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Data and analysis toolbox for modeling the nexus of food, energy, and water

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ABSTRACT

Energy, water, and food resources are highly interdependent. Agricultural irrigation accounts for 84% of global consumptive freshwater use, the food supply chain demands up to 30% of global primary energy use, and roughly 80% of global electricity generation depends on water for cooling (an average of nearly 100 L of water withdrawn per kWh). Improving understanding of the complex interactions of this resource nexus is, therefore, a top priority for human well-being, sustainable development, and policymaking. Here, we present an interactive analysis toolbox, **Ne**xus of **F**ood, **E**nergy, and **W**ater (NeFEW), that synthesizes available global data to enable modeling and analysis of these resources and their interdependencies at the country-level and for user-specified categories and quantities. Sample analyses also presented here include country-specific estimates of water resources required to produce different types of food and energy, energy required per quantity of water or agricultural product supplied, and CO_2-equivalent emissions associated with water and energy provision.

1. Introduction

Energy, water, and food systems are complex and intertwined. Globally, irrigation accounts for 84% of annual consumptive freshwater use (Brauman, Richter, Postel, Malsy, & Flörke, 2016; Shiklomanov, 2000), extraction of which requires large quantities of energy. Power generation is also highly dependent on water, accounting for 15% of global freshwater withdrawal in 2010 (International Energy Agency (IEA) (2012)). Although water consumption in the energy sector is much less than 15%, the returned water quality can be significantly deteriorated mainly due to increased temperature. Power generation makes up the largest fraction of water withdrawals in the United States (Blackhurst, Hendrickson, & Vidal, 2010), with nearly half of the fresh and seawater withdrawal used for cooling in thermoelectric power plants (Finley & Seiber, 2014). Agricultural irrigation, however, remains the largest water consumer in the U.S. (Schnoor, 2011), and most places around the world. Fig. 1 schematically depicts the interdependencies at the nexus of energy, water, and food at the global scale.

Energy, water, and food resources are planned for and managed by different institutions based on different priorities and perspectives (Harris, 2002). When policymakers are concerned about food, both water and energy are considered as inputs/constraints to food/agricultural production. One illustrative example of policymaking based on the food perspective is that of the East and Southeast Asian countries, which substantially reduced the number of hungry individuals from 134 million in 1990−92 to 65 million in 2010−12 (Food and Agriculture Organization of the United Nations (FAO) (2012); Lele, Klousia-Marquis, & Goswami, 2013). These countries achieved this goal through *"rapid agricultural intensification, diversification of agriculture and international trade in food and agriculture, while increasing water use efficiency and water productivity"* (Food and Agriculture Organization of the

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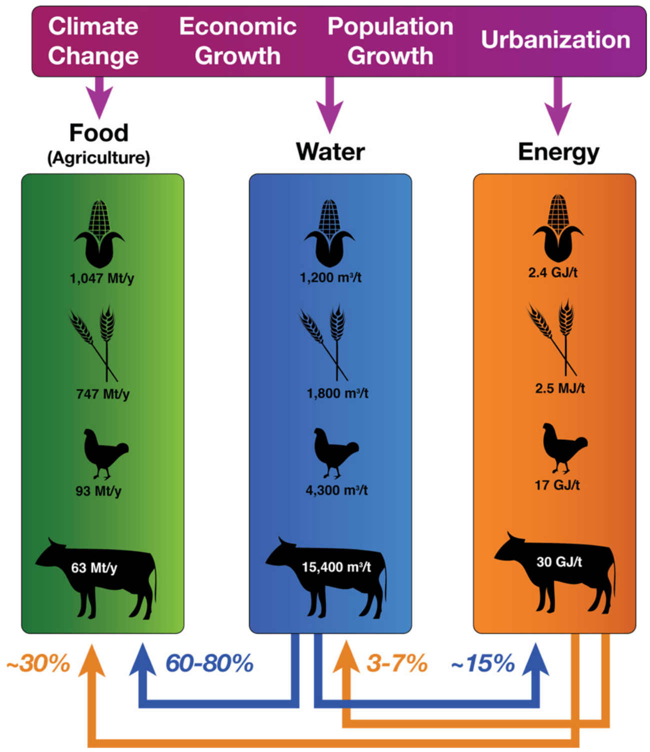

Fig. 1. NeFEW schematic. Interdependencies at the nexus of food, energy, and water at the global scale, and challenges that further necessitate an integrated and "system-thinking" approach for management of these resources.

United Nations (FAO) (2012)). Agricultural expansion in China has been largely supported by groundwater extraction that spiked from 10 km^3/y in the 1950s to 100 km^3/yin the 2000s (Wang, Huang, Rozelle, Huang, & Blanke, 2007, 2012). Groundwater pumping accounts for 3% of greenhouse gas (GHG) emissions in China (Wang et al., 2012), the leading emitter of GHGs in the world. India serves as another example that has largely stressed its groundwater resources to increase food production; however, low water use efficiency has been a major challenge in reducing hunger in India (Lele et al., 2013).

Such a "siloed" approach that addresses a single resource results in sub-optimal and unsustainable practices (Bazilian et al., 2011). For example, production of crop-based biofuels such as corn ethanol has sought to reduce fossil CO_2 emissions but neglected substantial impacts on other environmental problems and food security (Hardy, Garrido, & Juana, 2012; Ringler, Bhaduri, & Lawford, 2013; Yang, Zhou, & Liu, 2009). Over the period of 2008–2018 roughly half of the projected demand growth for corn and wheat, as well as one third of the growth in demand for oilseeds are related to biofuel production (Howells et al., 2013). This intensifies the competition for *"water, land, labor and capital"* among different sectors (Ringler et al., 2013) and stimulates ecosystem degradation by overdrafting already stressed water resources and changing natural ecosystems to agricultural land.

The ever-increasing stress on these systems due to population growth, migration to urban areas, economic development and climate change (Foley et al., 2011; Lobell & Asner, 2003; Lobell, Schlenker, & Costa-Roberts, 2011; Ray et al., 2012; Ray, Mueller, West, & Foley, 2013; Rulli, Saviori, & D'Odorico, 2013) have further magnified the need to jointly manage them. Due to the projected population growth by 2050, some studies have projected that a 70% increase in agricultural production (compared to the 2005 level) will be required (Foran, 2015; Hoff, 2011; Northoff, 2009; Tilman, Balzer, Hill, & Befort, 2011). Tilman (Tilman et al., 2011) also predicted a 100–110% increase in calories and protein demand between 2005 and 2050. Expansion of cropland onto remaining arable lands would come with large carbon and conservation costs (Ramankutty, Foley, Norman, & McSweeney, 2002; Searchinger et al., 2015; West et al., 2010); and water resources, the main limiting factor, are already stressed and exploited unsustainably in many regions (Brauman et al., 2016; Dalin, Qiu, Hanasaki, Mauzerall, & Rodriguez-Iturbe, 2015). In addition, overdrafting such resources can render disastrous environmental impacts (Dalin & Rodriguez-Iturbe, 2016; West et al., 2014).

