

Reply to the referees for hess-2018-398

Article title: Assessment of food trade impacts on water, food, and land security in the MENA region

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Dear reviewers and editor,

thank you for considering the manuscript for publication in the HESS and in-depth review of the manuscript. We believe food trade bring important impacts on water-food-lands management in the MENA region. Therefore, this study focused on quantifying domestic water-lands savings by food trade, and we analyzed the virtual water trade in terms of volume and connectivity.

In reviewer's comments, we identified the main critiques directed towards the weak explanation of the situation of the MENA region, limitations and contribution of this study, and proposed methodology. We have made substantial changes to the manuscript to improve upon these points. For example, in revised manuscript, we added more reference studies for identifying the situation of the MENA region, and clarify the limitation of this study in terms of policy application for example, only historical data use and lack of geopolitical issues. In addition, we rewrote the methodology of eigenvector centrality with more references, and added more explanation about the difference between water saving and virtual water import. On the next pages you will find an overview of changes and a point-by-point reply to specific comments.

We appreciate again your thoughtful comments, and look forward to hearing your reply.

Kind regards, on behalf of all co-authors,

Sanghyun Lee

Overview of changes

We tried to revised the paper with your comments. Please find the overview of changes and point-by-point reply to specific comments. In terms of general comments, first we revised the introduction by adding more references about the situation of the MENA region, and added more explanation about the differences between water saving and virtual water import. In addition, we added more limitations in terms of spatial and temporal issues of VWT, and mentioned contribution and future works in conclusions. Finally, we checked entire manuscript and revised some paragraph and typo.

1. We revised the introduction by adding more references about the situation of the MENA region.

Page 1: Line 27– Line 36

Food security and water scarcity are urgent socio-economic and environmental issues in the Middle East and North Africa (MENA) region (Saladini et al., 2018), which are highly interlinked, and Water-Energy-Food Nexus has been suggested as a proper and integrated approach for resource management (Bazilian et al., 2011; Rasul, 2014; Mohtar and Daher, 2014; Lee et al., 2018). For example, food security in the MENA region has become complicated by increased risks owing to the geopolitical challenges and inability to satisfy needs with domestic production because of the lack of adequate arable land and water resources (Rastoin and Cheriet, 2010). In addition, food imbalance in the MENA region is forecast to reach 60 % in 2050 and food security in MENA region could be extremely compromised (Rastoin and Cheriet, 2010). Climate change could lead to more frequent occurrence of extreme climatic events in Mediterranean region, accompanying 50 % decrease of agricultural production by the end of the century (Porter et al., 2014). In particular, water saving through food trade can be suggested as a solution for mitigating groundwater depletion in the MENA region (Lezzaik et al., 2018).

2. We added more explanation about the differences between water saving and virtual water import.

Page 4: Line 133– Line 144

Food import is also related to domestic water and lands savings. In particular water saving has a different meaning from virtual water import. For example, Saudi Arabia imported wheat from various exporters and virtual water import indicates the sum of the products obtained from multiplying the quantity of imported wheat by the respective water footprint of each exporter. However, water saving indicates the amount of water needed to produce the same quantity of imported products domestically. Therefore, water saving by wheat import in Saudi Arabia is estimated by multiplying the quantity of imported wheat with the water footprint of wheat in Saudi Arabia.

In this study, we applied green and blue water footprints of crops in each country in the MENA region, as shown in Table 1. However, the availability of water footprint data in the MENA region was limited in some cases. For example, the water footprint of wheat was available in all countries except for Bahrain. Lands saving has the same implication as water savings, thus we calculated lands saving using land footprint of each country in the MENA region, as shown in Table 2. The land footprint indicates the land requirement for producing 1 ton of crops, and it was calculated based on the harvest area and crop production data collected from FAOSTAT.

3. We revised the entire part of section 3.1 to clarity the results.

Page 6: Line 219– Line 238

This study considered trade-offs between food security and food trade in terms of national resource management. For example, the increase of domestic food products instead of imports of them could be one policy for food security but additional water and land for domestic products would be considered at the same time. In other words, food imports could contribute domestic water and land management, therefore, we estimated the national water and land savings by importing crops as shown in Table 3. In Saudi Arabia, blue water savings by barley, maize, and wheat imports were estimated to 5.0, 2.0 and 0.8billion m³/year, respectively. In comparison to the internal water resource of Saudi Arabia which is 2.4 billion m³/year as shown Table 1(World Bank, 2014), the water saving through import of barley, maize, and wheat could be considered as significant amount in Saudi Arabia. In the case of Egypt, most of the water saving occurred based on the imports of wheat and maize. Approximately 7.5 billion m³/year of blue water was saved by importing wheat. Specifically, the internal water resources in Egypt are only 1.8 billion m³/year (Table 1), therefore, water scarcity could be an issue for food security policy in Egypt. Lebanon was strongly influenced by the impact of crop import on land savings. Approximately 0.24 million ha could be saved by crop imports, comprising 36% of the agricultural area in Lebanon, that indicates that the crop trade in Lebanon has significant benefits in terms of land resources compared to water resources.

Food imports could be regarded as a negative factor in food security, and it is obvious that food security would accompany water and lands for domestic food products. These results showed that food imports could bring positive impacts on numerous water and lands savings in the MENA region. However, there are limitations of these results. First, water saving estimated in this study was based on the hypothetical situation that meat there were no international trade situation, and sometimes it was larger than the internal water resources in some countries such as Saudi Arabia and Egypt. Additionally, some crops are required for the specific type of climate but this study assumed that MENA region was suitable for cultivating maize, wheat, barley, and rice.

4. In previous version, virtual water import diagram of only Lebanon was showed as a case but in revised version, we added virtual water import diagram of total MENA region and added explanation in section 3.3.

Page 8: Line 289 –Line 297

From 2000 to 2012, both the volume and connectivity of VWT was changed. For example, the virtual water imported in the MENA region slightly increased and the VWT was distributed with more exporters in 2006, as shown in Figure 4. However, the volume of virtual water imported in the MENA region was increased more than 50 % from 2006 to 2012 but the distribution of VWT seemed to consistent. In case of Lebanon, VWT in Lebanon was strongly dependent on the USA, Argentina, and Australia. However, Lebanon expended the VWT in 2006 and Russian Federation, Turkey, and Kazakhstan, contributed to virtual water imports in Lebanon, as shown in Figure 4. Accordingly, the structure of VWT in Lebanon approached a distributed network. However, the VWT in 2012 showed that it was dominated by Ukraine and Russian Federation, though Lebanon imported more virtual water in 2012 than 2006.

Figure 4. Virtual water imports at the MENA region and Lebanon in 2000, 2006, and 2012

5. We added more limitations in terms of spatial and temporal issues of VWT.

Page 9: Line 358– Line 363

Third, there are spatial and temporal issues of VWT in the study. The VWT could be affected by geopolitical issues such as topography, and distances between importers and exporters. For example, the changes of exporting countries in the MENA region could be related to energy use for transporting products, thus trade policy should consider the economic benefit or cost of transportation. Therefore, the VWT should be discussed with geopolitical issues such as benefit and cost of transportation. In addition, VWT and water-lands savings by food trade in this study were calculated based on historical database, thus it was difficult to apply the results to future policy.

6. We mentioned some future works in conclusions, for example, relationship between trade and energy part (energy use for transportation and food production).

Page 10: Line 383 – Line 398

In summary, this study showed that the significant water in comparison to internal water resource could be saved by food trade in the MENA region, and policy makers can benefit by considering both the quantitative impacts of VWT and the structural changes of VWT, such as vulnerable expansion (or reduction) in the MENA region. For example, when a country in the MENA region set a plan for increasing food security, this country first should identify the amount of water and land savings that can be achieved by food import, and consider the trade-off between food security and food import. In addition, the stable trade could be a component for stable food supply in the MENA region, thus this study contributes to the understanding of the dependency on each trade partner for countries in the MENA region and can help with setting the food trade policy in terms of extension (or reduction) of trade partners and increase (or decrease) in volume of trade.

However, this study only focused on food trade and water-land savings, thus energy part was not considered. The MENA region represents an extreme case globally in terms of water and energy resources, for example, 66% of the world's known crude oil reserves, but only 1.4% of the world's fresh water supplies is attributed to the region (Khater, 2001). The increase or decrease of water withdrawal for irrigation is related to the energy used for water extraction such as pumping surface or ground water. For example, 5 % or more of the total electricity consumption can be attributed to water pumping in Saudi Arabia (Siddiqi and Anadon, 2011). Energy use for food production and water supply could be the main factor in integrated resource management in the MENA region, and the lack of energy part was a limitation in this study.

7. We checked entire manuscript and revised some paragraph and typo. Please find them in the revised manuscript.

Point-by-point reply to specific comments

Referees #1

A general comment

Generally, the methods are concisely described, figures are mostly meaningful, tables support the text, yet both of the two latter can be enhanced. There are some occasions where statements are unnecessary or unproven which should be revised (see specific comments below). The introduction cites many valid references, but I think that the manuscript should discuss many more. I had a very quick search for "food nexus MENA" in ScienceDirect which brought the following results that definitely should be discussed:

I am sure, there are many more, but I tend to leave this research to the authors. I also miss a discussion of the analysis that is solely based on the data from the last years with different societal, political and environmental aspects; currently, the manuscript only shows the changes in food supply security and interprets the results without considering the bounding conditions for the MENA countries, which strongly differ.

Finally, I think that especially the conclusions section should be more detailed and overhauled - currently, this is only a collection of vague statements, but the analysis and the presented results show much more potential of detailed conclusions; for example, the results could be synthesized for all the countries of focus in a comparable way. If the authors can address the issues above (broader coverage/discussion of relevant publications, country-specific aspects influencing food trade, clearer conclusions) together with the specific comments listed below, I suggest the editors to accept the manuscript for publication. If the authors consider my comments to be valuable, I would be available for a second revision.

- We tried to revised the paper with your comments. Please find the overview of changes and point-by-point reply to specific comments. In terms of general comments, first we revised the introduction by adding more references about the situation of the MENA region, and added more explanation about the differences between water saving and virtual water import. In addition, we added more limitations in terms of spatial and temporal issues of VWT, and mentioned contribution and future works in conclusions. Finally, we checked entire manuscript and revised some paragraph and typo. Please find these changes in a point-by-point reply to specific comments on the next pages.

Line 27: Please add adequate sources to state that the primary resource gaps will grow. (Maybe, the ones in L69 will work?) L29: What do you mean by saying "the food portfolio [...] has been complicated by and increased degree of risks..."? L30: Please provide sources that the MENA region shows tendencies for an inability to satisfy needs with domestic production. L32: You say that (food) trade has been understudied - one might argue that as trade is a central part of food security (which you likewise support), it is quite well understood by the relevant trading actors. L29, 33: I think, MENA & VWT (and all other abbreviations) should be defined in the text (not in the abstract).

→ We applied reviewer's comments and revised the introduction by adding more references about the situation of the MENA region.

Page 1: Line 27–Line 36

Food security and water scarcity are urgent socio-economic and environmental issues in the Middle East and North Africa (MENA) region (Saladini et al., 2018), which are highly interlinked, and Water-Energy-Food Nexus has been suggested as a proper and integrated approach for resource management (Bazilian et al., 2011; Rasul, 2014; Mohtar and Daher, 2014; Lee et al., 2018). For example, food security in the MENA region has become complicated by increased risks owing to the geopolitical challenges and inability to satisfy needs with domestic production because of the lack of adequate arable land and water resources (Rastoin and Cheriet, 2010). In addition, food imbalance in the MENA region is forecast to reach 60 % in 2050 and food security in MENA region could be extremely compromised (Rastoin and Cheriet, 2010). Climate change could lead to more frequent occurrence of extreme climatic events in Mediterranean region, accompanying 50 % decrease of agricultural production by the end of the century (Porter et al., 2014). In particular, water saving through food trade can be suggested as a solution for mitigating groundwater depletion in the MENA region (Lezzaik et al., 2018).

Concerning the meaning of VWT: if a product uses 1000 l/kg water to be produced in one region, it might have a much more severe impact in an arid climate than in a humid one (you cannot grow coffee in Libya, but in Chile). If the value is to be interpreted locally, doesn't it lose its meaning and transferability?

→ We are not sure that we understood your comments correctly but we tried to answer your comments. We would like to explain the global water saving and national water saving by virtual water trade. If one country in arid region exports products to a country in humid region, global water saving would be negative value. But still the country in humid region could have water saving by importing products. However, some crops could limit to cultivate in some specific area, thus global water saving or national water saving in importing country was not meaningful but in exporting country water was used for producing exportable crops and it could convert to virtual water export.

L56: You say that Fader et al (2011) show water savings of 263 km³/a due to beneficial agricultural production in other countries; does this calculation include the additional costs that arise from transport? Additionally, I am wondering how much the import of exotic products to western countries (an unnecessary trade in comparison to the import of basic crop products to arid countries) contributes to in the large savings (17 billion m³ blue water, L65) of global extent?

→ Water savings indicate the water requirement for producing the same amount of imported product, thus we hardly include additional cost for transportation. This study also did not consider the cost of transportation and energy parts, thus we added some paragraph about future works in conclusion.

Page 10: Line 392 –Line 406

However, this study only focused on food trade and water-land savings, thus energy part was not

considered. The MENA region represents an extreme case globally in terms of water and energy resources, for example, 66% of the world's known crude oil reserves, but only 1.4% of the world's fresh water supplies is attributed to the region (Khater, 2001). The increase or decrease of water withdrawal for irrigation is related to the energy used for water extraction such as pumping surface or ground water. For example, 5 % or more of the total electricity consumption can be attributed to water pumping in Saudi Arabia (Siddiqi and Anadon, 2011). Energy use for food production and water supply could be the main factor in integrated resource management in the MENA region, and the lack of energy part was a limitation in this study.

In spite of this limitation, the intensity and connectivity of VWT, which were analyzed in this study, can be the major components needed for integrating resources management in the MENA region. Accordingly, VWT is regarded as the important factor in determining food security and water-lands management, and it can be a useful interlinking parameter among resources in WEF Nexus approach, which identify key issues in food, water, and energy securities through the lens of sustainability, seeking to predict and protect against future risks and resource insecurities (Biggs et al., 2015). The core of the Nexus concept is that the production, consumption, and distribution of water, energy, and food, are inextricably interlinked, thus this study would provide important information to policy makers for evaluating scenarios about integrated resource management toward sustainability in the MENA region.

L111: please add units to WS/LS.

➔ Yes, I added it.

L114/115: Two sentences starting with "In addition" - please revise. I also do not understand the meaning of "In addition, each variable is dependent on local characteristics."

➔ I thought these sentences were relevant, thus I removed them.

L118: If you irrigate a crop with rain harvested water, either directly as water is used from the reservoir or indirectly as the reservoir water is used for enhanced groundwater recharge, is this blue or green water?

➔ As followed by definition of green water by Falkenmark, it is the water captured by soil and used by crops. Thus, first we can calculate the soil moisture and crop water requirement, and if soil have enough water from rainfall for crop evapotranspiration, we do not need to irrigate. However, soil does not have enough water, we supply water by irrigation facility. But some irrigated water can go through ground water or runoff. Thus, technically speaking the green water indicate the amount of soil moisture which is used by evapotranspiration, and blue water indicated the amount of irrigation water used by evapotranspiration.

L120: "Thus, the study for national water footprint should be executed for each country, basin, or specific area; however, this was outside the scope of the current study." -this sentence is unclear to me, especially the first part: what is the difference between "national" and "country"? For which regional unit did you carry out your study?

➔ Mekonnen and Hoekstra (2010) estimated water footprint of each country in the world including the MENA region, thus water footprint applied in this study was country level data. We revised a little the paragraph about the water footprint reference.

Page 3: Line 120 – Line 123

Water footprint is a localized index for countries, accounting for the climate, productivity, and irrigation. In this study, we considered water footprints of all countries in the world, however, a lot

of effort should be required for estimating water footprints of all countries and it was outside the scope of the current study. Therefore, we applied water footprint data of 147 countries, including those in the MENA region, from the study executed by Mekonnen and Hoekstra (2010).

Can you please name the countries of the MENA region that you studied in the beginning, e.g. around L87ff?

