Sustainable Virtual Water Transfers: A Comparative Assessment of the Topical Condition of Water Scarcity and Water Savings in Africa

H. Hirwa[1,2], Y. Peng[1,2], Q. Zhang[3], Y. Qiao[1,2], P. Leng[1,2], C. Tian[1], G. Yang[4], F. Muhirwa[2,5], S. Diop[6], A. Kayiranga[2,7], F. Li[1,2,4 *]

[1] State Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[2] University of Chinese Academy of Sciences, Beijing 100049, China

[3] Chinese Research Academy of Environmental Sciences, Beijing 100012, China

[4] College of Water and Architectural Engineering, Shihezi University, Shihezi, 832003 China

[5] Key Laboratory for Resources Use and Environmental Remediation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[6] National Academy of Sciences of Senegal, P.O. Box 4344 Dakar, Senegal

[7] State Key Laboratory of Resource and Environmental Information, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[*] Corresponding author: Fadong Li (lifadong@igsnrr.ac.cn)

Key Points:

- Africa's virtual water transfers, water scarcity, and water savings/losses assessed.
- Virtual water trade relied on population, GDP, crop production, and arable land.
- Southern African countries showed a high net virtual water export in Africa.
- Global water loss of 2820.7 km^3/a from the trade of major grains in Africa.

Abstract

Humanity is facing an increasing challenge with respect to water scarcity (WS). This issue is driven by climate change, population growth, and socioeconomic growth combined with inadequate water resources management. In particular, there is considerable concern over virtual water (VW) transfers, which pose difficulties for water resources and food security sustainability. In this study, we assessed the i) VW content of crops, ii) VW flows, iii) WS, iv) water dependency (WD), v) water self-sufficiency, and vi) water savings/losses in African countries at different time series. We also addressed censorious issues and challenges for sustainable development in water-scarce regions. The results showed that the average net VW import was positive (108.9×10^9 m^3/a). The WS values for East African countries were > 100, indicating overexploitation. In addition, the overall WD in Africa was 4655% in recent years. The trade of main grains between Africa and the rest of the planet corresponded to a global water loss of 2820.7×10^9 m^3/a. However, a shift was observed in the ranking of commodities imported from one region to another owing to the evolution of a country's economic development. The VW export of a country depended on the population size, gross domestic product, agricultural production, and area of arable land. Finally, we highlight opportunities for enhancing water use efficiency by increasing food production in water-scarce regions, thereby contributing to the achievement of Sustainable Development Goals.

Keywords: virtual water; water footprint; water scarcity; water dependency; sustainable development; Africa

Plain Language Summary

Our study assesses the interlinkages between virtual water transfers, water security, and water savings, and provides clear implications for optimal water use and sustainable agriculture. Virtual water denotes the water that is required to produce food, fiber, and non-food products, as well as the related energy and services. We believe that our study makes a significant contribution to the literature because the results showed that the trade of main grains between Africa and the rest of the world corresponded to a global water loss of 2820.7 × 10^9 m^3/a. In addition, the average net virtual water import was positive (108.9 × 10^9 m^3/a). Some opportunities to improve water use efficiency with increased food production in water-scarce regions are illustrated in effective ways to achieve Sustainable Development Goals, we need for all.

1. Introduction

Virtual water (VW) is embodied in traded commodities (J. A. Allan, 2003) and is required for producing food, fiber, and non-food products, as well as for the related energy and services (J.A. Allan, 1998; Antonelli & Sartori, 2015; D'Odorico et al., 2019; Gawel & Bernsen, 2013; Mayer et al., 2016; Tian et al., 2018; Yang & Zehnder, 2007); thus, VW is quite complex and unequally distributed globally (Buytaert & De Bièvre, 2012). Although VW is a key component of, and limiting to, production, it remains a neglected and hidden aspect of water resource management (Lillywhite, 2010; Zwane, 2019). Several water-scarce regions are unable to meet their domestic food demand locally and tend to import food from other nations (Godfray et al., 2010; Oki et al., 2017). Moreover, water scarcity (WS) and water stress (i.e., water resource challenges) are among the major global issues that adversely affect countries' sustainable development. These issues could induce poor health, low productivity, food insecurity, and constrained socioeconomic growth. Accordingly, Africa should adopt novel management techniques for water resources to enhance its equitable, efficient, and sustainable use of water in the future.

Africa currently holds approximately 16% of the world's population, which equates to ~1.2×10^9 people. This is expected to increase to > 10^{10} people by 2050; therefore, global food production will need to expand by between ~70% and > 100% by 2050 (World Bank, 2020). A recent study by Ritchie and Roser (2017) indicated that 85%, 10%, and 20% of water resources are for agriculture, community water supply, and industrial purposes, respectively. Water withdrawals include those from rainfall and internal renewable water resources. As Africa accounts 9% of the world's freshwater, this resource could play a vital role in responding to Africa's socioeconomic crisis. To achieve the associated Sustainable Development Goals (SDGs) of the United Nations, particularly SDG 2 (zero hunger), SDG 6 (availability and sustainable management of water and sanitation), SDG 13 (climate action), and SDG 15 (sustainable use of ecosystem services), there is a need for institutional and financial arrangements, adequate data, infrastructures, and innovative technologies to cope with the water crisis (Garrick et al., 2020).

Meanwhile, the issue of WS could be tackled by i) enhancing international trade (i.e., exports and imports of goods and services between regions), ii) developing food trade(A. Hoekstra, 2010; Tian et al., 2018), iii) globalizing water flows (Friel et al., 2020), and iv) supporting crop growth at the national level in line with the water footprint (WF) (Rockström et al., 2014). The significant limitations of VW trade (VWT) include high food consumption, inappropriate agricultural practices (in compliance with water use efficiency principles), and unfavorable climate change, thus causing a decline in crop productivity in arid and semiarid regions of Africa.

Water accessibility for farmers is limited both temporally (i.e., droughts and dry seasons) and spatially (e.g., arid and semiarid regions). The linkages between energy inputs and yields are not linearly correlated and are considered as a blockade to agricultural production, thus leading to ever-smaller yield gains (Woods et al., 2010). These factors contribute to a high VW import (VWI) and WF in countries such as Senegal, Mali, Sudan, and Chad (Arjen Y Hoekstra & Chapagain, 2006). The VW used by a business for production must be less than the total available VW (Stefania Tamea et al., 2016). Although an increased crop water use efficiency can be correlated with increased crop exports in some cases, this is not the case for Africa. Moreover, it is not yet clear how African nations will regulate the export–import balance between sectors (Carr et al., 2013). Understanding VW transfers, WS, and water savings could potentially serve as a tool for optimal water use and food security; however, this assumption still needs to be verified for Africa.

After the introduction of VW and WF concepts, pioneering studies were undertaken in various parts of the world for various products using different methodologies at different temporal and spatial scales. Related studies have been performed on a global basis (D'Odorico et al., 2014; D'Odorico et al., 2019; Dalin et al., 2012), on a regional or national basis (Abdelkader et al., 2018; Dalin & Conway, 2016; Hanna, 2020; Konar & Caylor, 2013), in specific cities (Akoto-Danso et al., 2019), and from crop production and product perspectives (Dabrowski et al., 2009; Fair et al., 2017). Some countries now consider the notion of VW and WF to be important and have begun extensive studies (e.g., in China, India, Germany, and the United States of America) (Brindha, 2020; Han et al., 2017; Katyaini & Barua, 2017). Notably, findings have shown that Asia and Africa are net importers of VW, representing 46% of the total imported VW. Africa lags behind Asia, with values equal to 1.1 m^3/capita/d (Zimmer & Renault, 2003). At present, there is a lack of information and no reported research on VW budgets in terms of VW transfers, WS, water savings, and the related implications for water use efficiency in Africa.

This study aims to i) assess the interlinkages between VW transfers, WS, and water savings, and ii) provide clear implications for optimal water use and sustainable agriculture. The results are expected to contribute considerably to the existing body of knowledge. The standard calculation methods proposed by (Arjen Y Hoekstra et al., 2011) were employed, and both direct and indirect water use by consumers and producers led to several clear outcomes (Dalin et al., 2014). In addition, the approach described by (S Tamea et al., 2014) was used to analyze the driving factors underlying the net VW fluxes.

At present, the VW transfer, WS, and water savings associated with crop products in Africa have been under-researched. To the best of our knowledge, this paper is the first to present a comprehensive, in-depth assessment that entails insights for integrated and adequate policy development with respect to water and agricultural, thus contributing to the achievement of SDGs. This study also focuses on the primary agricultural products traded within Africa and the rest of the world (ROW) over different timespans. It is essential to understand the VW trends of major crops, driving forces of VW flows, WS status, water dependency (WD), water self-sufficiency, and water savings/losses with respect to the policy reforms established for a given period. Accordingly, we seek to address these issues by 1) estimating how much VW is associated with the major grains of Africa, 2) determining the driving forces of VW flows in Africa, and 3) assessing whether water savings/losses matter for VW transfer in Africa. Finally, we highlight the current and future policies that should help governments uphold sustainable water resource management principles.

