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RESEARCH ARTICLE

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Domestic water versus imported virtual blue water for agricultural production

A comparison based on energy consumption and related greenhouse gas emissions

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Abstract

The supply of water, food, and energy in our global economy is highly interlinked. Virtual blue water embedded into internationally traded food crops has therefore been extensively researched in recent years. This study focuses on the often neglected energy needed to supply this blue irrigation water. It provides a globally applicable and spatially explicit approach to the watershed level for water source specific quantification of energy consumption and related greenhouse gas (GHG) emissions of irrigation water supply. The approach is applied to Israel's total domestic and imported food crop supply of 105 crops by additionally including import-related transportation energy and emissions. Total energy use and related emissions of domestic crop production were much lower (551 GWh/422 kt CO_2-equivalents [CO_2e]) than those embedded into crop imports (1639 GWh/649 kt CO_2e). Domestic energy and emissions were mainly attributable to the irrigation water supply with artificial water sources (treated domestic wastewater and desalinated water, 84%). Transport accounted for 79% and 66% of virtually imported energy and emissions, respectively. Despite transport, specific GHG emissions (CO_2e per ton of crop) were significantly lower for several crops (e.g., olives, almonds, chickpeas) compared to domestic production. This could be attributed to the high share of energy-intensive artificial water supply in combination with higher irrigation water demands in Israel. In the course of an increasing demand for artificial water supply in arid and semi-arid regions, our findings point to the importance of including "energy for water" into comparative environmental assessment of crop supply to support decision-making related to the water–energy–food nexus.

KEYWORDS
agricultural water use, energy for water, industrial ecology, Israel, virtual water flows, greenhouse gas emissions

1 | INTRODUCTION

The highly interdependent system of supplying water, energy, and food to human societies has been recognized as the water–energy–food nexus (Bazilian et al., 2011; Keairns et al., 2016). One important subsystem of the nexus is the link between water use and food production (water–food nexus). Agriculture is responsible for 69% of global water withdrawal (FAO, 2016). Every food (and material) product "embeds" a certain volume of water consumed or polluted during its production process. This has been referred to as its "virtual water" content (Allan, 2001) or (volumetric) water footprint (Hoekstra et al., 2011). In a crop production context, the blue water (ground and surface water) footprint denotes the volume of irrigation water consumed via evapotranspiration during plant growth (Mekonnen & Hoekstra, 2011; Pfister & Bayer, 2014; Siebert & Döll, 2010).

Irrigated agriculture involves another important subsystem of the water–energy–food nexus: The energy demand for water supply ("energy for water") (Kyle et al., 2016). It was estimated to contribute 1.7% to 2.7% of global primary energy consumption in all economic sectors, with one fourth attributed to the agricultural sector (Liu et al., 2016). Studies on regional energy-related greenhouse gas (GHG) emissions of irrigation agriculture have often focused on groundwater (Daccache et al., 2014; Wang et al., 2012). However, non-conventional water sources are becoming increasingly popular for crop irrigation in arid and semi-arid regions to reduce pressure on local freshwater resources (Pedrero et al., 2010; Qadir et al., 2007). Desalinated seawater is still mainly utilized for municipal and industrial water supply and then used for irrigation after treatment (Burn et al., 2015; Jones et al., 2019). But it has also been reported to be used directly for irrigation purposes, for example, in Israel and Spain (Martínez-Alvarez et al., 2016; Yermiyahu et al., 2007). With regards to energy consumption, the desalination of seawater is usually much more energy demanding than other water sources (Plappally & Lienhard, 2012; Stokes & Horvath, 2009).

Another strategy for ensuring local water security in countries with limited water resources is the import of water-intense goods. Virtual water imports embedded in food products contribute to immense water savings in the Middle East and North Africa (MENA) region (Lee et al., 2019). On the other hand, it is estimated that globally 11% of non-renewable groundwater used for irrigation is embedded into internationally traded food products (Dalin et al., 2017). By embedding virtual irrigation water, food products also embed the corresponding energy utilized for water supply, and the accompanying GHG emissions. There are other energy-demanding and GHG-emitting processes involved in crop production and supply, but irrigation-related energy consumption alone can substantially contribute to total production-level energy requirements. Irrigation energy accounted for 23% of total on-farm energy in US crop production (Lal, 2004). The share was even higher for irrigated millet (33.2%) and wheat (48.6%) in India (Safa et al., 2010) and reached up to 78.4% for irrigated wheat in Iran (Singh et al., 2002). With regard to the entire energy and GHG emissions embedded into crops, the question whether domestic food production is more environmentally friendly than food imports has been frequently addressed in recent years (Jones, 2002; Kreidenweis et al., 2016; Webb et al., 2013). It is, however, worth noting that these studies seldomly included a quantification of "energy for water."