Migration to urban areas has also changed the distribution of supply and demand, which leads to large point-source consumption quantities and requires resource transport from distant regions (Djehdian, Chini, Marston, Konar, & Stillwell, 2019; Paterson et al., 2015; Rao & Chandrasekharam, 2019). This along with economic development alters the consumptive behavior of the population requiring more resources (Dalin, Hanasaki, Qiu, Mauzerall, & Rodriguez-Iturbe, 2014). The primary diet in China, for example, included a protein supply quantity of 3.53 (g/capita/d) in 1961, which escalated to 39.64 (g/capita/d) in 2013 (Food & Agriculture Organization of the United Nations, 1998). Animal products are water and energy intensive, and conversion of biomass to animal product is highly inefficient with 5–10% of feed converting to edible beef and 10–15% of feed converting to edible poultry meat (Finley & Seiber, 2014). Moreover, climate change and variability affect energy, water, and food resources (Rasul, 2014). Changes in the distribution of precipitation and temperature have pushed these resources to their margins (Mourtzinis et al., 2015). Indeed, the IPCC (2007) report warns that crop yields in Southern Asia may be reduced up to 30% under current practices. Similar conclusions were drawn for Southern Africa for a variety of important crops (Lobell & Field, 2007; Lobell et al., 2008; Porter et al., 2014).

Recently, a paradigm shift has been occurring where energy, water, and food resources are managed/evaluated as an interlinked system by considering their tradeoffs and interdependencies (Bazilian et al., 2011; Bizikova, Roy, Swanson, Venema, & McCandless, 2013; Ringler et al., 2013). A *"system-thinking"* approach should be adopted at the nexus of energy, water, and food, with the potential to be translated to pragmatic policies to warrant sustainability, resource/economic efficiency, prosperity, and public health (Bazilian et al., 2011). Failure to address this issue may jeopardize resources, ecosystem services, and community security, among other concerns. As such, a "*system-thinking*" approach is presented herein to examine the interdependencies among energy, water, and food. This nexus also faces several more challenges that require special attention of policymakers. These resources are interlinked with security and functionality of societies (Bazilian et al., 2011) and are traded globally in heavily regulated markets that involve politicized and inefficient pricing (Allan, Keulertz, & Woertz, 2015). While policymaking occurs at different levels from local and regional to international scales, policy changes in some regions may render global effects. For instance, water availability and policy changes in the Yellow river basin in China may alter food prices globally (Lawford et al., 2013). Another example is the Russian grain export ban in 2010, due to drought, which impacted the global food market. One of the key challenges of water, food, and energy studies is the lack of data and/or analysis tools for mining available observations and studying the relationship between different components of the system.

In this study, we develop a data analysis toolbox that synthesizes available global data sets of food, energy, and water systems for use in modeling and analysis of their interdependencies at the country-level. This toolbox, entitled NeFEW (**Ne**xus of **F**ood, **E**nergy, and **W**ater), estimates the green, blue, and grey water required to produce a user-specified amount of food in the selected country, as well as the global average. Green water is sourced from precipitation and the root zone; blue water is supplied from surface or groundwater resources; and grey water is required to dilute pollutants to meet certain water quality criteria. The interactive toolbox also reports the amount of production, import, export, and waste of the selected food type. In addition, NeFEW approximates the energy required for supply of a user-specified amount of water, as well as associated potential food production. Moreover,

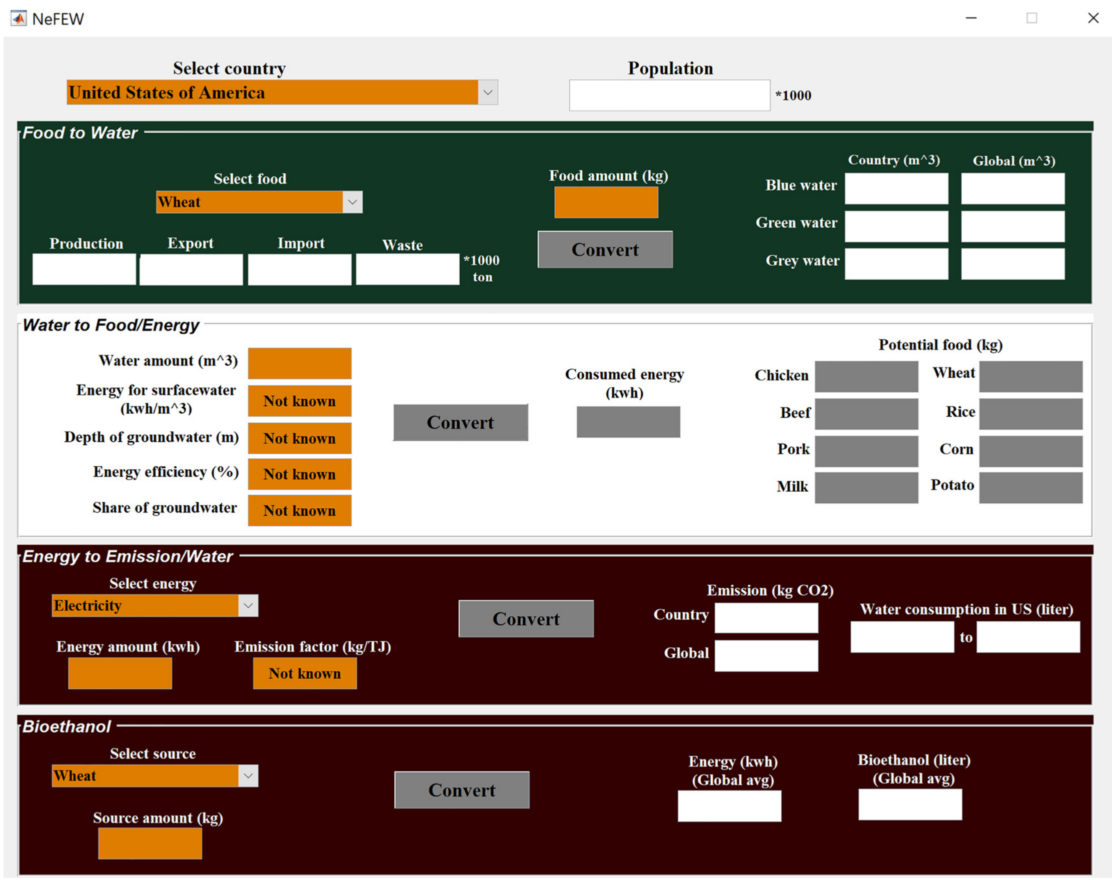

Fig. 2. Graphical user interface of the Nexus of Food, Energy, and Water (NeFEW) Toolbox.