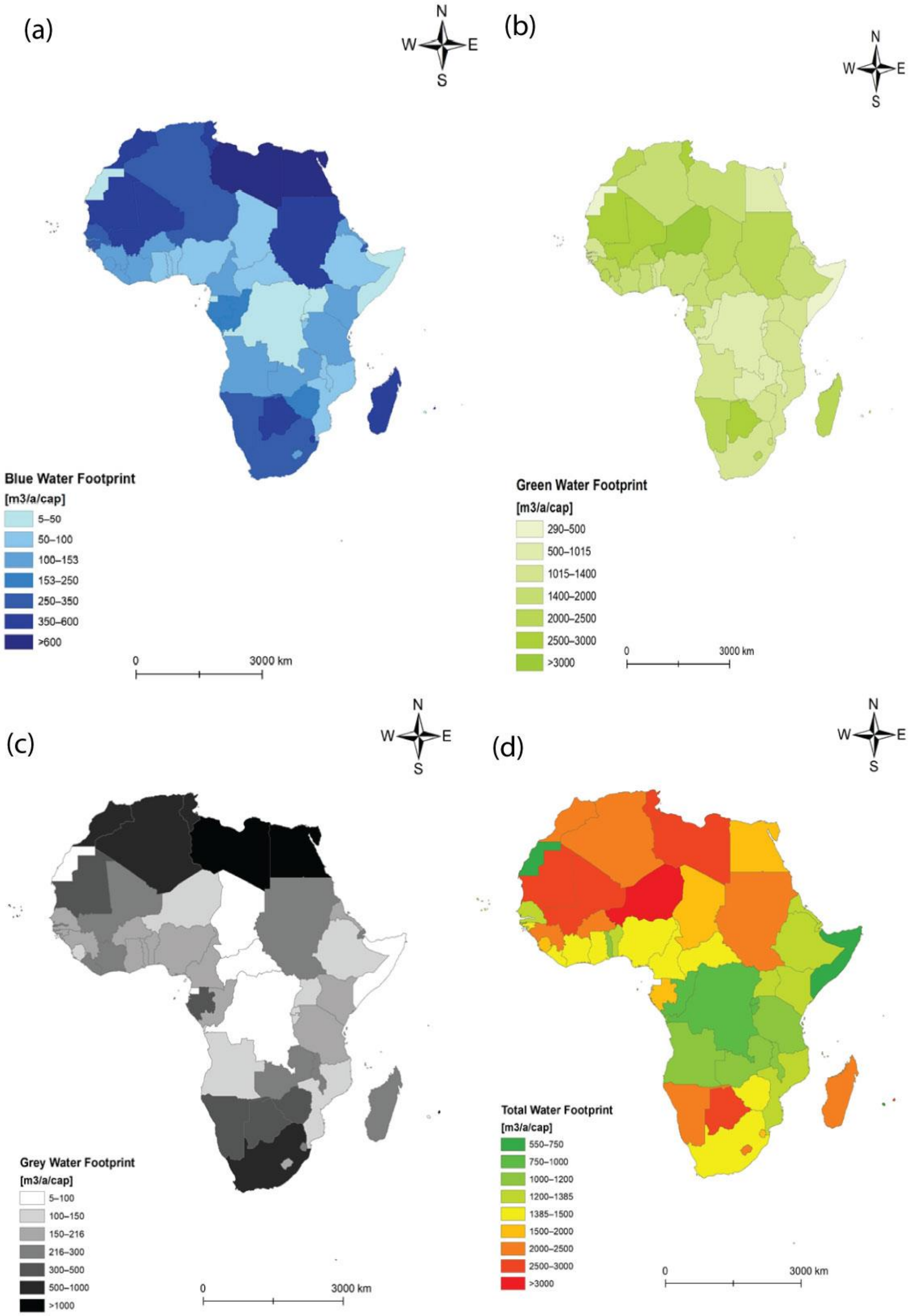
This paper is organized into six sections: after this introduction, Section 2 describes the study area, data utilized and methodologies applied in the study. Section 3, presents the findings of the analysis. This is followed by Section 4, which discusses the main results and limitations of the study. Section 5 highlights the future outlook in relation to policy implications for Africa's water resources management. Lastly, Section 6 concludes the study.

2. Materials and Methods

2.1. Study area

The present study considers Africa as a continent comprising 53 countries (total area of 30 370 000 km^2), which can be categorized into five climate zones: equatorial, humid tropical, semi-desert (e.g., Sahelian), Mediterranean, and desert climates (e.g., Sahara, Kalahari, and Namib) (Griffiths, 1958). Africa has abundant water resources, including ~17 major rivers, 160 large lakes (covering an area of > 27 km^2), vast wetlands (~131 × 10^6 ha), and limited but widespread groundwater (McClain, 2013). The latter accounts for just ~15% of the continent's total renewable water resources (Kharraz et al., 2012). In addition, rainfall varies spatially and temporally, with the highest annual rainfall occurring in the island countries (~1700 mm), Central Africa (~1430 mm), the Gulf of Guinea (~1407 mm), and the northern region (~71 mm) (Besada & Werner, 2015). Some African countries have WFs that greatly exceed the global average per capita WF of 1385 m^3/a, for example, such as Algeria, Libya, Mauritania, Mali, and Tunisia, whereas other countries have a below average WF such as Democratic Republic of Congo, Rwanda, and Burundi (Figure 1).

Africa's drylands cover 60% of the land surface area (Fadli et al., 2013; NGS, 2013), and soil water emerges as the dominant driver of ecosystem changes and food production. For instance, arid and semiarid areas of the Sahel, East Africa, and South Africa are characterized by a deficient organic matter content and clay content, which result in a low available water capacity (Walker, 2016; Wei et al., 2019). Approximately 16% of the land in Africa has high quality soil, and ~13% of the land has medium quality soil. Owing to the uneven distribution of water and largely poor soil quality, 55% of the land in Africa is unsuitable for agriculture. These regions have constraints on sustainable agriculture; nearly 30% of the population (~250 $\times 10^6$ people) either lives in these regions and/or is dependent on these land resources. In addition, 9×10^6 km^2 of land in Africa currently supports approximately 45% of the population (1.2×10^9 people) (Bationo et al., 2006; Nkonya et al., 2016). The African continent has ~296×10^6 ha of net cropland (260×10^6 ha of cultivated land and 36×10^6 ha of fallow land) and 330×10^6 ha of gross cropland. During 2014, the cultivated area of net cropland was 260×10^6 ha, of which 236×10^6 ha (90.6%) was rainfed and 24×10^6 ha (9.4%) was irrigated (Xiong et al., 2017). Chamberlin et al. (2014) reported that Africa has 52% of the remaining arable land in the world, most of which is in Algeria, the Democratic Republic of the Congo, Ethiopia, Morocco, Nigeria, South Africa, the Sudan, and Uganda.


(a)
N
W
E
S
Blue Water Footprint
[m3/a/cap]
5–50
50–100
100–153
153–250
250–350
350–600
>600
0
3000 km
(b)
Green Water Footprint
[m3/a/cap]
290–500
500–1015
1015–1400
1400–2000
2000–2500
2500–3000
>3000
(c)
Grey Water Footprint
[m3/a/cap]
5–100
100–150
150–216
216–300
300–500
500–1000
>1000
(d)
Total Water Footprint
[m3/a/cap]
550–750
750–1000
1000–1200
1200–1385
1385–1500
1500–2000
2000–2500
2500–3000
>3000

177

Figure 1. Spatial distribution of (a) blue, (b) green, (c) grey, and (d) total water footprints within Africa (1996–2005). Data extracted from Mekonnen and Hoekstra (2011).

2.2. Methods

Countries were selected based on their regional economic communities (RECs). This work is limited to four RECs: The East African Community (EAC), the Economic Community of West African States (ECOWAS), the Southern African Development Community (SADC), and the Union of Arab Maghreb (UMA). We selected 37 countries. Some countries are members of more than two RECs, for example, Tanzania. The data are available for different timeseries. The type of data, data sources, and input data used in this assessment are summarized in Table 1.

Table 1.

Types of data used and their sources.

Type of data	Source	Data input	Unit	Period	Data availability
Trade data	ChathamHouse (2018)	Agricultural products (i.e., maize, wheat, rice, and soybean)	kg	2000–2018	Chatham House Resource Trade Database, UN COMTRADE, and World Bank
Agricultural data	FAO (2020)	Crop yield (Y)	t	2012–2018	FAOSTAT Database
Water resources data	FAO (2016)	Total internal renewable water resources	m^3/a	2012–2018	AQUASTAT Database
Climate data	Antonio and Robert (2019)	Average annual evapotranspiration (PET)	mm/a	2012–2018	Global Aridity and Potential Evapotransipara tion (ET0) climate database v2
Driving forces	World Bank				World Bank

	(2019)	Population	inhabitants	2000–2018	Databank
		Gross domestic product (GDP) per capita	Constant US$	2000–2018	
		Crop production	t	2000–2018	
		Arable land	% of land area	2000–2016	

Source: Elaborated by the author

In addition, we selected four staple food crops (raw major grains) for the assessment (Table 2). Most staple food crops are classified as strategic agricultural products because of their high VW consumption and increased trading activity, which lead to a high water consumption (through irrigation) and high economic value in the world market (e.g., 125–240 US$/t), respectively. For example, rice, wheat, maize, and soybean use 21%, 12%, 9%, and 4% of global water respectively as agricultural crops (Delpasand et al., 2020; Arjen Y Hoekstra & Chapagain, 2011). Despite the above criteria, the selected crops revealed a high increase in production over the past three decades; rice, wheat, maize, and soybean accounted for 7.1%, 3.5%, 0.7%, and 3% of global crop production in the period of 1980–2018 (FAO, 2020). From 1961 to 2008, the yield of maize, rice, wheat, and soybean was increasing at a rate of 1.6%, 1%, 0.9%, and 1.3% per annum (Ray et al., 2013). The mean and standard deviation were calculated to describe the relationship between total internal water resources and crop production between 1980 and 2015 in 37 selected countries (Figure 2).

Table 2.

Characteristics of major grains (2000–2018).