This study assesses the energy consumption and related GHG emissions of domestic blue water versus virtually imported blue water used for agricultural production. We present a global approach for watershed-level quantification of irrigation "energy for water" and additionally include transport energy for imported crops. This is because the transportation is assumed to be a genuine process in order to make virtual blue water accessible. The analysis focuses on Israel as a case study—representing a water scarce country of the MENA region—in order to understand if domestic production or import of crops is "better" with regard to energy for water. Such a comparison can contribute to the decision-making process for national policies within the water–energy–food nexus. Energy input and GHG emissions for other processes in the life cycle of crops (e.g., fertilizer input and machinery use) as well as all other environmental impacts are considered beyond the scope of this study, but a full life cycle assessment would of course be important for profound decision support.

So the main contributions of this paper are to: (1) quantify the energy related to irrigation water provision which is often ignored or covered incompletely in energy/carbon accounts of global crop datasets; and (2) support national policy decision-making by questioning energy-intense artificial water use for irrigation in Israel in perspective to the energy demands related to providing freshwater in global crop production and transport.

2 | METHODS AND STUDY AREA

The methodological approach of this study was a watershed-level quantification of irrigation "energy for water" and transport energy for crops produced in or imported to Israel. In a first step, crop- and watershed-specific total blue water use of Israel's national crop equivalent consumption was quantified. Total blue water use was subsequently differentiated by water source according to national irrigation mix data. In a third step water-source-specific "energy for water" and related GHG emissions were calculated. Transport energy and GHG emissions were determined based on the crop production data and transport distances. The methodological process is shown in Figure 1 and described in the following paragraphs. Additional information can be found in Supporting Information 1 and 2.