→ We mentioned all name of countries of the MENA region that were considered as study countries.

Page 3: Line 99 – Line 101

The aim of this study is to evaluate the effects on water savings and land tenure from importing crops at 15 countries in the MENA region such as Algeria, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, UAE, and Yemen.

L127: What is the "limited water footprint"?

→ We removed it.

Table 1: - Do I understand it correctly that the information in Table 1 is taken from Mekonnen and Hoekstra (2010)? If so, please add this information in the table caption. - Please add the time period of the data in the caption. - Can you please explain why the blue water footprint is larger than the green water footprint? Why does a plant need less rainwater than groundwater? - Which footprint did you use to calculate the land footprint?

→ We added caption in Table 1.

* Water footprint data was referenced by Mekonnen and Hoekstra (2010)

** Land footprint was calculated by crop production and cultivated area provided from World Bank open data (<https://data.worldbank.org/>)

→ If there is not enough soil moisture from rainfall, irrigation should be required, thus if rainfall is very low, blue water requirement could be large than green water. Mekonnen and Hoekstra (2010) estimated the green and blue water footprint of various crop in more than 200 countries and reported them. More details about the calculation of green and blue water footprint is provided in https://waterfootprint.org/media/downloads/TheWaterFootprintAssessmentManual_2.pdf

Table 2: - Again, please add the source of this data in the caption. - This data is shown for the years 2000-2012; I assume there are all mean values - please add this information. - If these are mean values, what was the standard deviation of the data? Is there a trend in the data? - Can you please add how this data was acquired and certain this data is? - Can you add a row showing the sums of the individual columns?

→ We revised the Table 2 with your comments.

L154: It is good that you list previous network-based approaches that investigated VWT structures, but you should not only mention the citations and rather shortly summarize their works and how your work contributes to this.

→ We added summary of referenced studies.

Page 5: Line 165 –Line 170

A few studies have been conducted on the analysis of the structure of the VWT using a network-based approach (Konar et al., 2012; Dalin et al., 2012; Lee et al., 2016). For example, Konar et al (2012) analyzed the characteristics of the network change in virtual water trade (VWT), and found that a number of export trade partners followed an exponential distribution in 2000. Dalin et al (2012) found that constant organizational features were observed in the network of VWT even

though the number of trade connections and the volume of VWT has been growing. In addition, Lee et al (2016) analyzed vulnerability of the importing countries through the characteristics of network in VWT.

Equations 6 & 7: - is "j" in the sums as the starting counter equal to 1? I think, the usage of "j" is misleading, as it also refers to exporting countries. - is N (total number of countries) constant for all i (importing countries)? What if a country i only trades with one other country, i.e. N = 1; then, the equation gives a division by zero, correct? **Equation 7:** Why is the SInDC not related to the total volume of virtual water traded but to the number of total number of countries?

→ N is the number of entire network, thus it is constant to every country i, In addition, degree centrality is relative index for comparing country and N is constant number for all countries, thus the application of total number or total volume is not different for results.

L172 & 173: I think, it should be "high levels" and "low levels".

→ We revised it.

Eq 8: What is _alpha_ij?

→ We tried to clarity the methodology for Eigenvector centrality and added some example researches.

Page 5: Line 194 – Page 6: Line 216

In general, connections to nodes which are themselves influential could make a node more influence than connections to less influential nodes (Newman, 2016), and eigenvector centrality can be used for measuring the influential connections (Ruhnau, 2000). For example, the concept of eigenvector centrality has been used by the Web search engine Google in order to rank Web pages (Berry and Browne, 2005; Bryan and Leise, 2006; Newman, 2016).

In VWT network, the eigenvector centrality could be used for identifying influential countries that could affect the entire network. In other words, the entire VWT can be affected by a few influential countries, and it is important to identify these countries for understanding and estimating the change of the entire structure of the VWT. An eigenvector centrality can measure the influence of each country in the entire VWT, and it is related not only to its own connection pattern but also to the connections of other countries to it. Therefore, a country is more influential if it is considered in relation to the countries that are influential themselves (Ruhnau, 2000). The eigenvector centrality assigns relative centrality to all of the countries in the VWT, based on the principle that connections to high-level centrality countries contribute more to the centrality of the countries compared to equal connections to low-level centrality countries (Ruhnau, 2000; Lee et al., 2016). Bonacich (1972) defined the centrality (x_i) of a node i as the positive multiple of the sum of adjacent centralities in links (or volume) between nodes (A_{ij}). Therefore, if we denote the centrality of vertex i by x_i , then we can allow for this effect by making x_i proportional to the average of the centralities of i's network neighbours (Newman, 2016),

$$x_i = \frac{1}{\lambda} \sum_{j=1}^n A_{ij} x_j \quad (8)$$

where λ is a constant. Defining the vector of centralities $x = (x_1, x_2, \dots)$, we can rewrite this equation in matrix form as

$$\lambda x = Ax \quad (9)$$

This type of equation is solved using eigenvalues and eigenvectors, where A is a adjacency matrix of A_{ij} , and λ is a scalar, known as the eigenvalue associated with the eigenvector c defined as a column vector. Eigenvector centrality is determined by calculating the principal eigenvector that has the largest eigenvalue among all eigenvectors. A non-negative eigenvector with the maximal

eigenvalue exists. We refer to a non-negative eigenvector ($x \geq 0$) of the maximal eigenvalue as the principal eigenvector, and we call the entry x_i the eigenvector-centrality of node (country) i (Ruhnau, 2000).

L196ff - Please revise this paragraph: - The first sentence rather belongs to a summary, after you showed results, but you did not at this place in the manuscript. - The second sentence is given without reference/citation. - The third sentence contradicts the first two sentences. - The fourth sentence does not state whether Egypt imports from MENA countries or somewhere else. - The fifth sentence is not justified by the one example you state. - I also do not understand the intension of this paragraph, what do you want to convey here? Even the following sentence in L202 starts with "however" as if you wanted to say "but I actually want to talk about something else".

→ We revised the paragraph.

Page 6: Line 219 – Line 223

This study considered trade-offs between food security and food trade in terms of national resource management. For example, the increase of domestic food products instead of imports of them could be one policy for food security but additional water and land for domestic products would be considered at the same time. In other words, food imports could contribute domestic water and land management, therefore, we estimated the national water and land savings by importing crops as shown in Table 3.

L206: "This means that the contribution of import of barley, maize, and wheat on water security in Saudi Arabia was significant." - how do you come to this conclusion?

→ We added internal water resource of each country in the MENA region into Table 1, which was provided from World Bank, and compared the amount of water saving with the internal water resource.

Page 6: Line 223- Line 228

In Saudi Arabia, blue water savings by barley, maize, and wheat imports were estimated to 5.0, 2.0 and 0.8 billion m³/year, respectively. In comparison to the internal water resource of Saudi Arabia which is 2.4 billion m³/year as shown Table 1 (World Bank, 2014), the water saving through import of barley, maize, and wheat could be considered as significant amount in Saudi Arabia. In the case of Egypt, most of the water saving occurred based on the imports of wheat and maize. Approximately 7.5 billion m³/year of blue water was saved by importing wheat. Specifically, the internal water resources in Egypt are only 1.8 billion m³/year (Table 1), therefore, water scarcity could be an issue for food security policy in Egypt.

A general comment: for example, in L209, you state that Egypt would suffer from water shortage if the exporting countries banned wheat export to Egypt. I think that this is only partly true, i.e. only in those cases where the respective crops would actually grow in the individual countries. Considering rice, for example: I am sure that none of the MENA countries would be able to grow this crop even if the virtual water equivalent would be available. Please elaborate on this comment.

→ First, we need to explain the difference between water saving and virtual water import.

Virtual water import was based on water use in exporting country, thus virtual water import by rice could be quantified in terms of exporting country even through rice could not be suitable for growing in the MENA region.

Water saving is a kind of hypothetical number in this study because we assumed that all products were produced domestically, thus we did not include rice in water saving part. However, the results of

water saving could bring the importance of food import and showed how much water would be required for domestic production.

Page 4: Line 133– Line 144

Food import is also related to domestic water and lands savings. In particular water saving has a different meaning from virtual water import. For example, Saudi Arabia imported wheat from various exporters and virtual water import indicates the sum of the products obtained from multiplying the quantity of imported wheat by the respective water footprint of each exporter. However, water saving indicates the amount of water needed to produce the same quantity of imported products domestically. Therefore, water saving by wheat import in Saudi Arabia is estimated by multiplying the quantity of imported wheat with the water footprint of wheat in Saudi Arabia.

In this study, we applied green and blue water footprints of crops in each country in the MENA region, as shown in Table 1. However, the availability of water footprint data in the MENA region was limited in some cases. For example, the water footprint of wheat was available in all countries except for Bahrain. Lands saving has the same implication as water savings, thus we calculated lands saving using land footprint of each country in the MENA region, as shown in Table 2. The land footprint indicates the land requirement for producing 1 ton of crops, and it was calculated based on the harvest area and crop production data collected from FAOSTAT (Table 1).

L208: The statement of 1.8 billion m3/a water available for Egypt is missing a source.

→ We added source of internal water resource in Table 1

L210: "The crop import could result in a large amount of land savings." - this is an unnecessary statement. Likewise in L215: "These results can elicit useful information for analyzing the trade-off between food and water-land securities in the MENA region in terms of sustainable development."

→ We removed those expressions and revised whole paragraph.

L210ff: "In Saudi Arabia, land savings based on the import of barley, maize, and wheat, amounted to 1.6 million ha/year, and Lebanon was also strongly influenced by the impact of crop import on land savings. For example, approximately 0.24 million ha could be saved by crop imports, comprising 36% of the agricultural area in Lebanon, that indicates that the crop trade in Lebanon has significant benefits in terms of land resources compared to water resources." - please revise and do not mix two different countries in different sentences.

→ We revised those sentences.

Page 6: Line 228 – Line 231

Lebanon was strongly influenced by the impact of crop import on land savings. Approximately 0.24 million ha could be saved by crop imports, comprising 36% of the agricultural area in Lebanon, that indicates that the crop trade in Lebanon has significant benefits in terms of land resources compared to water resources.

L216: What do you mean by this: "However, water saving indicates the virtual water saving, and sometimes it is larger than the total water resources in some countries."

L216/217: "However" twice as starting word.

L217: "However, these results showed that the increase of food security is accompanied by

numerous water requirements in the MENA region." - I do not understand this. Please revise.
L218ff: "Additionally, the saved land is not always suitable for agricultural areas." – The "saved land", i.e. the equivalent required area to grow imported crops, is probably not available. Do you have information on this? "Some crops are required for the specific type of land, ..." - It is rather the other way: you require a specific soil for this or that crop."...and the productivity is also different based on soil." - Do you mean "the productivity is varies with different soils"? "Even if we can save land..." - Why do you think, the reason to import is to save land? - Why do you write "we"? "...there is the limitation for considering the land saving as an agricultural land saving in accordance to this study." - What do you mean by this?

→ We thought that above all comments were related to the same paragraph, and soil part was not related to this paper. Thus, we revised them. In revised paragraph we meant the limitation of virtual water trade, and removed the soil part.

Page 6: Line 232– Line 238

Food imports could be regarded as a negative factor in food security, and it is obvious that food security would accompany water and lands for domestic food products. These results showed that food imports could bring positive impacts on numerous water and lands savings in the MENA region. However, there are limitations of these results. First, water saving estimated in this study was based on the hypothetical situation that meat there were no international trade situation, and sometimes it was larger than the internal water resources in some countries such as Saudi Arabia and Egypt. Additionally, some crops are required for the specific type of climate but this study assumed that MENA region was suitable for cultivating maize, wheat, barley, and rice.

Table 3: - Please check for unnecessary line breaks (eg. Saudi Arabia, Blue water, Barley). - Do I understand it correctly that table 3 shows the results from the product of water footprint (table 1) and the annual import (table 2)? If so, how could you fill the gaps for the water footprint in blue water barley and green water maize? -> Oh, I see you wrote "0" for partly - please correct this and write "-".

→ We revised Table 3.

Section 3.1 should be shortened; often, statements are given that are unnecessary, unproven or uncited. The information from table 3 can and should be offered in a much more compact way.

→ We revised the entire section 3.1.

L227: Are the numbers for annual water import average values?

→ Yes, it is average value, thus we mentioned the “average” in revised manuscript.

Fig 1: - The grey scale (ie the total water import) uses uneven separating numbers and unequal intervals; I suggest to use even numbers (e.g. 1500 - 15000 instead of 1495 -15410 for the first green water import interval) and evenly spaced intervals. - I cannot read the number in the legend for annual water import - Some pie charts are very small (Qatar, Oman, Bahrain, Lebanon) - Why do the pie charts vary in size?

→ We removed the pie chart and focused on total virtual water import from 2000 to 2012.

Table 3 vs 4: I do not understand the difference between "water savings due to imported crops" (table 3) and "imported water" (table 4) - can you please explain this difference and describe why both values are different?

- We added more explanation about the differences between water saving and virtual water import.

Page 4: Line 133– Line 144

Food import is also related to domestic water and lands savings. In particular water saving has a different meaning from virtual water import. For example, Saudi Arabia imported wheat from various exporters and virtual water import indicates the sum of the products obtained from multiplying the quantity of imported wheat by the respective water footprint of each exporter. However, water saving indicates the amount of water needed to produce the same quantity of imported products domestically. Therefore, water saving by wheat import in Saudi Arabia is estimated by multiplying the quantity of imported wheat with the water footprint of wheat in Saudi Arabia.

In this study, we applied green and blue water footprints of crops in each country in the MENA region, as shown in Table 1. However, the availability of water footprint data in the MENA region was limited in some cases. For example, the water footprint of wheat was available in all countries except for Bahrain. Lands saving has the same implication as water savings, thus we calculated lands saving using land footprint of each country in the MENA region, as shown in Table 2. The land footprint indicates the land requirement for producing 1 ton of crops, and it was calculated based on the harvest area and crop production data collected from FAOSTAT (Table 1).

Section 3.2.2 / figure 3: how could you determine which water (blue or green) was used to grow the crops in the exporting countries?

- Mekonnen and Hoekstra (2010) estimated green and blue water footprint of each country in the world including the MENA region, thus we used green and blue water footprints applied in this study was country level data. We revised a little the paragraph about the water footprint from their study.

Fig. 3: Why do you give the numbers here in Gm3 while all other volumes are given as volume / time (Mm³/y)? I suggest to be consistent for comparability especially with such large numbers which are hard to imagine.

- We changed the unit to Mm³/yr.

Fig. 5: This is a very nice interpretation, but I have a suggestion: you could combine a and b and connect the individual countries' marks with arrows; currently, one has to search for a long time before a country's performance can be compared.

- We changed the order of Figures, thus previous Fig.5 is Fig. 6 in the revised manuscript.

We added the arrows in Fig. 5.

Fig. 6: - Please check for non-described countries and/or add them to "others". – The numbers of the individual eigenvectors are too small and cannot be read. - Can you show this figure also for the whole MENA region? Or in other words: why did you choose Lebanon here? Is the figure similar for the other countries?

- We changed the order of Figures, thus previous Fig.6 is Fig. 4 in the revised manuscript.

We made a new figure of the MENA region, and others indicate the countries who export less than 100 Mm³/yr to the MENA region or Lebanon

L359: If you write "Since the introduction of the virtual water concept, various studies have been conducted to quantify the volume of the VWT." you should provide proper citations and describe how you contribute to an extension of their findings.

➔ We thought this sentence is already mentioned in Introduction, thus we removed it in Conclusions.

L361: As above, the statement "The amount of imported virtual water is regarded as the most important factor in determining water and food security," should be backed up by citations or proof.

➔ Actually, that statement was derived from the results from this study, thus we revised them in Conclusions.

L364: "...the interlinkages of key natural resource sectors and the improved production efficiency are considered a win-win strategy for environmental sustainability..." - I do not understand why you address production efficiency here; that was not part of your previous analysis. Can you please explain this?

➔ We agreed with your opinion, thus removed that sentence.

L368: "Thus, decisions made in one sector typically impact the other sectors." - I think that this statement here does not belong to your core message of the paper: you never discuss / analyze how different sectors influence each other. You also do not show how virtual water or changes in virtual water fluxes may influence whatever sector.