		Overall production	Internal sale price	Forecast (2000–2025)	Export		Import		Virtual Water
					Quantity	Price	Quantity	Price	
grains	Unit	10^6 t	US $/t	US $/t	10^6 t	US $/t	10^6 t	US $/t	m^3/t

Maize	1156.62	161	183	36.03	271.5	271.50	215.5	1984
Rice	469.82	480	625	0.25	438.2	2.10	46.9	3182
Soybean	34.51	350	418	2.05	447.0	33.25	473.5	4126
Wheat	436.07	195	212	3.70	308.2	663.07	256.3	2506

Source: Elaborated by the author

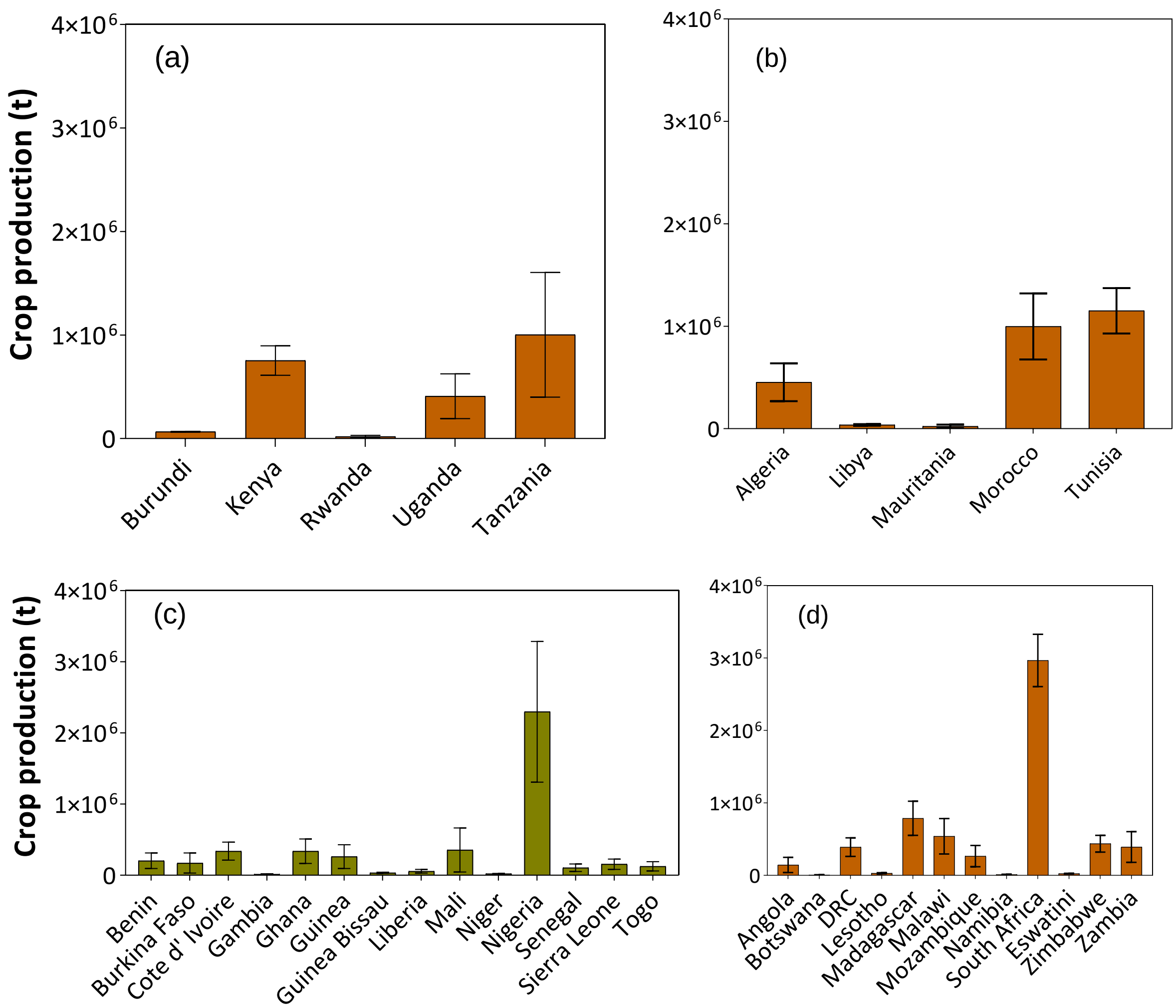


Figure 2. Trends in mean total internal water resources and crop production (CP) for 37 selected countries between 1980 and 2015 (data from: FAO (2020). (a) East African Community (EAC); (b) Union of Arab Maghreb (UMA); (c) Economic Community of West African States (ECOWAS); and (d) Southern African Development Community (SADC).

To estimate the virtual water content (VWC) of the four selected crops (i.e., maize, rice, soybean, and wheat), the VWC ($\mathrm{kg_{water}/kg_{crop}}$) of raw crop *c* in country *i* and year *y* was calculated as follows:

$$\mathrm{VWC}_{i,c,y} = \frac{\sum ET_{i,c,y}}{\mathrm{Y}_{i,c,y}} \quad (1)$$

where $ET_{i,c,y}$ ($\mathrm{kg_{water}}/m^2$) is evapotranspiration (ET) from cropland planted with *c* averaged over the growing season, and $\mathrm{Y}_{i,c,y}$ ($\mathrm{kg_{crop}}/m^2$) is the yield of crop *c* (both in year *y* and country *i*). From 2012 to 2018, the VWCs of maize, rice, soybean, and wheat were scaled with annual yield data (crop production (CP) data of the (FAO, 2020)). All VWC estimates combined green (i.e., soil moisture) and blue (i.e., rivers, reservoirs, and aquifers) sources of water for agricultural production.

Then, VW flows (VWFs) were quantified by multiplying the volume of trade (per trade commodity) by the respective VWC (average WF per ton of product) in the exporting nation (Roson & Sartori, 2015). The total VWF (VWF_{total}) was calculated as the sum of the VWFs of all farming products (including green, blue, and gray water), as expressed below:

$$VWF_{i\to j} = \sum_k VWF_{i\to j,k} = \sum_k \sum_c TV_{i\to j,k} \times VWC_{i,k,c} \quad (2)$$

where $VWF_{i\to j}$ represents the total VW flow from exporting nation *i* to importing nation *j*; $VWF_{i\to j,k}$ and $TV_{i\to j,k}$ represent the VW flow and trade volume of product *k* from nation *i* to nation *j*, respectively; and $VWC_{i,k,c}$ represents the VW content for component *c* (i.e., green, blue, and gray water) of product *k* from nation *i*.

To analyze the driving factors underlying the net VW fluxes, we employed the approach described by (S Tamea et al., 2014). The explanatory variables used in the gravity-law model are population, VW of per capita agricultural production, VW of per capita dietary demand, per capita gross domestic product (GDP), distance between countries, and per capita arable land.

Referring to the VW network complexity, a worldwide partnership that defines all exchanged fluxes as a function of the features of importers' and exporters proved to be inadequate (S Tamea et al., 2014). Thus, specific models describing the VW import (VWI) and export (VWE) of a country are essential. We deal with two gravity laws per country: (1) describing the export as a function of the characteristics of destination countries, and (2) describing the import as a function of the characteristics of source countries. Furthermore, the national WS (NWS) depends on temporal and spatial variations. This study considered the period 2012–2018. The WS values of a country can be categorized into four levels: (1) overexploited (WS > 100), (2) heavily exploited (60 ≤ WS < 100), (3) moderately exploited (30 ≤ WS < 60), and (4) slightly exploited (WS < 30) (Brown & Matlock, 2017). Comparatively, the blue water (BW) scarcity of a country is expressed as follows: low (WS < 1.0), moderate (1.0 < WS < 1.5), significant (1.5 < WS < 2.0), and severe (WS > 2.0). A WS value of 100 indicates the total consumption of available blue water, whereas a WS of > 100 means that environmental flow requirements are not met (Arjen Y Hoekstra et al., 2011). As an index of NWS, we used the ratio of total water use to water availability:

$$\mathrm{WS} = \frac{WU}{WA} \times 100 \tag{3}$$

where *WS* denotes NWS (%), WU is the total annual water use in the country (m^3/a), and WA is the annual national water availability (m^3/a). Defined in this manner, the WS value is generally 0–100%; however, in exceptional cases (e.g., groundwater mining) it can exceed 100%. As a measure of the national *WA*, we took the annual internal renewable water resources, which are the average freshwater resources renewably available over a year from precipitation falling within a country's borders. As mentioned in the preceding section, the total *WU* should ideally refer to the sum of blue and green *WU*; however, for practical reasons, we provisionally agreed to define WS as the ratio of blue *WU* to water availability, which is also generally done by other researchers (e.g., (Kummu et al., 2016; Rosa et al., 2020).

Thereafter, to understand the level at which a nation relies on foreign water resources (via the import of water embodied in commodities), we calculated the VWI dependency or WD using Eq. (4). The WD of a nation denotes the ratio of the net VWI (NVWI) to the total national water appropriation (Brindha, 2020; Arjen Y Hoekstra, 2003). When the NVWI values are positive (negative), the country is a VW importer (exporter):

$$WD = \frac{NVWI}{WU + NVWI} \times 100 \qquad \text{if NVWI} \geq 0$$
$$WD = 0 \qquad \text{if NVWI} < 0 \tag{4}$$

The WD index value ranges from 0 to 100%, with 0 implying that the gross VWI (GVWI) and exports are balanced, or that there is net VWE. If the WD value approaches 100%, the nation almost completely relies on VWI. As the counterpart of the WD index, the water self-sufficiency index (WSSI) is defined as follows:

$$WSSI = \frac{WU}{WU + NVWI} \times 100 \qquad \text{if NVWI} \geq 0$$
$$WSSI = 0 \qquad \text{if NVWI} < 0 \tag{5}$$

The WSSI of a nation relates to its WD as follows:

$$WSSI = 1 - WD \tag{6}$$

Eventually, the $WSSI$ measures the capability of a nation to supply the water needed to produce domestic goods and services. Water self-sufficiency is 100% when all the required water is available and taken from within the territory, whereas it approaches 0 if a country relies heavily on VWI.