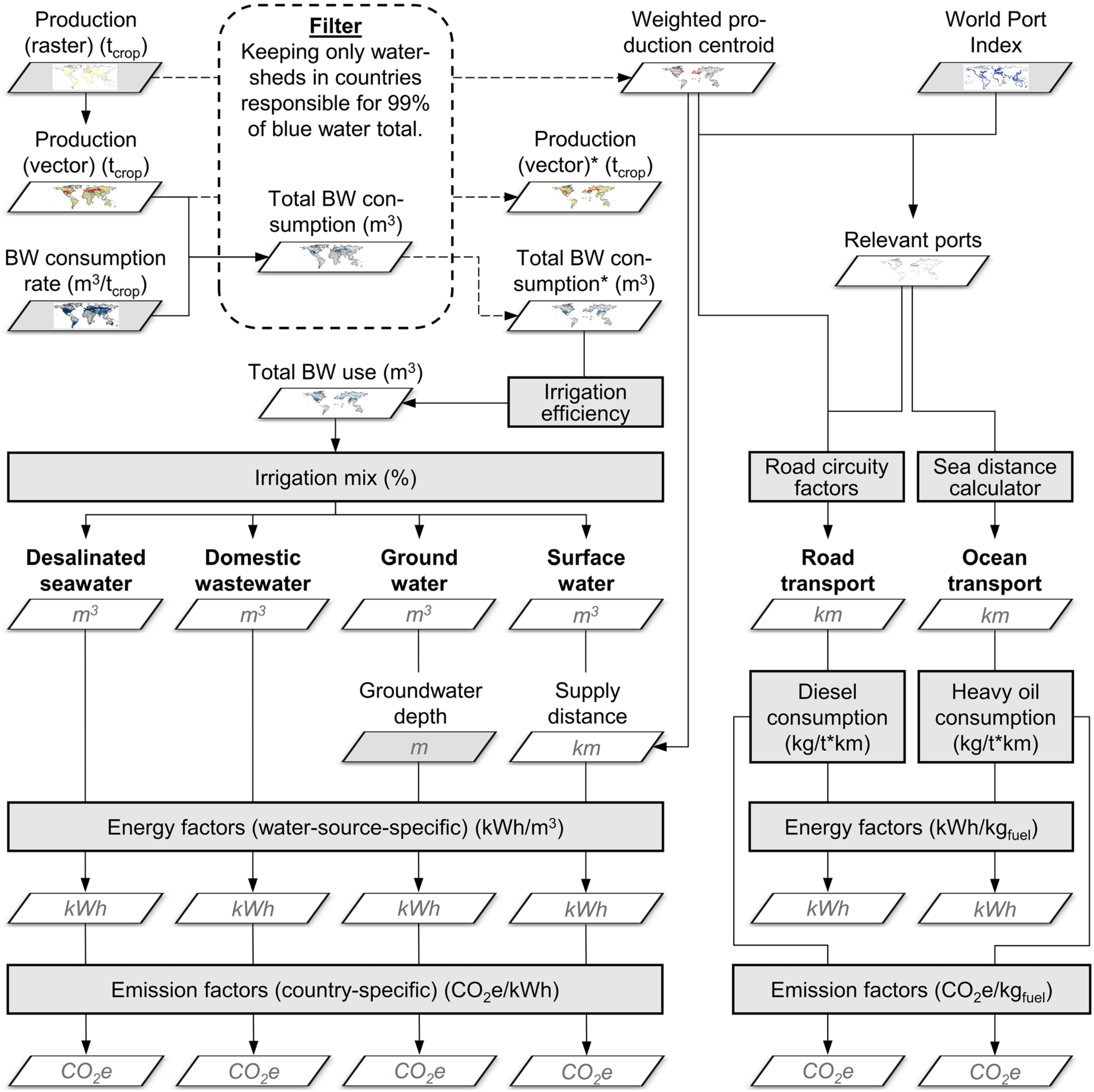

FIGURE 1 Flowchart summarizing the methodological procedure to calculate total energy consumption and greenhouse gas emissions of virtual blue water embedded into Israeli crop equivalent consumption exemplary for 1 out of 105 crops. Input data is indicated by a grey background. BW, blue water.

2.1 | Case study area

Israel belongs to the MENA region and is located at the Eastern end of the Mediterranean Sea. Half of its area is situated in semi-arid or arid climates (Oziransky et al., 2014). The natural recharge from rainfall of around 1720 million m^3 (MCM) cannot meet the current water demand of almost 2200 MCM. Adding to that, precipitation in the country has been decreasing throughout the last decades (Ziv et al., 2014) and is expected to continue (Hochman et al., 2019). For this reason, Israel has implemented several measures to increase its water supply by means of artificial water resources (Israel Water Authority, 2012). As of 2012, around 70% of domestic wastewater was treated, of which 75% was reused for irrigation. Also the country's desalination capacity has been continuously increasing in recent years (Oziransky et al., 2014). Due to its small size, high population density, and lack of arable land, Israel is highly dependent on food resources from abroad (Fridman & Kissinger, 2019; Kissinger & Gottlieb, 2010). Nevertheless, the blue water consumption (BWC) of domestic crop production for domestic consumption exceeds the imported virtual blue water (Shtull-Trauring & Bernstein, 2018).

2.2 | Quantification of total blue water use

BWC data used in this study was sourced in the form of geometric means of crop BWC for 160 crops on a watershed level (split by country) (Pfister, 2019; Pfister & Bayer, 2014). The crop production data for 2010 was derived in the form of a raster grid reflecting production quantity for raw crops and processed crops (in equivalents) of 105 food crops and crop groups allocated to Israeli consumption (Fridman & Kissinger, 2018, 2019). The production quantity of each of crop was summed to the watershed level and multiplied by BWC rate to obtain crop- and watershed-specific total BWC. For simplicity, all countries cumulatively contributing less than 1% of total BWC were excluded from further analysis.

The crop BWC data modeled with the FAO CROPWAT software represents net irrigation water requirements (Pfister, 2019). To obtain the gross irrigation water requirements, which we define as "blue water use" (BWU), total BWC was divided by country-specific application efficiency factors (Rohwer et al., 2007) to obtain total BWU.

2.3 | Irrigation mix

Country-level irrigation mix data (Leão et al., 2018) was used for the differentiation of BWU by water source. Water source categories were aggregated to surface water, groundwater, domestic wastewater, and desalinated seawater. Desalinated water is a product derived from seawater and should not be considered as BWU according to ISO 14046:2014 (Environmental management — Water footprint — Principles, requirements, and guidelines). However, this form of artificial blue water is included here as the required energy consumption and resulting emissions are reported in this paper. This decision is supported by recent literature, highlighting that the blue water framing—originally aimed at saving freshwater resources—has simultaneously been broadly used to quantify irrigation needs (Fridman et al., 2021).

Missing data could be partially obtained from AQUASTAT (FAO, 2016) following the same methodology as of the source dataset (Leão et al., 2018). Remaining (mainly tropical) countries were assigned an irrigation water supply of 100% surface water. Irrigation mix data for Israel was calculated separately and explicitly for the year 2010 based on data from Israel Water Authority (2011) and Central Bureau of Statistics (2013).

2.4 | Water energy consumption and GHG emissions

"Energy for water" for each crop in each watershed was derived from multiplication of the water-source-specific total BWU with corresponding energy consumption factors. The respective factors for each of the four water sources were derived from the literature (see Table S7 of Supporting Information 1). The surface water supply distance was estimated by calculating the linear distance from the geographical centroid to the crop-specific weighted production centroid of a watershed. Only 65% of this surface water supply was assumed to be powered, based on percental data of area irrigated by pressurized and gravitational systems in US irrigation agriculture (USDA ERS, 2022). The energy consumption factor for groundwater supply was determined based on pump-lift-specific values (Plappally & Lienhard, 2012). The pump lift height was estimated by means of global dataset on water table depths of Fan et al. (2017).

