.9	376.8	376.8
Barley	Green	1664.8	1587.4	1742.3	1587.4	2168.2	1568.1	1529.3	1277.7	1297.0
	Blue	6878.7	6558.8	7198.6	6558.8	8958.3	6478.8	6318.8	5279.0	5359.0
	Grey	1951.6	1860.8	2042.3	1860.8	2541.6	1838.1	1792.7	1497.7	1520.4
Maize (corn) starch	Green	952.3	1052.5	1253.0	1553.7	1804.3	1704.1	2004.8	1904.6	2255.4
	Blue	3299.2	3646.5	4341.1	5382.9	6251.1	5903.9	6945.7	6598.4	7813.9
	Grey	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production										
Wheat (Durum)	Green	286.1	214.5	166.9	166.9	190.7	0.0	0.0	119.2	166.9
	Blue	1311.8	983.9	765.2	765.2	874.6	0.0	0.0	546.6	765.2
	Grey	221.8	166.3	129.4	129.4	147.8	0.0	0.0	92.4	129.4
Maize (corn) starch	Green	50.1	50.1	50.1	50.1	50.1	50.1	50.1	50.1	50.1
	Blue	173.6	173.6	173.6	173.6	173.6	173.6	173.6	173.6	173.6
	Grey	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
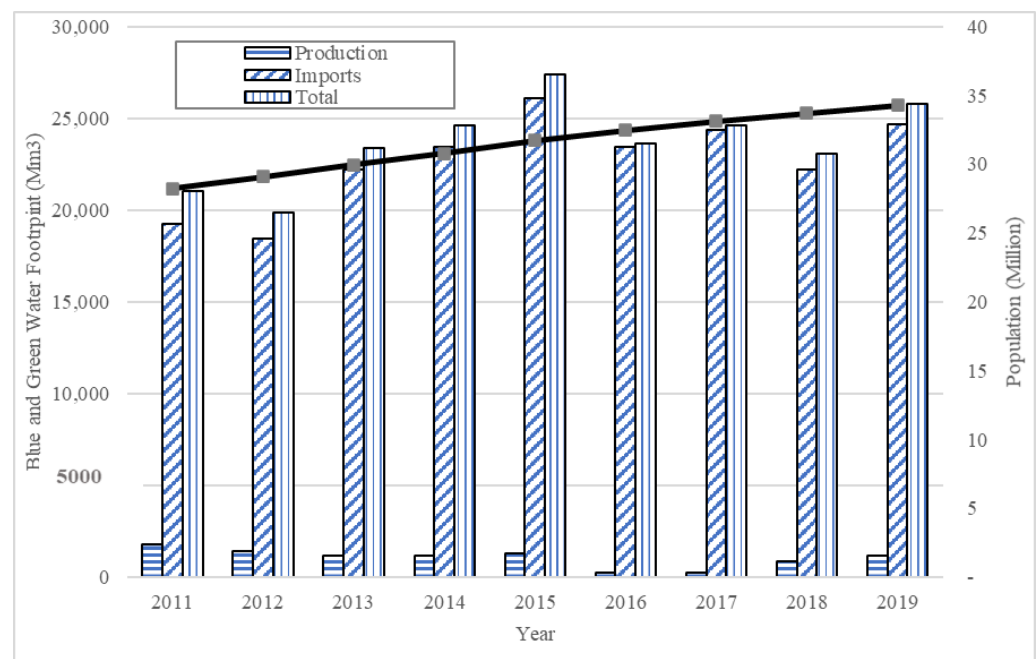
Figure 4. Trends of the consumable *WFs* of four major grains over the years.

Although green and blue *WFs* are precious and consumable, their values are not the same considering *WF* sustainability. The green *WF* is renewable (rainwater). The blue *WF* comes from scarce sources (non-renewable underground aquifers or surface water stored in the dams or shallow aquifers), and some of these are barely renewable. Therefore, extensive use of the blue *WF* may be a threat to sustainability. Crop production in Saudi Arabia requires a significantly higher blue *WF* than global averages due to the scarcity of rainfall and higher rates of evapotranspiration. The increased dependency on local crop

production will require an additional blue *WF*. Therefore, Saudi Arabia can import crops without exerting additional pressure on non-renewable water resources.