Further, the global water savings ($GWS_{i,e}$) (m^3/a) were calculated as follows:

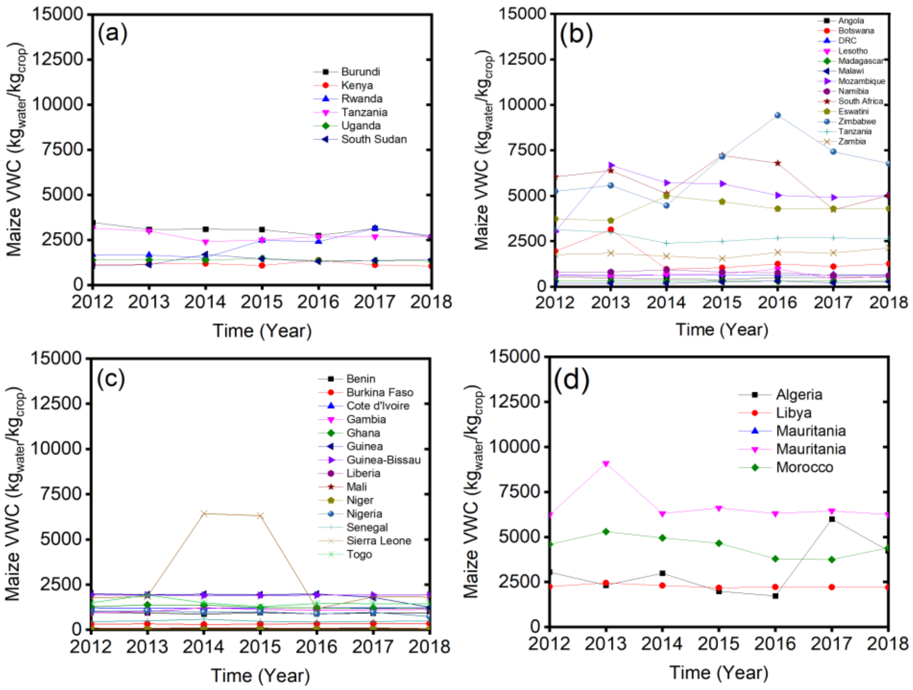
$$\sum_{p=1}^{n} T_{i,e,p}.(VWC_{i,p} - VWC_{e,p}) \quad (7)$$

where $TV_{i,e,p}$ is the product (*p*) amount (t/a) traded between importing region *i* and exporting region *e*; $VWC_{i,p}$ and $VWC_{e,p}$ are the VWCs (m^3/t) of product *p* for importing region *i* and exporting region *e*, respectively. Positive and negative $GWS_{i,e}$ values indicate that the country saves or loses water, respectively. However, for regional water savings, if the imported amount of a product exceeds the exported amount, then this region has a NVWI and saves domestic water resources to meet its food consumption (Supplementary information, Figure S1) (Liu et al., 2019).

3. Results

3.1. VWC of major grains in Africa

We estimated the VWCs of maize, wheat, rice, and soybean in Africa, which exhibited spatial and temporal variations, as illustrated in Figure 3 for maize, wheat, rice, and soybean. The VWC peaks in many countries occurred in 2013, 2015, and 2018 due to climatic conditions that resulted in a low crop productivity. The VWCs of crops varied widely between countries; for instance, during 2012–2018, the national mean VWC of rice was 1407.2 kg_{water}/kg_{crop} in Tunisia, whereas it was 7621 kg_{water}/kg_{crop} in Botswana. Similarly, the national mean VWC of maize during 2012–2018 was just 6748 kg_{water}/kg_{crop} in Mauritania, whereas it was 5836.0 and 6587.3 kg_{water}/kg_{crop} in Zimbabwe and South Africa respectively (Figure 4.a-d). The data revealed that agricultural productivity was relatively high regionally, and that the VWCs of major grain crops in North Africa (particularly in the UMA) were very low compared with other parts of the world (Supplementary information, Table S2).


(a)
Maize VWC (kg$_{water}$/kg$_{crop}$)
Time (Year)
Burundi
Kenya
Rwanda
Tanzania
Uganda
South Sudan
(b)
Angola
Botswana
DRC
Lesotho
Madagascar
Malawi
Mozambique
Namibia
South Africa
Eswatini
Zimbabwe
Tanzania
Zambia
(c)
Benin
Burkina Faso
Cote d'Ivoire
Gambia
Ghana
Guinea
Guinea-Bissau
Liberia
Mali
Niger
Nigeria
Senegal
Sierra Leone
Togo
(d)
Algeria
Libya
Mauritania
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7500
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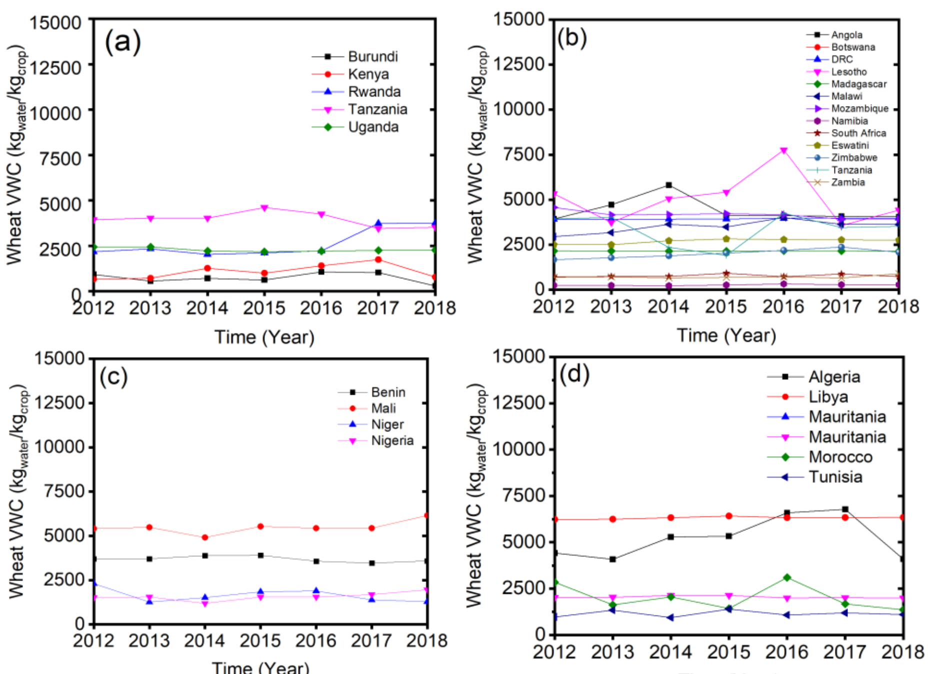
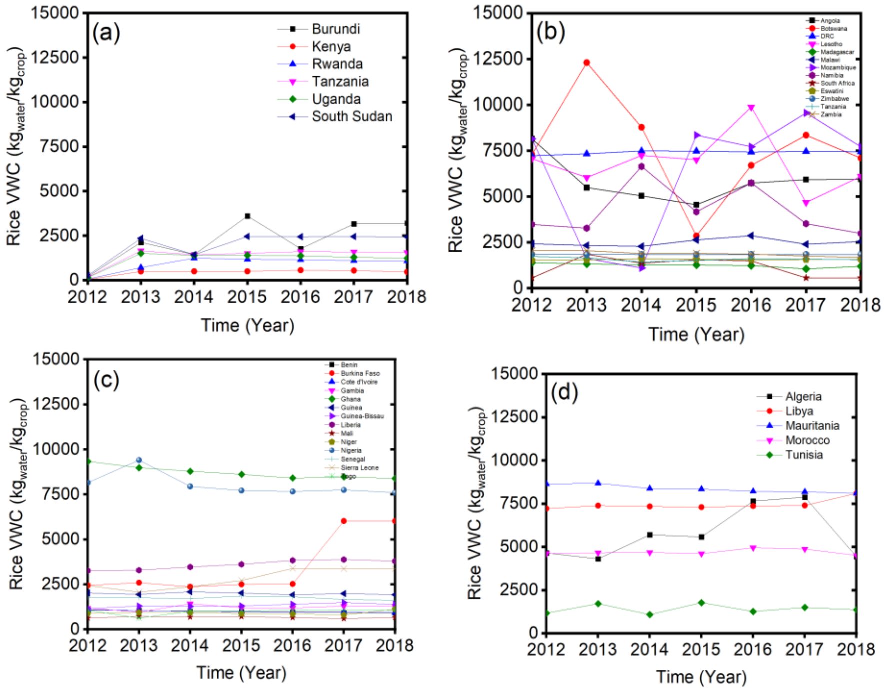
15000
2012
2013
2014
2015
2016
2017
2018


(a)
Wheat VWC (kg$_{water}$/kg$_{crop}$)
Time (Year)
Burundi
Kenya
Rwanda
Tanzania
Uganda
(b)
Angola
Botswana
DRC
Lesotho
Madagascar
Malawi
Mozambique
Namibia
South Africa
Eswatini
Zimbabwe
Tanzania
Zambia
(c)
Benin
Mali
Niger
Nigeria
(d)
Algeria
Libya
Mauritania
Mauritania
Morocco
Tunisia
0
2500
5000
7500
10000
12500
15000
2012
2013
2014
2015
2016
2017
2018



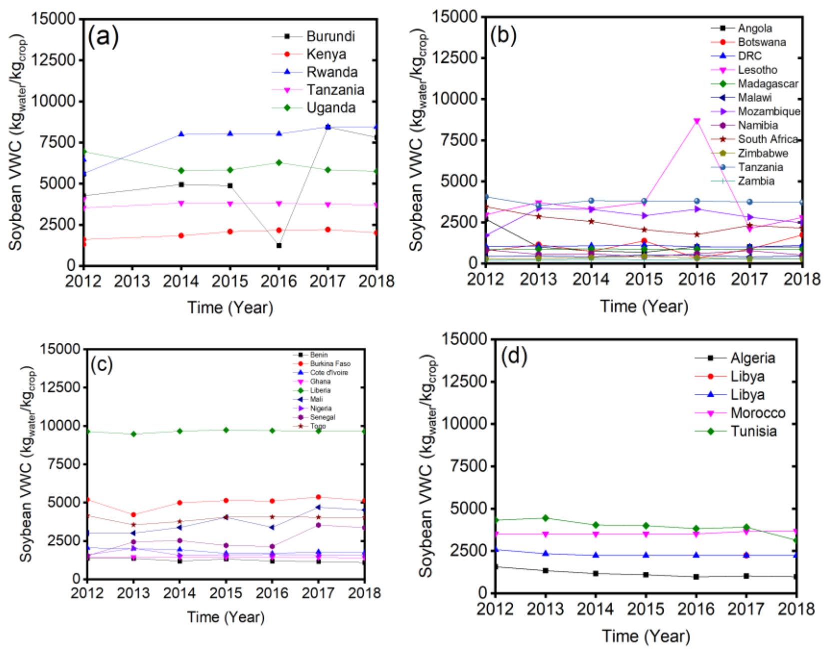


Figure 3. Trends of the average VWC of maize, wheat, rice, and soybean (2012–2018) in African countries within four RECs: (a) EAC; (b) SADC; (c) ECOWAS; (d) Union of Arab Maghreb (UMA). Calculated using data from the (FAO, 2020).