All energy requirements for irrigation water supply were assumed to be powered by grid electricity. Country-specific grid electricity emission factors of CO_2, N_2O, and CH_4 (Ecometrica, 2011) were aggregated to CO_2-equivalents (CO_2e) using the IPCC conversion factors (Global Warming Potential 100 years) (Myrhe et al., 2014).

2.5 | Transport energy consumption and GHG emissions

Specific transport-related energy and emissions were calculated for each crop produced in a watershed outside of Israel. Israel inland transport was neglected for simplicity and due to the small country size. Generally, the transport calculation consists of (1) road transport (lorry) from field to port and (2) ocean transport (ship) from the respective port to Haifa (Israel).

Road transport routes per crop and watershed were computed as the linear distance between the crop-specific weighted production centroid and the closest large port within the same country extracted from the World Port Index dataset (National Geospatial-Intelligence Agency, 2019). For countries without seaport, the distance to the closest foreign port was taken. The distance was multiplied by a country-specific road circuity factor (Ballou et al., 2002). Distances for ocean transport from each relevant foreign port to Israel's largest port Haifa were obtained from searoutes.com (Searoutes S.A.S, 2019). The corresponding energy consumption and GHG emissions were calculated by means of specific fuel consumption and emission factors (see Table S9 of Supporting Information 1).

2.6 | Specific energy consumption and GHG emissions

"Specific" energy consumption (kWh/t_{crop}) and GHG emissions (kg CO_2e/t_{crop}) were obtained by dividing "total" energy consumption and GHG emissions for each crop by the corresponding crop production quantity per watershed. This quantity specific measure allows for a direct comparison of energy consumption and related GHG emissions between watersheds. To directly compare between countries, the average of specific crop energy consumption and GHG emissions of all watersheds within a country was weighted by the corresponding crop production quantity.

3 | RESULTS

3.1 | Specific energy consumption and GHG emissions

For a more straightforward presentation of specific energy consumption and GHG emissions, one crop of each relevant crop group of the FAOSTAT Commodity List was chosen to be analyzed in more detail. To that end, the one most energy-consuming crop per crop group produced both domestically and externally was selected. The weighted averages of domestic specific energy and emissions exceeded the imported ones in the case of wheat, olives, apples, almonds, and chickpeas (Figure 2). The difference was significant for almonds and olives (p-value < 0.001) as well as chickpeas (p-value < 0.01 and < 0.05 for specific emissions and energy, respectively). At the same time, domestic production quantity of these three crops surpassed imported quantity. The opposite was true for potatoes and tomatoes. Specific energy and emissions of domestic production were significantly lower for these two crops, which were predominantly produced domestically. A complete overview of domestic versus imported specific energy for all crops per crop group as well as country- and watershed-level differentiation for the eight selected crops is provided in Section S12 of Supporting Information 1.

Wheat is one of the most important crops for Israeli consumption. While most of the wheat consumed in Israel is imported, the crop is also produced domestically to some extent (see Figure 2). Figure 3 depicts country- and watershed-level energy consumption and GHG emissions of wheat imported and produced in Israel. A more detailed map of Israel and its five most important wheat source countries (Russia, Ukraine, USA, Turkey, Romania), differentiating specific energy by process, is shown in Figure 4 (for specific emissions see Figure S11 of Supporting Information 1). For Israel itself, specific energy and emissions varied strongly between the watersheds of the country. The two watersheds with most wheat production showed specific energy values of 215 and 1128 kWh/t as well as specific emission values of 165 and 864 kg CO_2e/t, respectively. This could mainly be attributed to the variability of blue water use rate and resulted in a domestic weighted average of 515 kWh/t (energy) and 394 kg CO_2e/t (emissions). Wheat from Ukraine, Romania, and Turkey was connected to comparatively low specific energy consumption and GHG emissions of 47—254 kWh/t and 16—198 kg CO_2e/t. Specific energy and emissions of wheat from Russia showed much larger variability (70–944 kWh/t, 24–350 kg CO_2e/t), but the majority of production was located in watersheds with low to intermediate specific energy and emissions, resulting in weighted averages of 293 kWh/t and 103 kg CO_2e/t. From the five most important wheat source countries, weighted average specific energy of wheat imports was only higher than the domestic one in the case of the United States (584 kWh/t). Weighted average specific emissions were instead lower for all five countries. The difference between domestic and imported wheat was, however, only significant ($p < 0.05$) for specific GHG emissions of wheat imports from Ukraine (and a few less important countries in terms of import quantity).