This study estimated water savings from wheat, barley, and maize considering global perspectives. By importing crops, Saudi Arabia is saving the blue *WF* locally; however, the production of the imported crops will cost the *WF* in the exporting countries. The *WF* savings by crop imports in Saudi Arabia is presented in Figure 5.
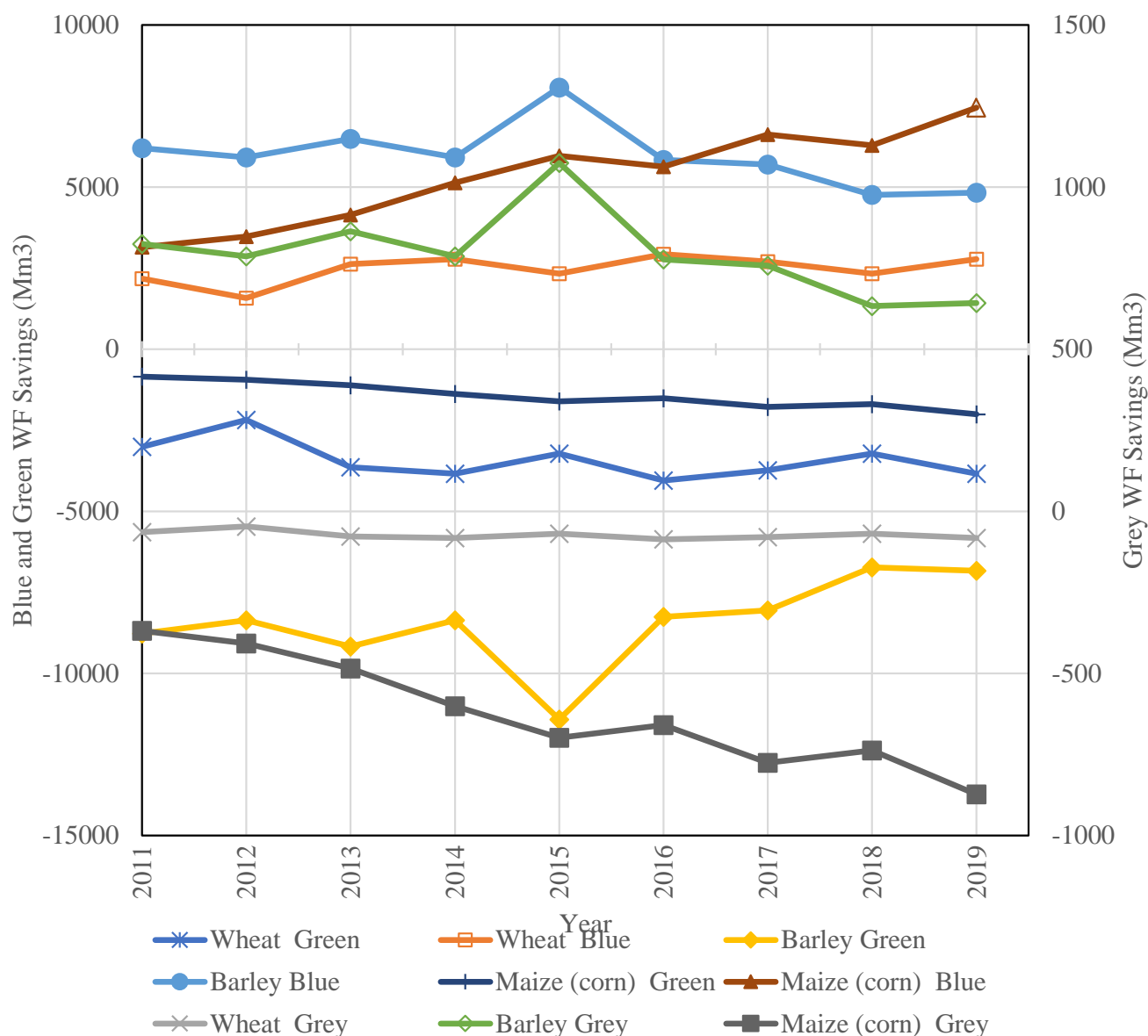

Figure 5. Saudi Arabia *WF* savings from the import of three major crops.

