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Ecological balance emerges in implementing the water-energy-food security nexus in well-developed countries in Africa

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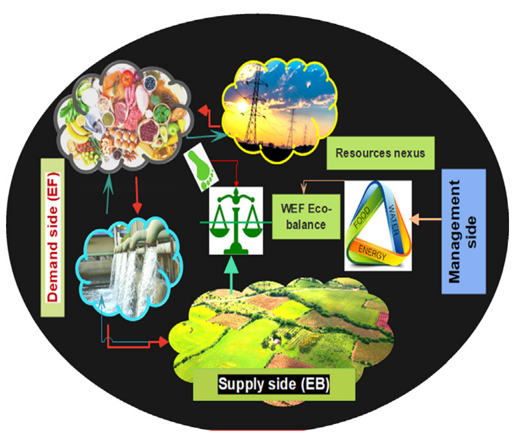
HIGHLIGHTS

- The conventional global hectare approach with the indicators; Ecological Footprint, Biocapacity, and Eco-balance are used to assess the environmental sustainability profile of water-energy-food production
- The WEF security nexus and the SDGs of the concerned African countries are achieved with increased pressure on ecological sustainability.
- The increase in water consumption affects the water eco-balance, especially in countries with limited renewable water resources
- High dependence on food from cereals, livestock, and energy from non-renewable resources increases demand for land biocapacity.
- The WEFEB Nexus Index is an important approach to maintaining the functional WEF eco-balance with human and natural ecosystem demand.

GRAPHICAL ABSTRACT



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ABSTRACT

Although many African countries have made significant progress towards universal access to water, energy, and food resources (WEF), assessing the ecological response to the increasing productivity of these resources is not well researched, which carries the risk of ecological deficit, resource degradation, and inefficient policy responses to resource management. This study seeks to assess the ecological sustainability response to the high increase demand for WEF resources in well-developed African countries. The study developed new measurement metrics for the WEF production system, including three indicators of ecological footprint (EF), ecological biocapacity (EBC), and eco-balance. The overall analysis considers data from four distinct types of water and energy use activities, and eight

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distinct types of food consumption, in nine African countries with the highest WEF nexus performance. An evaluation tool for the Water, Energy, Food and Ecological Balance (WEFEB) nexus index is proposed as one of the study's outcomes. Despite having 100% access to WEF resources related to the SDG targets. The results reveal the significant levels of imbalance and large ecological deficits existing in many of the concerned countries, especially North Africa, Mauritius, and South Africa, which need to rethink their economic models. Projecting a sustained increase in resource demand so that each country achieves at least 1700 m^3/capita/year as the minimum amount of water needed, most countries would suffer from a steady increase in ecological imbalance. According to the results, managing the ecological imbalances with increasing demand for WEF resources in well-developed African countries may require well-designed policies to effectively reduce certain types of human demand that have a large ecological footprint.

1. Introduction

Over the last few years, some African countries have made significant progress towards achieving the Sustainable Development Goals (SDGs), most notably Goal 2 (zero hunger), Goal 6 (clean water and sanitation), and Goal 7 (clean and affordable energy) (SDGN, 2020). Following this progress, excessive resource demand jeopardizes the ecosystem's ability to maintain a balance with the demand, leading to ecological deficits, resource depletion, and increased climate change impacts (Nassani et al., 2021). Today's population worldwide uses 1.75 times more natural resources than ecosystems can produce, which puts ecological sustainability at risk of deficiency and imbalance (Lin et al., 2021). Although Africa uses less natural resources than that global average of only 0.82 times, several African countries have already exceeded this range (Marti and Puertas, 2020).

In literature, Huimin (2013) revealed that energy ecological footprint (EEF) is rapidly increasing in demand, exceeding tenfold that of 1961 in 2003 and accounting for about half of the entire ecological footprint (EF). It is also mentioned by Alessandro and Laetitia (2017) that recent food production and consumption contribute significantly to global ecological overshoot, accounting for 26% of people EF and has continued to increase at an unsustainable rate. The portents of an increasing EF in many African countries were also cited; for instance, it increased 8% between 1961 and 2014 (Lin et al., 2018b). In 2050, Africa expects to face a high ecological deficit of −2.07 compared to −0.65 in 2009 (Hanna et al., 2013). The dramatic increase in resource consumption patterns in African countries has also coupled with dramatic climate change that compromises the quality and quantity of WEF resources available on the continent (Muhirwa, 2021). These have led researchers to conduct this study to examine whether the biological capacity of some African countries with strong economic attempts is in good balance to meet the demand.

Existing studies related to ecological sustainability issues have also gained momentum with numerous assessment methods that analyze resource flows, such as the EF and resource footprint (Hoekstra, 2003; Wackernagel and Rees, 1998). Other new approaches have been proposed, such as the water ecological footprint (WEFt) model developed by Huang et al. (2008), as well as the energy ecological footprint (EEF) approach proposed by Stöglehner (2003) and later modified in Yang and Fan (2019) new findings. The food ecological footprint (FEF) was another method proposed to assess different food resources' carrying capacity (Kissinger, 2013; Wansink and Sobal, 2007). In sum, although extensive literature has developed in the theories and practices concerning ecological sustainability, some new challenges and shortcomings occur rapidly that compromise the current conventional methods and approaches.

The water footprint (WF) is an example of a useful conventional approach in most water management studies that focus on assessing human freshwater consumption under rainwater, surface, and groundwater and water evapotranspiration (Pahlow et al., 2015). However, ecological water is rarely considered in WF, although it has an important role in balancing human water needs and water for natural ecosystem restoration (Summers et al., 2012). In addition, following the analyses of EF in resource management, many studies have used the conventional method based on five ecological land productivities: cropping, grazing, forest, marine, and building activities (GNF, 2021). This method dominates many recent studies conducted in Africa, especially in urbanization, economic growth, and energy resources (Ekeocha, 2021; Nathaniel et al., 2020; Owusu-Sekyere et al., 2017; Usman et al., 2020). While the method has the potential to provide a comprehensive picture of the EF of a region or country, it does not sufficiently account for specific activities that make significant contributions to the resource production system. For example, the method may not adequately highlight the human activities that are more efficient or environmentally friendly in minimizing the EF demand for sustainable WEF management.

Furthermore, many previous studies have calculated the ecological sustainability of regions or countries using the EF and biocapacity indicators when assessing ecological sustainability (GNF, 2021). This study also introduces the third indicator of eco-balance and proposes an integrated approach to evaluate the ecological balance of three resources: human demand, natural ecosystem supply, and natural ecosystem demand. The new WEFt, FEF, and EEF methods have been proposed to improve on existing conventional methods are still new to the literature and recently used with very few studies. In particular, no study has been done in Africa. This study aims to contribute to this context of African literature on WEF resources. In addition, the WEFt, EEF, and FEF also need an additional approach that captures the interconnectedness and interdependence of WEF resources as they are analyzed in each sector's benefits. The lack of such integrative understanding and management would cause siloed governance with increasing trade-offs and conflicts between sectoral benefits (Rosa et al., 2020; Scott et al., 2018).

This study also introduces a new approach considering how each resource's EF management affects the other resources under the WEF nexus perceptive (Hoff, 2011). The new framework is consistent with an attempt to assess the ongoing progress of SDGs related to the WEF resource security in an integrative manner and counterbalances with resource ecological carrying capacity. The nine most developed countries in Africa are used as models for the other fast economic growing countries in Africa.

In more detail, the core purposes of this study are to (i) obtain a baseline for the EF of WEF resources in nine African countries with a high WEF security nexus; (ii) introduce the eco-balance indicator as a new way to measure ecological sustainability in WEF resources; (iii) investigate the impact of increasing or decreasing water demand on the per capita water ecological balance (WEB); and (iv) create a new quantitative index of water energy, food, and ecological balance (WEFEB) nexus index. The highlight of this study is the first attempt to combine different competing sectoral methodologies used to assess the ecological footprint of WEF resources in an integrated nexus-based research perspective in Africa and globally.

2. Theoretical background

This work is based on the theory of EF with an adaptation of the WEF nexus approach to minimize the shortcomings of sectoral benefit analysis that exist in current theories based on conventional EF analysis research. The first attempt of this theory was proposed by Wackernagel and Rees (1998) to study human impacts on EF, but was later used by many researchers in ecological and economic studies related disciplines. The EF has identified a crucial indicator of the biologically productive areas of the world needed for the production of basic human needs such as energy and food (Lee, 2019). Using this approach, many researchers have analyzed the impact of human demand on EF based on five categories of land equivalents: Cropland, Forest and Pasture, Construction, Fishing, or Carbon

Production (Karwacka et al., 2020; Tam et al., 2019). Many other research studies use this theory to assess the impact of economic increase, energy, and urbanization on increasing EF. For example, Udemba (2020) applied the EF analysis and found that income, agriculture, foreign investment and energy consumption in Nigeria are related to EF increase and resource degradation.

Further findings show that countries' reliance on economies based on non-renewable resource exploitation and agricultural activities has an excess demand for EF (Ekeocha, 2021; Marti and Puertas, 2020). In assessing the EF of countries, the Global Network Footprint (GNF) has established two measures to assess the ecological sustainability of nations, regions, or individuals in the form of demand and supply where the EF is on the demand side of human needs and biocapacity is on the supply side. Sustainability exists in this evaluation when biocapacity exceeds EF (GNF, 2021). The latest GNF annual report showed that only 19 out of 54 African countries have a total biocapacity greater than their EF, with only 2 in our case study (Table 1).

Moving a bit further away from the old-style used in the WEF resource EF assessment, Huang et al. (2008) proposed the WEFt approach to calculate the EF of human water demand and the ecosystem. Few studies have been conducted with the WEFt, such as the study on assessing and quantifying the amount of water consumed in a terrestrial water resource area (Su et al., 2018). Studies evaluating required for watershed utilization (Cai and Zhang, 2018; Ramachandra et al., 2020) and other studies proposed new EF models for land-to-water allocation in ecological domestic water requirements (Wang et al., 2020).

Besides WEFt, EEF was also proposed to evaluate the influence of energy use and human economic activities on the environment, biological resources, and fossil energy (Stöglehner, 2003). Stöglehner (2003) states that the EEF can be evaluated in three steps: the first is the area needed to produce the same energy as fossil fuels. The second is the area needed to absorb the carbon emissions from fossil fuels, and another step is the land required to offset the energy consumption with renewable resources (Haberl et al., 2001). Stöglehner (2003) also proposed a new EEF model incorporating Krotscheck and SPI analysis, while Papathanasopoulou and Jackson (2009) included the Gini coefficient approach in the existing EEF approach. Using EEF, different indicators are developed to evaluate different energy resources' contributions to ecological carrying capacity (Borucke et al., 2013; Yang and Fan, 2019).

The FEF analysis approach is applied to quantify the EF in the consumption of different types of food, whether crops, processing industries, or livestock. The Kissinger (2013) study in Canada's food supply has shown the relevance of applying FEF methodologies to compare food consumption at national and international levels. With the FEF approach, the researchers concluded that the amount of land required for meat production depends on different livestock systems, feeds, and livestock types (Elferink and Nonhebel, 2007). Other studies showed that promoting FEF can influence people's food consumption behaviors to the reality of ecological demand (Wansink and Sobal, 2007). This involves educating people about the EF of different types of food and beverages consumed in their homes (Collins and Fairchild, 2007). It could also be done by promoting land-use efficiency and yield management (Galli et al., 2017; Van Noordwijk and Brussaard, 2014).