➔ We agreed with your opinion, thus removed that sentence.

L372: "...policy makers can benefit..." - how should they benefit? What would be the key parameter policy makers can use? How should they decide on the future if your study is only based on the analysis of data from the past? Also: you compared the different countries of the MENA region among each other and derived values for SInDC and NSInDC. The comparison is thus only a qualitative comparison. How should a single country decide now whether its food import strategy generally is stable?

Finally: considering political differences in the MENA region, do you think that any singular country or a coalition of countries could use your evaluation to increase its food stability?

➔ Still, it is limitation of virtual water concept that it is hard to apply virtual water to real policy. We tried to study some real cases, but it is still lack of the study. We keep trying to find the appropriate example.

➔ We added more sentences about the contribution of this study in terms of policy making.

Page 10: Line 381– Line 391

The import of water in virtual form based on VWT could develop into a major water portfolio that dominates water management in the water-scarce countries of the MENA region. In water-deficit areas, such as the MENA region, the VWT can offer new perspectives for understanding and solving water stress and scarcity. In summary, this study showed that the significant water in comparison to internal water resource could be saved by food trade in the MENA region, and policy makers can benefit by considering both the quantitative impacts of VWT and the structural changes of VWT, such as vulnerable expansion (or reduction) in the MENA region. For example, when a country in the MENA region set a plan for increasing food security, this country first should identify the amount of water and land savings that can be achieved by food import, and consider the trade-off between food security and food import. In addition, the stable trade could be a component for stable food supply in the MENA region, thus this study contributes to the understanding of the dependency on each trade partner for countries in the MENA region and can help with setting the food trade policy in terms of extension (or reduction) of trade partners and increase (or decrease) in volume of trade.

Page 10: Line 399– Line 406

In spite of this limitation, the intensity and connectivity of VWT, which were analyzed in this study, can be the major components needed for integrating resources management in the MENA region. Accordingly, VWT is regarded as the important factor in determining food security and water-lands management, and it can be a useful interlinking parameter among resources in WEF Nexus approach, which identify key issues in food, water, and energy securities through the lens of sustainability, seeking to predict and protect against future risks and resource insecurities (Biggs et al., 2015). The core of the Nexus concept is that the production, consumption, and distribution of water, energy, and food, are inextricably interlinked, thus this study would provide important information to policy makers for evaluating scenarios about integrated resource management toward sustainability in the MENA region.

Point-by-point reply to specific comments

Referees #2

Reviewer's Comment: The water footprints of a given crop vary widely by country: for barley, green WF ranges from 193.6 to 6417.6 m³/ton. Adding together green and blue still gives a very wide range: ~8200 m³/ton in Libya vs 1000 m³/ton in Saudi Arabia. Are these numbers and their spatial variability realistic? Is it possible that producing barley in Libya consumes 8 times as much water as in Saudi Arabia? I don't imagine that potential ET varies that much over the region. Is the very wide range in WF because yields are so much higher in Saudi Arabia, but water consumption is assumed to be independent of yield? Some explanation is needed.

Answer: In this study, national water footprint of various crops from Mekonnen and Hoekstra, 2010 was applied. In my opinion, water footprint is affected by not only crop water requirement but also productivity. Thus, even if there is not much big difference in crop water requirement based on ET_c, the productivity at each country in MENA region could be huge different. For example, the production and cultivated area of barley in Libya provided from World Bank were 191,641 ha and 94,107 ton, thus the productivity is 0.49 ton/ha but Saudi Arabia has 5.67 ton/ha (12,279 ha, and 68,366 ton). It was almost 10 times difference. Therefore, the difference of productivity could be one of main reason of wide range of water footprint.

Reviewer's Comment: I found the methods description for Eigenvector centralities confusing (L176-193). Please rewrite for clarity.

Answer: We tried to clarity the methodology for Eigenvector centrality and added some example researches.

Revision: Page 5: Line 194 – Page 6: Line 216

In general, connections to nodes which are themselves influential could make a node more influence than connections to less influential nodes (Newman, 2016), and eigenvector centrality can be used for measuring the influential connections (Ruhnau, 2000). For example, the concept of eigenvector centrality has been used by the Web search engine Google in order to rank Web pages (Berry and Browne, 2005; Bryan and Leise, 2006; Newman, 2016).

In VWT network, the eigenvector centrality could be used for identifying influential countries that could affect the entire network. In other words, the entire VWT can be affected by a few influential countries, and it is important to identify these countries for understanding and estimating the change of the entire structure of the VWT. An eigenvector centrality can measure the influence of each country in the entire VWT, and it is related not only to its own connection pattern but also to the connections of other countries to it. Therefore, a country is more influential if it is considered in relation to the countries that are influential themselves (Ruhnau, 2000). The eigenvector centrality assigns relative centrality to all of the countries in the VWT, based on the principle that connections to high-level centrality countries contribute more to the centrality of the countries compared to equal connections to low-level centrality countries (Ruhnau, 2000; Lee et al., 2016). Bonacich (1972) defined the centrality (x_i) of a node i as the positive multiple of the sum of adjacent centralities in links (or volume) between nodes (A_{ij}).

Therefore, if we denote the centrality of vertex i by x_i , then we can allow for this effect by making x_i proportional to the average of the centralities of i 's network neighbours (Newman, 2016),

$$x_i = \frac{1}{\lambda} \sum_{j=1}^n A_{ij} x_j \quad (8)$$

where λ is a constant. Defining the vector of centralities $x = (x_1, x_2, \dots)$, we can rewrite this equation in matrix form as

$$\lambda x = Ax \quad (9)$$

This type of equation is solved using eigenvalues and eigenvectors, where A is a adjacency matrix of A_{ij} , and λ is a scalar, known as the eigenvalue associated with the eigenvector x defined as a column vector. Eigenvector centrality is determined by calculating the principal eigenvector that has the largest eigenvalue among all eigenvectors. A non-negative eigenvector with the maximal eigenvalue exists. We refer to a non-negative eigenvector ($x \geq 0$) of the maximal eigenvalue as the principal eigenvector, and we call the entry x_i the eigenvector-centrality of node (country) i (Ruhnau, 2000).

Reviewer's Comment: Some numbers are claimed to be significant, but without context. For example, Saudi Arabia saves 2 billion m³ per year by importing barley. Is that big number? Compared to what?

Answer: In previous manuscript, it was difficult to evaluate the results of water savings. Therefore, we added internal water resource of each country in MENA region into the Table 1, and compared the water savings with the internal water resource.

Revision: Page 6: Line 223 – Line 229

Answer: In Saudi Arabia, blue water savings by barley, maize, and wheat imports were estimated to 5.0, 2.0 and 0.8billion m³/year, respectively. In comparison to the internal water resource of Saudi Arabia which is 2.4 billion m³/year as shown Table 1(World Bank, 2014), the water saving through import of barley, maize, and wheat could be considered as significant amount in Saudi Arabia. In the case of Egypt, most of the water saving occurred based on the imports of wheat and maize. Approximately 7.5 billion m³/year of blue water was saved by importing wheat. Specifically, the internal water resources in Egypt are only 1.8 billion m³/year (Table 1), therefore, water scarcity could be an issue for food security policy in Egypt. Lebanon was strongly influenced by the impact of crop import on land savings.

Reviewer's Comment: The authors correctly note that it is important to identify countries that rely on only a few exporters. I'm not so sure that this means that countries with high dependence on one exporter should re-evaluate their policy, since I don't know enough about international trade strategy. Is there literature that can show that, historically, countries that rely on a single exporter are vulnerable to food sanctions? Can the authors cite historical precedent? Also, I found the shift in exporting countries from the US and Australia to other nations of potential importance to explain, both its causes and consequences. Is there more you can say about that in the paper?

Answer: We tried to search for historical precedent about impacts of trade structures on the international trade strategy. However, we could not find the specific examples. In terms of geopolitical issues and historical data use, we added some paragraph as limitations and future work parts.

Revision: Page 9: Line 358 – Line 363

Third, there are spatial and temporal issues of VWT in the study. The VWT could be affected by geopolitical issues such as topography, and distances between importers and exporters. For example, the changes of exporting countries in the MENA region could be related to energy use for transporting products, thus trade policy should consider the economic benefit or cost of transportation. Therefore, the VWT should be discussed with geopolitical issues such as benefit and cost of transportation. In addition, VWT and water-lands savings by food trade in this study were calculated based on historical database, thus it was difficult to apply the results to future policy.

Assessment of food trade impacts on water, food, and land security in the MENA region

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Abstract

The Middle East and North Africa (MENA) region has the largest water deficit in the world. It also has the least food self-sufficiency. Increasing food imports and decreasing domestic food production can contribute to water savings and hence to increased water security. However, increased domestic food production is a better way to achieve food security, even if irrigation demands increase in accordance to projected climate changes. Accordingly, the trade-off between food security and the savings of water and land through food trade is considered as a significant factor for resource management, especially in the MENA. Therefore, the aim of this study is to analyze the impact of food trade on food security and water-land savings in the MENA region. We concluded that the MENA region saved significant amounts of national water and land based on the import of four major crops, namely, barley, maize, rice, and wheat, within the period from 2000 to 2012, even if the food self-sufficiency is still at a low level. For example, Egypt imported 8.3 million ton/year of wheat that led to 7.5 billion m³ of irrigation water and 1.3 million ha of land savings. In addition, we estimated the virtual water trade (VWT) that refers to the trade of water embedded in food products and analyzed the structure of VWT in the MENA region using degree and eigenvector centralities. The study revealed that the MENA region focused more on increasing the volume of virtual water imported during the period 2006–2012, yet little attention was paid ~~on to~~ the expansion of connections with country exporters based on the VWT network analysis.

Keyword: *Food security; Food self-sufficiency; Food trade; Virtual water; MEAN.*

1 Introduction

Food security and water scarcity are urgent socio-economic and environmental issues in the Middle East and North Africa (MENA) region (Saladini et al., 2018), which are highly interlinked, and Water-Energy-Food Nexus has been suggested as a proper and integrated approach for resource management (Bazilian et al., 2011; Rasul, 2014; Mohtar and Daher, 2014; Lee et al., 2018). For example, food security in the MENA region has become complicated by increased risks owing to the geopolitical challenges and inability to satisfy needs with domestic production because of the lack of adequate arable land and water resources (Rastoin and Cheriet, 2010). In addition, food imbalance in the MENA region is forecast to reach 60 % in 2050 and food security in MENA region could be extremely compromised (Rastoin and Cheriet, 2010). Climate change could lead to more frequent occurrence of extreme climatic events in Mediterranean region, accompanying 50 % decrease of agricultural production by the end of the century (Porter et al., 2014). In particular, water saving through food trade can be suggested as a solution for mitigating groundwater depletion in the MENA region (Lezzaik et al., 2018).

In this study, we focused on the role of food trade in the MENA region in terms of resource management. Accordingly, we applied the concept of virtual water trade (VWT), which refers to the trade of water embedded in food products (Allan, 1993; Aldaya et al., 2010; Antonelli and Tamea, 2015), in order to assess the food trade impact on water savings in MENA region. International trade in food commodities has been shown to save water, thus food trade is an important element of both food

41 and water security in water-scarce regions (Hoekstra, 2003; Chapagain et al., 2006; Hanjra and Qureshi, 2010; Fader et al.,
42 2011; Konar et al., 2012). In addition, food trade could contribute to global water savings if food is exported by countries with
43 a higher water productivity than the countries of import (Konar et al., 2012). The concept and quantitative estimates of virtual
44 water can help to realistically assess water scarcity for each country, projecting future water demand for food supply, thus
45 increasing public awareness on water and identifying water-wasting processes in production (Oki and Kanae, 2004). For water-
46 scarce countries, achieving water security by importing water intensive products could be a more attractive option compared
47 to producing all water-demanding products domestically (Hoekstra and Hung, 2005). The global volume of international crop-
48 related virtual water flows averaged 695 billion m³/year over the period 1995–1999, which means that 13% of the water used
49 for crop production in the world was not used for domestic consumption but rather for export in virtual forms (Hoekstra and
50 Hung, 2005). Falkenmark and Lannerstad (2010) estimated that it would be necessary to double the VWT by 2050 to
51 compensate for agricultural water deficits because of climatic change, population increase, and the pattern of food supply per
52 capita. For example, an average of 20% of the per capita food energy supply was assumed to originate from animal foods to
53 ensure sufficient protein content, and additional water was required to produce animal foods compared to other food types
54 (Falkenmark and Lannerstad, 2010).

55 The VWT could contribute to the relief of water stress through the use of global water in a more efficient manner in the event
56 of an increase in the global food trade (Molden, 2007). Additionally, the VWT and the respective savings garnered through
57 the trade of agricultural goods have been quantified in a number of studies. Oki and Kanae (2004) investigated that
58 approximately 1140 km³/year of virtual water could be used for altering the import of food products to domestic products, e.g.,
59 cereals, soybeans, and meat; however, 680 km³/year of water was used to produce these food types in exporting areas. Yang
60 et al. (2006) revealed that the VWT could generate global water savings because virtual water has flown primarily from
61 countries of increased crop water productivity to countries of low-crop water productivity. In their study, 336.8 km³/year of
62 water were saved globally by the international trade of major food crops from 1997 to 2001, while 20.4% of the total global
63 net virtual water import was imported by countries that have water availability below 1700 m³ per capita, such as the Arab
64 countries. Fader et al. (2011) calculated the VWT based on the trade of crop products, and compared it with the water
65 requirements for producing crop products in each country for domestic consumption without international trade. Generally,
66 exporters use less water for production of crop products than importers. Thus, the trade of crop products saves 263 km³/year
67 of water globally, thereby representing 3.5% of the annual precipitation on cropland (Fader et al., 2011). In particular, water-
68 scarce countries, such as China and Mexico, as well as land-scarce countries such as Netherlands and Japan, saved large
69 amounts of water by importing goods that require water in the range from 25 to 73 km³/year, because they would otherwise
70 need relatively large amounts of water to produce the goods they import. According to the study by Biewald et al. (2014), blue
71 water, which refers to the irrigation water supplied from artificial facilities, such as reservoirs, ground water pumping or
72 desalination stations, was saved in importing countries by importing products in accordance to international trade. It is expected
73 that this can elicit enormous benefits in water-scarce regions. For example, 17 billion m³ of blue water per year were saved by
74 the global food trade, and the value of blue water saving was estimated to 2.4 billion US\$.

75 Previous studies showed that the effective import of virtual water may reduce water use for domestic food production in
76 importing countries and help alleviate water stress in the MENA region where the largest water deficit in the world exists
77 (Gleick, 2000; World Bank, 2009). The critical condition of water scarcity in the MENA region will reach severe levels by
78 2025 (Tolba, 2009). In addition, if population increases rapidly and urbanization continues fast, availability of water could be
79 reduced in the Arab countries by approximately 50% by the year 2025 (Abahussain et al., 2002). Water shortages will certainly
80 speed up the rate of desertification in the Arab countries ~~with a larger deficit in freshwater~~ (Abahussain et al., 2002). Agricultural water withdrawals account for over 85% of the total water withdrawn by the various countries of the MENA
81 region (FAO, 2014). Irrigation systems in the MENA region are based on pumping groundwater resources, such as aquifers,
82 and water security is being threatened by the declining aquifer levels and the extraction of nonrenewable groundwater

(Antonelli and Tamea, 2015). In addition, Immerzeel et al. (2011) expected that the unfulfilled water demand in the entire MENA region would increase from the current level of 16% to 51% in 2040–2050 owing to climate changes. The zone of severely reduced rainfall extends throughout the Mediterranean region and the Northern Sahara (Hennessy et al., 2007). Milly et al. (2005) ~~estimated~~ ~~identified~~ that climate change will cause a decrease in water run-off by 20% to 30% in most of the MENA region by 2050, mainly owing to the rising temperatures and lower precipitation. In addition, the regions that include Syria, Lebanon, Israel, and Jordan, will get drier, with significant rainfall decreases in the wet season.