Overall, there is limited yearly *WF* savings in the greywater footprint compared to the blue and green *WFs* (Figure 5). Further, the barley grey *WF* savings is positive, whereas it is negative for wheat and maize. The reason for the barley grey *WF* being positive, unlike the wheat grey *WF* savings and maize grey *WF* savings, is that the grey *WF* of barley is lower than the global averages (Figure 3). This means when barley is produced locally it pollutes less water compared to global averages, unlike wheat and maize. However, there is a significant blue *WF* savings due to the import of the three main crops, and there is a loss of the green *WF* due to crop imports as the green *WF* is wasted. Therefore, the imports of cereal crops save the blue *WF* locally at the cost of the green *WF* in the global perspective (Figure 5). The energy and emission footprint savings due to the trading of

crops are shown in Figure 6. These savings have resulted due to the replacement of the blue *WF* by the green *WF*. According to Figure 6, the energy savings due to the barley trade was highest among the three crops from 2011 up to 2015, whereas after that the maize trade resulted in the highest savings. Energy savings due to the wheat trade was the least among the three crops that ranged between 1–1.9 billion Kwh/year. The *WF* savings leads to energy and emission footprint savings. The emission intensity of 0.73 Kg-CO_2/kWh for Saudi Arabia was used to estimate carbon dioxide (CO_2) footprint savings from energy reduction [37]. The yearly CO_2 footprint reduction due to crop imports was in the range of 5.80–8.66 MT during 2011–2019 (Figure 6), which is around 1.5% of Saudi Arabia's total yearly emissions [39]. Similar to the energy savings, the emissions savings due to barley have been decreasing since 2015 while the opposite is true for maize. These fluctuations can be attributed to the import of amount of imports of these crops (Table 2). The emission footprint savings from wheat has a relatively stable trend between 2011 and 2019.
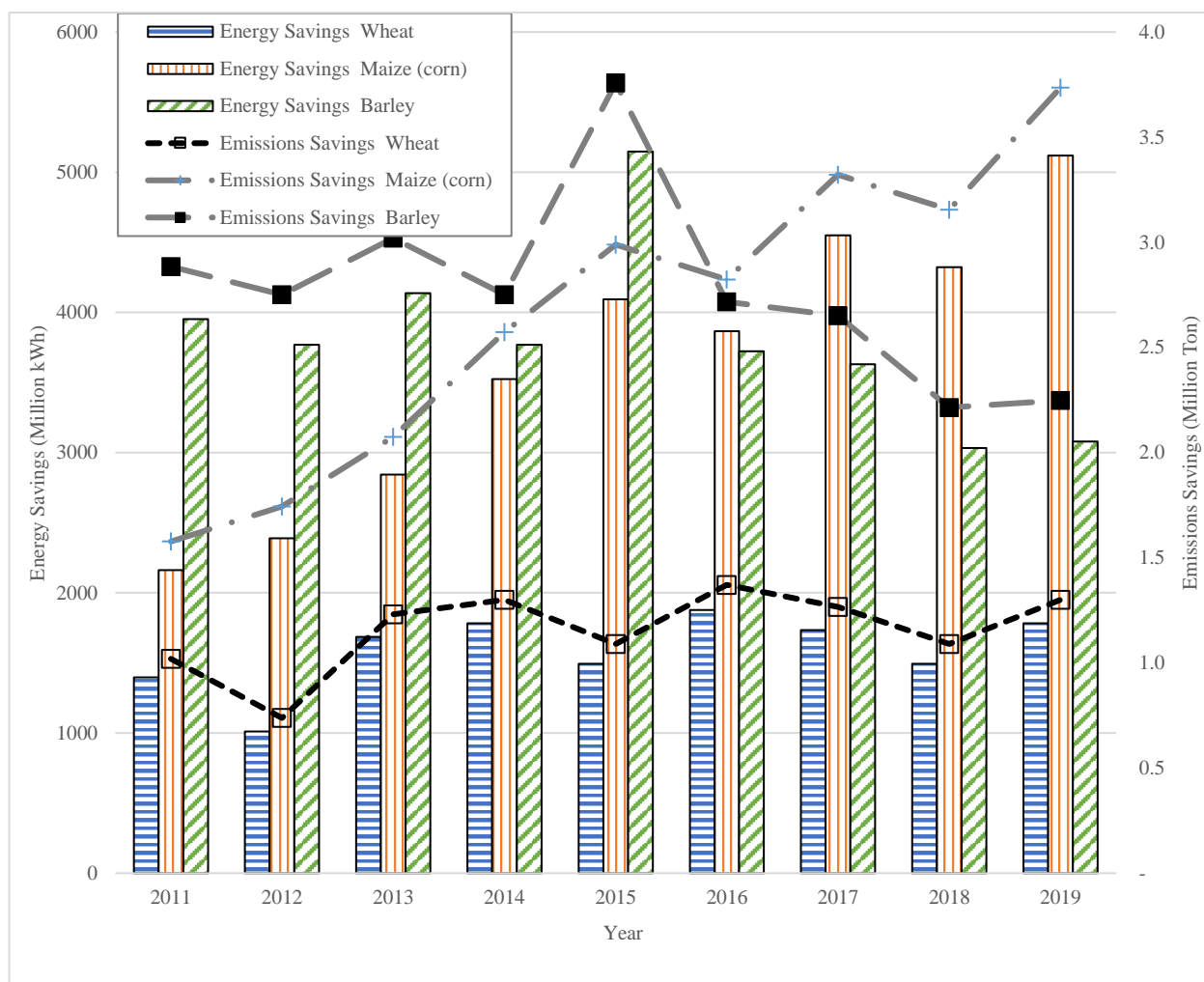