Table 1
Per capita footprint and biocapacity comparison.

Country	Footprint per capita (Pc)	Biocapacity per capita (Pc)	Biocapacity deficit per capita (Pc)
Gabon	2.02	26.31	24.29
Cameroon	1.17	1.69	0.52
Nigeria	1.16	0.7	−0.47
Ghana	1.97	1.35	−0.62
Tunisia	2.34	0.93	−1.4
Algeria	2.12	0.59	−1.53
Egypt	2.15	0.56	−1.59
South Africa	3.31	1.15	−2.16
Mauritius	3.46	0.71	−2.75

Thus, based on these and other theories summarized in Table 2, the authors attempt to extend them by considering several areas of the complexity and challenges of WEF resource sustainability from the WEF nexus perspective.

3. Methodology

The methodology consists of four steps of analysis: 1) assessing the EF of each water, energy, and food resource; 2) calculating the ecological biocapacity of the resources concerned; 3) assessing the ecological balance by comparing the EF and EB of a given resource. Based on the WEF nexus perspectives, the fourth step evaluates the nexus index between the ecological balance of water, energy, and food resources. This fourth step is based on standardized EF and EB results for each resource by country. Fig. 1 depicts the approach used in this study to estimate the WEBEB nexus index with many other variables.

3.1. Study areas

The study was conducted in nine African countries: Algeria, Egypt and Tunisia in North Africa; South Africa and Mauritius in Southern Africa; Ghana and Nigeria in West Africa; Cameroon in West Central Africa; and Gabon in Central Africa. Case study countries are selected based on their WEF-related SDGs performance and their highest WEF security nexus index, above half of the maximum (Fig. 2).

The data presented was collected from a global study of the WEF nexus indices calculated by Simpson et al. (2020), where Mauritius has the highest WEF security nexus score with 6.6, followed by Gabon with 0.59, and all other countries have an index above 0.5 as the maximum score is 1. In addition, the most selected countries are positively ranked in the Global Hunger Index (GHI), especially the countries of North Africa and GDP per capita. Regarding energy security (SDG7), Algeria, Egypt, Mauritius, and Tunisia all have 100% access to electricity and 100% access to clean cooking technologies (SDGN, 2020). South Africa has 85% access to electricity, while Gabon has 91% access to electricity and over 80% access to clean cooking (SDGN, 2020). Countries in the western to central parts (Nigeria, Ghana, and Gabon) have less access to energy per capita, but more than 80% of their energy types come from renewable resources, which is critical to achieving the SDGs (SDGN, 2020).

3.2. Calculating water ecological footprint (WEFt)

The WEFt is calculated in agriculture, industrial, domestic, household activities and the water reserve for ecosystem functions. Data used in this calculation are from water consumption, including total water renewable withdrawal (10^9 m^3/yr) for each country in different demand sectors mentioned above. The data considered from different global known platforms, including the World Bank (2017), Food and Agriculture Organization (FAO, 2018a; FAO, 2018b; FAO, 2019a; FAO, 2019b), and the UN SDGs national profile (SDG6) databases (Van Noordwijk and Brussaard, 2014), which is based on the most recent data available (from 2017 to 2018). The calculation of WEFt was based on the following formula equation Eqs. (1) and (2)–(5) (Su et al., 2018).

$$WEFt = P.efw = rw\left(\frac{w_{Ai}}{Pw}\right) \tag{1}$$

where WEFt (ghm^2) is the sum of EF of water resources and P is the people, ewf is the EF (per capita) of water resources, rw is denoted as the global balance factor of the water resources, W_{Ai} is water withdrawal for each sector i. Hence in detail, the WEFt is calculated as:

$$WEFt_a = rw\left(\frac{Wa}{Pw}\right) \tag{2}$$

$$WEFt_h = rw\left(\frac{Wh}{Pw}\right) \tag{3}$$

Table 2
A Summary literature reviewed in WEFEB index contextualization.

Author + years	Research key content with EF.	Country	Outputs
Amowine et al. (2021), Borucke et al. (2013), Wackernagel and Rees (1998), Sarkodie (2021), Lin et al. (2021), Charfeddine and Mrabet (2017), Hanna et al. (2013), Wackernagel et al. (1999), Udemba (2020), Ekeocha (2021)	Developing and Expanding methodology of EF in human economy, country economy, natural resource use, carbon emissions Evaluate EF in agriculture, energy consumption, urbanization, economic development, Sustainable economy	Canada, global, African countries 15 countries per continent, 200 global countries Africa, Ghana, Nigeria, 15 MENA countries	Global and some national EF profiles. EF nowcasting, Status conditions of the African Global Biological Capacity, Introduce a comprehensive model of continent EF
Author + years	**Water ecological footprint (WEFt)**	**Country**	**Outputs**
Huang et al. (2008), Li et al. (2020), Su et al. (2018), Lenzen et al. (2003), Zhao et al. (2021), Budihardjo et al. (2013), Dai et al. (2019), Wackernagel and Rees (1996).	Introduce approach, integrating WEFt in urban water resource management, Global water balance, water quantification	China, Australia, Indonesia	Analyze water production for water resources, including surface and groundwater, human and environmental water demand.
Author + years	**Energy ecological footprint (EEF)**	**Country**	**Outputs**
Yang and Fan (2019), Chavez-Rodriguez and Nebra (2010), Stöglehner (2003)	Developing EEF concept and its applications in different fuel, land type equivalence factor for producing certain energy and GHG	Brasilia, USA, China, 52 global countries, Silk Road Economic Belt countries	An approach for evaluating sustainable energy demand and supply.
Author + years	**WEF nexus**	**Country**	**Outputs**
Belinskij (2015), Yang et al. (2017), Willis et al. (2016), Simpson et al. (2020), Fernández-Ríos et al. (2021), Mahlknecht et al. (2020)	Index quantifications	Global countries, Southern African countries, Mekong transboundary shared river countries, Latin America and the Caribbean	Give evaluation progress profile in WEF security of given countries
Author + years	**Food ecological footprint**	**Country**	**Outputs**
Kissinger (2013), Lin et al. (2016), Alexander et al. (2016), Richts et al. (2011)	Developing concept, food process conversion into flesh EF, Yield factor assessment	Canada, USA, Global countries	Global consumption patterns, agricultural land use area requirements
Author + years	**Ecological balance**	**Country**	**Outputs**
Tamburino and Bravo (2021), Shao (1986), Eliseeva (2017), May (2005), Yang (2016), Mahdavi and Ries (1998), Kimura et al. (2007), Opp (2015)	Use eco-balance for human development, agriculture land, food production and consumption, in Economics of Ecosystems and Biodiversity (TEEB), solar electricity transmission, construction design	Global countries, tropical African counties, Tanzania, USA, Brazil, Argentina, China, North Africa and Europe,	Global countries' status of eco-balance with natural resource consumption. Eco-balance with food production. Pathways, agricultural system, and building design.

$$WEFt_i = rw\left(\frac{Wi}{Pw}\right) \tag{4}$$

$$WEFt_e = rw\left(\frac{We}{Pw}\right) \tag{5}$$

where $WEFt_a$ is denoted as the water ecological footprint in agriculture, w_a is the water withdrawal in agriculture; eq is denoted as an equation. The $WEFt_h$ is for household and W_h water consumption in households. The $WEFt_i$ is the ecological footprint for water use in industries, w_i as water consumed in industrial stages. Meanwhile, $WEFt_e$ is the footprint for environmental water,

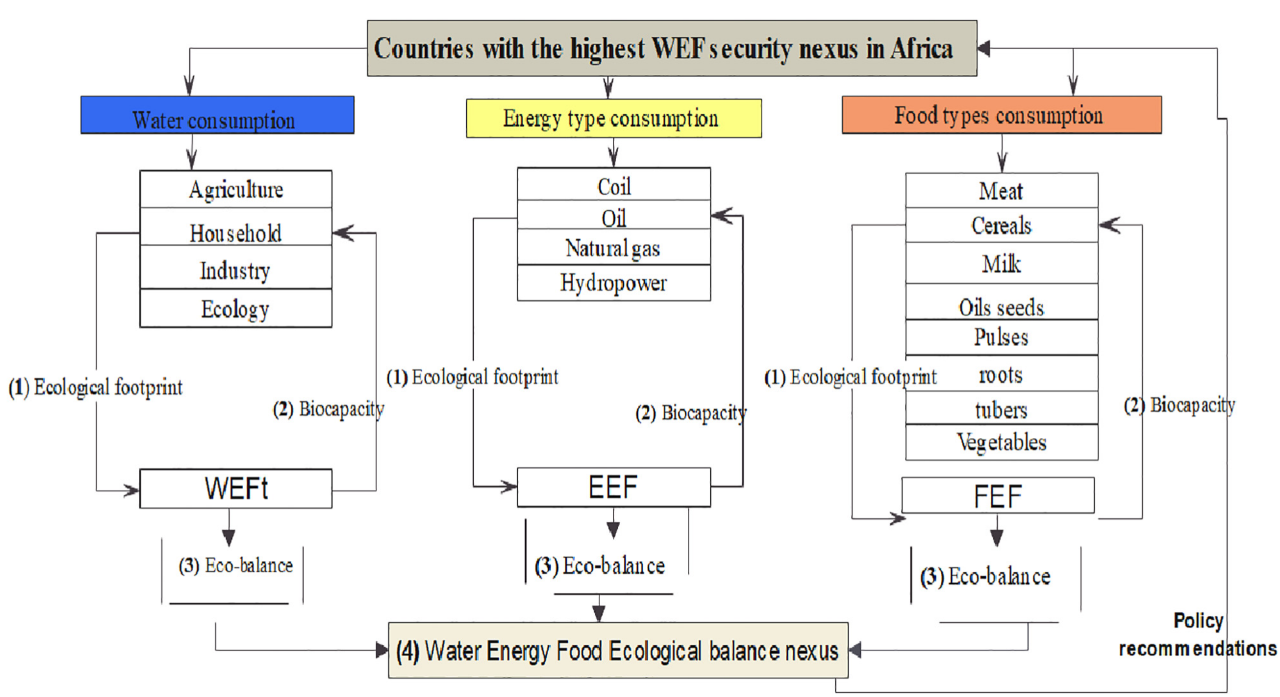

Fig. 1. The methodological approach in developing the WEFEB nexus index.