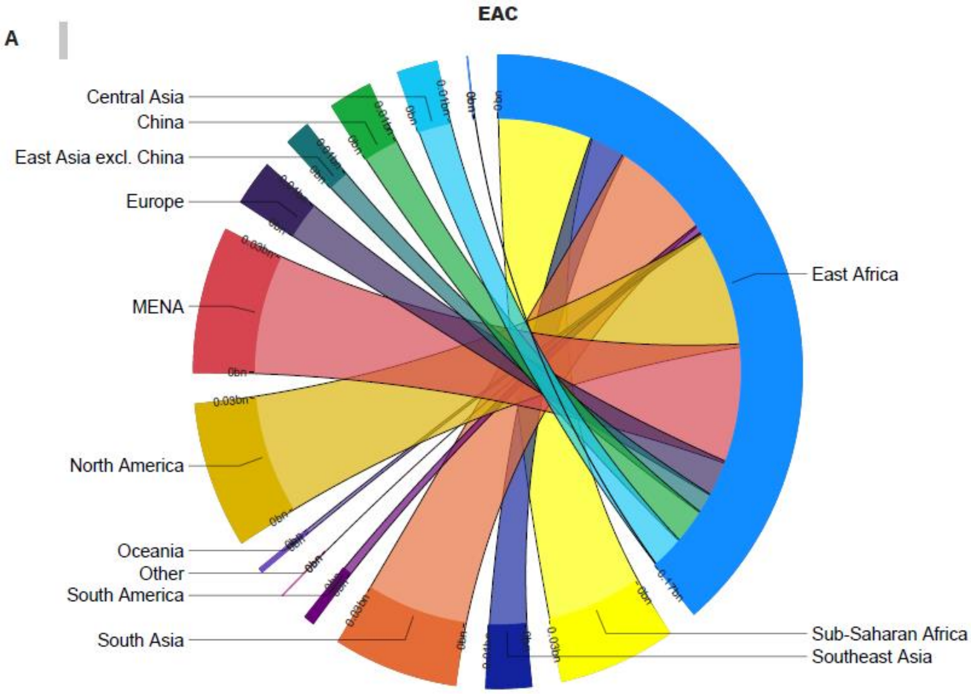
3.2. Understanding the trade flow dynamics of Africa and its partners

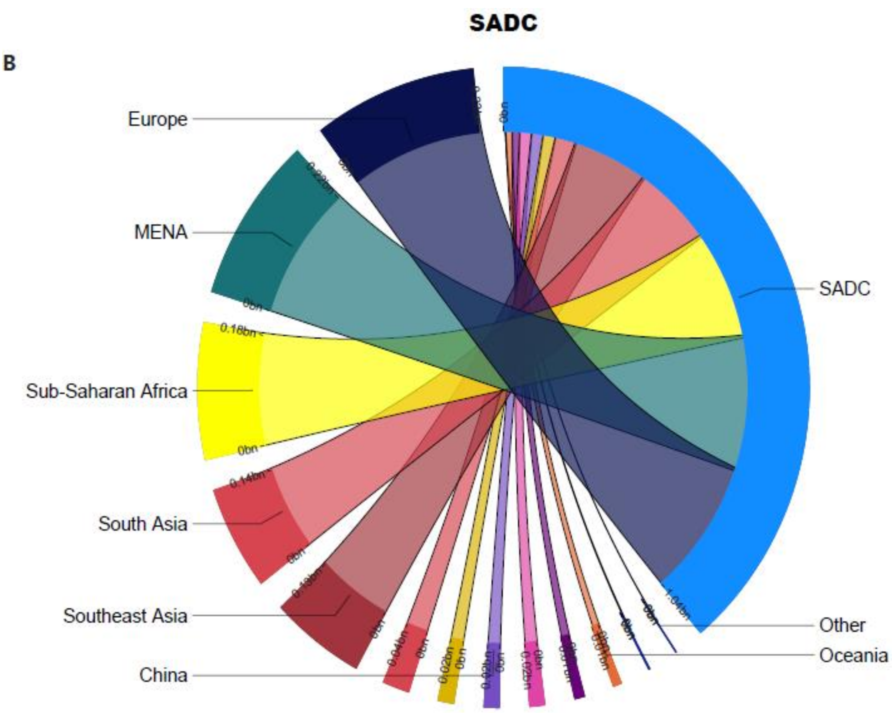
To assess the trade flow networks (import and export of goods) within Africa, we categorized four major regional integrations (i.e., the EAC, SADC, ECOWAS, and UMA) based on foreign goods and domestic products from 2012 to 2018 (Figure 4). We then assessed the shift patterns of agricultural products from 2000 to 2018. The five top commodities were found to be agricultural products (e.g., cereals, dairy, eggs, honey, fish, and meat), fossil fuels, metals and minerals, forestry products, and fertilizers. Additionally, the top import (from commercial affiliate regions to Africa) VW flows showed a significant diversity across countries and sectors, thus influencing the VW transfer between countries. For instance, the Middle East and North Africa (MENA), North America, and South Asia were the top three VW exporters of the EAC from 2012 to 2018. These findings revealed a diverse trade structure and final consumption between EAC countries and their trade partners. According to the interpretations made, there was an irregular movement in the ranking of commodities imported from one region to another because of the evolution of a country's economic development. We consider that geographic location did not influence Africa's WV trade during the studied period.

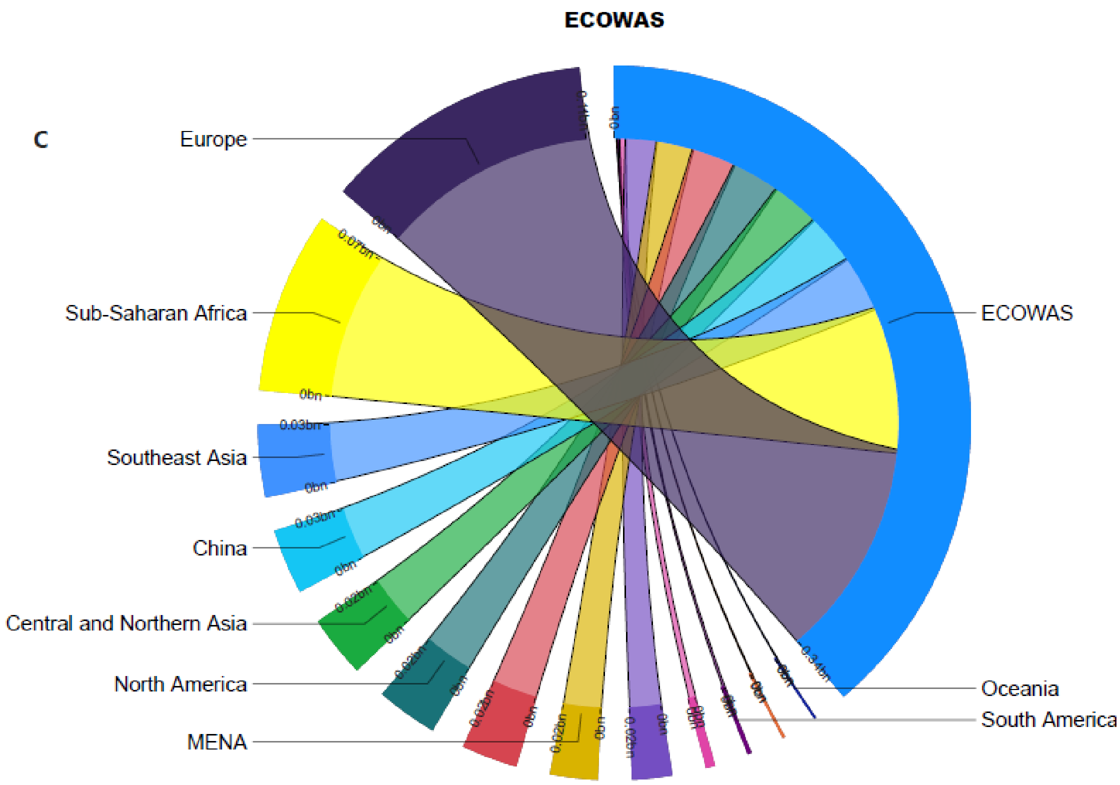
After rigorous assessment, the total products imported and exported within sub-Saharan African countries from 2000 to 2018 increased from 6.1×10^6 t to 11.2×10^6 t, respectively. Figures 5a–d show the importers and exporters of products between Africa and its partners for 2012–2018. The most significant observation is that the principal exporters in the EAC, SADC, ECOWAS, and UMA were MENA, East Asia (China), and Europe with 33.3×10^6 t, 228.0×10^6 t, 106.2×10^6 t, and 220.0×10^6 t, respectively.