NeFEW estimates CO_2-equivalent emissions associated with different energy resources, provides a rough appraisal of water quantities necessary to produce/extract/refine/convert energy (depending on the source), and finally approximates the potential biofuel production of different crops. This interactive toolbox enables policymakers (users) to evaluate the impacts a certain policy regarding one resource may have on the others and assesses the interdependencies for well-informed decision making. It can also be used as a tool for public education about the nexus of food, energy, and water.

2. Methods

The following sections move through the graphical user interface (shown in Fig. 2) and provide descriptions and information about the various inputs/outputs used in the NeFEW toolbox.

2.1. Food to water

The agricultural sector is the largest consumer of water resources globally (Konar et al., 2011). The interdependency of food and water resources is well documented (Lawford et al., 2013). Mekonnen (Mekonnen & Hoekstra, 2010, 2011) adopted a spatially-explicit gridded (5 by 5 arc minute grid) water balance model to estimate the green, blue, and grey water footprint of different crops. Their dynamic model with a temporal resolution of 1 day includes soil water balance and climatic conditions, as well as fertilizer usage, to estimate different crop water demands and crop yield for the period of 1996 – 2005. Their modeling framework is based on the CROPWAT approach of Allen (Allen, Pereira, Raes, & Smith, 1998), and the concept of "water footprint" by Hoekstra (Hoekstra & Chapagain, 2008; Hoekstra & Hung, 2002). The crop consumptive needs and the growing season length return the quantity of blue, green, and grey water consumed in each grid (m^3/y), which along with the crop yield (ton/y), provide estimates of the water footprint (m^3/ton) for 126 crops and 200+ crop derived products.

The water footprint of animal products is also well documented. Mekonnen (Mekonnen & Hoekstra, 2010) conducted a detailed analysis of different farm animals and animal products taking into consideration the *"feed conversion efficiency of the animal, feed composition, and origin of the feed"*. All three factors impact the water footprint of animal products. For example, beef cattle have an unfavorable feed conversion efficiency factor, signifying that a large amount of feed is necessary to produce a unit of beef product. This explains the high-water footprint (15,400 m^3/ton) of beef meat. Feed composition also plays an important role in the water footprint of animal products and is related to the *"ratio of concentrates versus roughages and the percentage of valuable crop components versus crop residues in the concentrate"* (Mekonnen & Hoekstra, 2010). Chickens (4300 m^3/ton) and pigs (6000 m^3/ton), for example, rely on a high fraction of water-intensive cereals and oil meal in their feed, which neutralizes their favorable feed conversion efficiency factor (Mekonnen & Hoekstra, 2010). Finally, the origin of feed is also a significant factor, since different regions diverge in climatic conditions and exercise disparate farming practices. Indeed, water deficient countries depend on virtual water (by importing their food and feedstock) to satisfy their needs (D'Odorico, Carr, Laio, Ridolfi, & Vandoni, 2014; Dalin, Konar, Hanasaki, Rinaldo, & Rodriguez-Iturbe, 2012; Dalin, Suweis, Konar, Hanasaki, & Rodriguez-Iturbe, 2012; Konar, Dalin, Hanasaki, Rinaldo, & Rodriguez-Iturbe, 2012; Konar, Hussein, Hanasaki, Mauzerall, & Rodriguez-Iturbe, 2013; Siddiqi & Anadon, 2011; Suweis et al., 2011).

We employ the FAOSTAT and Water Footprint Network's rich and detailed data set (available through http://www.fao.org/faostat/ and http://waterfootprint.org) to convert the amount of selected food to the quantity of green, blue, and grey water consumed for its production.

The NeFEW toolbox presents results for the specified country, as well as the global average. It also displays the production, import, export, and waste statistics for the selected food and country based on the data from the Food Balance Sheets of the United Nation's Food and Agriculture Organization (FAO). Food balance sheets offer *"a comprehensive picture of the pattern of a country's food supply during a reference period"* (Food and Agriculture Organization of the United Nations (FAO) (2001)). FAO assembles food balance sheets provided by different governments, the consistency and accuracy of which is influenced by the data source. For a detailed description of the food balance sheets, their importance, data gathering methods, challenges, and potentials refer to Jacobs (Jacobs & Sumner, 2002) and the FAO's handbook(Food and Agriculture Organization of the United Nations (FAO) (2001)).

The importance of the information in this module is twofold: first, it estimates the green, blue, and grey water footprint of the selected food in the specified country and how it compares to the global average; and second, it indicates the status of the country in terms of receiving (through food import) or donating (through food export) virtual water, as well as the country's status on the waste of food and its associated water. Moreover, it provides an estimate of the quantity of water that was used for production of the selected food. It is also worth mentioning that the green, blue, and grey water footprint information helps water managers make well-informed policies. Although irrigated agriculture (blue water) returns higher crop yields, a water resources management perspective would favor green water consumption as blue and grey water consumption directly affect available freshwater resources.

In the NeFEW toolbox, the user may select from a set of 21 main food types including wheat, barley, rice, corn, potato, sweet potato, sugar (cane), soybeans, tomato, onion, vegetables, banana, orange, apple, beef meat, chicken meat, lamb meat, goat meat, pig meat, egg, and milk. For simplicity, only the most widely used crops and animal products were incorporated in NeFEW. The original data set that accompanies this toolbox includes several more food types.

While such valuable and detailed information is available for the interactions of food and water at the country-level, the scientific community could greatly benefit from a detailed data set at the nexus of food and energy. The FAOSTAT database provides an overview of energy use in and emissions from the agricultural sector (refer to http://www.fao.org/faostat/, Tubiello (Tubiello et al., 2014) and Section "Biofuel" in current manuscript for more information). However, a detailed global data set for the energy footprint of different crops and animal products is missing, to the best of the authors' knowledge. We are, therefore, not able to deliver detailed energy consumption information for the selected crops/animal products in this module; but since a large portion of agricultural energy consumption is used to meet the water demand, the user is encouraged to use the "Water to Energy" conversion of the NeFEW toolbox. For a review of food-energy interactions, refer to Woods (Woods, Williams, Hughes, Black, & Murphy, 2010) and Finley (Finley & Seiber, 2014).