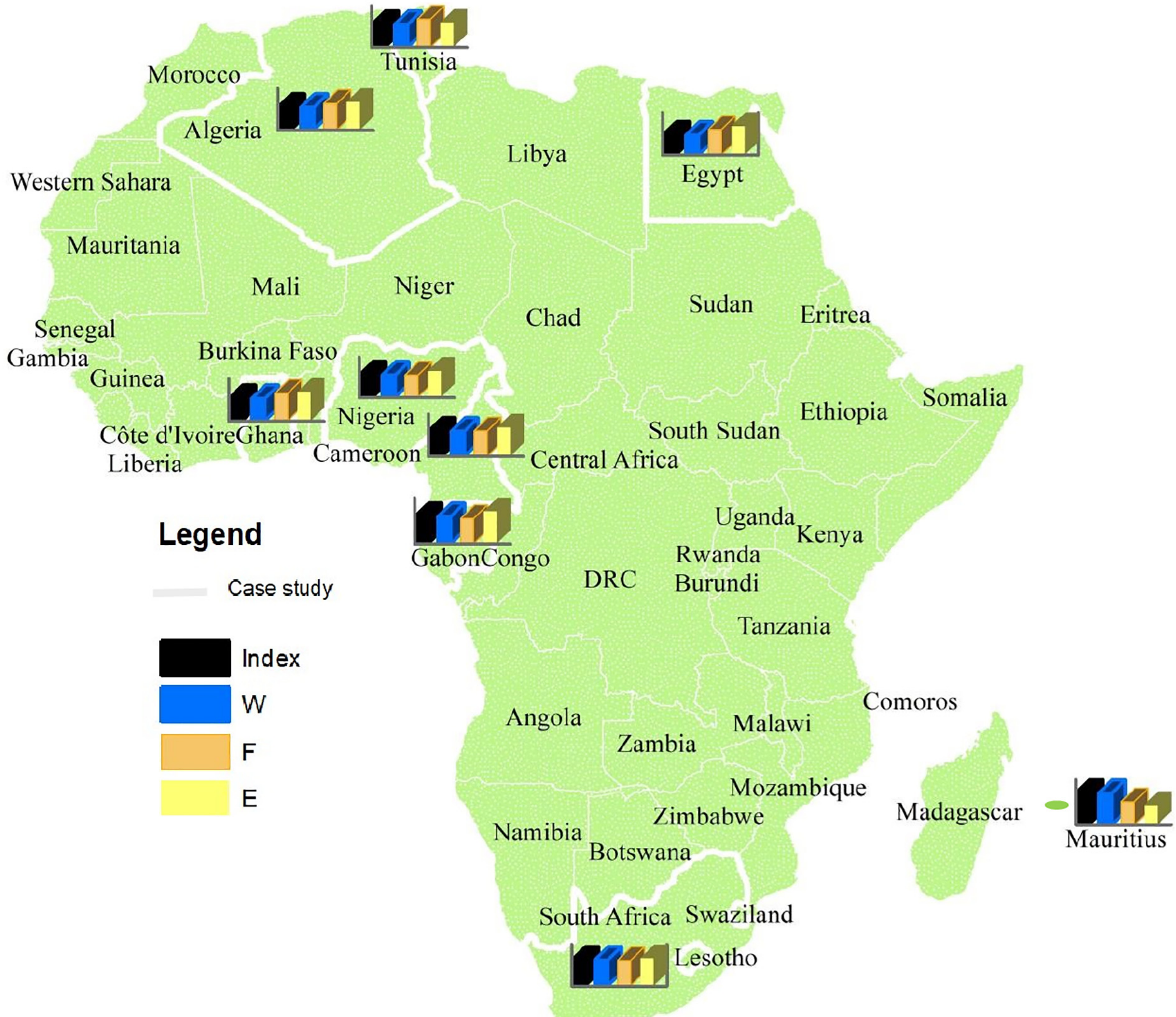

Fig. 2. Case study countries with the highest WEF nexus index. The index represents the WEF nexus index. W represents the value of the water sub-index, F for the food sub-index, and E for the energy sub-index.

and W_e are water saved for ecological functions. For global balance, this study uses global equivalent factors such as 3140 m^3/hm^2 as the global average productivity of water resources (pw) and 5.19 as the water balance factors taken from WWF2002 (Huang et al., 2008; Zhao et al., 2021). Further ecological biocapacity (EBC) for water was obtained through the following expression of Eq. (6) (Budihardjo et al., 2013; Wackernagel and Rees, 1996).

$$EBC = A_i \cdot y_d \cdot rw \tag{6}$$

where Ai is the total of inland water areas and groundwater coverage in ha by country. The inland water coverage is gathered from (FAO, 2019b), while data of groundwater coverage land are collected from different literature of national or global studies, mainly from a study of Waltina Scheumann (2008) on Africa's transboundary groundwater distribution and other studies (Gumma and Pavelic, 2013; Margat and Van der Gun, 2013; Richts et al., 2011). Yd yield factor is calculated as the sum of renewable water produced per capita in a country compared to the global water production per capita (Dai et al., 2019).

3.3. Energy ecological footprint (EEF) calculation

From previous studies, calculations of EEF were expressed as the land need for fossil energy (Stöglehner, 2003; Wackernagel et al., 1999). It is also taken as the land bio-productivity required to take off carbon emissions from energy used which expresses global woodland average carbon sequestration (Borucke et al., 2013). Within this study, EEF is calculated by considering four core energy consumption types (coal, oil, natural gas, hydropower) in terajoule (TJ) with data from (IEA, 2018). This study follows the ideas of land area required to absorb carbon emissions with Eq. (7) to calculate EEF (Borucke et al., 2013; Yang and Fan, 2019):

$$EEF = P \times \text{eef} = P \times \sum_{C=1}^{n} \frac{Ei \times ri}{Ai} \tag{7}$$

where *eef* is the per capita *EEF*; *Ei* is the energy used *i*; *ri* is the equivalence factor for the area type of the *i*th energy resource; and Ai is the global average heat output of type of energy i, for which coal is 0.055 TJ/ha, oil is 0.071TJ/ha, natural gas is 0.0 93TJ/ha, and hydropower is 1TJ/ha (Wackernagel and Rees, 1998). The land type equivalence factor for producing certain energy types is taken from the previous study of Stöglehner (2003) that assumed that to produce 1 MJ of coal need 20 m^2a/M.J., fuels oil need 11.99 m^2a/M.J., natural gas 10.42 m^2a/M.J. while Electricity water power needs 0.01 m^2a/M.J.

Further EBC is also calculated using forest land and grassland as defined in previous literature as main land types used to absorb CO_2 emissions apart from other land types that exist in EF calculation (Lin et al., 2018a; Ni, 2002) with the following formula (Yang and Fan, 2019):

$$EBC = P \times ebc = P \times \sum_{l=1}^{n} A_l \times ri \times yi \tag{8}$$

where *ebc* is the per capita *EBC*, A_i is the area of land type *i*, and *ri* and *yi* denote the equivalence factor and yield factors of land type *i*. Each country's yield factor for forest and cropland use (Table 3) was taken from the GNF database, while the equivalent factors are 1.28 for forest and 0.46 for grassland (GNF, 2021).

3.4. Food ecological footprint (FEF) calculation

The analysis of FEF is also calculated in 8 different types of food sources cereals, meat, milk, oilseeds, pulses, roots and tubers, fruits and vegetables consumed at latest years 2018–2019, from FAO (2018a) and Helgi (2017) with given equation Eqs. (9)–(10) proposed by Kissinger (2013):

$$FEF = \frac{Qc}{Gy} \times EQF \tag{9}$$

where *QC* is denoted as the annual food consumed (tones) from agriculture and food commodity in 8 different food types mentioned above, *Gy* is the global average yield of each food type (hg/ha) collected from (FAO, 2019a); EQF is cropland equivalent factors which are 2.39 (GNF, 2021). Furthermore, Food Ecological Biocapacity (FEB) is calculated through the following expression (Wackernagel and Rees, 1998):

$$EBC = An \times Ywp \cdot EQF\prime \tag{10}$$

An is the quantity of land compulsory to produce each type of food consumed from domestic food sources. In assessing the surface of land required (An) to provide the consumer needs, some conversion has been made for some food types that are not consumed at fresh level, which mostly need to be processed back into their raw or fresh equivalent (Kissinger, 2013). These include food grains and other food types that are not grown in land areas, such as foods derived from livestock products like meat and milk (Alexander et al., 2016; FAO, 2000; Ritchie, 2017). Two values of EQF, such as 2.39 for cropland, are used for agricultural food sources and 0.46 for grassland used for livestock food productions. The Yields factor (YWP) was calculated following Eq. (11) (Lin et al., 2016)

$$\mathrm{Ywp} = yF_N^L = \frac{Y_N^L}{Y_G^L} \tag{11}$$

where:
YF^L_N is denoted as Yield factor for a certain nation and land use type, Y_N^L is Yield for a given country and food type, t nha-1, and Y_G^L is the global-average yield for a given food type.

3.5. Eco balancing of water, energy, and food ecological footprint indexing

Eco-balance is a new concept based on the EF framework and reflects the actual ecological load of the country while maintaining comparability across countries (Tamburino and Bravo, 2021). This analysis uses the EF biocapacity indicators calculated above for each resource and population through Eqs. (13)–(15) (Tamburino and Bravo, 2021).

$$\mathrm{WEB} = 1 - \frac{\mathrm{WEFt}}{\mathrm{WBC}} \tag{12}$$

$$\mathrm{EEB} = 1 - \frac{\mathrm{EEF}}{\mathrm{EBC}} \tag{13}$$

$$\mathrm{FEB} = 1 - \frac{\mathrm{FEF}}{\mathrm{FBC}} \tag{14}$$

While WEB is water eco-balance, EEB is energy eco-balance while FEB is food eco-balance. Ecological balance indicates that sustainability has a positive value from $(-\infty, 1)$. In other words, having a positive biocapacity have a chance to be in a positive balance. After each sector eco-balance calculation, the water-energy-food eco-balance (WEFEB) nexus index was also calculated following Eq. (15) (Yang et al., 2017).

$$WEFEB\ nexus\ index = [V_1(WEB) + V_2(EEB) + V_3(FEB)] \tag{15}$$

The WEFEB nexus index is denoted as the water-energy-food nexus balance index within the same range of $(-\infty, 1)$ and is a positive score, close to 1, indicating a high ecological balance between the three sectors productivity within their ecological biocapacity. The coefficients *V1*, *V2*, and *V3* are weighting factors equal in all sectors at 0.33 due to the WEF nexus philosophy that all resource sectors should be treated equally and summed up to 1 (Yang et al., 2017). Finally, the study results were analyzed and presented using R software (version R.4.0.3).

4. Results

4.1. Water, energy, and food ecological footprint

4.1.1. Water ecological footprint

The results presented in both Fig. 3a and b give the percentages of water withdrawal activities and the percentage of WEFt sector activities relatively. The percentage ratio of water withdrawn for each sector in Fig. 3a maintains its percentage ratio in the WEFt with no obvious change, except for the withdrawal dominance ratio in Fig. 3b. In a geospatial context, many Western to Central African countries have a high percentage of ecological water supply relative to their WEFts. For example, 93% of the WEFt is taken by ecological water in Gabon; 98% for Cameroon, 80% for Ghana, and South Africa holds 80% and Nigeria 78%. This ecological water is referred to as water needed to maintain the environment.

Agriculture presents significant demand for water resources relative to their WEFt requirements; for instance, in Egypt, agriculture accounts for 80% of total WEFt, 71% in Tunisia, 69% in Mauritius, and 55% in Algeria. Further results in Fig. 3c show WEFt per capita in each sector by a country where Gabon is the highest, with a WEFt per capita of 102 gha, and most of its percentage goes to the ecological water demand. Mauritius has the second-highest WEFt per capita (16.3gha), detrimental to human activities, including agriculture. Countries like Gabon and Cameroon also have a high WEFt per capita from ecological water.