Specific transport energy exceeded specific "energy for water" for wheat production in most watersheds of the five most important source countries (Figure 4). However, the water component became more important than transport in the case of GHG emissions for a number of watersheds, in the United States, Turkey, and Romania (see Figure S10 of Supporting Information 1). The relative share of road transport energy was particularly high in Russian watersheds. By contrast, ocean transport contributed the largest share in most watersheds of the United States. The proportional contribution of each water source to specific energy consumption within Israel was relatively uniform across watersheds. The artificial water sources dominated watershed-specific energy consumption. Only the southernmost watershed reached a comparatively high surface water share with around 20%.

3.2 | Total energy consumption and GHG emissions

Figure 5 depicts total domestic and import energy consumption and GHG emissions aggregated over all crops as well as the corresponding total BWU and production quantities. The total energy consumption amounted to 2190 GWh. It was attributable to domestic production 25% (551 GWh) and to the imported crops 75% (1639 GWh). The import component was so high mainly due to the energy consumption related to transport, 79%, compared to 21% "energy for water." The 343 GWh of import "energy for water" (blue colors in Figure 5) were attributable to surface water 84.8%, groundwater 14.9%, and to a minor extent (0.3%) to artificial water sources. In contrast, artificial irrigation water supply with desalinated sea water (50%) and domestic wastewater (34%) was responsible for most of the domestic "energy for water." In a country comparison, energy consumption was highest for the United States. It contributed around 30% of total energy consumption, 67% of which was contingent on transport.