2.2. Water to energy and food

The NeFEW toolbox provides a rough estimate of the energy used to supply a user-specified quantity of water, as well as the potential amount of food that could be produced with it. The energy required to extract, purify, and deliver water is estimated by quantifying the energy footprint of surface and groundwater resources. In the absence of detailed energy footprint data for the water supply in different countries, the NeFEW toolbox allows the user to provide a reasonable estimate of the energy requirement for surface water supply (kWh/m^3), as well as the depth of groundwater and energy efficiency factor. The latter two inputs are used to approximate the energy footprint of groundwater, using Wang's approach (Wang et al., 2012):

$$EN = \frac{9.8(\text{m. s}^{-2}) \times H(\text{m}) \times M(\text{kg})}{3.6 \times 10^{6} \times EF(\%)} \quad (1)$$

in which, EN signifies energy, H stands for groundwater depth, M is the water mass, and EF represents the energy efficiency factor. Note that this conversion formula assumes a constant dependency between groundwater abstraction and energy consumption, which might change overtime for different reasons (e.g., climate change, energy price, change in withdrawal technology). However, the user can readily update this equation by altering the energy efficiency factor to account for climatic factors and/or technological advancements.

NeFEW also asks for the fraction of the total energy consumption associated with groundwater withdrawal as an input to the toolbox. If the user does not provide this information, the toolbox automatically uses the global average values of 0.48 and 0.37 kW h/m^3 for groundwater and surface water, respectively, based on Fig. 2 of U.N. report (2014) (UN Water, 2014). To estimate the share of groundwater in the total water supply, we use the Aquastat database of FAO available at http://www.fao.org/aquastat/en/. For simplicity, only groundwater and surface water, as the main sources of water, are considered in the toolbox and therefore other sources such as recycled water and desalination were not used. For more information about the range of the energy footprint associated with different water sources, refer to Hardy (Hardy et al., 2012).

This module of NeFEW also converts the user-specified water quantity to the potential amount of food, in terms of crops (wheat, rice, corn, and potato) and animal products (beef, chicken, and pork, as well as milk). This provides a more tangible account of water quantity to the user, which could also be used for public education.

2.3. Energy to emissions and water

This module converts the user-specified quantity of selected energy sources to the associated emissions in terms of CO_2-equivalent using an emission factor. NeFEW allows the user to input a specific emission factor (kg/TJ), if available. Otherwise, it will extract the corresponding emission factor from the agricultural emission data set available through the FAOSTAT database (http://www.fao.org/faostat/en/#data/GN). A global average emission factor is also obtained from Table 2.5 of the IPCC guidelines for national greenhouse gas inventories (Intergovernmental Panel On Climate Change (IPCC) (2006)). This allows for comparison of energy emissions at the country-level to that of the global average. The challenge is that emission factors, if not provided by the user, are extracted from the agricultural sector data.

Moreover, an estimate of the water consumption to extract/purify/generate/process different energy sources is provided in this module. The provided conversion is based on the water consumption of different energy sources in the United States, obtained from Figs. 1 and 2 of Siddiqi (Siddiqi & Anadon, 2011). There is a wide range of uncertainty for the water consumption depending on the technology and the methodology used to generate/process/convert energy resources. In the absence of a detailed global data set of water footprints for all of the different energy resources, this approach provides a rough estimate.

2.4. Biofuel

In this module, NeFEW provides an approximation of the conversion of a certain quantity of food into bioethanol, presented in terms of energy (kWh) and volume (liter). This conversion employs the global average conversion factors based on Table 2 of Mekonnen (Mekonnen & Hoekstra, 2010), in the absence of a specific country-level conversion factor. NeFEW allows the user to select among a cohort of 6 widely used crops, namely wheat, barley, corn, potato, rice, and sugarcane. More crops, as well as biodiesel which generally has a higher water footprint could be added to the list; however, these additional factors were avoided in this version for simplicity.

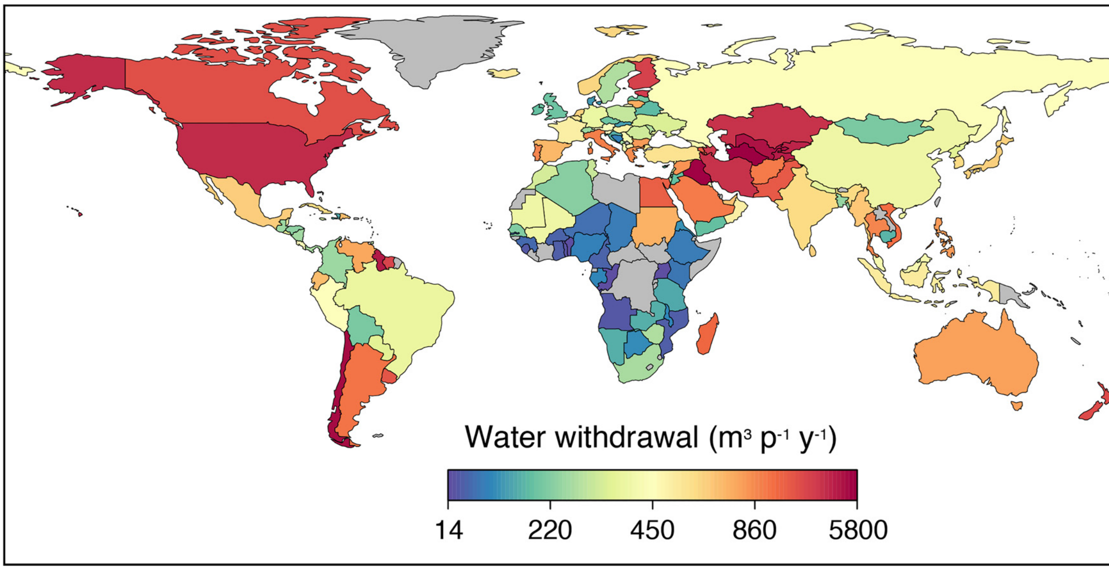

Fig. 3. Per capita water withdrawals. Map shows rate of water withdrawals in m^3 per person per year for agricultural, municipal, industrial, and other purposes, collectively. Grey areas represent countries with missing data.