4.1.2. Energy ecological footprint

EEF analysis results for coal, natural gas, oil, and hydropower are presented in Fig. 4. Oil and natural gas are the primary energy resources consumed in many countries (Fig. 4a). Mauritius and South Africa also have extensive use of coal, while Cameroon, Gabon, and Ghana also significantly

Table 3
Yield factor of cropland and forestland by country.

Countries	Algeria	Cameroon	Egypt	Gabon	Ghana	Mauritius	Nigeria	South Africa	Tunisia
Yield forest	0.44	0.73	0.003	1.09	0.61	0.60	1.84	0.09	0.44
Yield cropland	0.36	0.73	0.7	0.36	1.13	1.50	0.84	0.51	0.28

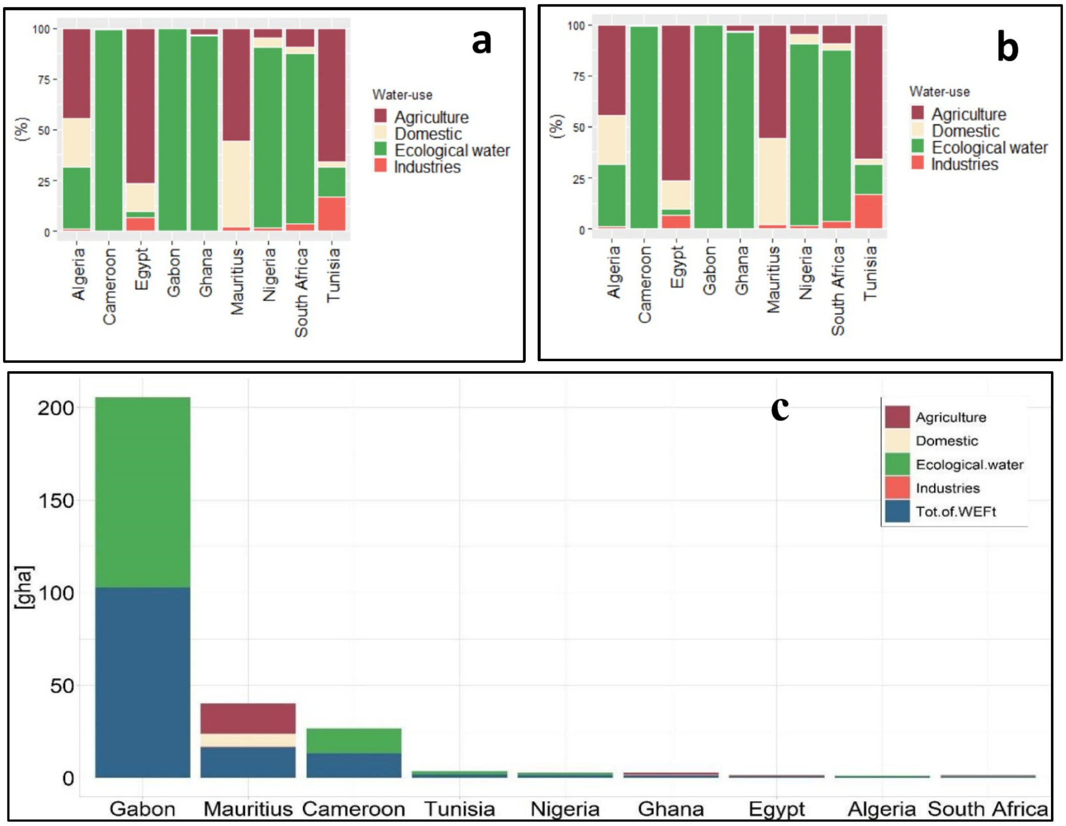

Fig. 3. Percentage of water withdrawal in given sectors by countries (a), Percentage of the WEFt in given sectors by countries (b), WEFt per capita in given sectors by country (c).

consume hydropower resources compared to other countries. Mauritius, Algeria, and South Africa have the highest EEF per capita. For example, Mauritius's high EEF is predominantly from coal consumption; Algeria is used for natural gas, and South Africa is used for coal energy. The evidence found that hydropower energy resources have less influence on EF demand than other energy resources. For example, in Gabon, hydropower accounts for 19.5% of the total energy consumed in the country, but its percentage share of EEF, among other energy resources, is only 2.05%.

On the contrary, the percentage of oil and coal in the EEF steadily increases compared to the shared rate of total energy consumption. In the case of Nigeria, coal accounts for 0.15% of total energy consumption, but in terms of EEF, it is shared at 1.02% of total energy resources. Similarly, oil shared 53.4% of Nigeria's total energy consumption, which took 66% of total EEF, and such an increase is common to all countries. Although Mauritius is a small national island, it has the highest per capita EEF with 1.602 gha. Mauritius, for example, uses coal and oil, which it shares with 0.926 and 0.676 EEF, respectively, and consumes very little hydroelectricity. Meanwhile, Cameroon has the lowest EEF with 0.116 gha per capita.

4.1.3. Food ecological footprint (FEF)

The FEF analysis results in Fig. 5a show percentages of food consumption among the eight food types, namely cereals, meat, fruit, milk, vegetable oils, root, and vegetables. In most countries, vegetables account for the highest percentage of food tonnage consumed compared to the other food types. This is the case, for example, for 75.8% in Algeria, 75.9% in Egypt, 83.5% in Tunisia, and 69.5% in Mauritius. However, there are some exceptions, like Ghana, which has a higher consumption of roots than vegetables (64%).

Compared to the FEF and the WEFt, the FEF showed an interesting note of significant variations in the percentage of consumption of food types with their relative FEF (Fig. 5b). Vegetables and fruits dominate the total percentage of food consumption in most countries but appear to be less insignificant in total FEF demand. In Algeria, vegetables represent 75.9% of the total tonnage of food, but their percentage in the total FEF is almost zero (0.001%). Cereal, on the other hand, represents 8.7% of Algeria's total food consumption but requires 68.5%of the total food types FEF. Meat also accounts for 0.8% of Algeria's total food consumption but contributes to the FEF with 15.2%.

In Gabon, meat represents 5.7% of total food consumption but uses 40.5% of total FEF. Nigerians were found among high consumers of pulses, which account for 36.4% of total food consumption and have an ecological footprint of 15.6%. Cereals and root foods are also dominant in FEF demand in Nigeria, which takes 38.2% and 37.8% of the total FEF, respectively. The results of Fig. 5c also show the FEF pc for each crop type; Ghana has the highest FEF with 0.29 gha/pc, followed by South Africa with 0.28 gha/pc. In detail, Ghana is a high per capita FEF from root with 0.19 gha/pc, South Africa is the highest for meat consumption with 0.12 gha/pc, and Egyptians have the highest FEF for cereals with cereals 0.19 gha/pc.

4.2. Water, energy, and food eco-balance (WEBEB) index

4.2.1. Water eco-balance (WEB) index

The results in Fig. 6a compare countries WEFt required in water resources activities with their corresponding eco-balance (EB). Having a high EB relative to EF indicates that countries are able to manage resource use at a level that is not higher than their ecosystem resource supply capacity (GNF, 2021). The results show that four countries, Gabon, Cameroon, Ghana, Nigeria, and Tunisia, have a higher EBC than their WEFt. Cameroon is the highest, followed by Gabon. In the same analysis in Fig. 6b, a WEB is calculated, Nigeria and Cameroon have the highest score of 0.84 and 0.81, and other countries such as Gabon, Ghana, and Tunisia are in a positive range above zero, which proves their improvement in water resource ecological sustainability. In contrast, countries such as Algeria, Egypt, Mauritius, and South

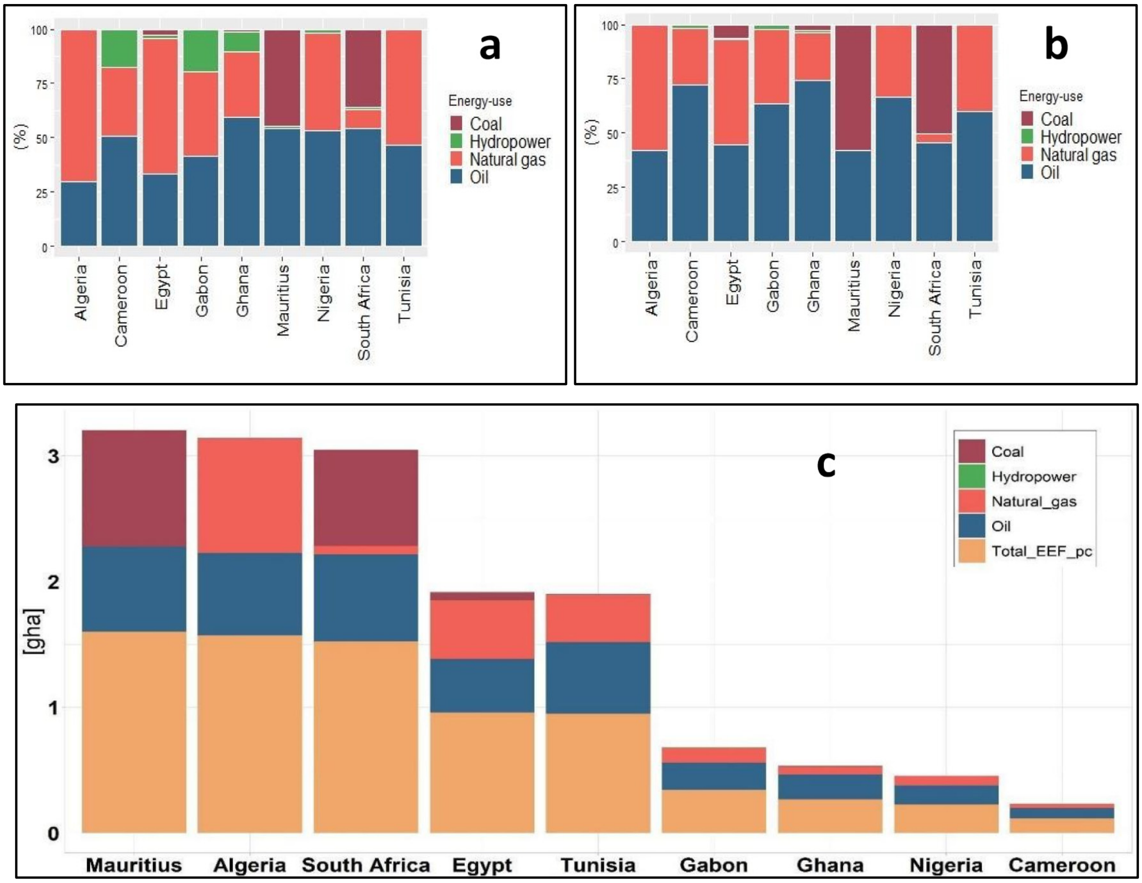

Fig. 4. Percentage of energy type consumption by country (a), percentage of EEF in a given energy resource by country (b), and Per capita EEF in a given energy type by country (c).

Africa have a negative WEB range, meaning that they use significantly more water than their land can provide (Fig. 6).