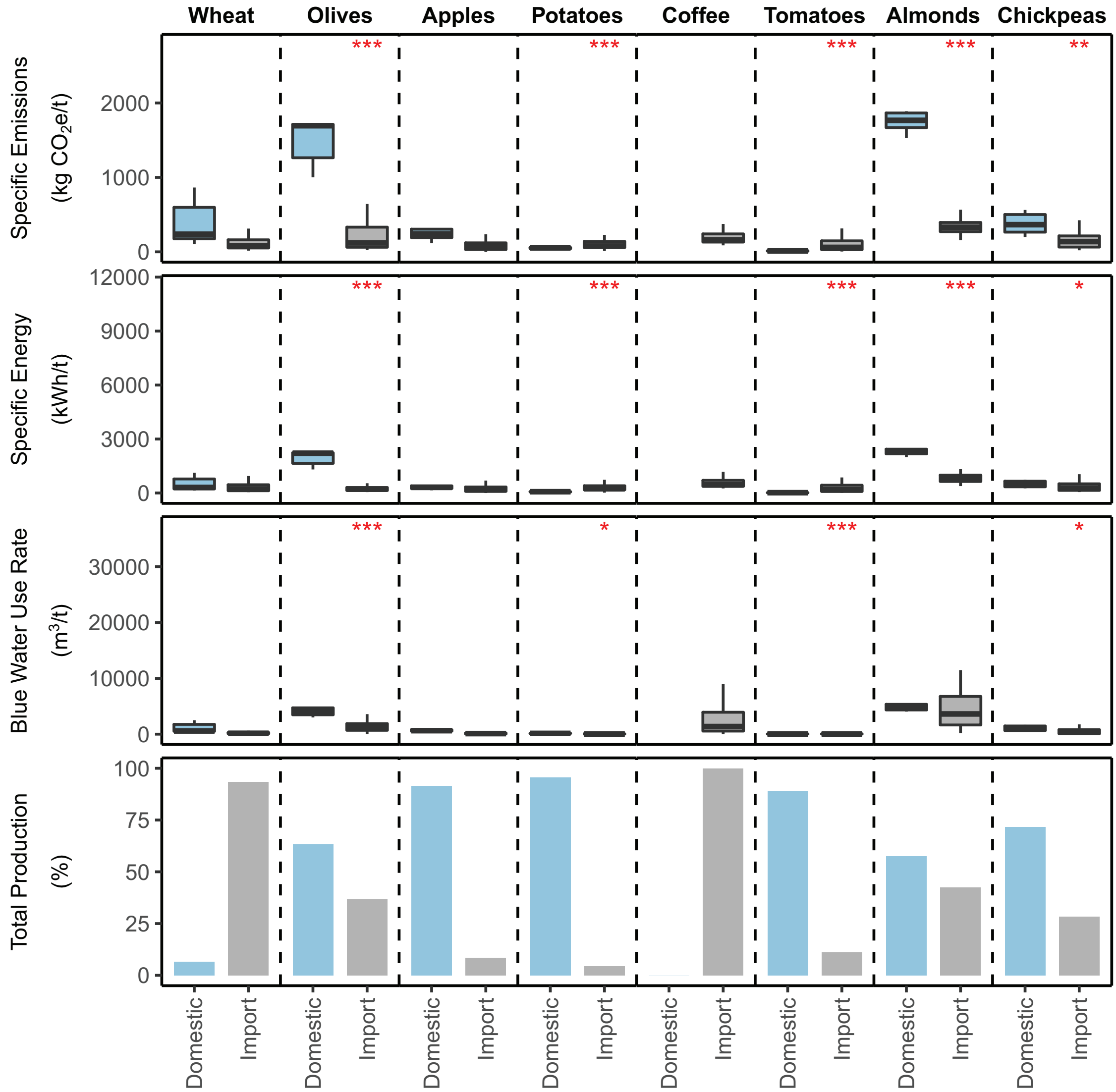

FIGURE 2 Specific greenhouse gas emissions (kg CO_2e/t), energy consumption (kWh/t), blue water use rate (m^3/t) as well as relative production quantity (%) of domestic and imported virtual blue water for agricultural production of selected crops. Boxplots are shown in black and red dots indicate the weighted mean of specific energy or emissions of all watersheds within Israel or all import countries weighted by the corresponding production quantity. Significant differences between weighted means of Israel and import countries are marked by red asterisks: (*) $p < 0.05$, (**) $p < 0.01$, (***) $p < 0.001$. The underlying data for this figure can be found in Supporting Information S3.

The total GHG emissions of 1071 kt CO_2e split into 39% (422 kt CO_2e) domestic and 61% (649 kt CO_2e) import. One main difference compared to energy consumption was the lower relative importance of import transport, which decreased to only 66% of total import emissions compared to 79% in the case of energy. While total energy attributable to the USA were 17% higher than Israel's domestic energy consumption, GHG emissions were 44% lower.

Considering only the "energy for water" components without transport, domestic total energy and GHG emissions exceeded import energy and emissions by 60 % and 91%, respectively.

4 | DISCUSSION

Virtual water flows in international trade have been extensively researched in recent years, mainly from the perspective of water scarcity. Within the scope of the water–energy–food nexus, this study takes another point of view by focusing on the embedded energy consumption and related GHG emissions of internationally traded virtual blue water for agricultural production. To that end, we compared Israel's domestic and imported