3. Results and discussion

Recently, holistic management of food, energy, and water resources as one interdependent system has received a great deal of attention. Such an important task requires a deep understanding of how these resources are interconnected, and how supply of one resource translates to consumption/conversion of others. The NeFEW toolbox enables users to infer such relationships from available global data. NeFEW and its supporting data can be used to draw conclusions and visualize information at the nexus of food, energy, and water. For example, Fig. 3 depicts the annual total per capita water withdrawal (m^3/person/y) for agricultural, industrial, and municipal purposes. Note that NeFEW provides the data used for plotting this figure. It is noticeable in Fig. 3 that the water scarce countries of the Middle East and Central Asia withdraw water at a very high rate (e.g., Saudi Arabia withdraws 21 km^3/y water for agricultural purposes, whereas its total internal renewable freshwater resources are 2.4 km^3/y; similarly Iran and Turkmenistan withdraw 86 and 27 km^3/y of freshwater for agriculture, respectively, whereas their total internal renewable freshwater resources are 49 and 1.4 km^3/y). Several of these countries depend on transboundary rivers and groundwater to supply their needs and they are faced with unprecedented challenges in fulfilling their water demand (Zhang et al., 2019). The United States, Chile, and Guyana also suffer from a high rate of per capita water withdrawals (1529, 2126, 1818 m^3/person/y, respectively), which is not inevitably unsustainable in light of their available internal renewable water resources (8948, 51132, 304,677 m^3/person/y, respectively). However, spatial distribution of water availability in such countries is not necessarily consistent with the demand (Mendoza-Espinosa, Burgess, Daesslé, & Villada-Canela, 2019), prompting regional unsustainable water withdrawal rates. China and India also withdraw massive quantities of water (575 and 771 km^3/y, respectively), but they show a relatively lower per capita water withdrawal rate (406 and 615 m^3/person/y, respectively), which can be explained by their high population. Although data is unavailable in several countries in Africa; the available data indicates that African nations generally exhibit low water withdrawal rates.

Groundwater overexploitation threatens many aquifers across the globe (Marston, Konar, Cai, & Troy, 2015). To better understand the breakdown of water sources in the context of global water withdrawal, Fig. 4 shows the fraction of the total freshwater supply that is derived from groundwater for each country. The number of countries with missing data (grey areas) is most striking in Fig. 4, indicating that groundwater extraction data is rather scarce at the global level and in particular for countries in Africa and South America. It is interesting how some Asian and African countries highly depend on groundwater resources for their development (e.g., the share of groundwater in the total water supply of Saudi Arabia is 95%, Yemen is 68%, Bangladesh is 79%, and Botswana is 67%). In particular, countries in the Arabian Peninsula are highly dependent on groundwater with Saudi Arabia serving as an exemplary story of the interdependencies at the nexus of food, energy, and water. Saudi Arabia has followed an ambitious plan for agricultural development to become self-sufficient in wheat production (http://www.the-saudi.net/). In a water scarce region and unfitting cultivation land, the development is mainly founded on groundwater extraction from meager subterranean resources that are non-renewable and highly energy intensive in terms of extraction/pumping. Indeed, groundwater pumping consumes 9% of total electricity production in Saudi Arabia (Marston et al., 2015). A similar strategy has been taken in Iran (the share of groundwater is 57%), which has rendered the vulnerable water resources of the country in a desolate situation. Some countries such as Iceland also show a high share of groundwater in the total water supply (96%, Fig. 4), which is most likely due to high groundwater withdrawal rates for geothermal power generation.

Inspired by the holistic system-thinking approach and through mining the available global data sets (more discussion later), NeFEW estimates the interdependencies of the water withdrawal for specific applications such as food production. Fig. 5 depicts the ratio of agricultural water withdrawal per unit of food production (m^3/kg) for each country (regardless of food type). Again, data is unavailable for some African countries (grey area), but the situation is less severe compared to the lack of groundwater data (Fig. 4). The Middle Eastern and Central Asian countries exhibit a rather high water withdrawal footprint per unit food production (for e.g. Saudi Arabia: 1.1 m^3/kg, Iran: 0.5 m^3/kg, Turkmenistan 2.05 m^3/kg, Pakistan: 0.5 m^3/kg, and Tajikistan: 1.03 m^3/kg) since this region is hot and receives low annual precipitation (green water). The Middle Eastern countries not only suffer from a high water withdrawal footprint per agricultural production unit, but also depend highly on groundwater extraction (Fig. 4) rendering the water consumption in the region unsustainable. Moreover, groundwater pumping requires high quantities of energy. The Central Asian countries, although relying less on the groundwater, are highly dependent on transboundary rivers. Indeed, the unfortunate destiny of the

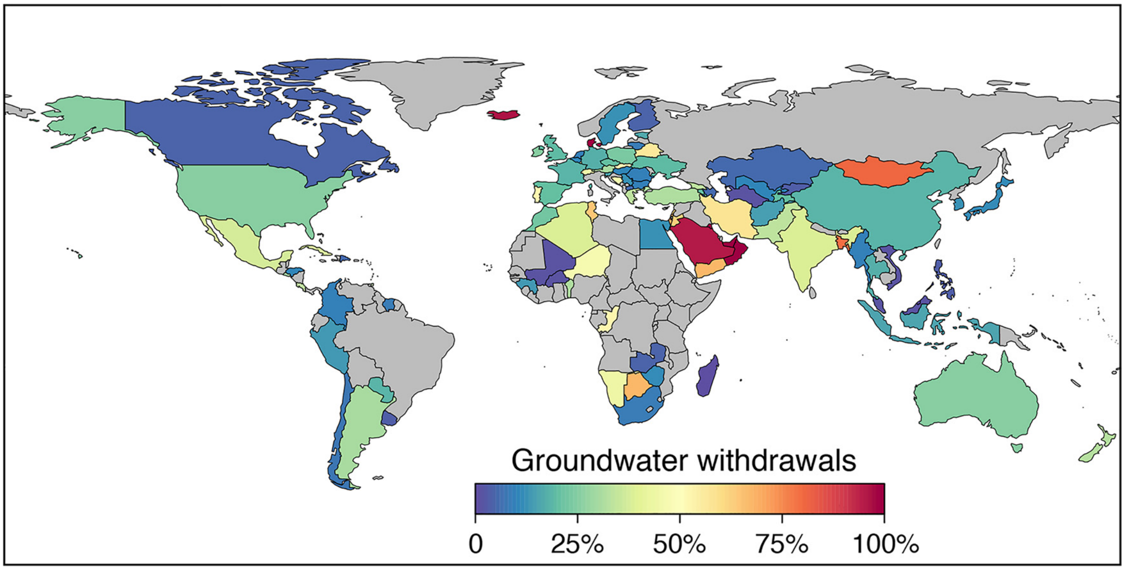

Fig. 4. Share of groundwater in total water withdrawals. Map shows the percent of total water withdrawals represented by groundwater. Grey areas represent countries with missing data.

shrinking Aral Sea can be attributed to the over-extraction of water from its feeding rivers by these countries. Chile is another example of a country with a high-water withdrawal footprint per agricultural production unit (0.54 m^3/kg).