However, the high dependency on food import can be a risk of food security, even if it can elicit domestic water, energy, and land savings, in water-scarce regions. Therefore, we should consider a trade-off between food security and resource savings, using a holistic approach, such as Trade-WFL(Water-Food-Land) Nexus. Furthermore, the VWT can be suggested as relevant to the water policy of a nation (Schyns and Hoekstra, 2014), thus establishing a new point-of-view from which both food security and sustainable water management are considered (Novo et al., 2009).

This study addresses three questions that relate to the role and impact of the VWT in the MENA region, that are raised to draw attention to the complexity of the issue and the need for a broader view in assessment. Specifically, 1) what are the effects of the VWT on water savings and land tenure in the MENA region, 2) has the structure of the virtual water import in the MENA region been vulnerable or robust? 3) Who are the influential importers and exporters in the VWT network in the MENA region? The aim of this study is to evaluate the effects on water savings and land tenure from importing crops ~~in at 15 each countries~~ ~~in the MENA region such as Algeria, Egypt, Iraq, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syria, Tunisia, UAE, and Yemen~~. In addition, we quantified the amount of VWT from 2000 to 2012, and analyzed a structure of the VWT, such as the connectivity and influence in the MENA region using degree and eigenvector centralities.

2 Materials and Methods

2.1 VWT based on international trade

The VWT represents the water embedded in international trade, and it indicates the water used in the exporting country to produce crops for export. ~~Therefore, the VWT is calculated based on the water footprint of exporters, which indicates the total amount of water used for producing crop, and the export of virtual water in the exporting country has the same meaning as the import of virtual water has in the importing country.~~ For example, Saudi Arabia imported wheat from various exporters, and the ~~virtual water import(or export)~~ ~~VWT~~ was calculated by multiplying the quantity of traded wheat with the respective water footprint of exporters. ~~In other words, the VWT is calculated based on the water footprint of exporters. Thus, the export of virtual water in the exporting country has the same meaning as the import of virtual water has in the importing country.~~ Accordingly, the main factors for quantifying a VWT are the trade data and water footprint, and the VWT is calculated by multiplying the trade by its associated water footprint in the exporting country, as follows:

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

where the variable VWT denotes the virtual water trade from the exporting country, n_e , to the importing country, n_i , in year t, as a result of trade in crop c, CT represents the crop trade from the exporting country, n_e , to the importing country, n_i , in year t as a result of trade in crop c, and WFP represents the water footprint of crop c in the exporting country, n_e .

The international trade data of the four major crops, namely, barley, maize, rice, and wheat from 2000 to 2012 was obtained from FAOSTAT (<http://www.fao.org/faostat/>), as shown in Table 21. The crop with the largest amount of import was wheat, with 27.6 million ton/year imported by the MENA region from 2000 to 2012, followed by maize (14.4 million ton/year), barley (9.0 million ton/year), and rice (3.7 million ton/year).

~~Water footprint is a localized index for countries, accounting for the climate, productivity, and irrigation. In this study, we considered water footprints of all countries in the world, however, a lot of effort should be required for estimating water footprints of all countries and it was outside the scope of the current study. Therefore, we applied water footprint data of 147~~

125 countries, including those in the MENA region, from the study executed by Mekonnen and Hoekstra (2010). The water
126 footprint for a crop is divided into green and blue water footprints based on the water resources (Hoekstra and Chapagain,
127 2008). The green water footprint indicates that water supplied by precipitation is retained in the soil of the root zone
128 (Falkenmark, 1995), and blue water footprint is the water stored at the surface or in the ground. Therefore, the green water
129 footprint is related to rain-fed agriculture and the blue water footprint is related to irrigation water provided by aquifers or
130 surface bodies of water. As the water footprint is divided into green and blue water footprints, water saving could be considered
131 as green and blue water saving as well.

132 **Table 1.** Cultivation area, production, the quantity of crops imported, and internal water resource in the MENA region from
133 2000 to 2012

134 **2.2 Water and lands savings by an international food trade in importing country**

135 Food import is also related to domestic water and lands savings. In particular water saving has a different meaning from virtual
136 water import. For example, Saudi Arabia imported wheat from various exporters and virtual water import indicates the sum of
137 the products obtained from multiplying the quantity of imported wheat by the respective water footprint of each exporter.
138 However, water saving indicates the amount of water needed to produce the same quantity of imported products domestically.
139 Therefore, water saving by wheat import in Saudi Arabia is estimated by multiplying the quantity of imported wheat with the
140 water footprint of wheat in Saudi Arabia.

141 In this study, we applied green and blue water footprints of crops in each country in the MENA region, as shown in Table 1.
142 However, the availability of water footprint data in the MENA region was limited in some cases. For example, the water
143 footprint of wheat was available in all countries except for Bahrain. Lands saving has the same implication as water savings,
144 thus we calculated lands saving using land footprint of each country in the MENA region, as shown in Table 2. The land
145 footprint indicates the land requirement for producing 1 ton of crops, and it was calculated based on the harvest area and crop
146 production data collected from FAOSTAT (Table 1).

147 The water and lands savings could be assessed the impacts of failure of trade on domestic water and land requirements in the
148 importing country. Although this assumption about water and land savings considers an extreme trade situation, these results
149 could be used to understand the importance of the international crop trade in the MENA region. In other words, the water and
150 land savings indicated the amount of water and land requirements for crops imported to substitute domestic production, and
151 the water and land savings were calculated as follows,

$$152 WFP[n_i, c] = \frac{CWR[n_i, c]}{P[n_i, c]} \quad (2)$$

$$153 LFP[n_i, c] = \frac{Area[n_i, c]}{P[n_i, c]} \quad (3)$$

$$154 WS[n_i, c] = CI[n_i, c] \times WFP[n_i, c], \quad (4)$$

$$155 LS[n_i, c] = CI[n_i, c] \times LWP[n_i, c] \quad (5)$$

156 in which variable $WFP[n_i, c]$ (m^3/ton) is the water footprint of crop c in the importing country n_i , CWR is the crop water
157 requirement (m^3), and P is the production (ton). Equivalently, $LFP[n_i, c]$ (ha/ton) is the land footprint of crop c in the importing
158 country n_i , and $Area$ is the cultivated area (ha). The symbol WS (m^3) or (or LS (ha)) indicates the amount of water (or land)
159 savings in the importing country n_i . CI is the import of crop c in the importing country n_i .

160 **Table 2.** Water and lands footprints of four major crops in the MENA region

161 **2.3 Degree and eigenvector centralities for analyzing the structure of VWT**

162 **2.3.1 Nonscaled and scaled in-degree centralities of VWT**

163 Understanding the VWT structure is important for quantifying the amount of import and export because the VWT structure
164 can represent whether it would be sustainable or vulnerable. For example, if a country imports considerable amounts of virtual

water through the food trade from just a few exporters, the structure of VWT in this country might be impressionable by exporters. However, if a country is connected with many exporters in VWT, it can have a resilient structure for global changes. A few studies have been conducted on the analysis of the structure of the VWT using a network-based approach (Konar et al., 2012; Dalin et al., 2012; Lee et al., 2016). For example, Konar et al (2012) analyzed the characteristics of the network change in virtual water trade (VWT), and found that a number of export trade partners followed an exponential distribution in 2000. Dalin et al (2012) found that constant organizational features were observed in the network of VWT even though the number of trade connections and the volume of VWT has been growing. In addition, Lee et al (2016) analyzed vulnerability of the importing countries through the characteristics of network in VWT.

In this study, we analyzed the links of the VWT network for identifying the VWT structure using degree centrality, that is the number of degree incidents on a given node (Freeman 1979). In addition, the degree centrality is divided into in- and out-degree centralities, depending on the direction. In-degree is based on the number of lines (or volume) directed to the node, and out-degree is based on the number of lines (or volume) that the node directs to. A node indicates the country in global trade network, and incidents mean the trade between countries which can be amounts of products or number of connections, for example if one country exports product to five countries, that country has five incidents. In this study, In this study, we focused on the in-degree centrality because the MENA region includes representative importing countries. An importer accompanying an increased in-degree centrality has expanded connectivity with a large number of exporters, meaning that this importer could cope with an accidental disconnection from a certain exporter. In addition, the volume of products exported or imported can be applied to incidents as weight of links. In this study, In addition, the in-degree centrality, based on the number and volume of links in the VWT network, is expressed according to the nonscaled in-degree centrality (NSInDC), that is based on the number of links (or connections), and the scaled in-degree centrality (SInDC), that is based on the volume of links.

$$NSInDC_i = \sum_j^N Link_{ij} / (N - 1), \quad (6)$$

$$SInDC_i = \sum_j^N Flow_{ij} / (N - 1), \quad (7)$$

where $NSInDC_i$ is the nonscaled in-degree centrality of country i , and $Link_{ij}$ is the number of links between the i th and j th countries. The symbol $SInDC_i$ is the scaled in-degree centrality of country i , and $Flow_{ij}$ is the volume of virtual water traded between the i th and j th countries. Moreover, N is the total number of countries that trade with a given MENA countries.

Through NSInDC and SInDC, we analyzed the vulnerable expansion (or reduction) and robust expansion (or reduction) in the VWT network in the MENA region. For example, the vulnerable expansion in the network indicates that the amount of flow to a node increases but the number of connections to other nodes decrease. This is represented by high-levels of SInDC and low-levels of NSInDC. The importer country that is associated with vulnerable expansion has an increased quantity of products from only a few exporters.

2.3.2 Eigenvector centralities of VWT

In general, connections to nodes which are themselves influential could make a node more influence than connections to less influential nodes (Newman, 2016), and eigenvector centrality can be used for measuring the influential connections (Ruhnau, 2000). For example, the concept of eigenvector centrality has been used by the Web search engine Google in order to rank Web pages (Berry and Browne, 2005; Bryan and Leise, 2006; Newman, 2016).

In VWT network, the eigenvector centrality could be used for identifying influential countries who that could affect the entire network. In other words, the entire VWT can be affected by a few influential countries, and it is important to identify these countries for understanding and estimating the change of the entire structure of the VWT. An eigenvector centrality can measure the influence of each country in the entire VWT, and it is related not only to its own connection pattern but also to the connections of other countries to it. Therefore, a country is more influential if it is considered in relation to the countries that are influential themselves (Ruhnau, 2000). The eigenvector centrality assigns relative centrality to all of the countries in the VWT, based on the principle that connections to high-level centrality countries contribute more to the centrality of the

207 countries compared to equal connections to low-level centrality countries (Ruhnau, 2000; Lee et al., 2016). Bonacich (1972)
208 defined the centrality (x_i) of a node i as the positive multiple of the sum of adjacent centralities in links (or volume) between
209 nodes (A_{ij}). Therefore, if we denote the centrality of vertex i by x_i , then we can allow for this effect by making x_i proportional
210 to the average of the centralities of i's network neighbours (Newman, 2016).

211
$$x_i = \frac{1}{\lambda} \sum_{j=1}^n A_{ij} x_j \quad (8)$$

212 where λ is a constant. Defining the vector of centralities $x = (x_1, x_2, \dots)$, we can rewrite this equation in matrix form as

213
$$\lambda x = Ax \quad (9)$$

214 This type of equation is solved using eigenvalues and eigenvectors, where A is a adjacency matrix of A_{ij} and λ is a scalar,
215 known as the eigenvalue associated with the eigenvector c defined as a column vector. Eigenvector centrality is determined
216 by calculating the principal eigenvector that has the largest eigenvalue among all eigenvectors. A non-negative eigenvector
217 with the maximal eigenvalue exists. We refer to a non-negative eigenvector ($x \geq 0$) of the maximal eigenvalue as the principal
218 eigenvector, and we call the entry x_i the eigenvector-centrality of node (country) i (Ruhnau, 2000).

219 3 Results and Discussion

220 3.1 Trade-offs between national water-land savings and food security through food trade in the MENA region

221 This study ~~However, we need to consider~~ trade-offs between food security and food trade in terms of national ~~water land~~
222 ~~resource management.~~ For example, the increase of domestic food products instead of imports of them could be one policy
223 for food security but ~~In order to increase the food security,~~ additional water and land ~~for domestic products~~ ~~should~~ would be
224 ~~considered at the same time required for increasing domestic production.~~ In other words, food imports could contribute
225 domestic water and land management. ~~T~~herefore, we estimated ~~we estimated~~ the national water and land savings by importing
226 crops as shown in Table 3, ~~that is a negative factor for food security.~~ In Saudi Arabia, ~~Table 3 shows that the green and blue~~
227 water savings by barley, maize, and wheat imports ~~in Saudi Arabia~~ were estimated to 5.0, 2.0 and 0.8 ~~2.0 and 7.8~~ billion m³/year,
228 respectively. In comparison to the internal water resource of Saudi Arabia which is 2.4 billion m³/year as shown Table 1(World
229 Bank, 2014). This means that the water saving through contribution of import of barley, maize, and wheat could be considered
230 as significant amount on water security in Saudi Arabia ~~was significant.~~ In the case of Egypt, most of the water saving occurred
231 based on the imports of wheat and maize. Approximately 7.5 billion m³/year of blue water was saved by importing wheat.
232 Specifically, the internal water resources in Egypt are only 1.8 billion m³/year (Table 1), therefore, water scarcity could be an
233 issue for food security policy in Egypt. Lebanon was ~~also~~ strongly influenced by the impact of crop import on land savings.
234 For example, a~~A~~pproximately 0.24 million ha could be saved by crop imports, comprising 36% of the agricultural area in
235 Lebanon, that indicates that the crop trade in Lebanon has significant benefits in terms of land resources compared to water
236 resources.

237 Food imports could be regarded as a negative factor in food security, and it is obvious that food security would accompany
238 water and lands for domestic food products. These results showed that food imports could bring positive impacts on numerous
239 water and lands savings in the MENA region. ~~These results can elicit useful information for analyzing the trade-off between~~
240 ~~food and water land securities in the MENA region in terms of sustainable development.~~ However, ~~However, there are~~
241 limitations of these results. First, w~~w~~ater saving estimated in this study was~~is~~ based on the hypothetical situation that meat~~is~~
242 there were~~are~~ no international trades~~s~~ situation, indicates the virtual water saving, thus ~~and~~ sometimes it was~~is~~ larger than
243 the total internal water resources in some countries such as Saudi Arabia and Egypt. ~~However, these results showed that the~~
244 ~~increase of food security is accompanied by numerous water and lands requirements in the MENA region.~~ Additionally, some
245 crops are required for the specific type of climate but this study assumed that MENA region was~~is~~ suitable for cultivating
246 maize, wheat, barley, and rice.

247 **Table 3.** The amount of water and land savings through importing crops in the MENA region from 2000 to 2012.

248 **3.2 The VWT in the MENA region from 2000 to 2012**

249 *3.2.1 Virtual water import in the MENA region*

250 The total amount of green and blue water imported by each **MENA Arab** country from 2000 to 2012 respectively reached 921.2
251 and 80.5 billion m³ in the MENA region, as shown in Table 4 and Figure 1. The largest volume of green water was imported
252 annually by Egypt (19.1 billion m³/year), followed by Saudi Arabia (11.9 billion m³/year). In addition, the largest amount of
253 blue water was imported annually by Saudi Arabia (1.2 billion m³/year), followed by the UAE (0.9 billion m³/year). Over 70%
254 of the green water imported annually into the MENA region based on the trade of barley (approximately 8.5 billion m³/year)
255 was occupied by Saudi Arabia. The amount of virtual water imported based on the trade of maize was 13.0 billion m³/year,
256 with Egypt being the primary importer of 31% of the total imported amount into the MENA region.

257 Generally, rice is cultivated in paddy fields, and the blue water footprint of rice in these fields is larger than other cereal crops
258 in various countries. For example, the global average of the blue water footprint of rice is 584 m³/ton but that for wheat is 343
259 m³/ton (Chapagain and Hoekstra 2011; Mekonnen and Hoekstra 2010). Therefore, the importers of rice also import a lot of
260 water. Approximately 3.0 billion m³/year of blue water were imported in the rice trade from 2000 to 2012, and Saudi Arabia,
261 UAE, and Iraq, were the primary importers. The largest volume of virtual water imported by the MENA region was owing to
262 the trade of wheat. The annual amount of virtual water imported based on the trade of wheat in the MENA region from 2000
263 to 2012 was approximately 42.6 billion m³/year, ~~and, but the amount of blue water was only 2.0 billion m³/year.~~ Over 35% of the virtual water imported through the wheat trade was imported by Egypt (15.7 billion m³/year). However, the amount of blue water was only 2.0 billion m³/year because the green water footprint is much larger than blue water footprint in main exporters such Russian fed, Australia, and Canada that might indicate wheat has been cultivated in rain-fed area with less irrigation.