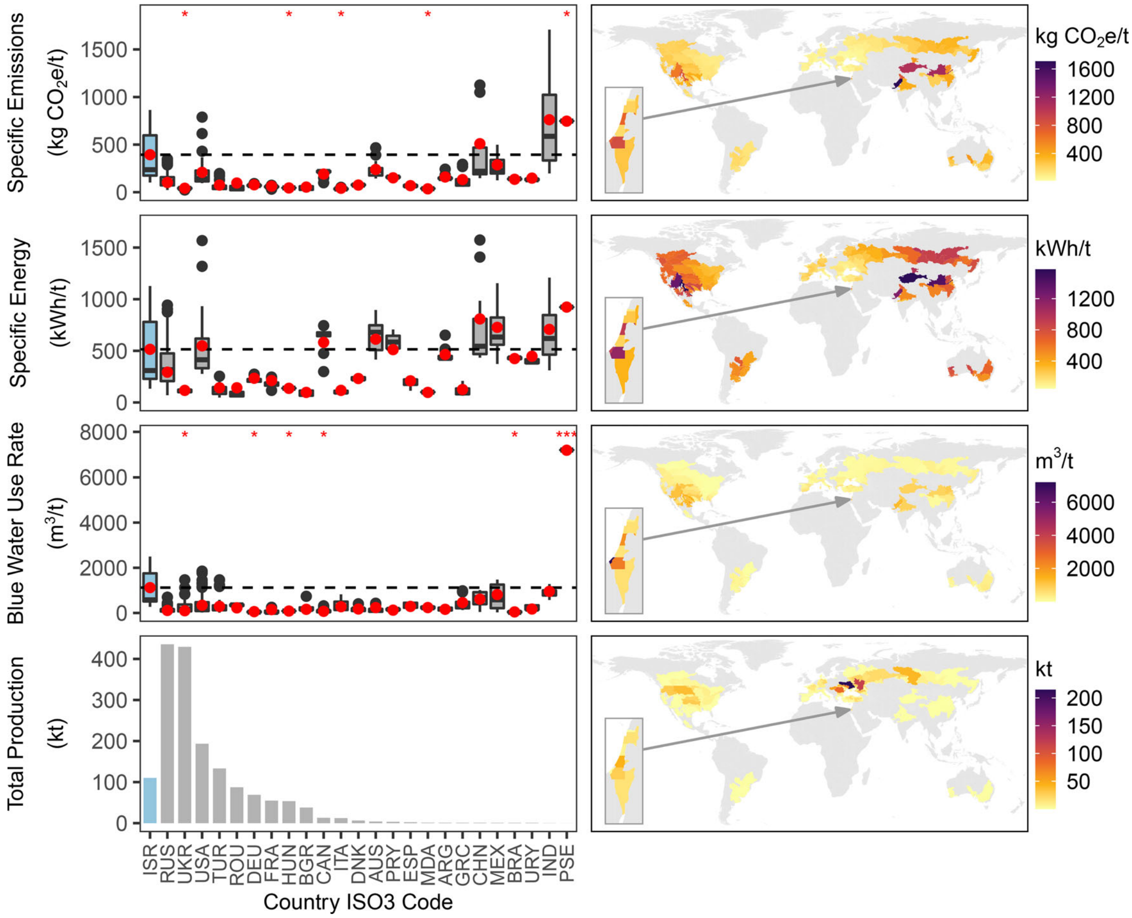

FIGURE 3 Country- and watershed-level specific GHG emissions (kg CO_2e/t), energy consumption (kWh/t), and blue water use rate (m^3/t) ordered by per-country total production (t) of wheat. Data are shown as boxplots in black and red dots indicate the weighted mean of specific energy or emissions of all watersheds within Israel or all import countries weighted by the corresponding production quantity. Significant differences between weighted means of Israel and import countries are marked by red asterisks: (*) $p < 0.05$, (**) $p < 0.01$, (***) $p < 0.001$. The underlying data for this figure can be found in Supporting Information S3.

food crop supply. A similar analysis can be easily adapted for any country. However, Israel was a particularly interesting case study due to its large share of artificial water supply. Our water source-specific quantification of "energy for water" expands on previous studies that have focused on energy for groundwater irrigation (Daccache et al., 2014; Wang et al., 2012). A first global and water source-specific assessment of overall "energy for water" (Liu et al., 2016) only provided data on a country level, while our approach is applicable to the watershed level. In order to compare energy for domestic water use against virtually traded water we included the energy required to "transport the virtual water." The inclusion of transport energy allows for a first identification of crop source countries that could be preferred over other ones based on the "energy for water."

However, this study does not claim to replace a comprehensive energy and GHG assessment of domestic versus external crop production. This would have required the inclusion of several other processes such as energy consumption and GHG emissions related to fertilizer and pesticides, machinery use and fuel consumption, or refrigeration during transport (Webb et al., 2013). While machinery use can be assumed to be relatively independent of the location of production, average fertilizer inputs per hectare can vary greatly between countries. Consistent country- and crop-specific fertilizer input datasets for the 105 crops subject to this analysis were not available. As the focus of this study lies on the "energy for water," it was therefore neither feasible nor within the scope of this global analysis to include all energy-consuming processes.

4.1 | Domestic versus import energy consumption and GHG emissions

The high energy intensity of well-established artificial water supply in Israel was clearly reflected in our results: Whereas total domestic BWU was 9% lower than import-related BWU, total "energy for water" and related GHG emissions were higher, by 60% and 91%, respectively (see blue color bars in Figure 5). The difference was larger for the GHG emissions due to the relatively high Israeli grid electricity emission factor of 0.76 kg CO_2e/kWh compared to a weighted mean emission factor of all import countries of only 0.53 kg CO_2e/kWh. This is because Israel mainly