We note that the quantity of VW traded in agricultural products differs based on the number of items assessed. During 2000–2018, the SADC was a net exporter of VW within

Africa due to its share in regional VWT, which exhibited an increasing trend between 2000 and 2018.



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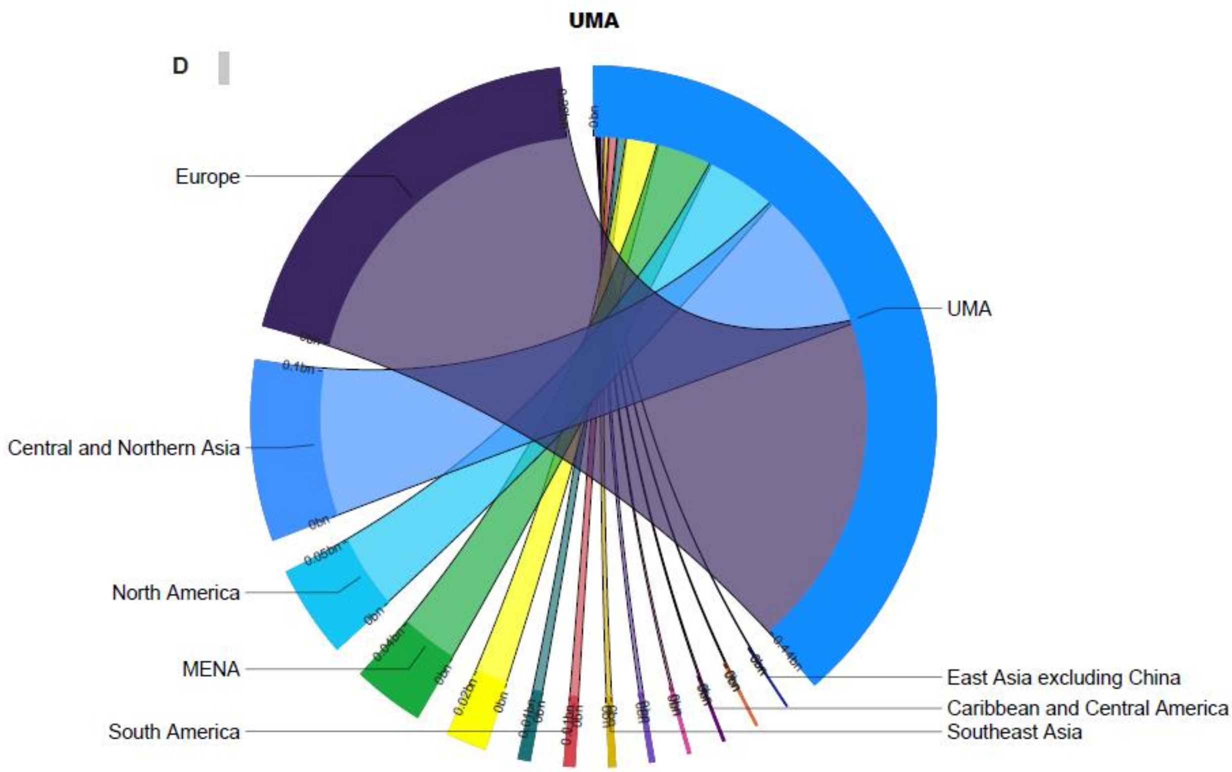
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Figure 4. Importers and exporters of products between Africa and its partners during 2012–2018: (A) EAC; (B) SADC; (C) ECOWAS; (D) UMA. The numbers indicate the weight (1000 kg). These figures were produced using the network visualization software of (Krzywinski et al., 2009).

3.3. Driving forces of VW fluxes, the case of a single country: Ethiopia

Generally, gravity laws are applied to the VWT of any country (S Tamea et al., 2014). The results of this application are demonstrated in Figure 5 for Ethiopia from 2000 to 2018. The VW export of Ethiopia depended on population, GDP, agricultural production, and arable land. These four factors increased sharply between 2000 and 2018. The per capita dietary demand and distance between countries were not considered due to a lack of data.

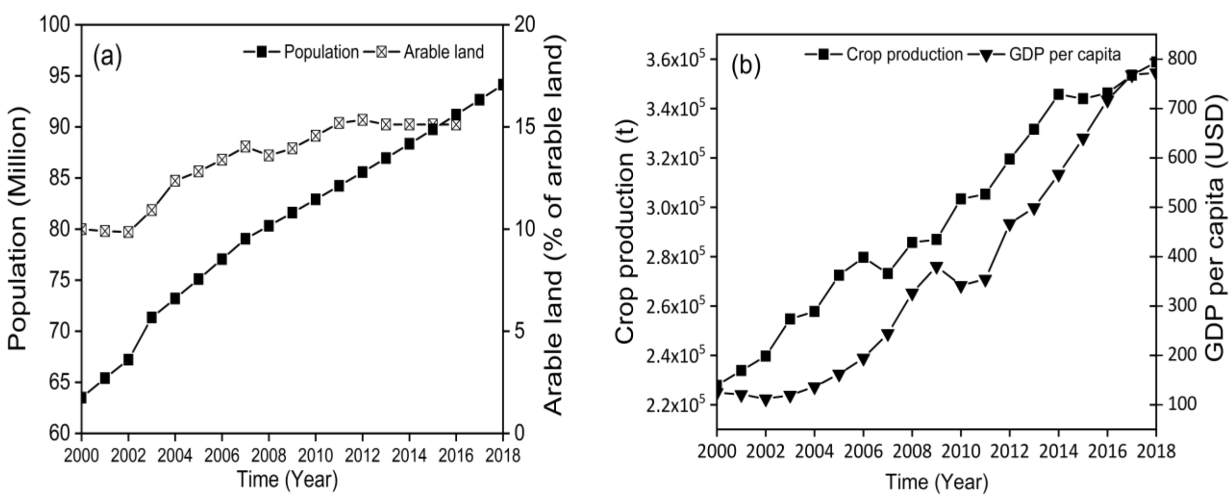


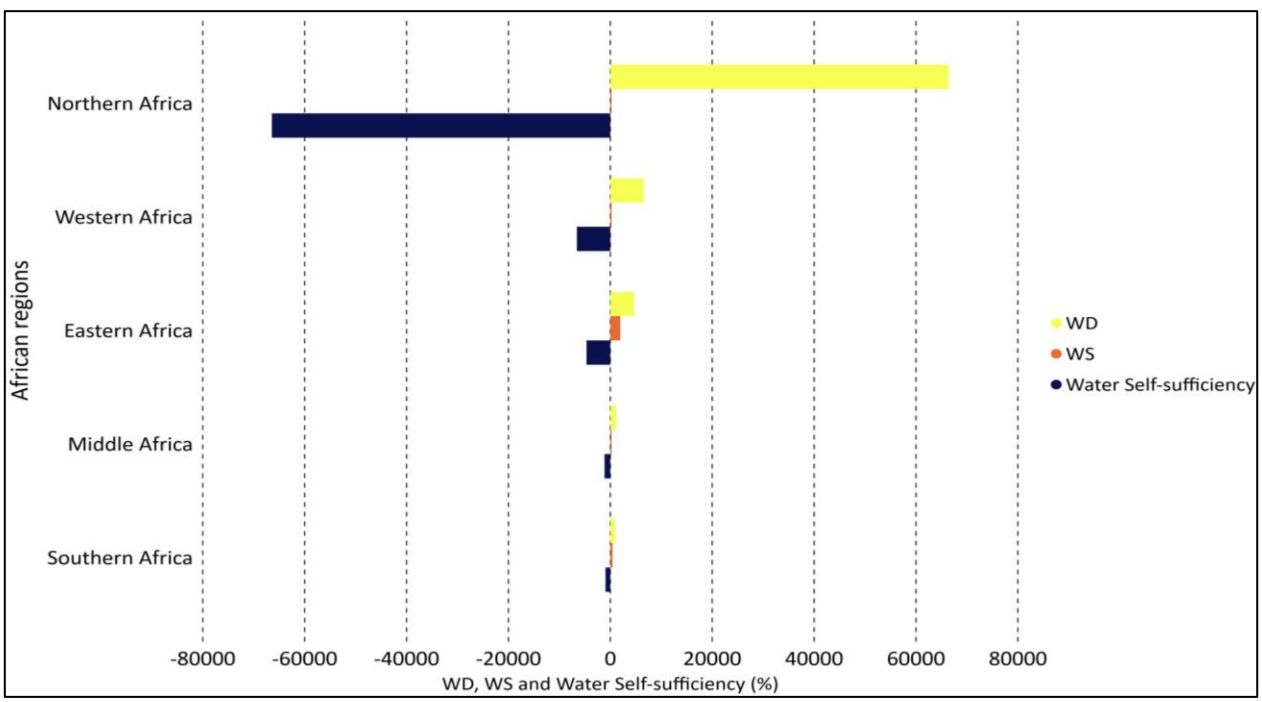
Figure 5. Determinants of VW flow in Ethiopia. (a) Population and arable land, and (b) CP and gross domestic product (GDP) per capita (data extracted from: FAO 2020).

3.4. Estimation of national WS, WD, and water self-sufficiency

From 2012 to 2018, the VWI values of maize, rice, wheat, and soybeans varied from 59.05 × 10^9 m^3 to 654.11 × 10^9 m^3, whereas the VWE values ranged from 2.76 × 10^9 m^3 to 3.37 × 10^9 m^3. The NVWI was 56.29 × 10^9 m^3 in 2012 and increased to 62.04 × 10^9 m^3 in 2018 (average of 108.85 × 10^9 m^3/a). On the one hand, the average NVWI was always positive, implying that African countries imported more VW. On the other hand, some eastern, northern, and southern countries had negative NVWI values for soybean and maize.