264 We also estimated the amount of virtual water imported per capita (VWIcap), as shown in Figure 2, which shows the differing
265 viewpoints regarding food and water securities. If we consider only the total amount of imported virtual water, the UAE may
266 not be considered to be a significant importer because the population and area of UAE is much smaller than those of the MENA
267 other countries, such as Saudi Arabia. However, the virtual water import per capita in the UAE is larger than that of Saudi
268 Arabia, thus indicating that the dependency on virtual water imported from exporters in the UAE is much more significant
269 than in Saudi Arabia. For example, the VWIcap was 1266.6 m³/cap/year in the UAE, which was the largest value in the MENA
270 region. The UAE is strongly dependent on the import of virtual water, even though the UAE imports only 4.2 billion m³/year
271 of virtual water. The VWIcap increased significantly in Saudi Arabia and Libya from 2000 to 2012. Saudi Arabia and Libya
272 imported approximately 453.4 and 497.8 m³/cap/year, respectively, of virtual water more in 2012 than in 2000. Saudi Arabia
273 was the second largest importer in the MENA region, and its VWIcap was also the fifth highest in the MENA region.

274 **Table 4.** The amount of green and blue water imported in the MENA region from 2000 to 2012.

275 **Figure 1.** The total amount of virtual water imported by each country in the MENA region from 2000 to 2012, separated into
276 green (upper) and blue (lower) water. ~~The pie graph shows the annual import and proportion of each crop, and the size of the pie indicates the amount of annual virtual water imported from 2000 to 2012.~~

277 **Figure 2.** Virtual water imported per capita in the MENA region from 2000 to 2012.

278 *3.2.2 Virtual water export to the MENA region*

279 We also focused on the volume of virtual water exported to the MENA region by each exporter from 2000 to 2012, as shown
280 in Figure 3. Based on the trade of barley, Ukraine exported 41.1 billion m³ of green water to the MENA region that amounted
281 to 27% of the total green water imported in the MENA region ~~based on barley~~. In terms of blue water traded through barley,
282 five exporters (Germany, Australia, the Russian Federation, Ukraine, and India) provided 78% of the total blue water imported

288 in the MENA region based on barley. Based on the trade of maize, Argentina contributed 40% of the total amount of green
289 water imported by the MENA region based on maize, but the blue water imported by the MENA region was primarily from
290 the USA. Based on the trade of rice, the major virtual water exporters to the MENA region were India, Thailand, and Pakistan.
291 In particular, 30.4 billion m³ of blue water were imported from these countries from 2000 to 2012, which comprised 78% of
292 the blue water imported by the MENA region based on rice. Wheat was the most representative crop imported by the MENA
293 region. The Russian Federation and the USA provided 25% (140.6 billion m³) and 21% (111.2 billion m³) of the total amount
294 of green water imported in the MENA region based on the trade of wheat in 2000 to 2012, respectively, and the remaining 55%
295 was divided among several exporters, including Australia, Canada, France, and Ukraine.

296 **Figure 3.** Quantities of green water export (GWE) and blue water export (BWE) from the primary exporters to the MENA
297 region from 2000 to 2012

298 3.3 The temporal change of VWT structure in the MENA region

299 From 2000 to 2012, both the volume and connectivity of VWT was changed. For example, the virtual water imported in the
300 MENA region slightly increased and the VWT was distributed with more exporters in 2006, as shown in Figure 4. However,
301 the volume of virtual water imported in the MENA region was increased more than 50 % from 2006 to 2012 but the distribution
302 of VWT seemed to consistent. In case of Lebanon, VWT in Lebanon was strongly dependent on the USA, Argentina, and
303 Australia. However, Lebanon expended the VWT in 2006 and Russian Federation, Turkey, and Kazakhstan, contributed to
304 virtual water imports in Lebanon, as shown in Figure 4. Accordingly, the structure of VWT in Lebanon approached a
305 distributed network. However, the VWT in 2012 showed that it was dominated by Ukraine and Russian Federation, though
306 Lebanon imported more virtual water in 2012 than 2006.

307 **Figure 4.** Virtual water imports at the MENA region and Lebanon in 2000, 2006, and 2012

308 These changes are more related to the structure of VWT and the MENA region should consider not only the amount of virtual
309 water but also the structure of VWT for sustainable food security subject to the condition of a strong dependency on crop
310 import. Therefore, we analyzed the degree centralities of NSInDC and SInDC from 2000 to 2012 in the MENA region, and
311 identified the countries who had the vulnerable expansion or reduction in the VWT network. Figure 4-5 shows the NSInDC
312 and SInDC patterns in the VWT network in accordance to each country in the MENA region. If the specific country has both
313 large NSInDC and small SInDC, this country ~~constructs~~ has the connections with various exporters but imports a small amount
314 of virtual water. Specifically, Egypt and Yemen showed that NSCInD was lower but SInDC was higher than other countries,
315 thus indicating the intensive connectivity with a few exporters. In contrast, Saudi Arabia had larger SInDC than other countries
316 expect for Egypt, while the NSCInD was also highest ~~in of~~ the MENA region. Accordingly, Saudi Arabia had a more
317 distributed structure regarding VWT. UAE and Iraq had similar SInDC in 2012 but NSInDC was quite different (UAE (0.46)
318 and Iraq (0.27)). Furthermore, SInDC in Morocco (96.45) was larger than UAE (83.41) but NSInDC in Morocco (0.26) was
319 smaller than UAE (0.46). In comparison to UAE, Morocco had intensive connections with fewer exporters compared to UAE.
320 Based on the temporal changes of NSInDC and the SInDC during two periods (2000–2006 and 2006–2012), the MENA region
321 countries were divided into four types (I–IV), as shown in Figure 5-6. ~~The listed numbers in Figure 5-6 represent each MENA~~
322 ~~Arab country. For example, the number 1 is assigned to Algeria.~~ The x-axis indicates the NSInDC and the y-axis indicates
323 the SInDC. ~~Therefore, if the specific country in the MENA region is located at a higher level in the x axis and at a lower level~~
324 ~~in the y axis, this country has established connections with more exporters but has a decreased virtual water imports.~~
325 Type I countries is located at higher levels both in the x-axis and y-axis, and show a robust expansion in the virtual water
326 import. Additionally, the countries in this type increased the connectivity and volume of virtual water imported, simultaneously.
327 Type II countries increased the volume of virtual water imported without expansion of connectivity. Type III ~~and type IV~~
328 countries showed reductions in the virtual water import with ~~and without~~ reduction of connectivity, and type IV countries,
329 ~~respectively.~~ has established connections with more exporters but has a decreased virtual water imports.

331 In the early 2000s, most of countries in the MENA region ~~tried to expand~~ their trade structure by increasing both the
332 connectivity to the exporters and the volume of the imported virtual water. In Bahrain, Oman, Qatar, Yemen, Saudi Arabia,
333 Lebanon, and UAE, the NSInDC of the VWT network increased significantly from 2000 to 2006, which means that the trade
334 connectivity expanded. The expanded structure of the VWT indicates that the MENA Arab countries were connected to various
335 exporters, and that this structure can be a resilient structure for global changes. In particular, the import of food crops is an
336 essential factor in food security in the MENA region, even if food self-sufficiency is increased by increasing domestic
337 production. However, Egypt had the largest SInDC but NSInDC was ranked 6th among the MENA region countries. In 2006,
338 Egypt and Saudi Arabia both expanded the connectivity in the VWT network, as shown by the increasing NSInDC.

339 However, the type of VWT structure in many MENA countries such as Yemen, Qatar, Bahrain, and Lebanon has moved to
340 Type II which means that become a more vulnerable structure in the MENA region in recent years. Most of the Arab the
341 countries increased the volume of the imported virtual water, but the number of exporters that linked to the Arab MENA
342 countries decreased or increased insignificantly from 2006 to 2012. In particular, in 2012, most ~~of~~ countries kept their
343 connectivities or reduced them, except for Algeria, Iraq, Libya, and UAE. These results indicate that the dependence of the
344 MENA region on virtual water import increased rapidly recently with the large increase in the imported volume of virtual
345 water. However, the connectivity of the VWT in the MENA region has not increased as much as the volume of virtual water
346 imported increased.

347 The degree centrality in this study could be useful for identifying the connectivity and volume of trade of each country, but it
348 is limited to show the influence of each country on entire trade network, thus we analyzed estimated the influence of each
349 country on the entire VWT network of the MENA region using eigenvector centrality, as shown on Figure 7. In 2000, Egypt
350 and Saudi Arabia were identified as the most influential importers in the MENA region, and the USA and Australia were the
351 most influential exporters. Accordingly, the entire VWT in the MENA region could be affected by these importers and
352 exporters. This means that the change of the trade policy or food management in these countries could change the structure of
353 VWT in the MENA region. In 2006 and 2012, the influential countries in the MENA region were still Egypt and Saudi Arabia,
354 but the influential exporters moved to the Russian Federation, Ukraine, and Brazil.

355 **Figure 5.** Nonscaled and scaled in-degree centralities of each country in the MENA region in 2000, 2006, and 2012

356 **Figure 6.** Country types in the MENA region according to the changes of nonscaled and scaled in-degree centralities

357 **Figure 7.** Eigenvector centrality of virtual water trade network in the MENA region at 2000, 2006, and 2012

358 **3.4 Importance and limitations of water footprint and VWT in the MENA region from a policy perspective**

359 Generally, the VWT is more related to resource management in exporting countries rather than importing countries because
360 the embedded water in food trade indicates water resources that are consumed for producing food products in the exporting
361 country. However, VWT is also considered as an important issue in importing countries in terms of water and food security.
362 For example, the reduction of VWT might be related to water consumption by replacing imported food products by domestic
363 food products.

364 However, the application of the concept of VWT is under critical discussion (Wichelns, 2010). First, water footprints formulate
365 new concepts of water management, but we need to realize that water footprint can be changed in accordance due to various
366 factors such water requirement, productivity, production system, development of technologies, fertilizer usage, and irrigation
367 scheduling and operations of the water facilities.

368 Second, VWT could contribute to the connection of water management to food security. However, food trade is affected by
369 the scarcity or affluence of other important resources, such as capital, labor, and land (Biewald et al., 2014). In particular,
370 economic values, such as the price of food products, are is the main driver in global food trade, but there is no global value
371 established for virtual water. Therefore, it is difficult to apply virtual water to trade policy in terms of the economic efficiency.

372 Therefore, policy makers or resource managers in the MENA region should not only consider the effects of VWT but also the
373 difficulty in adapting virtual water to policies for resource management.

374 Third, there are spatial and temporal issues of VWT in the study. The VWT could be affected by geopolitical issues such as
375 topography, and distances between importers and exporters. For example, the changes of exporting countries in the MENA
376 region could be related to energy use for transporting products, thus trade policy should consider the economic benefit or cost
377 of transportation. Therefore, the VWT should be discussed with geopolitical issues such as benefit and cost of transportation.
378 In addition, VWT and water-lands savings by food trade in this study were calculated based on historical database, thus it was
379 difficult to apply the results to future policy.

380 Despite these limitations, we believe that virtual water has a role in the achievement of sustainable water, land, and food
381 security, even if there are limitations and difficulties in applying the virtual water concept. As mentioned above, the VWT can
382 be a major resource in the MENA region. Accordingly, vulnerable VWT, for example, low connectivity, can be a risk element
383 for future food security risk management. In particular, the MENA region is strongly dependent on food products from
384 exporting countries ~~that~~which implies a strong dependency on water resource from exporting countries. Therefore, water
385 shortages or low-food production in exporting countries might cause increasing food prices in the MENA region, but also
386 increasing domestic water use for increasing domestic food production. The primary resources of water, energy and food are
387 naturally interlinked. The degree of their interlinkages in the MENA is exceptionally high, thus creating a higher degree of
388 risks and vulnerability. Therefore, understanding these interlinkages and quantifying them in an attempt to better understand
389 this complex system of systems is crucial. This requires the synergistic effort of multiple disciplines, including contributions
390 from various technologies, science, policies, health, communication, and economics, at local processes and system level scales.
391 In this study, we believe that the VWT in the MENA region can be the key factor for bridging water and food, and it is
392 important to quantify the influence of trade on water and food management. In addition, this study revealed vulnerability (or
393 robust) expansion (or reduction) and influential traders in the VWT network in the MENA region, based on in-degree and
394 eigenvector centrality indices. If a country in the MENA region has low connectivity but an increased import of virtual water,
395 this country should re-evaluate their vulnerable trade structure and change the trade policy or water-food management.

396 4. Conclusions

397 The import of water in virtual form based on VWT could develop into a major water portfolio that dominates water
398 management in the water-scarce countries of the MENA region. In water-deficit areas, such as the MENA region, the VWT
399 can offer new perspectives for understanding and solving water stress and scarcity. In summary, this study showed that the
400 significant water in comparison to internal water resource could be saved by food trade in the MENA region, and policy makers
401 can benefit by considering both the quantitative impacts of VWT and the structural changes of VWT, such as vulnerable
402 expansion (or reduction) in the MENA region. For example, when a country in the MENA region set a plan for increasing
403 food security, this country first should identify the amount of water and land savings that can be achieved by food import, and
404 consider the trade-off between food security and food import. In addition, the stable trade could be a component for stable
405 food supply in the MENA region, thus this study contributes to the understanding of the dependency on each trade partner for
406 countries in the MENA region and can help with setting the food trade policy in terms of extension (or reduction) of trade
407 partners and increase (or decrease) in volume of trade.

408 However, this study only focused on food trade and water-land savings, thus energy part was not considered. The MENA
409 region represents an extreme case globally in terms of water and energy resources, for example, 66% of the world's known
410 crude oil reserves, but only 1.4% of the world's fresh water supplies is attributed to the region (Khater, 2001). The increase or
411 decrease of water withdrawal for irrigation is related to the energy used for water extraction such as pumping surface or ground
412 water. For example, 5 % or more of the total electricity consumption can be attributed to water pumping in Saudi Arabia

413 (Siddiqi and Anadon, 2011). Energy use for food production and water supply could be the main factor in integrated resource
414 management in the MENA region, and the lack of energy part was a limitation in this study.
415 In spite of this limitation, the intensity and connectivity of VWT, which were analyzed in this study, can be the major
416 components needed for integrating resources management in the MENA region. Accordingly, VWT is regarded as the
417 important factor in determining food security and water-lands management, and it can be a useful interlinking parameter among
418 resources in WEF Nexus approach, which identify key issues in food, water, and energy securities through the lens of
419 sustainability, seeking to predict and protect against future risks and resource insecurities (Biggs et al., 2015). The core of the
420 Nexus concept is that the production, consumption, and distribution of water, energy, and food, are inextricably interlinked,
421 thus this study would provide important information to policy makers for evaluating scenarios about integrated resource
422 management toward sustainability in the MENA region.