In addition to the previous analysis, which was based on how countries balance their EBC against the WEFt in terms of current water withdrawal (Fig. 6b), Fig. 6c describes the impact of increasing consumption of water resources in the face of meeting EF demand and water supply. A scenario was proposed using the Falkenmark index; the country is water secure once withdrawal exceeds 1700 m^3/capita/year (Mahlknecht et al., 2020). The results revealed unexpected variations across countries using more or less than the minimum water balance. Egypt, for example, recently withdraw 561.8 m^3/(capita/year) but already has a score of −20, indicating that the country is unbalanced; but once the country reaches 1700 m^3/capita/year, the WEB score will steadily decrease to −159. Tunisia also withdraws 390.5 m^3/(capita/year), which is equivalent to a positive balance index of 0.68, but once it reaches 1700 m^3/capita/year, the country will face an imbalance in the ecological index of −0.44. Algeria recently uses 270.9 m^3/capita/year, which is equivalent to an imbalance of −15.7, and the country could gradually fall to an imbalance of −63.5 when it withdraws 1700 m^3/capita/year. On the other hand, Mauritius showed a positive gain score of −0.6 to 0.54, like the other countries, because they have already used more than 1700 m^3/capita/year, and the initiative to reduce the present quantity of water withdrawal can positively affect their current state of the water balance.

4.2.2. Energy ecological balance (ECB) index

The results in Fig. 7a indicate that many countries, including Algeria, Egypt, Mauritius, South Africa, and Tunisia, use a higher EEF than their EBC. Gabon, Cameroon, Ghana, and Nigeria are in a positive range with high EBCpc greater than their EEFpc demand indicating a good indicator of eco-balance.

Fig. 7b shows the ECB results; Cameroon is the most ECB country, with a score of 0.71, and Nigeria also showed some good performance with 0.44, while the lowest was Mauritius with −3, followed by Algeria with −2.88 and South Africa with −2.80.

4.2.3. Food ecological balance (FEB) index

The results in Fig. 8 show the extent to which the countries' FEF is balanced against the corresponding EBC per capita. Only four countries, Gabon, Ghana, Nigeria, and Cameroon had a positive EB in their food consumption, while the remaining six countries showed a negative balance. Such disparities in many countries show that most countries use more food resources than their land productivity, especially countries like Mauritius have a high negative FEB index of 10.07.

a. Water, energy, food, ecological balance (WEFEB) nexus index

The WEF Eco-balance Nexus Index (WEFEB) shows that some countries perform better in the resource sector than others (Table 4). The negative score of one sector should influence the failure of the entire system of three resources' productivity due to its intrinsically connected nature, which should motivate sectors to work closely and brings mutual benefits (Hoff, 2011). Table 4 results show an imbalance between productivity and ecological capacity. Critically within the results, some countries have a negative balance in all three production sectors: South Africa, Algeria, Mauritius, and Egypt.

The WEFEB index scores illustrated some countries with positive ecological balance in production and consumption of WEF resources, such as Cameroon with an index of 0.59, Gabon, Nigeria with 0.41, Ghana with 0.31, and Gabon with 0.29, while other countries ranged in negative-index indicating being vulnerable ecological unsustainability.

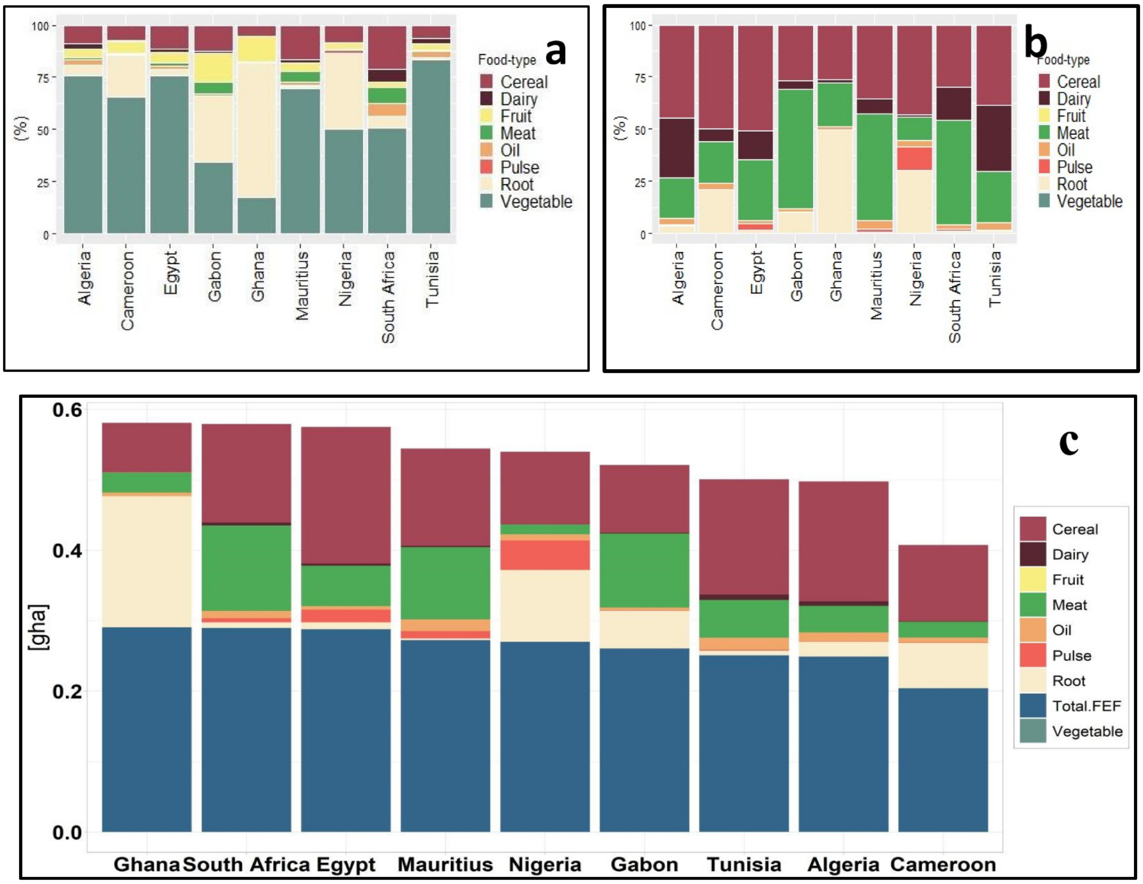

Fig. 5. Percentage of food type consumption by country (a), percentage of FEF in a given food resource by country (b), and Per capita FEF in a given food type by country (c).

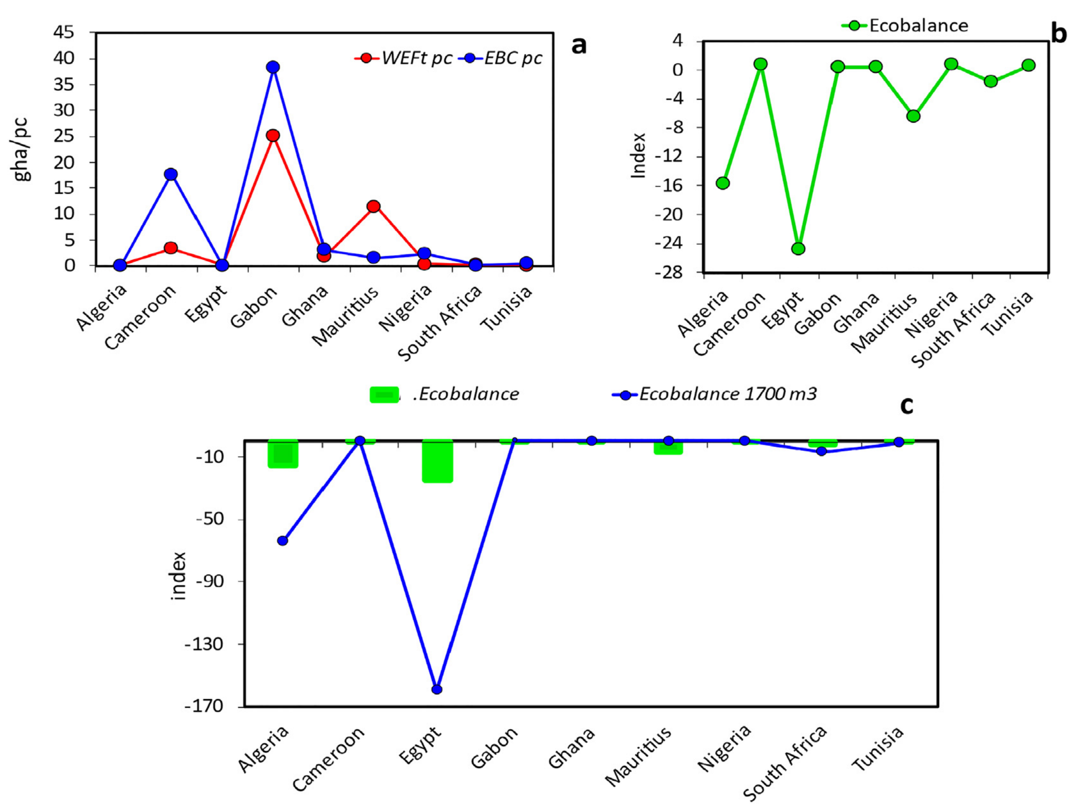

Fig. 6. Gha water ecological sustainability score: per capita WEFt versus per capita EBC (a), per capita eco-balance index (b), percapita eco-balance index of national water consumption versus a 1700 m^3/(capita/year) per capita water consumption scenario (c) of nine highest consumers of WEF resources.

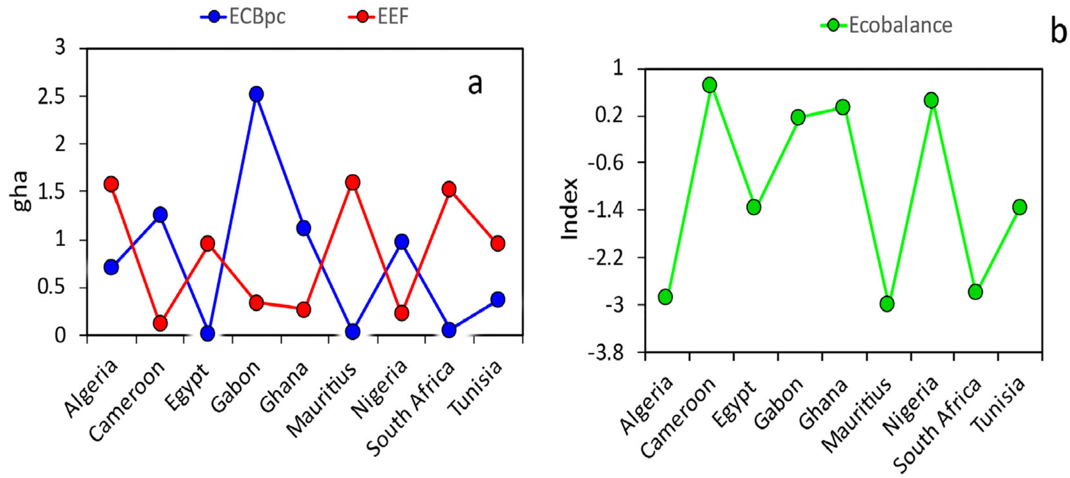

Fig. 7. Per capita EEF versus per capita EBC (a), per capita eco-balance index (b) of nine highest consumers of WEF resources.