Figure 6. Energy and emissions footprint savings due to crop trade in Saudi Arabia.

The Kingdom has been increasing energy and emission savings during the last few years. However, water conservation and self-sufficiency have a trade-off. Typically, the country imports different crop items from more than 70 countries [12]. Due to the diversified supply chain, it is expected that the Kingdom's food security may not suffer significantly due to uncertainty in crop imports. However, it can only be verified through more detailed analysis focusing on location of importing countries, type, price, and quantity of crop, and mode of transportation. Recently, the Kingdom has been investigating diversified ways to meet water demand in a sustainable manner including artificial cloud seeding [40].

Therefore, the results of this study should be assessed with due consideration of other available opportunities in the Kingdom to reduce *WF*, energy, and emission savings.

WF trading has been growing among countries including Saudi Arabia. Water-intensive crop imports have reduced stress on the scarce groundwater resources of Saudi Arabia. Therefore, the country may continue *WF* trading for achieving water sustainability, by trading barley, wheat, maize, and rice. However, a nation's extensive exports of water-intense products will lead to water depletion and cause unsustainable solutions on a global scale. Based on the results of this study, the local crop trades have been benefitting Saudi Arabia without compromising global sustainability. On the other hand, being a water-scarce country with significant energy reservoirs, Saudi Arabia faces the risk of embodied water in energy export, water consumed by energy extraction, and transformation called embodied water on energy resources. As a result, it faces water scarcity and water embodied in energy lost due to energy export [41]. The crop-trading-related policies have a significant positive impact on the WEF nexus.

4. Conclusions

Proper management of essential resources such as water, energy, and food requires interaction among these resources. Policymakers can take advantage through incorporating the nexus in these resources to optimize the trade-off and synergies among the resources and protect environmental quality. In this study, water, energy, and food nexus dynamics for few major crop trading were investigated for Saudi Arabia. This study quantified the effects of crop trades on the savings of three types of *WFs*. Additionally, the *WF* savings that would lead to energy and emission savings was investigated. The recent trades of four major crops significantly improved *WF* savings, leading to energy and emission footprint savings.

In recent years, the trade of crops has saved 1100 to 16,000 Mm^3/year of blue *WF* at the cost of probable green *WF* in the exporting countries. The savings will reduce pressure on local groundwater resources. Further, the effects of crop trades on energy consumption footprint and emission footprint savings were estimated. The energy savings from trading three major crops (wheat, maize, and barley) in Saudi Arabia was around 9 billion kWh. This energy savings leads to emission savings of about 7 million tons of CO_2 yearly. However, these results should be evaluated with appropriate consideration of other available opportunities in the Kingdom to reduce *WF*, energy, and GHG emissions.

This study used the global averages to estimate *WF* indicators related to crop imports. Nevertheless, water productivity differs among countries due to different rates of rainfall and temperature. In the future, country-specific *WF* information can be used to accurately identify the global impact of Saudi Arabia's crop trades. Additionally, this study considered the impact of trading the major crops. The other crops should be included in future for exploring the impact of their trades on the *WF*, as well as energy savings and GHG reduction.

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