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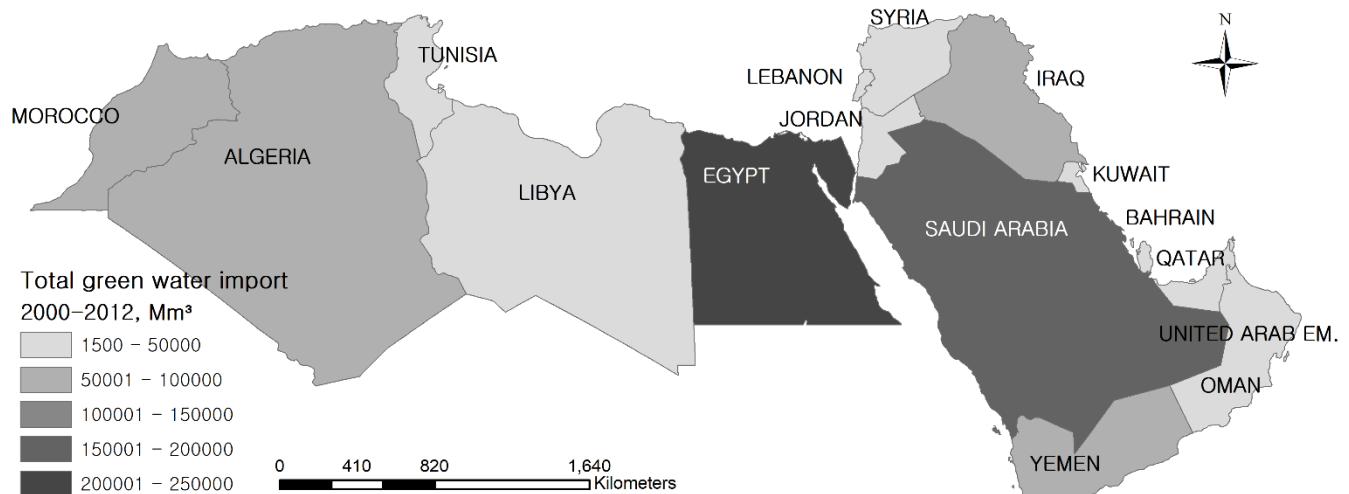
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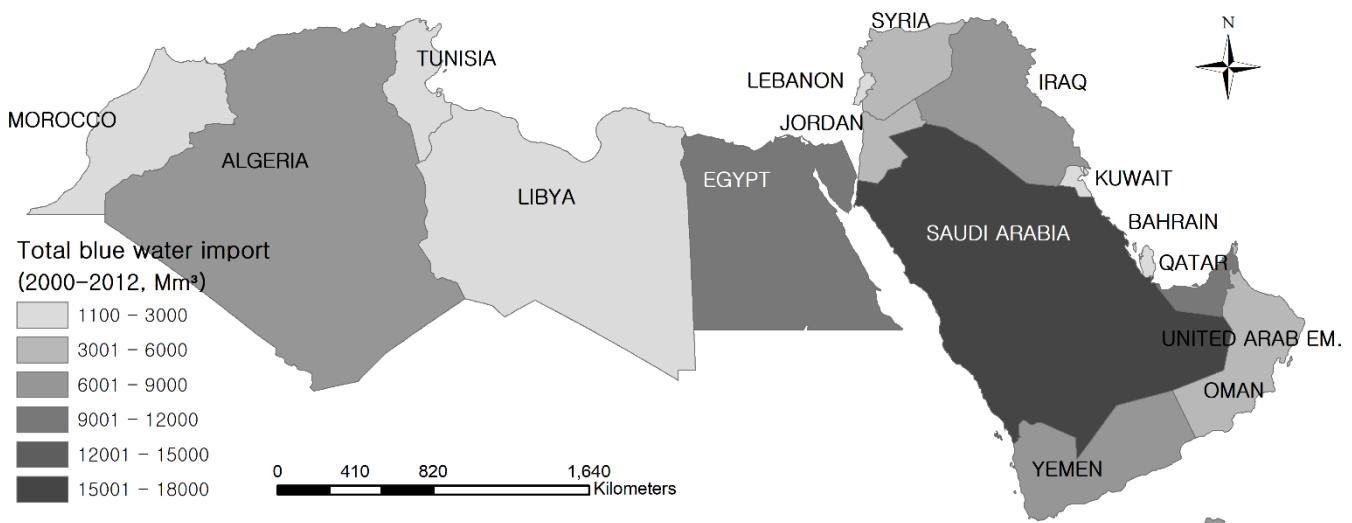
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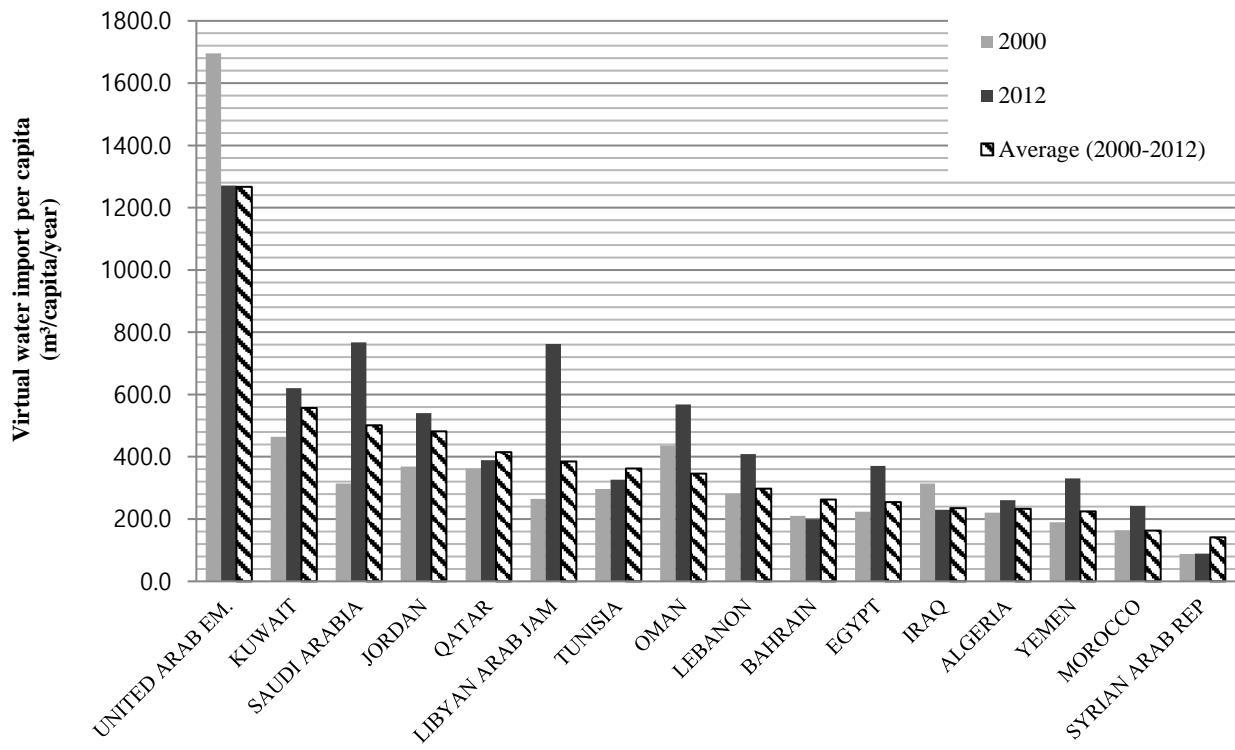


(a) Green water imports



(b) Blue water imports

Figure 1. Total amount of virtual water imported by each country in the MENA region from 2000 to 2012 classified into green (upper) and blue (lower) water

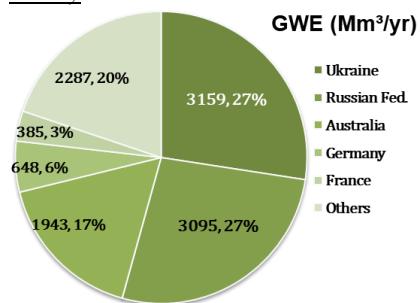
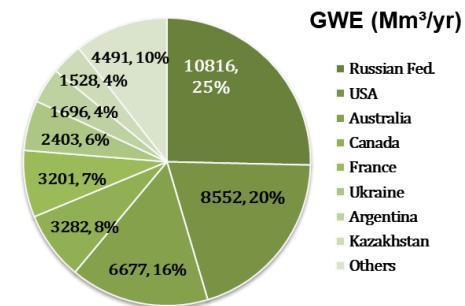
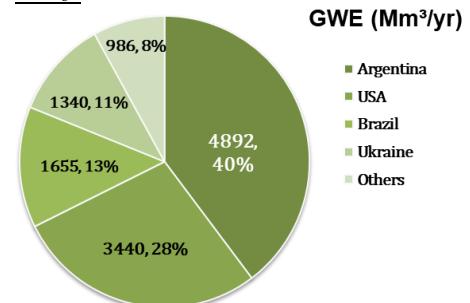
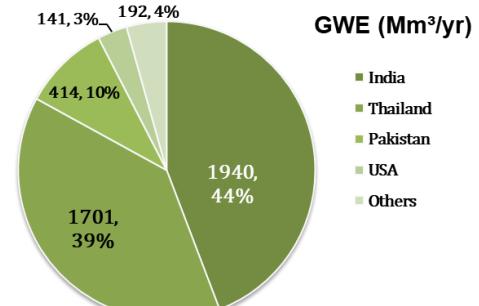


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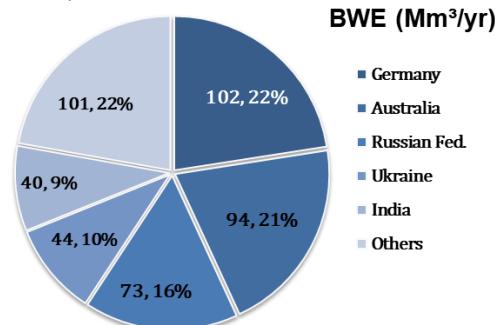
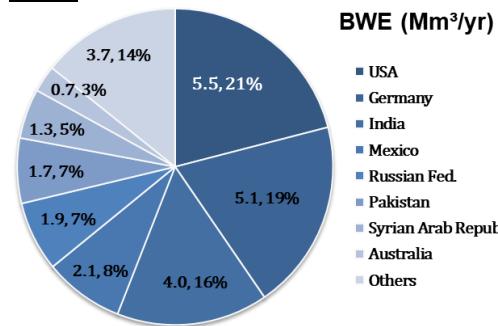
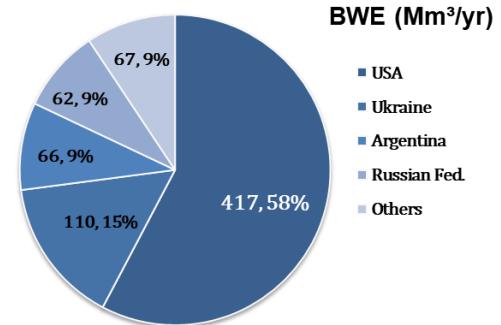
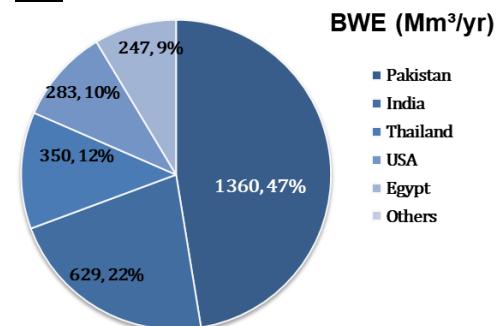
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Figure 2. Virtual water imported per capita in the MENA region from 2000 to 2012

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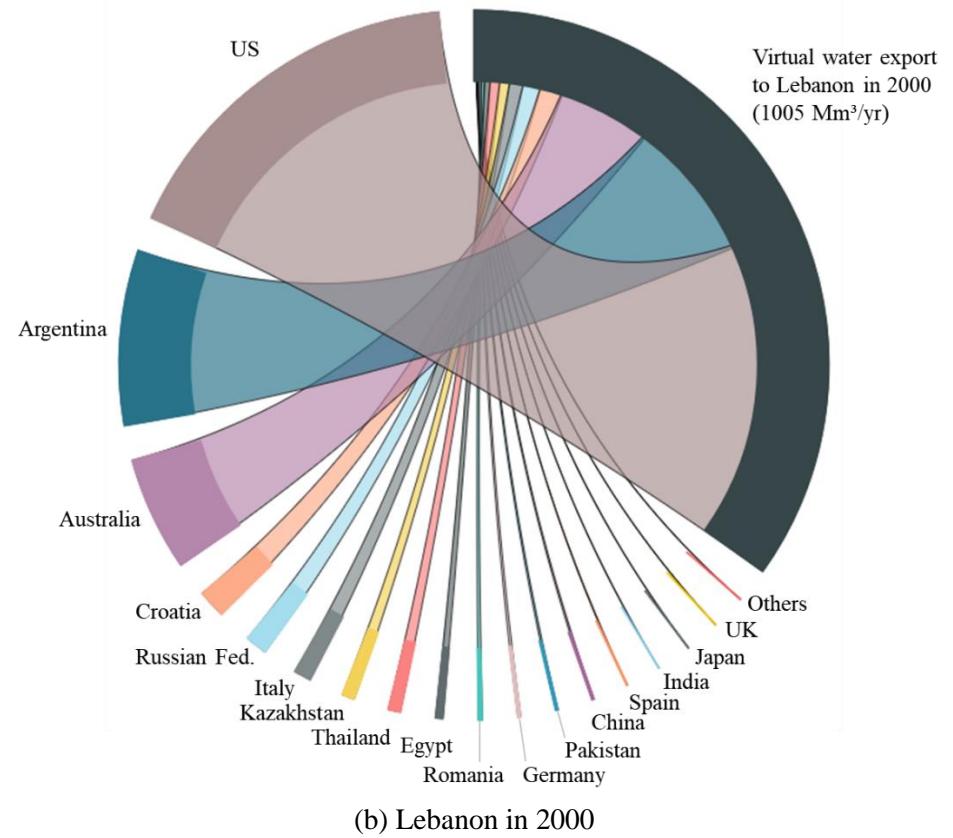
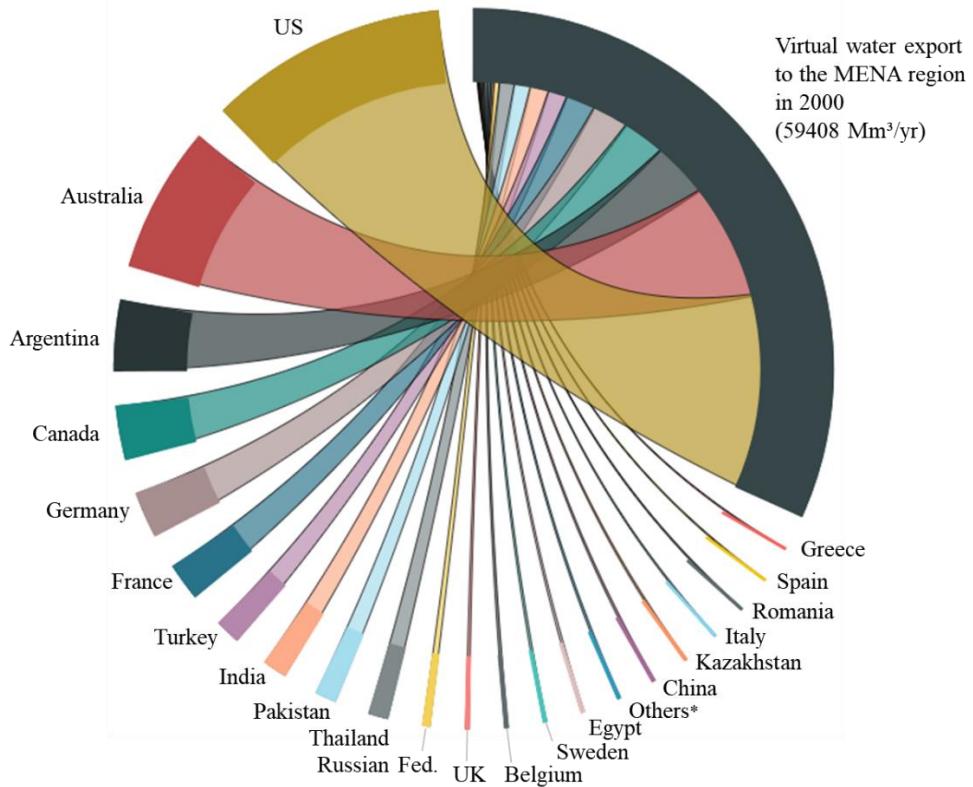
BarleyWheatMaizeRice