Not only can agricultural production require substantial water withdrawals (as discussed above), but the agricultural sector can also be a large consumer of energy. China (413 TW h), U.S. (219 TW h), India (150 TW h), Brazil (96 TW h), Egypt (89 TW h), Russia (70 TW h), Iran (56 TW h), Canada (56 TW h), and France (52 TW h) are the largest consumers of energy in the agricultural sector as shown in Fig. 6a. Africa, on the other hand, is the lowest agricultural consumer of energy which is likely attributed to low-tech farming (note that data for several countries in Africa are missing). Fig. 7 indicates that China (3.9 Gt), Brazil (2.3 Gt), India (2.3 Gt), U.S. (1.7 Gt), and Russia (0.55 Gt) are also among the largest food producers in the world as well as Indonesia (0.47 Gt), Thailand (0.4 Gt), France (0.37 Gt), and Nigeria (0.36 Gt). It is interesting that Indonesia and Nigeria rank among the highest food producers, while their agricultural energy consumption would not rank as high (3 TW h and 0.05 TW h, respectively). These facts are visible in Fig. 6b, which displays energy consumption per unit of agricultural production in each country. It is noticeable that arid countries such as Yemen (1.35 kW h/kg) and Egypt (0.49 kW h/kg), and cold countries such as Iceland (0.86 kW h/kg), Norway (0.65 kW h/kg), and Finland (0.37 kW h/kg) have the highest rate of energy consumption per unit of food production. South Korea (0.49 kW h/kg) and Japan (0.30 kW h/kg) also use a high quantity of energy per unit of agricultural product which might be related to their modern and industrial agricultural practices as opposed to traditional, less energy intensive approaches.

The presented data set and analysis toolbox (NeFEW) allow investigation of efficiencies with respect to one or more components of the system. Fig. 8 ties normalized agricultural water withdrawal (m^3/kg/y) and energy consumption (kWh/kg/y) with per capita agricultural production (regardless of food type) for selected countries across the globe. Each country in this scatterplot is color-coded based on its per capita agricultural production rate (tons/person/y), with red (blue) indicating lower (higher) rates. Fig. 8 shows that with respect to water and energy use, the agricultural sector is not efficient in some countries including Iran, Azerbaijan, and Japan. Their water use and

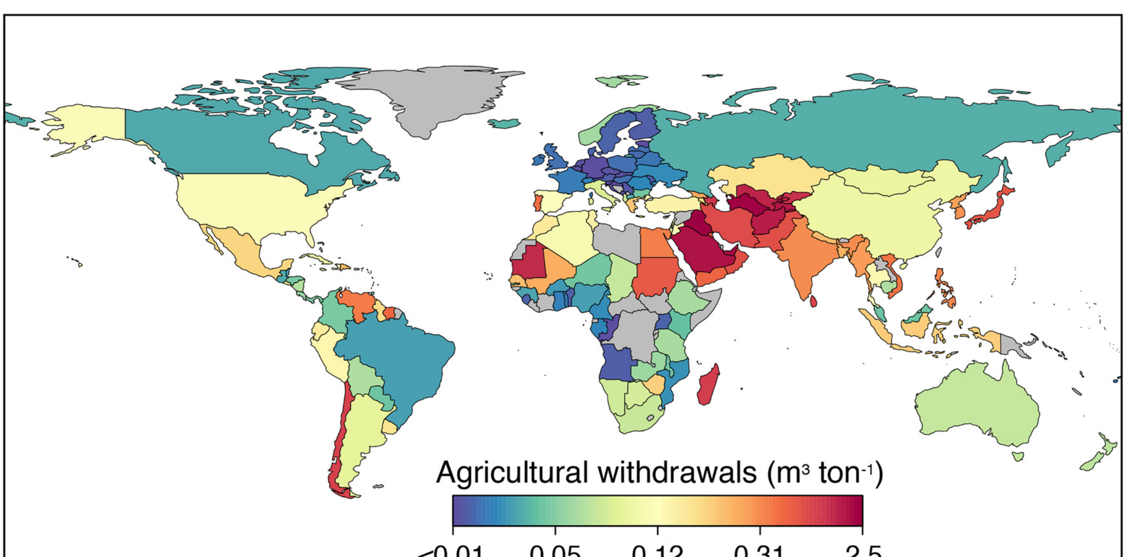

Fig. 5. Agricultural water withdrawals. Map shows water withdrawals per unit of agricultural production (m^3/ton). Grey areas represent countries with missing data.