Figure 6a show that the WS values were > 100 (overexploitation) in eastern countries, whereas they ranged from 60 to 47 (heavily exploited) in southern countries and from 30 to 20 (slightly exploited) in western countries. In northern countries, the WS values varied, for example, Algeria had a WS of ~30 (moderately exploited), whereas Morocco had a WS of > 100 (overexploited).

(a)



(b)

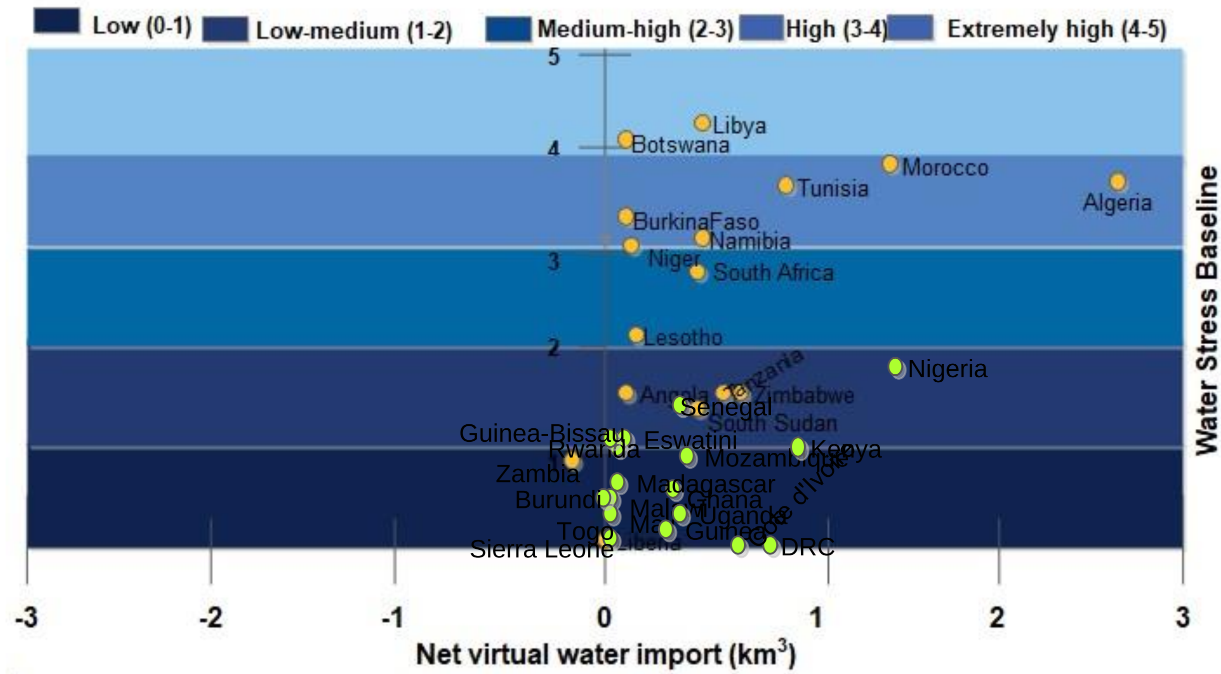


Figure 6. (a) WD and water self-sufficiency against water scarcity in African sub-regions between 2012 and 2018. (b) Relationship between the net virtual water import (NVWI) and water stress index for 37 selected countries.

Moreover, most southern countries put high pressure on their limited water resources to attain water self-sufficiency, while their WS was high, and in some cases far beyond the sustainability level. Burundi, Kenya, Rwanda, Uganda, and Tanzania (eastern countries) produced crops in an unsustainable manner, with WS values of 452.30%, 218.47%, 420.77%, 385.67%, and 432.74%, respectively, while experiencing an overall WD of 4655% from 2012 to 2018 (Figure 6a). The water stress index in Africa varies from low (-2.66) to extremely high level (2.64). Some regions overexploited their limited groundwater resources to achieve their preferred WSSI in agricultural production, while others relied on undeveloped or small farming practices. Similar to other types of grains, cereals were the main crop either exported from or imported to different regions. The proportion of imported products increased over the studied period in terms of the WS of any area, as in the case of northern countries (Figure 6b).

3.5. Water savings and losses

The VWT can help save water resources at different scales. The determination of water savings/losses is one of the significant progressive outcomes of VWT between regions (A. K. Chapagain et al., 2006). The volume of water saved or lost by Africa through VWT with the ROW can be quantified by calculating the difference between the volume of water required to produce a desired imported product and the volume of water needed to produce the same product in Africa. This assessment identifies whether Africa contributed to global water savings or losses by importing the product instead of producing them domestically.

The results presented in Table 3 illustrate relationship between virtual water content (VWC) of major crops from trade partners, VWC of food produced, and water savings/losses in Africa. The findings indicate that rice contribute to a high water loss followed by maize, soybean, and wheat in the study period (2012–2018).

Table 3.

Water savings and losses from the trade of single major grains in Africa during 2012–2018.

	VWC of food from trade partners 10^9 m^3/a	VWC of food produced in Africa 10^9 m^3/a	Water savings/losses 10^9 m^3/a
Maize	998.03	128.70	-869.33
Rice	17.52	1.28	-16.24
Wheat	1369.59	309.56	-1060.04
Soybean	892.17	17.09	-875.08
Total	3277.32	456.62	-2820.70

Source: Elaborated by the author

An estimated total VWC of 456.62 × 10^9 m^3/a was used to produce maize, rice, wheat, and soybean in Africa, whereas this was 3277.32 × 10^9 m^3/a for trade partners (Table 3). Overall, the trade of major grains between Africa and the ROW corresponded to a global water loss of approximately 2820.70 × 10^9 m^3/a. The average annual agricultural water withdrawals in Africa during 2008–2012 and 2013–2017 were 118.0 × 10^9 m^3 and 103.6 × 10^9 m^3, respectively, while the total annual agricultural water withdrawals were 144.97 × 10^9 m^3 and 135.37 × 10^9 m^3, respectively.

4. Discussion

The current study estimated the VWCs of selected staple food crops in Africa from a chronological perspective. The variation in agricultural VWC depends on the spatial and temporal dimensions, resource and crop management, means of production, and climatic conditions. However, the main challenge in calculating the VWC of a crop is to accurately estimate the amount of consumptive water used for CP (essentially crop evapotranspiration). The VWCs of crops in Africa are highly variable across crop products; for instance, soybean (~3500 m^3/t) has a higher total VWC than wheat (~2600 m^3/t) (Ercin et al., 2012). Africa has high VWC values for some crops as a result of the arid climate and low crop yields (Dalin & Konar, 2019; Tuninetti et al., 2015). Our findings showed a high average VWC of rice in arid areas of southern and northern Africa countries while western Africa regions registered a high VWC of soybean during 2012–2018. The former agrees with results reported for China (Sun et al., 2013) and the Korean Peninsula (Lim et al., 2017). During 2000–2004, the global average WF of paddy rice was 1325 m^3/t (48% green, 44% blue, and 8% gray water), which was much lower than previous estimates (Ashok K Chapagain & Hoekstra, 2011). Although agricultural productivity in Africa increased at a moderate rate between 1980 and 2018, there were regional variations in the growth rates of cropland, agricultural labor, and total factor productivities, thus resulting in a high amount of VW being transferred in each production sector. However, to some extent, this VW reflects an enormous quantity of real water that Africa requires to draw from its resource endowment.

Many researchers have focused on applying a cautious concept and approach, proposing that VW is an advantageous, albeit limited, tool for addressing water issues in any country (Yang & Zehnder, 2007) and it is a potential opportunity to alleviate water scarcity (Borgomeo et al., 2020; Cui et al., 2018). On the contrary, other researchers consider that VW calculations are inconsistent or inaccurate, and that volumetric indicators neglect important local socioeconomic factors related to water consumption. Some studies have argued that, if used to guide trade or water allocation policies, such an approach could negatively affect those at risk of WS issues (Chenoweth et al., 2014; Arjen Y. Hoekstra, 2017). Simultaneously, several potentially valuable tools for influencing trade and water policies to promote conservation and combat WS have been cited in relevant studies. The present study is the first step toward a more profound understanding of the agrarian VWC of major grains in Africa, offering a fundamental tool for sustainable agricultural water resource management on the continent and enhancing farm water use efficiency.

The VW transfer determinants of a country include population, agricultural production, dietary demand, GDP, cultivated land, and distance between nations. Carr et al. (2013) reported that the VW fluxes moving in or out of Africa are consistently relatively small. This is illustrated in Figure 4d, which shows that the trade flows from i) Spain to Morocco, ii) France to Algeria, and iii) Italy to Tunisia corresponded to US $2.9 Bn, $2 Bn, and $1.8 Bn, respectively, whereas that from the Netherlands to Nigeria was US $4.3 Bn (Figure 4c). The largest net VW importers were northern countries, where the major exporters were European countries (mainly the Netherlands, Belgium, Germany, France, Spain, and Italy) and Central/Northeast Asian countries (mainly China, Japan, and South Korea), which was verified by previous studies (e.g., (Dalin et al., 2012; Graham et al., 2020). Notably, since the early 1980s, Africa became a net importer of food and agricultural products, despite its vast agricultural potential, which is puzzling (Rakotoarisoa et al., 2011). Therefore, the rate of increase of food imports was faster than that of agricultural and food exports in Africa. Agricultural imports have increased at a consistently faster rate than agricultural exports and reached a record high of US $47 Bn in 2007, yielding a deficit of ~US $22 Bn (for more details see *https://faostat.fao.org*). According to the African Progress Panel, the food import bill of Sub-Saharan Africa stands at ~US $35 Bn/a (~3% of the GDP) (Arment, 2020). The forecast for 2050–2059 suggests that, without action, Sub-Saharan Africa will be the region with the largest increases in imports of coarse grains, oilseeds, paddy rice, and wheat as the population increases (Porfirio et al., 2018).