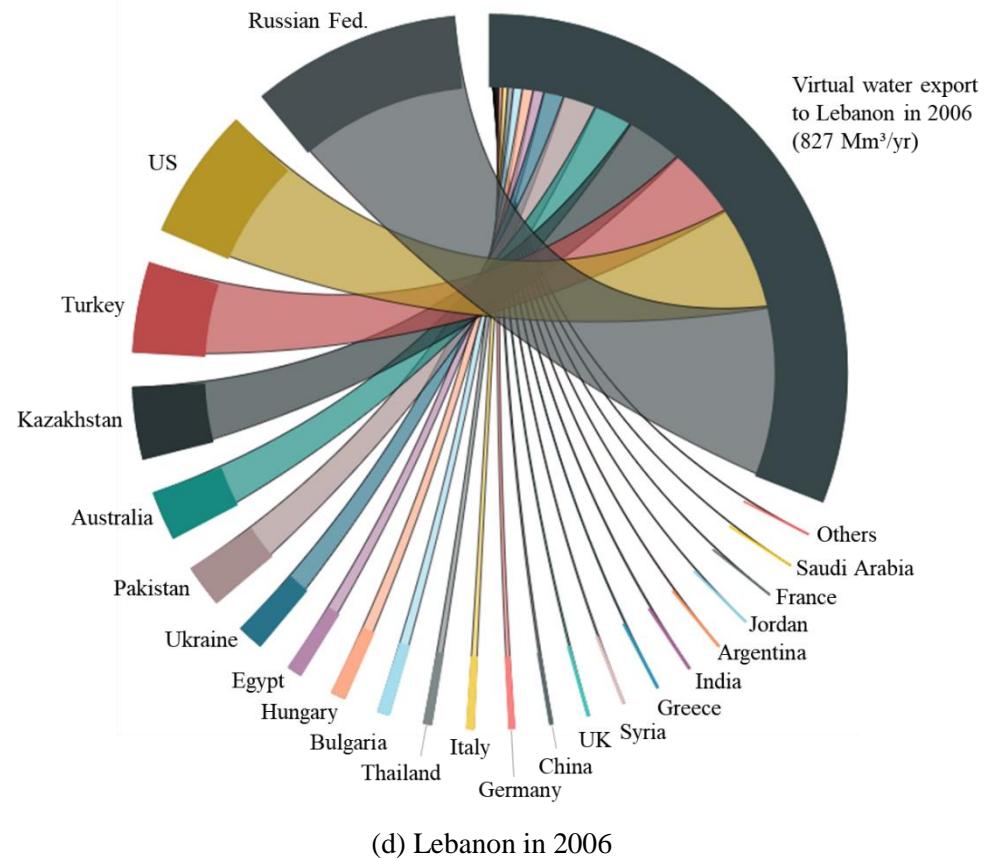
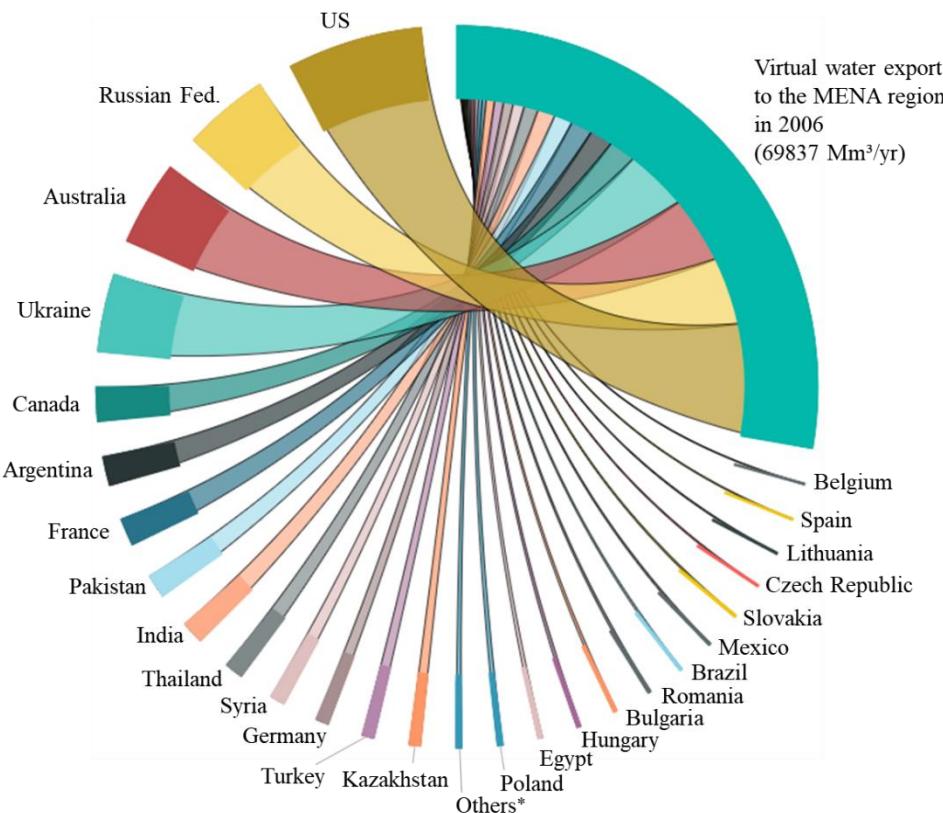
(a) Annual green water export (GWE) during 2000-2012

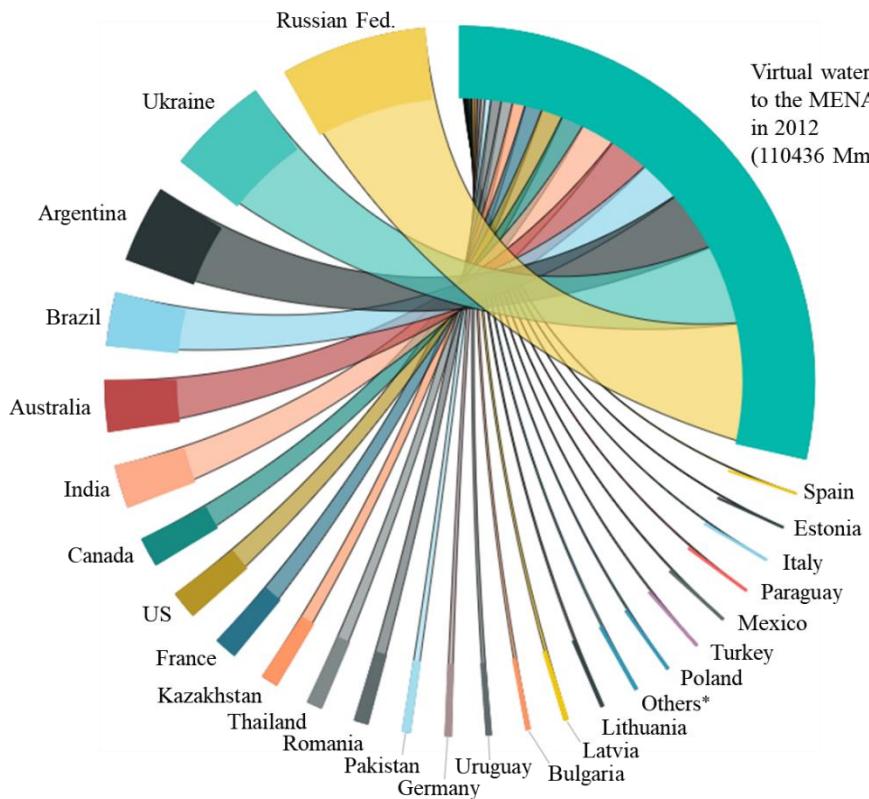
BarleyWheatMaizeRice

(b) Annual blue water export (BWE) during 2000-2012

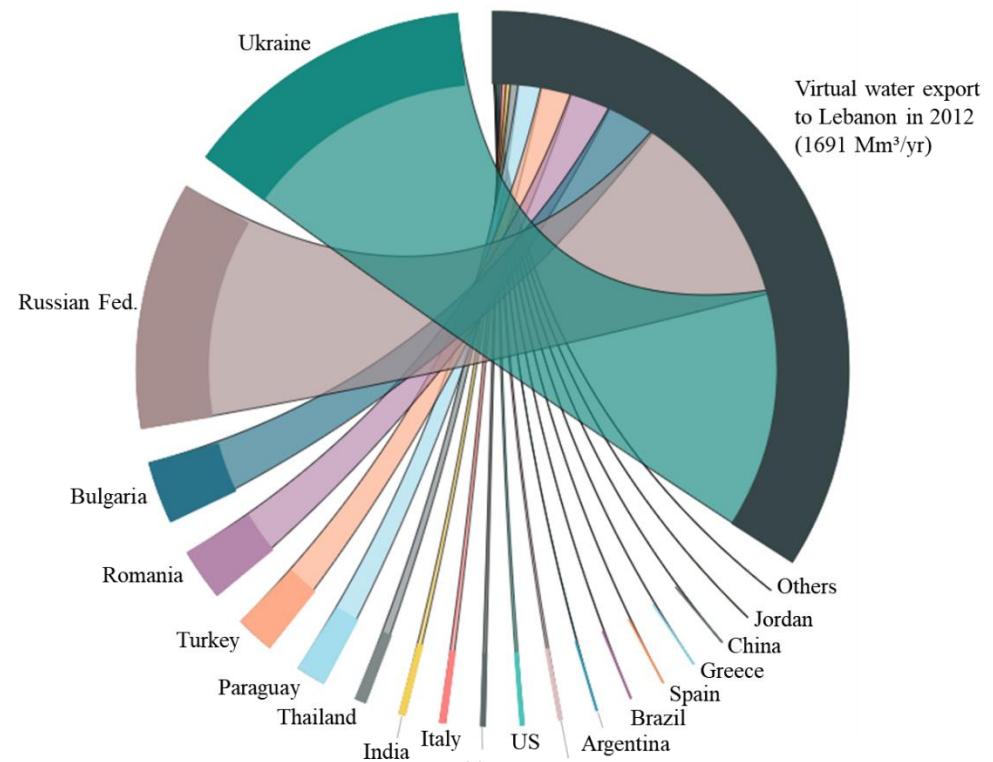
Figure 3. Quantities of annual green water exports (GWE) and blue water exports (BWE) from the primary exporters to the MENA region from 2000 to 2012







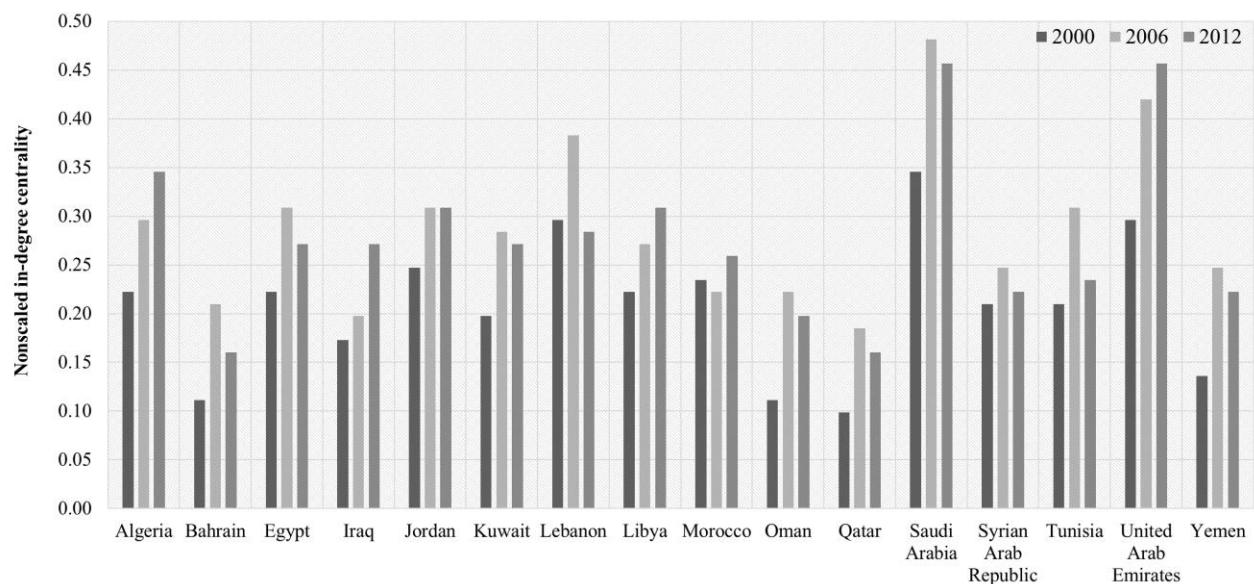
(e) MENA region in 2012



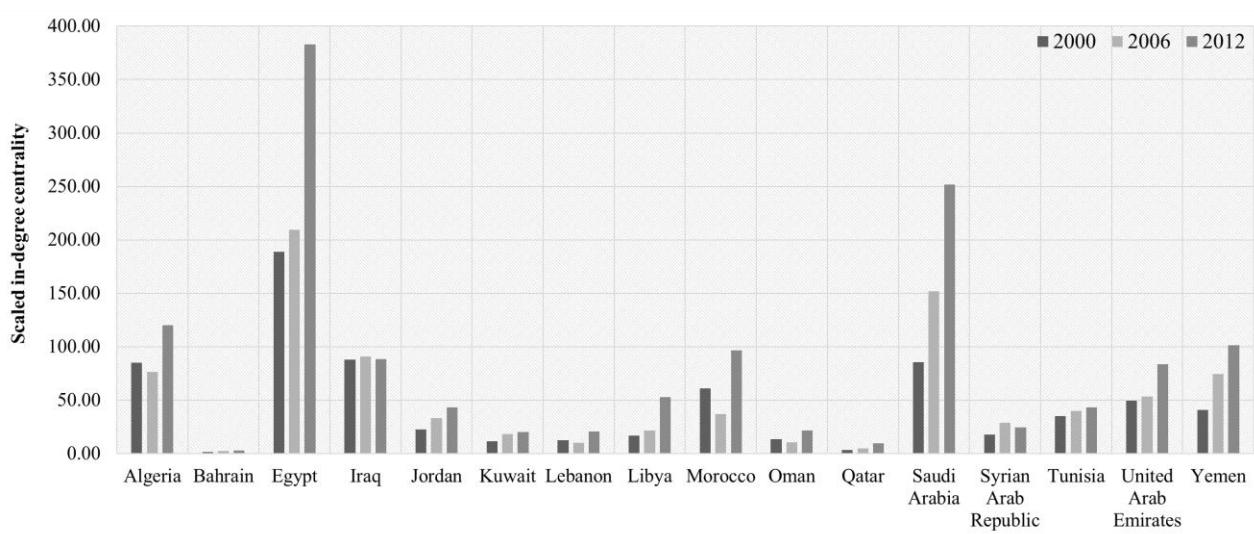
(f) Lebanon in 2012

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Figure 4. Virtual water imports from exporters to at the MENA region and Lebanon in 2000, 2006, and 2012. Others indicate the countries who export less than 100 Mm³/yr to the MENA region or Lebanon