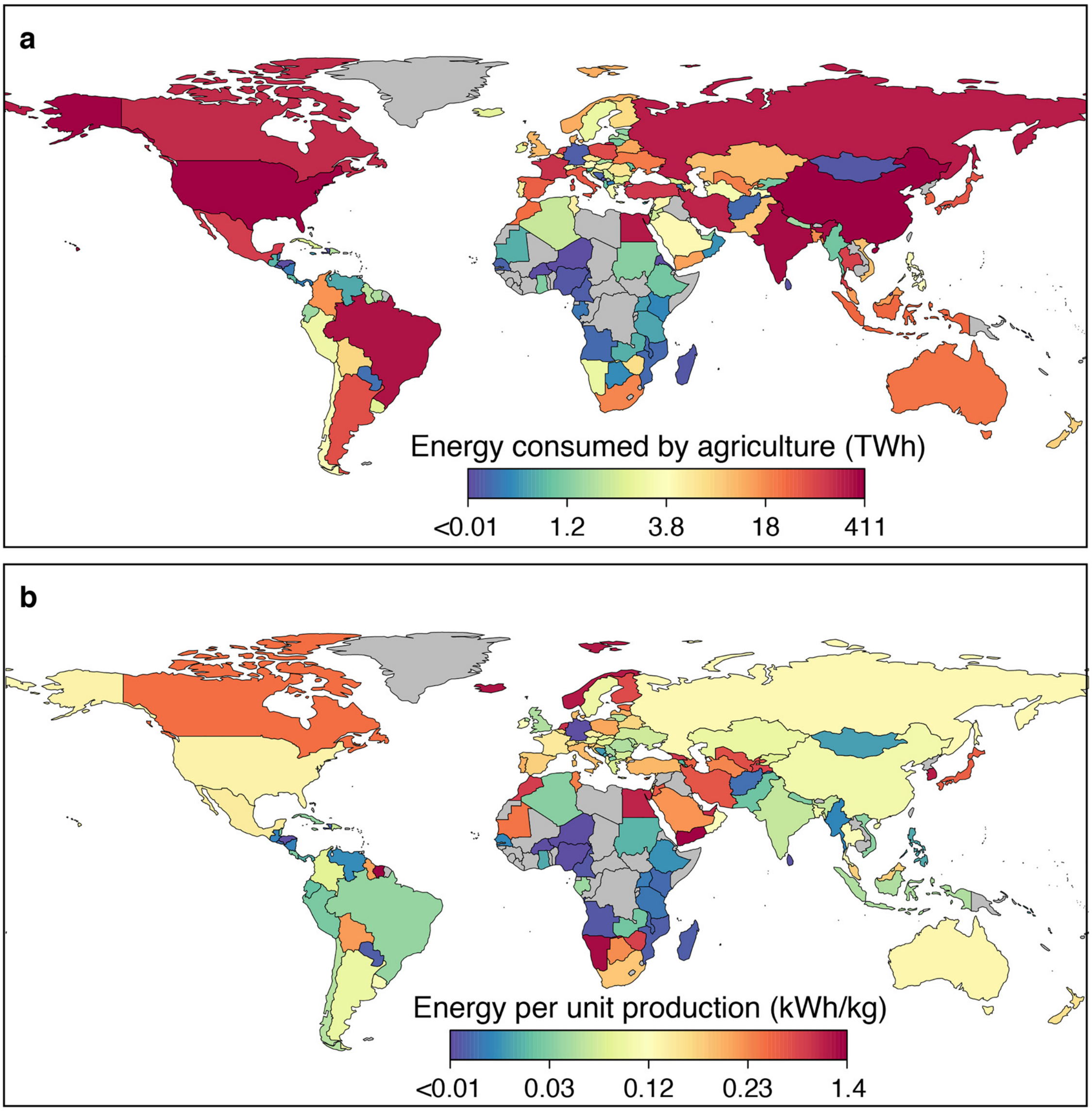

Fig. 6. Energy for food. a. Maps show total energy consumption by the agricultural sector in each country (TWh), and b. Energy consumption per unit of agricultural production (kWh/kg). Grey areas represent countries with missing data.

energy consumption surpass global averages (dashed lines in Fig. 8) while their per capita agricultural production (tons/person/y) is relatively low. On the other hand, countries such as the United States, France, Thailand, Brazil, and Argentina appear to be more efficient in energy and water use with respect to their per capita agricultural production. With the source data that comes with this paper, the interested user can generate different types of graphics for linking global energy, water, and food data.

Finally, the presented data set includes time series of all of the variables mentioned earlier in this paper. For example, Fig. 9 shows time series of per capita food supply from animal products (kcal/person/d) in the period of 1961–2013 for France, United States, Canada, Brazil, Russia, China, Thailand, Iran, India, Indonesia, and Nigeria. This figure shows while dependency of developed countries such as United States, France, and Canada on animal products remains constant or exhibits a slightly decreasing trend, growing economies such as China and Brazil are increasingly consuming animal products for food. The water and energy footprint of animal products are several times higher than crops (e.g., the water footprint of beef is 15,400 m^3/ton whereas the water footprint of corn is 1222 m^3/ton). This alongside the high population of China and India place higher pressure on already stressed food, energy, and water resources, which magnifies the necessity of modeling their interactions and highlights the need for new tools that can depict such interactions.

4. Conclusion

Energy, water, and food resources are highly intertwined, and improving our understanding of their complex interactions is fundamental for improving efficiencies and producing sustainable development plans. In this paper, we present an interactive analysis toolbox, **Ne**xus of **F**ood, **E**nergy, and **W**ater (NeFEW), that synthesizes the available global country-level food, energy, and water information from different sources (mostly the United Nations Food and Agriculture Organization and the Water Footprint Network). This toolbox can be used for both research and education as well as for outreach purposes. NeFEW allows modeling and analyzing the interdependencies for different user-specified categories and quantities. The overarching goal of this paper is to provide a single, integrated data set and an analysis toolbox for enhancing research and educational efforts related to the food, energy, and water nexus. We provide a wide range of example applications of the presented toolbox for estimating the amount of water and energy

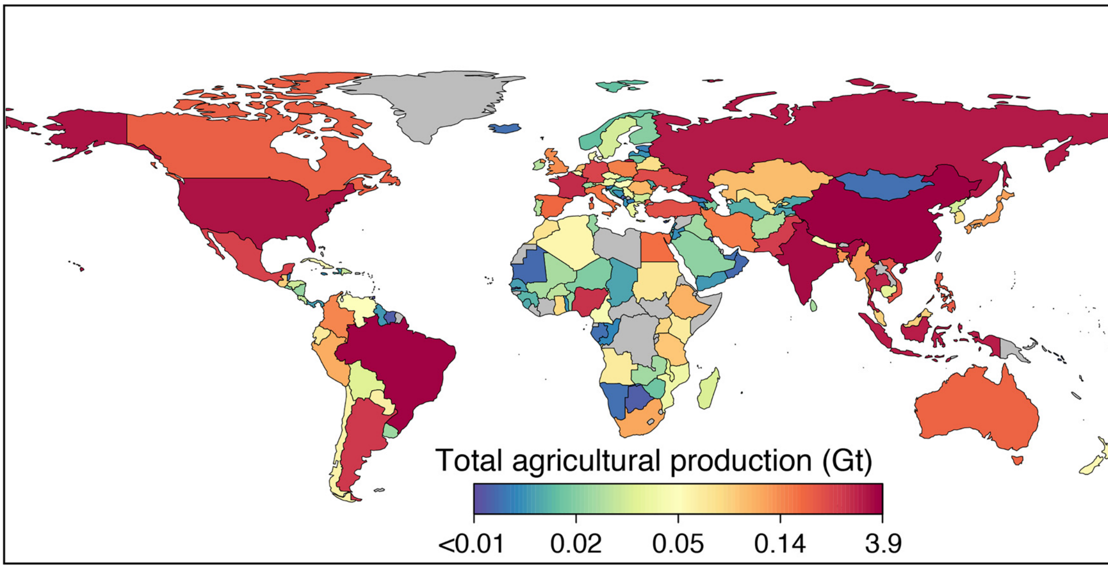

Fig. 7. Food production. Total agricultural production by country (Gt). Grey areas represent countries with missing data.

needed to produce food in different parts of the world.

It should be noted that the quality of the data and outputs of the toolbox relies upon country-level information provided to the agencies in charge of data collection. The conversion factors used in this toolbox to characterize the interdependencies of the food, energy and water sectors rely on the long-term annual averages reported by different countries for different temporal ranges. Accuracy and lengths of country-level records vary around the world, and hence the conversion factors are subject to uncertainty.

5. Code and toolbox availability

This toolbox is freely available to the public at http://amir.-eng.uci.edu/software.php. The NeFEW toolbox uses the described data in the following paragraphs to analyze, for each country, the interdependencies of the water, food, and energy elements. The graphical user interface of this toolbox is presented in Fig. 2. The orange boxes and drop-down menus require user input, whereas white and grey boxes present the toolbox outputs. Upon the selection of the country, its most updated (no later than 2013) population will be reported to the user. Then, any conversions from one element of the nexus to the other(s) is simply conducted using the NeFEW toolbox at the long-term annual average scale.