5. Discussion and research implications

5.1. Water energy ecological footprint and balance index

Using the WEFt approach adds a new dimension of valuing the ecological water role in regulating ecological sustainability, which does not count in the water footprint approach (Su et al., 2018; Yang et al., 2019). For instance, a country or region with a large amount of ecological water can maintain its ecological balance despite having a large water footprint. This is in the case of Gabon's highest WEFt per capita with 102.8 gha, but 93% of this water is dedicated to ecological restoration (Fig. 3), making it one of the few countries with a positive eco-balance (Fig. 6). Furthermore, many West African countries, such as Nigeria, Ghana, and Cameroon, have the largest annual water footprint per capita but maintained the countries' positive eco-balance due to the ecological water reserved (Hoekstra and Mekonnen, 2012).

The scenario Falkenmark index (1700 m^3/capita/year) showed many countries are already in ecological imbalance; any change that leads to higher water consumption is likely to worsen the situation significantly. The analysis is similar to the previous study, which indicated that the Middle East and North Africa are at high vulnerability to water scarcity despite extracting an average of 609 m^3/capita/year or less than a tenth of the global average of 6080 m^3/capita/year (Mourad et al., 2019). Egypt, Algeria, Tunisia, Mauritius, and some arid regions of South Africa are leaving a considerable EF to meet the immense demand generated by daily human life, as water availability in the region is limited (Mourad et al., 2019). The study is also similar to the latest findings of Tuyishimire et al. (2022) on water footprint assessment in Africa. The case study countries have presented the largest water deficit over the period 200–2018, especially for food agriculture and livestock water footprint (Tuyishimire et al., 2022).

Many case study countries have limited internal water resources, with less than 1000 m^3/capita/year of total renewable water resources. But still, they are among the highest water footprints consumers in Africa, for example, Tunisia, with 2226 m^3/capita/year of WF, Algeria, 1606 m^3/capita/year, and South Africa, 1261 m^3/capita/year (Mourad et al., 2019; Mwendera and Atyosi, 2018). This may explain why the results of concerned countries are in an ecological water imbalance, implying that they consume significantly more water than they have. The challenges of high-water demand are a global problem. Recent studies in China using the WEFt approach have shown a dramatic increase in ecological water imbalance with economic growth, modernization and population growth (Dai et al., 2019; Su et al., 2018; Wang et al., 2020). More generally, physical and socio-economic problems, such as the country's location in unsuitable areas, population growth, climate change, unsustainable use of resources, poor policy management, and lack of collaboration, should also contribute to the country's water resource shortage (Cumming et al., 2018; Hamed et al., 2018).

5.2. Energy ecological footprint and balance index

The energy ecological footprint (EEF) assists in understanding the coupled usage of energy of a country or given region or energy resource

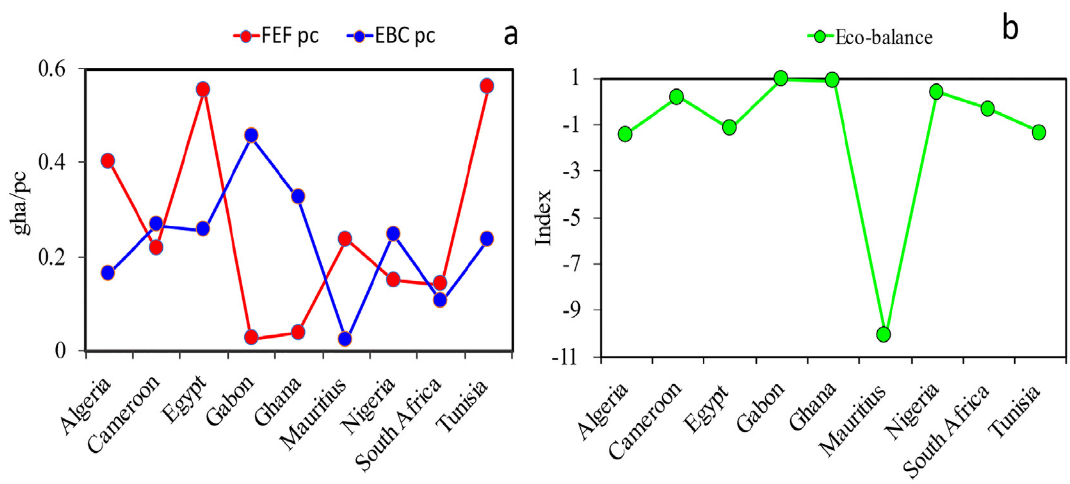

Fig. 8. Per capita FEF versus per capita EBC (a), per capita eco-balance index (b) of nine highest consumers of FEF resources.

Table 4
Water energy food eco-balance index value.

Countries	WEB	EEB	FEB	WEFEB nexus index
Egypt	−8.291	−0.456	−0.069	−8.82
Mauritius	−2.163	−1.001	−3.865	−7.02
Algeria	−5.247	−0.961	−0.262	−6.47
South Africa	−0.535	−0.936	−0.675	−2.14
Tunisia	0.228	−0.452	−0.099	−0.32
Ghana	0.138	0.113	0.038	0.29
Gabon	0.115	0.056	0.139	0.31
Nigeria	0.282	0.145	−0.017	0.41
Cameroon	0.27	0.239	0.078	0.59

type (Yang and Fan, 2019). The study's findings revealed that preserving the ecological balance in the energy consumption of a given country has still compromised with different challenges. One explanation is that more countries are consuming non-renewable energies, which relative to high EF, particularly for oil, coal, and natural gas (Fig. 5). Algeria, for example, has been shown to consume more than 31% of all the LPG consumed in Africa, and Egyptians consumed 41.1% of all LPG from 1990 to 2017 (Muhirwa et al., 2021). Coal and gasoline are two of the most explored resources in South Africa, and coal accounts for 95% of the country's electricity, while Nigeria is the top consumer of kerosene, making both countries the major contributors to EEF in Africa (Muhirwa et al., 2021; Olowu et al., 2018).

Similarly, the dominance of oil and coal in EEF is substantiated in a case study conducted in China between 1978 and 2010 (Huimin, 2013). The extensive use of non-renewable energy sources is also harmful to the environment and contributes significantly to climate change impacts (Usman et al., 2020). For example, the case study countries contribute 48.14% of total greenhouse gas emissions in Africa (Muhirwa et al., 2021). Despite a study indicating that a 1% increase in renewable energy in Africa's energy consumption could result in a 0.04% reduction in the EEF in Africa (Usman et al., 2020), the results indicate that renewable energy does not contribute significantly to the Middle East and North African (MENA) region's EEF footprint balance in Africa (Letafat and Tarazkar, 2021). This is because renewable energy resources contribute a negligible amount of energy to the continent's total, as demonstrated in this study's case of the EEF hydro resource (Fig. 3a). It was also mentioned in a study of solar energy consumption in Africa, which found that it accounts for less than 1% of the energy used in the world and only 0.03% of the total energy used on the continent (Gonzalez Sanchez et al., 2020). Similar to the WEFt, the current EEFt imbalance of countries are relative to their biocapacity deficit as classified by the GFN (Table 2). For example, a country like Mauritius, one of the smallest countries in Africa, has the worst ecological imbalance in energy consumption part, which corresponds to the GFN classification of biocapacity deficit per capita (Pc) of 2.75.

5.3. Food ecological footprint and balance index

The findings indicated that EF varies by food type, which can assist consumers in selecting foods with a lower FEF demand. The average land requirement for food in all the case study countries is 48.8% cereals, 23.7% root crops, and 16% meat. These results contrast with a recent similar study in Canada, which found that 63.6% of FEF was for livestock feed, 36.4% for crops, including 9% for cereals, 9.5% for oils and 9.5% for others (Kissinger, 2013). However, some countries, such as South Africa and Gabon, require 43% and 41% more land to meet their total food consumption demand for meat FEF. High consumption of animal-based foods in some countries may be related to developing food industries unique to Africa, such as dairy and meat processing (Reardon et al., 2021). In Africa, industrial food processing is limited, and over 70% of Africans obtain their food directly from the farm, especially root crops pulses (Biteye, 2021). Furthermore, animal-based food production in Africa is still insufficient compared to other continents, and it accounts for 5.9% of global output, compared to 41% in Asia, 31.5% in America, 15% in North America, and 14% in the European Union (Ritchie and Roser, 2019).

Furthermore, the results of this study show that the maximum FEF per capita is 0.3 gha/capita among the countries studied, which is in contrast with a study conducted in Africa by Hanna et al. (2013), which found an average of 2.02 gha/capita land need for food production. Apart from the range of years of the study conducted, the significant difference could be due to the different methodologies or data that two studies used; for example, Hanna et al. (2013) calculated FEF according to the conventional calculation of EF considering cropland, forest ecosystems, and grazed land. On the other hand, the results are in some sense consistent with the findings of another study that FEF in Africa was about 0.44 gha/capita (Ewing et al., 2010).

Although some crops, such as root crops, do not require as much FEF as cereals or livestock feed, some countries have surprisingly shown that they need more FEF to grow root crops, such as Ghana, Cameroon, and especially Nigeria, where starchy roots have a high land requirement because they are a commonly consumed food (Chiaka et al., 2022). The concern is that a large land area is used to grow root crops whose yield is minimal compared to the global yield. This requires the government to improve agricultural practices to achieve efficient production on limited land.

5.4. Research implications and policy recommendations

In addition to the existing EF theories, this study also considers the WEF nexus theory to minimize the siloed governance in analyzing the three sectors that cannot allow policymakers to map out their collaboration in well-managing resource sustainability (Botai et al., 2021; Hoff, 2011). This study presents a new assessment tool that helps align current economies, policies, and pathways towards achieving the WEF security-related SDGs in selected African countries. The motivation behind this study is the salient increase in ecological unsustainability towards increased consumption of WEF resources. Despite the fact that many scientific theories and practice approaches for the WEF resources have been developed, the majority of them compromise when assessing the WEF resource inputs in terms of economic growth priorities, ecological sustainability, and balance between human demand and the planet's planet biocapacity. Thus, provisioning the water energy food ecological balance analysis provides new insight in existing research that may help policymakers and practitioners to determine whether their economic growth goes hand in hand with ecological balance.

This study's methodological structure and results are most useful for the African literature and elsewhere due to its unique perceptive of an integrated set of WEF resources EF approaches into nexus-based research perspective in Africa and the world. The strategy and results of the study should help reduce the fragmented understanding of WEF resource assessment in different sectoral research analyses by providing a good motivation for the management of the three sectors involved to develop collaborative projects and cross-sectoral mutual benefits. In other studies, ideas determining WEF production and consumption, for example, are based on community behaviors and consumption patterns, food waste management, green production awareness, and diet change (Keren et al., 2019; Galli et al., 2017).

Thus, this study shows a useful pathway for policymakers and practitioners to determine how much land is needed to produce food energy and shape consumer behavior by selecting the best types of resources to adopt. It can help practitioners, industrials, and investors to be informed about the flow of supply and demand of WEF resources and which types of resources are most environmentally friendly to consume or invest in while minimizing increases in EF. For example, people should invest in vegetables, mushrooms, and meat from animals with limited WEF, such as poultry and fish, rather than lamb and beef, which have more than twice the demand for WEF than other meat animals. Others should think about carbon market projects that favor renewables while exploiting the considerable impact of the dominance of non-renewables and their contribution to increased EEF, which leads to many other negative human impacts such as climate change. Countries are urged to reduce the ecological impact of water demand by promoting technologies used in wastewater management and virtual water (Nikiel and Eltahir, 2021).