Increasing global trade and intra-regional agricultural trade have the potential to improve food security and agricultural development in Africa by stabilizing local/regional food markets. This would make them less vulnerable to economic shocks, even though the overall trade levels would remain low compared to other regions or continents. Over the last two decades, intra-African trade increased by approximately 12%/a. The main challenges for improving intra-regional trade performance in Africa include weak productive capacity and the lack of trade-related infrastructure and services. Furthermore, to tackle the above issues, Africa must adopt diverse economic instruments to promote free trade both within countries and worldwide. Africa must learn from successful economic integration programs such as the Belt and Road Initiative

(BRI), which targets the trade links between China and the ROW. For example, in 2013, the VW that China exported to the countries included in the BRI accounted for ~39.2% of the total Chinese exports, whereas the imported amount accounted for 28.6% of the total Chinese imports (Zhang et al., 2018). Similar projects with the same purpose could help to cope with water-related issues (WS and shortages), enhance the rational allocation of water resources in numerous departments, and provide references for trade structure optimization. Our results may have implications for a promising alternative to achieve SDG 6 (mainly target 4: "substantially reduce the number of people suffering from WS") by 2030.

Previous works on WS (Arjen Y Hoekstra et al., 2012; Islam et al., 2007) underestimated the NWS of nations, while many people are suffering from WS at a severe level throughout the year, which hampers sustainable ecosystems and livelihood development. For instance, in Africa, Nigeria and Egypt experience major WS issues. Other countries that have a severe WS situation include Libya and Somalia (affecting 80%–90% of the population), and Morocco and Niger (affecting 50%–55% of the population) (Mekonnen & Hoekstra, 2016). However, the WS problem in Africa is not caused by a physical lack of water (Xie et al., 2014). This understanding is supported by our findings, which indicate that some countries with abundant water resources have been suffering from WS issues. For instance, in 2013–2017, the WS score in the EAC ranged from ~200% to 450% (i.e., water overexploitation), whereas that in the SADC was 40%–60% (i.e., moderately to heavily exploited). Today, the MENA countries depend highly on VW imports because local water resources are lacking, thus leading to a high vulnerability with respect to water. The issue of WS could be managed by establishing adequate agricultural policies (Stefania Tamea et al., 2016). Importantly, we found that countries with WS could use major grain imports as a coping strategy to tackle the food security issue and save limited national water resources. However, the increasing amount of grain could also be an integral component of integrated water resources management for water-scarce countries to meet SDGs in 2030.

We note that there were some limitations to this study as it was not based on field measurements of VW transfers. Because water use for production does not account for the environmental issues related to water consumption, there is a lack of related data (e.g. the per capita dietary demand and distance between countries). Therefore, the annual internal renewable water resources for countries were estimated and averaged rather than being actual data. Ideally, it would be better to obtain real data to be more accurate and reliable. However, this study has different sources of uncertainty including lack of up-to-date data, high quality data. Most of secondary data errors are transmitted from one step to another step while analyzing the data. We identified that the methodology used to calculate VWC, WS, water savings or losses are simple, resulting to uncertainty in measurement accuracy and precision. In addition, there is a statistical uncertainty due to a combination of many factors that impact the VWC of major grains, and WS.

5. Future outlook and implications for policy

In the coming decades, future global agricultural VW and its trade could serve as a durable solution for areas suffering from high WS (Graham et al., 2020), considering human and socioecological systems. There are policy implications for sustainable water resource consumption and management. Globally, a high increase in water consumption makes water resource conservation policies more difficult to manage and implement (Tian et al., 2018). However, there is a clear need to understand the social, economic, and environmental implications of allocation decisions. Even though VW transfer and WF assessment lack a clear and supporting conceptual framework, through regional integration, Africa could implement optimal policies and strategies (or strengthen existing ones) of water resource consumption (e.g., water pricing, water ownership, global trade, agricultural products, supply chain risk and resilience, and sustainability footprints).

According to the results, discussion, and concerns mentioned above, future policy should seek to address and solve these issues by:

(1) ensuring the resilience of WS through effective strategic water governance, accountability, and immediate and reactive responses to re-calibrating local production and international trade in a long-term approach: It is difficult to establish a governance framework for groundwater management. As a potent approach, integrated water resources management offers the possibility to renew the social contract and reinforce the government. However, several countries have successfully used approaches that i) decentralize water resources stewardship to local areas and communities, ii) provide incentives for an increased water use efficiency through subsidies to water-conserving infrastructure (e.g., in-field pipe distribution, hydrants, and pressurized irrigation), and iii) provide advice on water management and irrigated cropping.

(2) strengthening food security and climate resilience through more productive use of green water and BW: Maximizing the productivity of rainfed agriculture may be achieved by building the capability of farmers and finance in innovative policy actions. Research, technology development, and transfer can further improve water use efficiency and crop productivity in any country. They can also significantly increase the resilience of rainfed agricultural systems; for example, by building agricultural resilience with conservation pasture, promoting land conservation and reclamation practices, and reducing the environmental risks of agricultural production using legumes.

(3) averting negative consequences of overuse by securing environmental flows and regulating the use of groundwater resources in case of expanding irrigation. Several areas of Africa already face moderate to severe blue WS for some of the year or the entire year. Therefore, any development and expansion of irrigation schemes should be planned and implemented with caution. Water availability and therefore the protection of ecosystems, both currently and under future climate change scenarios, should be assured before expanding the realm of irrigated agricultural land. Surface water can be supplemented with deep groundwater resources; though, their sustainable use must be secured with measurements, monitoring, and regulation to avoid future negative socioeconomic and environmental impacts from overuse.

(4) preventing conflicts between resource users by integrating policy for a holistic approach to sustainable development (i.e., socio-economic and ecological development). The ties between agriculture, trade, economic and energy policy, and the management of water resources need to be understood at all levels. A holistic approach to sustainable development will help ensure that the goals of each sector do not contribute to unintended impacts that delay progress and have a detrimental effect on water supplies and ecosystems linked to water. However, there is a need to investigate the trade-offs and synergies in food and water security from reliance on internal or external water resources for food, export value, and supply chain inputs for a balanced approach to development.

(5) enhancing global cooperation focusing on water security and international trade. Promoting international cooperation, especially the transfer of technology from developed regions to less developed regions, is of paramount importance (Fadong et al., 2018). In bilateral and international trade, a country sufficiently secured in production must support its economic partners (Huang et al., 2017). However, an open data platform (sharing of knowledge and

experience) with appropriate water and trade information linked to a multi-stakeholder participation policy platform and voluntary commitments will enable policymakers to build more realistic trade policies.

5. Conclusions

The agricultural sector is the leading consumer of water in Africa, and a rapidly rising population is increasing food demand and WS issues. Issues related to WS and water losses through production have become worse in most African countries over recent decades. Assessments of VW transfers through the VWC of major crops and their implications for WS and water savings/losses between regions are crucial for providing broader and foundational orientations for policy and decision-makers of any country toward sustainable socioeconomic and environmental development. This study addresses the importance of a comprehensive VW transfer assessment in the context of water resource management across water-scarce regions. Our findings illustrate that most water-stressed regions depend on importing water-intensive crop products from high freshwater areas (e.g., northern countries).

The results revealed that several studies have focused on the international perspective and average VWCs of products over large regions, often hiding potential water availability changes and consumption at a smaller scale. The VW export of a country depends on the population, GDP, agricultural production, and area of arable land. Meanwhile, based on limited data over the period considered, we found that the average VWCs of major crops in Africa were higher in northern countries. For instance, the VWC of rice was 1407.2 kg_{water}/kg_{crop} in Tunisia, whereas it was 7621 kg_{water}/kg_{crop} in Botswana. The VWC of maize was just 6748 kg_{water}/kg_{crop} in Mauritania, whereas it was 5836.0 and 6587.3 kg_{water}/kg_{crop} in Zimbabwe and South Africa respectively. Southern and northern countries of Africa registered a high crop VWC in the study period. The average NWVI was 108.9 × 10^9 m^3/a. This study indicates that eastern countries overexploited water resources (WS > 100) during the studied period, although agricultural production remained low. The overall WD was 4655%. The trade of major grains between Africa and the ROW showed a high global water loss of 2821.0 × 10^9 m^3/a.

Nonetheless, despite the major uncertainties and limitations to conduct this research, we conclude that our findings provide key information to water resources management, and revealing the way for a more detailed study of the advantages for VW conception of sound water management tools. Furthermore, the next steps for this research study would include sustainability assessment, agricultural footprint analysis across countries as a multi-regional tool for sustainable water and land resources management. Finally, it is crucial to model future water footprint of major grains production in Africa, particularly in East Africa and its regional implications for agricultural yield and consumptive water use, to inform water policy and progress sustainable water resources use.

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available at Chatham House Resource Trade Database (CHRTD) official website http://resourcetrade.earth/ and also freely downloadable at United Nations Commodity Trade Statistics Database (UN Comtrade), by United Nations Statistics Division official website https://comtrade.un.org/. Agricultural data such as crop yields for maize, wheat, and rice are available on FAOSTAT database and free to download at http://www.fao.org/faostat/en/#data/QC. The Total internal renewable water resources (IRWR) data are available at AQUASTAT and free to download at http://www.fao.org/nr/water/aquastat/data/query/results.html. The annual evapotranspiration (PET) data are obtained through Global Aridity and Potential Evapotransiparation (ET0) climate database v2 and available to download from figshare, open data repository published by Antonio and Robert (2019). The population, gross domestic (GDP) per capita, crop yield, and arable land data were collected from World Bank Databank and freely downloadable at https://data.worldbank.org/indicator.

Conflicts of interests

The authors report no conflict of interest in this paper.

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