The data sets used in this study include:

- Food Balances Sheet: This rich data set includes information on the "production, import quantity, stock variation, export quantity, domestic supply quantity, feed, seed, waste, processing, other uses, food, food supply quantity (kg/person/y), food supply (kcal/person/d), protein supply quantity (g/person/d), and fat supply quantity (g/person/d)" of different crops, their derived products, and animal products. This data is presented at the country-level and in terms of time series of values from 1961 to 2013. Data can be obtained from http://www.fao.org/faostat/en/#data/FBS/metadata.
- Aquastat: It provides, at the country-level, agricultural, industrial, municipal, and total water withdrawals, as well as fresh surface water and groundwater withdrawals. It also delivers useful information on the produced desalinated water, the direct use of treated municipal wastewater, and agricultural drainage water. The data, however, are not consistent on the year of measurement and can have observations ranging from 1993 to 2014. The data set is

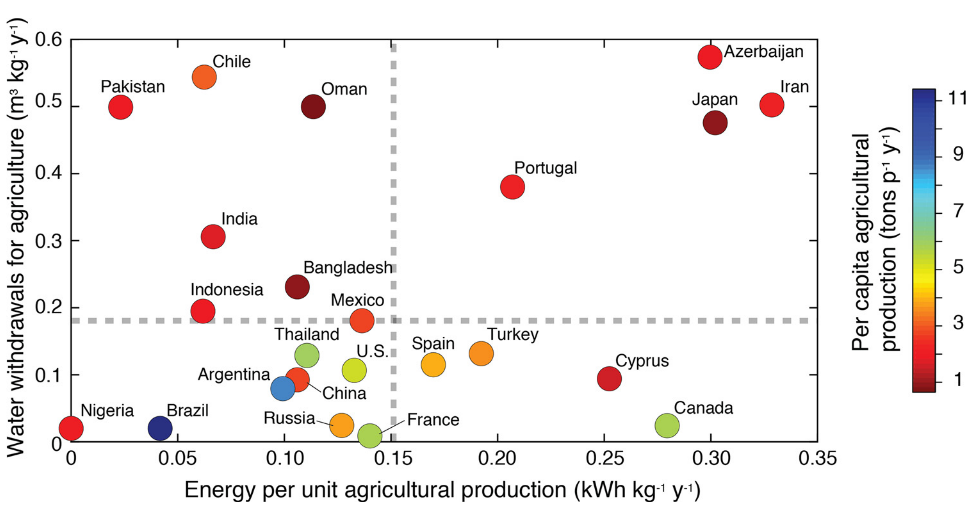

Fig. 8. Water and energy intensities of agriculture. Water withdrawal (m^3/kg/y) for and energy consumption (kWh/kg/y) in the agricultural sector for a representative set of 23 countries around the globe. Each country is color-coded based on its per capita agricultural production rate (tons/person/y). The vertical and horizontal dashed lines demarcate the global average energy consumption (kWh/kg/y) in and water withdrawal (m^3/kg/y) for the agricultural sector, respectively.

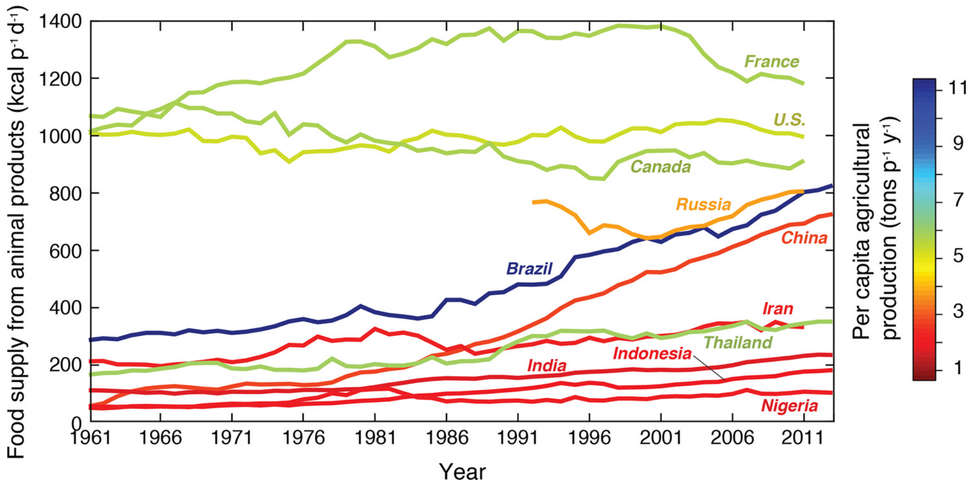

Fig. 9. Trends in meat consumption. Time series of per capita food supply from animal products (kcal/person/d) for the period of 1961-2013.

available at http://www.fao.org/nr/water/aquastat/data/.

- Water Footprint Crops: This data set provides the country average and state/province specific green, blue, and grey water demand for different crops and their derived products. More details on the modeling approach and background calculations of this data are provided in Section “Food to Water”. This data set is available at http://waterfootprint.org/en/resources/water-footprint-statistics/.
- Water Footprint Animal Products: This data set provides, at the country-level, the green, blue, and grey water footprint for grazing, industrial, and mixed production of animal products. More details on the modeling approach and background calculations of this data are provided in Section “Food to Water”. This data set is available at http://waterfootprint.org/en/resources/water-footprint-statistics/.
- Emissions Agriculture: This rich data set provides a time series (1970–2012) of agricultural consumption of gas-diesel, motor gas, natural gas, liquefied petroleum gas, fuel oil, electricity, and total energy. Each of these categories is presented in terms of consumption in agriculture (TJ), implied emission factor for CH_4 (kg/TJ), emissions (CH_4) (Energy: Gg), emissions (CO_2-equivalent) from CH_4 (Energy: Gg), implied emission factor for N_2O (kg/TJ), emissions (N_2O) (Energy: Gg), emissions (CO_2 -equivalent) from N_2O (Energy: Gg), implied emission factor for CO_2 (kg/TJ), emissions (CO_2) (Energy: Gg), and emissions (CO_2-equivalent) (Energy: Gg). Other available variables include gas-diesel oils, fuel oil, and total energy used in fisheries, as well as energy for power irrigation and transport fuel used in the agricultural sector. This data set is available at http://www.fao.org/faostat/en/#data/GN.
- Renewable Internal Freshwater Resources: This rich data set provides long-term averages of renewable internal freshwater resources for each country from 1962 to 2014. This data set can be freely obtained from the World Band Data repository available at http://data.worldbank.org/indicator/ER.H2O.INTR.K3?end = 2014&start = 1962.

Authors contributions

MS and AA developed the idea and conceived the study. MS developed the analytical toolbox, obtained data and wrote the first draft. SJD and IM contributed to analyzing data and created the figures. OM and MN contributed to the gathering and processing of data. MS, AA, LSH, IM, JB, AF, AM, NDM, MRA and SJD wrote the paper. All authors reviewed the manuscript and provided input.

Competing interests

The authors declare no competing interests.

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