Like other countries mentioned, Mauritius has the best developed financial sector and the best-performing country in terms of sustainable economic potential (Olowu et al., 2018), but it is ranked among the top vulnerable countries with ecological instability. This suggests a rethinking of the economic model by empowering sustainability principles. Along African countries are integrated into continental commitment or global commitment such as the Malabo Declaration on Growth and Transformation in Agriculture from the 2014 African Union Summit identified the development of agricultural methods to eradicate hunger by 2025 and create at least 30% of youth employment in Africa through the value of agriculture (AUC, 2014). The agricultural practices are also mentioned in the core strategies for achieving the 2030 SDG agenda and the African Agenda 2063. However, the findings mentioned that agriculture requires a significant high EF, both at the WEFt and the FEF. By recommendations, countries should align their green agricultural policies, green industrial policies, ecological consumer behavior, renewable energy resources, food processing, ecological protection of water resources, environmentally friendly technologies, and encouragement of self-assessment of dependence on ecological balance.

6. Conclusions

This study recognizes the importance of ecological boundaries in the supply of WEF resources to meet the WEF security nexus and related SDGs. Studies on ecological balance are a new aspect of the African WEF resources that will take considerable effort. Despite countries' efforts to achieve the WEF SDGs, some are most vulnerable to biocapacity deficits and ecological imbalances. The alternative of increasing the demand of water consumers from the total renewable resources may harm the countries' current ecological balance, so they recommend finding other water sources or reducing their use. The study made concrete policy and research recommendations for policymakers and practitioners to assess activities that consume WEF resources equally within ecological limits. Creating an approach that contextualizes the WEF nexus resources benefit into ecological sustainability responses is needed in the future region. Furthermore, national or regional research should improve the understanding of bottom-up management and reduce the risk of decision-makers producing far more resources than their ecosystem capacity.

This study faces some limitations, including the limited data availability, which forced the researchers to use the most recent data available in resource sectors of different sizes. The study uses a conventional global hectare technique (gha) approach, demonstrating the benefits and possibilities of comparing resource differences between countries based on global scale factors to overcome data gaps issues. However, the gha analysis has been limited to capturing national or regional EF factors and drivers behind comparisons that are relevant for the domestic share method (Kissinger, 2013). In addition, this study did not cover all food items, mainly aquatic food, due to limited data availability. Also, with the complexity of three sector variable analysis, this study is limited to considering the impact of one sector on the other weighted ecological balances, such as energy on water and food on energy, which should help sector practitioners track some trade-off that exists much more and initiates related collaborative projects and initiatives accordingly. But the studies followed the philosophy of the WEF nexus assessment by considering each sector indicator with equal weight in the calculation of the WEFEB nexus index, which could also help policymakers see the existing challenges in the production and consumption of WEF resources in the big picture of collaboration.

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CRediT authorship contribution statement

Fabien Muhirwa, Lei Shen and Ayman Elshkaki; Conceptualization, Methodology and formal analysis writing-original draft preparation Shuai Zhong, Shuhan Hu, Hubert Hirwa, Jeffrey Chiwuikem Chiakaa, Francoise Umarishavu, Narcisse Mulinga writing-review, and editing. Lei Shen and Ayman Elshkaki: - Supervise the work. Lei Shen: Project administration and funding acquisition. All the authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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

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References

Alessandro, G., Laetitia, M., 2017. GNF. Global Sustainability Transition Hinges on Food. Global Footprint Network (GNF), pp. 1–5.
Alexander, P., Brown, C., Arneth, A., Finnigan, J., Rounsevell, M.D.A., 2016. Human appropriation of land for food: the role of diet. Glob. Environ. Chang. 41, 88–98.
Amowine, N., Li, H., Boamah, K.B., Zhou, Z., 2021. Towards ecological sustainability: assessing dynamic total-factor ecology efficiency in Africa. Int. J. Environ. Res. Public Health 18, 9323.
AUC, 2014. Malabo Declaration on Accelerated Agricultural Growth and Transformation for Shared Prosperity and Improved Livelihoods. the African Union (AU), Malabo, pp. 1–12. https://www.resakss.org/sites/default/files/Malabo%20Declaration%20on%20Agriculture_2014_11%2026-.pdf Submitted for publication.
Belinskij, A., 2015. Water-energy-food nexus within the framework of international water law. Water 7, 5396–5415.
Biteye, M., 2021. 70% of Africans make a living through agriculture, and technology could transform their world. 2022. World Economic Forum.
Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., et al., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework. Ecol. Indic. 24, 518–533.
Botai, J.O., Botai, C.M., Ncongwane, K.P., Mpandeli, S., Nhamo, L., Masinde, M., et al., 2021. A review of the water–energy–food nexus research in Africa. Sustainability 13, 1762.
Budihardjo, S., Hadi, S.P., Sutikno, S., Purwanto, P., 2013. The ecological footprint analysis for assessing carrying capacity of industrial zone in Semarang. J. Hum. Resour. Sustain. Stud. 01 (02), 7.
Cai, Y., Zhang, L., 2018. Multi-scale Ecological Indicators for Supporting Sustainable Watershed Management. Elsevier.
Charfeddine, L., Mrabet, Z., 2017. The impact of economic development and social-political factors on ecological footprint: a panel data analysis for 15 MENA countries. Renew. Sust. Energ. Rev. 76, 138–154.
Chavez-Rodriguez, M.F., Nebra, S.A., 2010. Assessing GHG emissions, ecological footprint, and water linkage for different fuels. Environ. Sci. Technol. 44, 9252–9257.
Chiaka, J.C., Lin, Z., Yu, X., 2022. Changing food consumption patterns and land requirements for food in the six geopolitical zones in Nigeria. Foods 11 (2), 1–18. https://doi.org/10.3390/foods11020150 150. In this issue.
Collins, A., Fairchild, R., 2007. Sustainable food consumption at a sub-national level: an ecological footprint, nutritional and economic analysis. J. Environ. Policy Plan. 9, 5–30.
Cumming, G., Von, C., Taubadel, S., 2018. Linking economic growth pathways and environmental sustainability by understanding development as alternate social–ecological regimes. Proc. Natl. Acad. Sci. 115, 9533–9538.
Dai, D., Sun, M., Xu, X., Lei, K., 2019. Assessment of the water resource carrying capacity based on the ecological footprint: a case study in Zhangjiakou City, North China. Environ. Sci. Pollut. Res. 26, 11000–11011.
Ekeocha, D.O., 2021. Urbanization, inequality, economic development and ecological footprint: searching for turning points and regional homogeneity in Africa. J. Clean. Prod. 291, 125244.
Elferink, E.V., Nonhebel, S., 2007. Variations in land requirements for meat production. J. Clean. Prod. 15, 1778–1786.
Eliseeva, E., 2017. Economic impact of the metallurgical complex on the ecological balance: rational use of resources and evaluation of environmental measures. International Multidisciplinary Scientific GeoConference: SGEM. 17, pp. 249–254.

Ewing, B., Moore, D., Goldinger, S., Oursler, A., Reed, A., Wackernagel, M., 2010. Ecological footprint atlas 2010. Retrieved May. 25. Network. Global Brad EwingFootprint, p. 2014.

FAO, 2000. Technical Conversion Factors for Agricultural Commodities. Food and Agriculture Organization, Rome, pp. 1–782.

FAO, 2018. Food Balance Sheets. 2021. Knoema Database.

FAO, 2018. Water data. (2018-2022) AD, editor. 2021. The Food and Agriculture Organization (FAO), United Nations, Rome.

FAO, 2019. FAOSTAT Data. 2021. Food and Agriculture Organization of the United Nations.

FAO, 2019. Inland waters data. 2021. Knoema.

Fernández-Ríos, A., Laso, J., Campos, C., Ruiz-Salmón, I., Hoehn, D., Cristóbal, J., et al., 2021. Towards a water-energy-food (WEF) nexus index: a review of nutrient profile models as a fundamental pillar of food and nutrition security. Sci. Total Environ. 789, 147936.

Galli, A., Iha, K., Halle, M., El Bilali, H., Grunewald, N., Eaton, D., et al., 2017. Mediterranean countries' food consumption and sourcing patterns: an ecological footprint viewpoint. Sci. Total Environ. 578, 383–391.

GNF, 2021. The National Footprint and Biocapacity Accounts (NFAs). 2021. Global Footprint Network (GNF), Advancing the Science of Sustainability, York University.

Gonzalez Sanchez, R., Seliger, R., Fahl, F., De Felice, L., Ouarda, T.B.M.J., Farinosi, F., 2020. Freshwater use of the energy sector in Africa. Appl. Energy 270, 115171.

Gumma, M.K., Pavelic, P., 2013. Mapping of groundwater potential zones across Ghana using remote sensing, geographic information systems, and spatial modeling. Environ. Monit. Assess. 185, 3561–3579.

Haberl, H., Erb, K.-H., Krausmann, F., 2001. How to calculate and interpret ecological footprints for long periods of time: the case of Austria 1926–1995. Ecol. Econ. 38, 25–45.

Hamed, Y., Hadji, R., Redhaounia, B., Zighmi, K., Bâali, F., El Gayar, A., 2018. Climate impact on surface and groundwater in North Africa: a global synthesis of findings and recommendations. Euro-Mediterr. J. Environ. Integr. 3, 1–15.

Hanna, S.H.S., Osborne-Lee, I.W., Khalil, M.T., 2013. Sustainable economy of ecological footprint in Africa: an economic analysis and impacts. World Environ. 3, 9–17.

Helgi, 2017. Pulse Consumption Per Capita. 2021. Helgi Analytics, Eliasova, Prague.

Hoekstra, A.Y., 2003. Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade. IHE Delft, The Netherlands, pp. 1–244.

Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. 109, 3232–3237.

Hoff, H., 2011. Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute (SEI), Stockholm, Sweden.

Huang, L., Zhang, W., Jiang, C., 2008. Calculation method of ecological footprint of water resources. Acta Ecol. Sin. 3, 1279–1286.

Huimin, L., 2013. The impact of human behavior on ecological threshold: positive or negative?—Grey relational analysis of ecological footprint, energy consumption and environmental protection. Energy Policy 56, 711–719.

IEA, 2018. Total Energy Supply, Africa. 2021. The International Energy Agency (IEA).

Karwacka, M., Ciurzyńska, A., Lenart, A., Janowicz, M., 2020. Sustainable development in the agri-food sector in terms of the carbon footprint: a review. Sustainability 12, 6463.

Keren, D., Pnina, R., Nadav, D., et al., 2019. Environmental effects of the livestock industry: the relationship between knowledge, attitudes, and behavior among students in Israel. Int. J. Environ. Res. Public Health 16 (8), 1–16. https://doi.org/10.3390/ijerph16081359 1359. In this issue.

Kimura, S.D., Mu, Z., Toma, Y., Hatano, R., 2007. Eco-balance analysis of six agricultural land uses in the Ikushunbetsu watershed. Soil Sci. Plant Nutr. 53, 373–386.

Kissinger, M., 2013. Approaches for calculating a nation's food ecological footprint—the case of Canada. Ecol. Indic. 24, 366–374.

Lee, Y.-J., 2019. Ecological footprint and water footprint of Taipei. Sustainability 11, 5714.