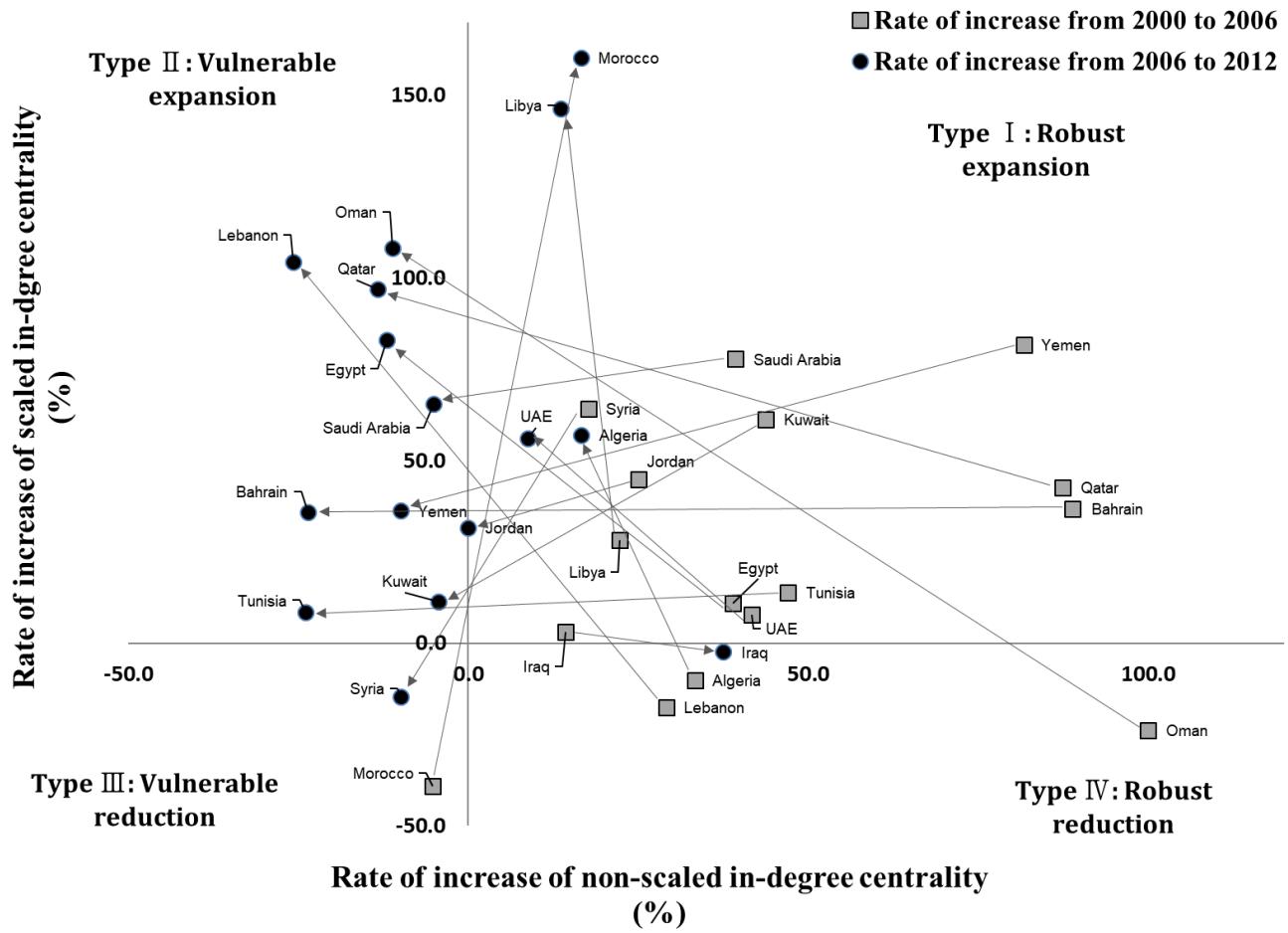


(a) Nonscaled in-degree centrality



(b) Scaled in-degree centrality

Figure 5. Nonscaled and scaled in-degree centralities of each country in the MENA region in 2000, 2006, and 2012



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Figure 6. Country types in the MENA region according to the changes of nonscaled and scaled in-degree centralities

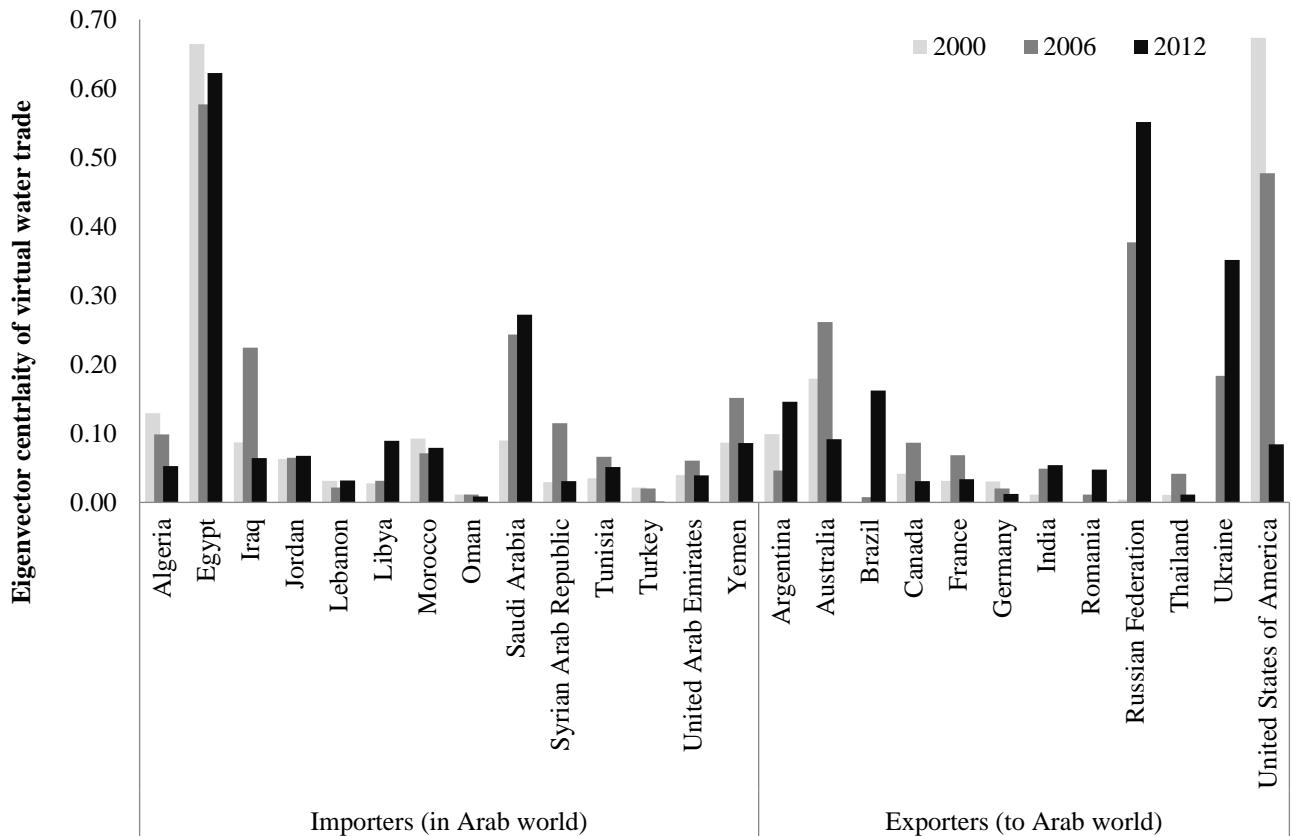


Figure 7. Eigenvector centralities of the virtual water trade network in the MENA region in 2000, 2006, and 2012

Table 1. Cultivation area, production, and the quantity of crops imported in the MENA region from 2000 to 2012

Countries in the MENA region	Cultivation area (ha/year)*					Production (ton/year)*					Import (ton/year)*					Internal water resource (10 ⁹ m ³ /year)**
	Barley	Maize	Wheat	Rice	Sum	Barley	Maize	Wheat	Rice	Sum	Barley	Maize	Wheat	Rice	Sum	
ALGERIA	760,545	308	1,658,197	-	2,419,050	1,049,710	1,128	2,313,464	-	3,364,302	233,887	2,112,527	5,363,580	47,080	7,757,074	11.25
EGYPT	68,103	876,153	1,180,644	625,626	2,750,526	134,034	6,812,845	7,549,253	6,023,684	20,519,816	24,805	5,073,779	8,295,988	46,292	13,440,864	1.80
IRAQ	914,074	128,842	1,451,219	85,182	2,579,317	751,099	307,682	2,009,972	232,040	3,300,793	35,378	18,960	2,545,919	742,394	3,342,651	35.20
JORDAN	31,158	947	20,116	-	52,221	22,757	17,514	23,379	-	63,650	487,593	385,936	792,508	137,442	1,803,479	0.68
KUWAIT	1,058	290	173	-	1,521	2,191	5,855	345	-	8,391	178,432	134,373	284,684	171,451	768,940	-
LEBANON	13,515	949	45,380	-	59,844	24,834	3,579	126,623	-	155,036	49,278	289,707	367,370	46,087	752,442	4.80
LIBYA	191,641	1,356	165,469	-	358,466	94,107	2,997	128,149	-	225,253	226,317	429,407	803,545	122,579	1,581,848	0.70
MOROCCO	2,118,032	226903	2,910,977	5,876	5,261,788	1,867,670	159,127	4,200,596	36,936	6,264,329	392,639	1,446,836	2,994,446	13,307	4,847,228	29.00
OMAN	1,002	-	426	-	1,428	3,027	-	1,432	-	4,459	35,829	99,525	288,134	118,802	542,290	1.40
QATAR	947	94	15	-	1,056	2,841	1,329	34	-	4,204	33,286	3,914	47,798	87,312	172,310	0.06
SAUDI ARABIA	12,279	16,689	374,414	-	403,382	68,366	86,181	1,997,598	-	2,152,145	6,252,893	1,600,081	700,703	1,009,384	9,563,061	2.40
SYRIA	1,313,101	53,405	1,667,229	-	3,033,735	817,609	211,675	4,008,420	-	5,037,704	393,029	1,319,461	454,904	201,690	2,369,084	7.13
TUNISIA	385,189	-	722,038	-	1,107,227	411,431	-	1,302,438	-	1,713,869	407,455	737,754	1,525,848	17,453	2,688,510	4.20
UAE	14	144	18	-	176	111	2,931	74	-	3,116	215,321	399,987	1,063,996	683,336	2,362,640	0.15
YEMEN	39,276	40,774	110,138	-	190,188	32,248	57,329	173,437	-	263,014	2,845	343,919	2,096,970	279,136	2,722,870	2.10

* Average value from 2000 to 2012 provided from FAOSTAT (<http://www.fao.org/faostat/>)** Average value from 2000 to 2012 provided from World Bank (<https://data.worldbank.org/>)

Table 2. Water and land footprints of four major crops in the MENA region

Countries in the MENA region	Water footprint (m ³ /ton)*								Land footprint (ha/ton)**			
	Barley		Maize		Wheat		Rice		Barley	Maize	Wheat	Rice
	Green water footprint	Blue water footprint	Green water footprint	Blue water footprint	Green water footprint	Blue water footprint	Green water footprint	Blue water footprint				
ALGERIA	2859.0	-	964.1	-	3290.0	65.2	1080.8	-	0.72	0.27	0.72	-
EGYPT	619.2	1694.7	140.8	1078.2	214.8	903.5	59.0	1003.1	0.51	0.13	0.16	0.10
IRAQ	3459.7	4321.4	587.3	1812.2	3069.2	2818.3	256.2	6574.7	1.22	0.42	0.72	0.37
JORDAN	3167.8	320.3	126.6	-	2267.0	988.7	-	-	1.37	0.05	0.86	-
KUWAIT	929.3	2256.3	41.2	207.9	955.4	2287.7	-	-	0.48	0.05	0.50	-
LEBANON	1919.9	-	507.6	14.4	1556.0	97.0	-	-	0.54	0.27	0.36	-
LIBYA	6417.6	1808.2	1151.1	-	4360.2	1542.9	-	-	2.04	0.45	1.29	-
MOROCCO	3692.3	-	3541.0	3182.9	2758.0	244.6	293.0	1278.0	1.13	1.43	0.69	0.16
OMAN	322.9	2336.2	-	-	842.4	1938.5	-	-	0.33	-	0.30	-
QATAR	485.6	1714.3	78.5	502.9	678.6	1626.3	-	-	0.33	0.07	0.44	-
SAUDI ARABIA	193.6	799.8	366.6	1270.1	238.4	1093.2	-	-	0.18	0.19	0.19	-
SYRIA	5084.0	41.6	347.3	1573.4	1454.2	440.1	273.2	-	1.61	0.25	0.42	-
TUNISIA	3561.1	75.1	-	-	2375.0	71.8	-	-	0.94	-	0.55	-
UAE	-	-	-	-	1563.5	507.7	-	-	0.13	0.05	0.24	-
YEMEN	1904.6	3234.4	1726.2	2950.8	1804.4	2355.5	-	-	1.22	0.71	0.64	-

* Water footprint data was referenced by Mekonnen and Hoekstra (2010)

** Land footprint was calculated by crop production and cultivated area provided from World Bank open data (<https://data.worldbank.org/>)

Table 3. The annual water and land savings based on imported crops in the MENA region from 2000 to 2012

Countries in the MENA region	Water savings (million m ³ /year)						Land savings (thousand ha/year)		
	Barley		Maize		Wheat		Barley	Maize	Wheat
	Green water	Blue water	Green water	Blue water	Green water	Blue water			
ALGERIA	669.0	-	2,037.2	-	17,647.6	349.9	169.5	577.0	3,844.7
EGYPT	15.5	42.4	714.3	5,470.5	1,781.9	7,495.6	12.7	652.5	1,297.4
IRAQ	121.1	151.3	11.2	34.4	7,814.1	7,175.5	42.6	8.0	1,838.2
JORDAN	1,545.9	156.3	48.9	-	1,797.7	784.0	668.2	20.9	682.3
KUWAIT	165.4	401.6	5.5	27.9	272.3	652.0	86.0	6.6	142.9
LEBANON	94.1	0.0	147.2	4.2	571.0	35.6	26.7	76.9	131.5
LIBYA	1,450.4	408.6	493.8	-	3,505.6	1,240.5	460.2	194.1	1,038.1
MOROCCO	1,451.1	-	5,123.8	4,605.6	8,257.3	732.3	445.7	2,063.3	2,074.8
OMAN	11.6	84.1	-	-	242.6	558.3	11.9	-	85.7
QATAR	16.0	56.6	0.3	2.0	32.6	78.1	11.0	0.3	21.2
SAUDI ARABIA	1,210.5	5,001.5	586.5	2,032.1	167.1	766.3	1,123.1	309.8	131.4
SYRIA	1,998.0	16.3	458.1	2,075.3	661.6	200.3	631.2	332.8	189.2
TUNISIA	1,449.4	30.5	-	-	3,624.2	109.6	381.0	-	846.0
UAE	-	-	-	-	1,663.6	540.2	27.1	19.7	258.8
YEMEN	5.7	9.7	593.8	1,015.1	3,783.8	4,939.4	3.7	244.7	1,331.7

* Water and land savings by rice import was not calculated because of the lack of the data of water and land footprints in the MENA region

Table 4. The amounts of green and blue water imported in the MENA region from 2000 to 2012

Countries in the MENA region	Import of green water (million m ³ /year)					Import of blue water (million m ³ /year)				
	Barley	Maize	Wheat	Rice	Total	Barley	Maize	Wheat	Rice	Total
ALGERIA	242.0	1,883.6	5,104.8	57.8	7,288.2	7.8	76.6	371.1	33.5	489.0
BAHRAIN	0.4	7.5	62.7	44.4	115.0	0.2	0.3	7.1	78.2	85.8
EGYPT	37.3	3,798.4	15,254.1	58.4	19,148.2	1.1	295.6	418.6	32.5	747.8
IRAQ	33.2	16.7	4,645.8	1,027.8	5,723.5	2.2	1.3	153.9	404.8	562.2
JORDAN	656.8	364.2	1,483.9	81.2	2,586.1	20.8	20.8	84.5	115.0	241.1
KUWAIT	257.0	159.1	557.7	211.6	1,185.4	9.7	2.3	10.2	138.1	160.3
LEBANON	84.7	211.0	749.5	30.0	1,075.2	2.3	25.6	18.9	36.0	82.8
LIBYA	359.6	408.9	1,245.4	56.0	2,069.9	8.4	26.8	75.3	99.7	210.2
MOROCCO	318.6	1,383.2	3,345.0	8.9	5,055.7	12.1	46.1	118.8	20.4	197.4
OMAN	52.7	123.2	470.8	107.6	754.3	5.4	4.1	67.8	201.3	278.6
QATAR	50.9	6.4	76.4	77.6	211.3	2.4	0.3	19.1	146.9	168.7
SAUDI ARABIA	8,154.5	1,521.4	974.0	1,225.9	11,875.8	324.3	68.9	70.8	696.0	1,160.0
SYRIA	556.4	947.3	900.0	120.8	2,524.5	12.8	90.2	17.8	165.6	286.4
TUNISIA	409.8	611.7	2,507.7	27.8	3,557.0	16.0	40.7	73.9	11.6	142.2
UAE	315.7	465.8	1,671.8	859.5	3,312.8	28.5	14.3	249.3	612.5	904.6
YEMEN	3.1	406.1	3,597.3	392.7	4,399.2	1.6	8.2	247.3	220.8	477.9