Lenzen, M., Lundie, S., Bransgrove, G., Charet, L., Sack, F., 2003. Assessing the ecological footprint of a large metropolitan water supplier: lessons for water management and planning towards sustainability. J. Environ. Plan. Manag. 46, 113–141.

Letafat, N., Tarazkar, M.H., 2021. Determinants of ecological footprint in MENA region: application of Extreme Bounds Analysis (EBA) approach. Environ. Sci. 19.

Li, H., Zhao, F., Li, C., Yi, Y., Bu, J., Wang, X., et al., 2020. An improved ecological footprint method for water resources utilization assessment in the cities. Water 12, 503.

Lin, D., L H, J MBCG, Lazarus, G.Z., K I, D E, 2016. Working Guidebook to the National Footprint Accounts: 2016. Global Footprint Network (GNF), pp. 1–73.

Lin, D., Hanscom, L., Martindill, J., Borucke, M., Cohen, L., Galli, A., et al., 2018. Working Guidebook to the National Footprint Accounts. Global Footprint Network, Oakland, CA 94612 USA, pp. 1–74.

Lin, D., Hanscom, L., Murthy, A., Galli, A., Evans, M., Neill, E., et al., 2018b. Ecological footprint accounting for countries: updates and results of the national footprint accounts, 2012–2018. Resources 7, 58.

Lin, D., Wambersie, L., Wackernagel, M., 2021. Estimating the Date of Earth Overshoot Day 2021-Nowcasting the World's Footprint & Biocapacity for 2021. Global Footprint Network (GFN), pp. 1–8.

Mahdavi, A., Ries, R., 1998. Towards computational eco-analysis of building designs. Comput. Struct. 67, 375–387.

Mahlknecht, J., González-Bravo, R., Loge, F.J., 2020. Water-energy-food security: a Nexus perspective of the current situation in Latin America and the Caribbean. Energy 194, 116824.

Margat, J., Van der Gun, J., 2013. Groundwater Around the World: A Geographic Synopsis. CRC Press.

Marti, L., Puertas, R., 2020. Analysis of the efficiency of African countries through their ecological footprint and biocapacity. Sci. Total Environ. 722, 137504.

May, N., 2005. Eco-balance of a Solar Electricity Transmission From North Africa to Europe. Technical University of Braunschweig Unpublished Diploma thesis.

Mourad, R., Jaafar, H.H., Daghir, N., 2019. New estimates of water footprint for animal products in fifteen countries of the Middle East and North Africa (2010–2016). Water Resour. Ind. 22, 100113.

Muhirwa, F., 2021. Environmental Education Profile in Rwanda. Global Environmental Profile. Global Environmental Education Partnership Secretariat North American Association for Environmental Education, Washington DC 20036.

Muhirwa, F., Shen, L., Elshkaki, A., Velempini, K., Hirwa, H., Zhong, S., et al., 2021. Decoupling energy, water, and food resources production from GHG emissions: a footprint perspective review of Africa from 1990 to 2017. Energies 14, 6326.

Mwendera, E., Atyosi, Y., 2018. A review of water storage for socio-economic development in South Africa. J. Water Resour. Prot. 10, 266–286.

Nassani, A.A., Aldakhil, A.M., Zaman, K., 2021. Ecological footprints jeopardy for mineral resource extraction: efficient use of energy, financial development and insurance services to conserve natural resources. Resour. Policy 74, 102271.

Nathaniel, S., Anyanwu, O., Shah, M., 2020. Renewable energy, urbanization, and ecological footprint in the Middle East and North Africa region. Environ. Sci. Pollut. Res. 27, 14601–14613.

Ni, J., 2002. Carbon storage in grasslands of China. J. Arid Environ. 50, 205–218.

Nikiel, C.A., Eltahir, E.A.B., 2021. Past and future trends of Egypt's water consumption and its sources. Nat. Commun. 12, 4508.

Olowu, G., Bein, M., Olasehinde-Williams, G., 2018. Examining the relationship between financial development, sustainable economic opportunity and ecological footprint in SADC countries. Appl. Ecol. Environ. Res. 16, 7171–7190.

Opp, C., 2015. Water analyses, eco-balance and socio-demographic analyses as prerequisites for solutions of the sewage treatment problems in rural areas. J. Geosci. Environ. Prot. 3, 73.

Owusu-Sekyere, E., Jordaan, H., Chouchane, H., 2017. Evaluation of water footprint and economic water productivities of dairy products of South Africa. Ecol. Indic. 83, 32–40.

Pahlow, M., Snowball, J., Fraser, G., 2015. Water footprint assessment to inform water management and policy making in South Africa. Water SA 41, 300–313.

Papathanasopoulou, E., Jackson, T., 2009. Measuring fossil resource inequality-a case study for the UK between 1968 and 2000. Ecol. Econ. 68, 1213–1225.

Ramachandra, T., Vinay, S., Bharath, S., Chandran, M.S., Aithal, B.H., 2020. Insights into riverscape dynamics with the hydrological, ecological and social dimensions for water sustenance. Curr. Sci. 118, 1379–1393.

Reardon, T., Tschirley, D., Liverpool-Tasie, L.S.O., Awokuse, T., Fanzo, J., Minten, B., et al., 2021. The processed food revolution in African food systems and the double burden of malnutrition. Glob. Food Secur. 28, 100466.

Richts, A., Struckmeier, W.F., Zaepke, M., 2011. WHYMAP and the Groundwater Resources Map of the World 1: 25,000,000. Sustaining Groundwater Resources. Springer, pp. 159–173.

Ritchie, H., 2017. How Much of the World's Land Would We Need in Order to Feed the Global Population With the Average Diet of a Given Country? 2021. Our World in Data.

Ritchie, H., Roser, M., 2019. Meat and Dairy Production. Our World Data.

Rosa, L., Chiarelli, D.D., Rulli, M.C., D'Odorico, P., 2020. Global agricultural economic water scarcity. Sci. Adv. 6, eaaz6031.

Sarkodie, S.A., 2021. Environmental performance, biocapacity, carbon & ecological footprint of nations: drivers, trends and mitigation options. Sci. Total Environ. 751, 141912.

Scott, C.A., Albrecht, T.R., De Grenade, R., Zuniga-Teran, A., Varady, R.G., Thapa, B., 2018. Water security and the pursuit of food, energy, and earth systems resilience. Water Int. 43, 1055–1074.

SDGN, 2020. Africa SDG Index and Dashboards Report: Leave No one Behind to Achieve the SDGs in Africa. SDGN (Sustainable Development Goal Network), pp. 1–248.

Shao, J., 1986. The villagization program and the disruption of the ecological balance in Tanzania. Can. J. Afr. Stud. 20, 219–239.

Simpson, G.B., Jewitt, G.P.W., BJ, Becker W., Neves, A.R., P. R, V P, 2020. The Water-Energy-Food Nexus Index. Jones & Wagene. The Water Research Commission, South Africa.

Stöglehner, G., 2003. Ecological footprint — a tool for assessing sustainable energy supplies. J. Clean. Prod. 11, 267–277.

Su, Y., Gao, W., Guan, D., Su, W., 2018. Dynamic assessment and forecast of urban water ecological footprint based on exponential smoothing analysis. J. Clean. Prod. 195, 354–364.

Summers, J.K., Smith, L.M., Case, J.L., Linthurst, R.A., 2012. A review of the elements of human well-being with an emphasis on the contribution of ecosystem services. Ambio 41, 327–340.

Tam, J.C., Fay, G., Link, J.S., 2019. Better together: the uses of ecological and socio-economic indicators with end-to-end models in marine ecosystem based management. Front. Mar. Sci. 6.

Tamburino, L., Bravo, G., 2021. Reconciling a positive ecological balance with human development: a quantitative assessment. Ecol. Indic. 129, 107973.

Tuyishimire, A., Liu, Y., Yin, J., Kou, L., Lin, S., Lin, J., et al., 2022. Drivers of the increasing water footprint in Africa: the food consumption perspective. Sci. Total Environ. 809, 152196.

Udemba, E.N., 2020. A sustainable study of economic growth and development amidst ecological footprint: new insight from Nigerian Perspective. Sci. Total Environ. 732, 139270.

Usman, M., Kousar, R., Yaseen, M.R., Makhdum, M.S.A., 2020. An empirical nexus between economic growth, energy utilization, trade policy, and ecological footprint: a continent-wise comparison in upper-middle-income countries. Environ. Sci. Pollut. Res. 27, 38995–39018.

Van Noordwijk, M., Brussaard, L., 2014. Minimizing the ecological footprint of food: closing yield and efficiency gaps simultaneously? Curr. Opin. Environ. Sustain. 8, 62–70.

Wackernagel, M., Rees, W.E., 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. New Society Publishers, Gabriola Island, BC, Canada.

Wackernagel, M., Rees, W., 1998. Our Ecological Footprint: Reducing Human Impact on the Earth. vol. 9. New Society Publishers.

Wackernagel, M., Onisto, L., Bello, P., Linares, A., Falfán, I.S., et al., García, J.M., 1999. National natural capital accounting with the ecological footprint concept. Ecol. Econ. 29, 375–390.

Waltina Scheumann, E.H.-P., 2008. Conceptualizing Cooperation on Africa's Transboundary Groundwater Resources, pp. 1–394 Bonn.

Wang, H., Huang, J., Zhou, H., Deng, C., Fang, C., 2020. Analysis of sustainable utilization of water resources based on the improved water resources ecological footprint model: a case study of Hubei Province,China. J. Environ. Manag. 262, 110331.

Wansink, B., Sobal, J., 2007. Mindless eating: the 200 daily food decisions we overlook. Environ. Behav. 39, 106–123.

Willis, H.H., Groves, D.G., Ringel, J.S., Mao, Z., Efron, S., Abbott, M., 2016. Developing the Pardee RAND Food-Energy-Water Security Index: Toward a Global Standardized, Quantitative, and Transparent Resource Assessment. RAND Corporation.

Worldbank, 2017. Annual Freshwater Withdrawals, (% of Total Freshwater Withdrawal). 2021. The World Bank, Washington, DC, United States.

Yang, A., 2016. Ecological Balance Determined by Human Choice: How Does Forestland Change With Consumer Preferences for GM Soybeans?

Yang, Y., Fan, M., 2019. Analysis of the spatial-temporal differences and fairness of the regional energy ecological footprint of the Silk Road Economic Belt (China Section). J. Clean. Prod. 215, 1246–1261.

Yang, M., Rabi, H.M., Qiong, S., 2017. Using Water-Energy-Food Nexus Analysis Index to Develop Sustainable Development Policy in Transboundary River Basin, a Case Study of Mekong River Basin. XVI World Water Congress. International Water Resources Association, Cancun, Quintana Rio Mexico, pp. 1–20.

Yang, X., Han, W., Mao, C., 2019. A comprehensive analysis on water resources carrying capacity in Tongliao based on ecological footprint method. IOP Conference Series: Earth and Environmental Science. 237. IOP Publishing, p. 052017.

Zhao, Y., Wu, F.-P., Li, F., Chen, X.-N., Xu, X., Shao, Z.-Y., 2021. Ecological compensation standard of trans-boundary river basin based on ecological spillover value: a case study for the Lancang-Mekong River Basin. Int. J. Environ. Res. Public Health 18, 1251.