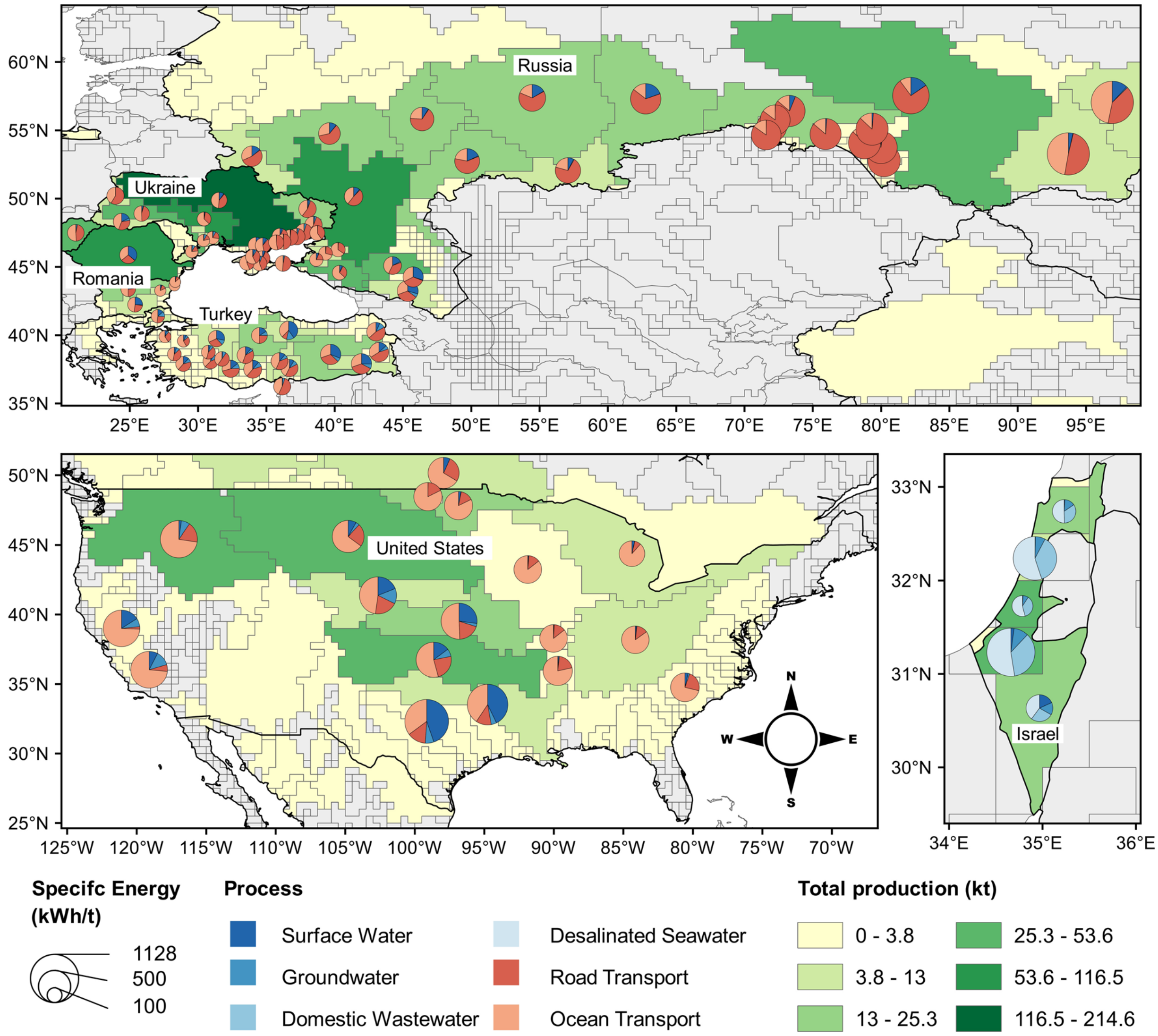

FIGURE 4 Maps of total wheat production (kt) for Israeli consumption per watershed within Israel and the most important external source countries. Information on quantity and partitioning of specific energy consumption (kWh/t) for wheat supply from each watershed is given in pie charts. Pie charts are only shown for watersheds with a total production greater than 1 kt. The underlying data for this figure can be found in Supporting Information S3.

relies on fossil fuel imports for electricity generation rather than renewables (Meindertsma et al., 2010). Regarding transport, the energy-related emission factors for road (0.266 kg CO_2e/kWh) and ocean (0.287 kg CO_2e/kWh) transport were even lower than that. In short, each kWh of domestic "energy for water" translated into higher GHG emissions than a kWh of imported "energy for water" or import transport.

While this comparison of total energy consumption and GHG emissions was useful to identify general patterns as well as key countries and processes, the analysis of crop- and country-specific energy and emissions allowed for a much more differentiated point of view. Weighted averages of domestic specific energy and emissions were indeed higher than import energy and emissions for individual crops—despite transport (Figure 2). This difference was statistically significant for olives, almonds, and chickpeas, all of which were predominantly produced domestically. Considering the water- and transport-related energy consumption and GHG emissions assessed, 59.8 GWh and 48.9 kt CO_2e (olives), 3.2 GWh and 3.3 kt CO_2e (almonds), and 1.6 GWh and 2.2 kt CO_2e (chickpeas) could be saved if one half of the current domestic production of these crops was instead imported—given the current distribution of production. The higher domestic specific energy and GHG emissions were to some extent related to the high share of artificial water supply in Israel and to its relatively high grid electricity emission factor. On the other hand, the imported crops were often associated with lower BWU (see Figure 2). In the previous example, Israel would also save 85.9 MCM (olives), 2.2 MCM (almonds), and 6.3 MCM (chickpeas) of blue water. However, international crop trade decisions are yet seldomly based on the idea of saving domestic water or energy. Israel, for example, not only covers most of its fruit and vegetable consumption by domestic production (see Figure S7 of Supporting

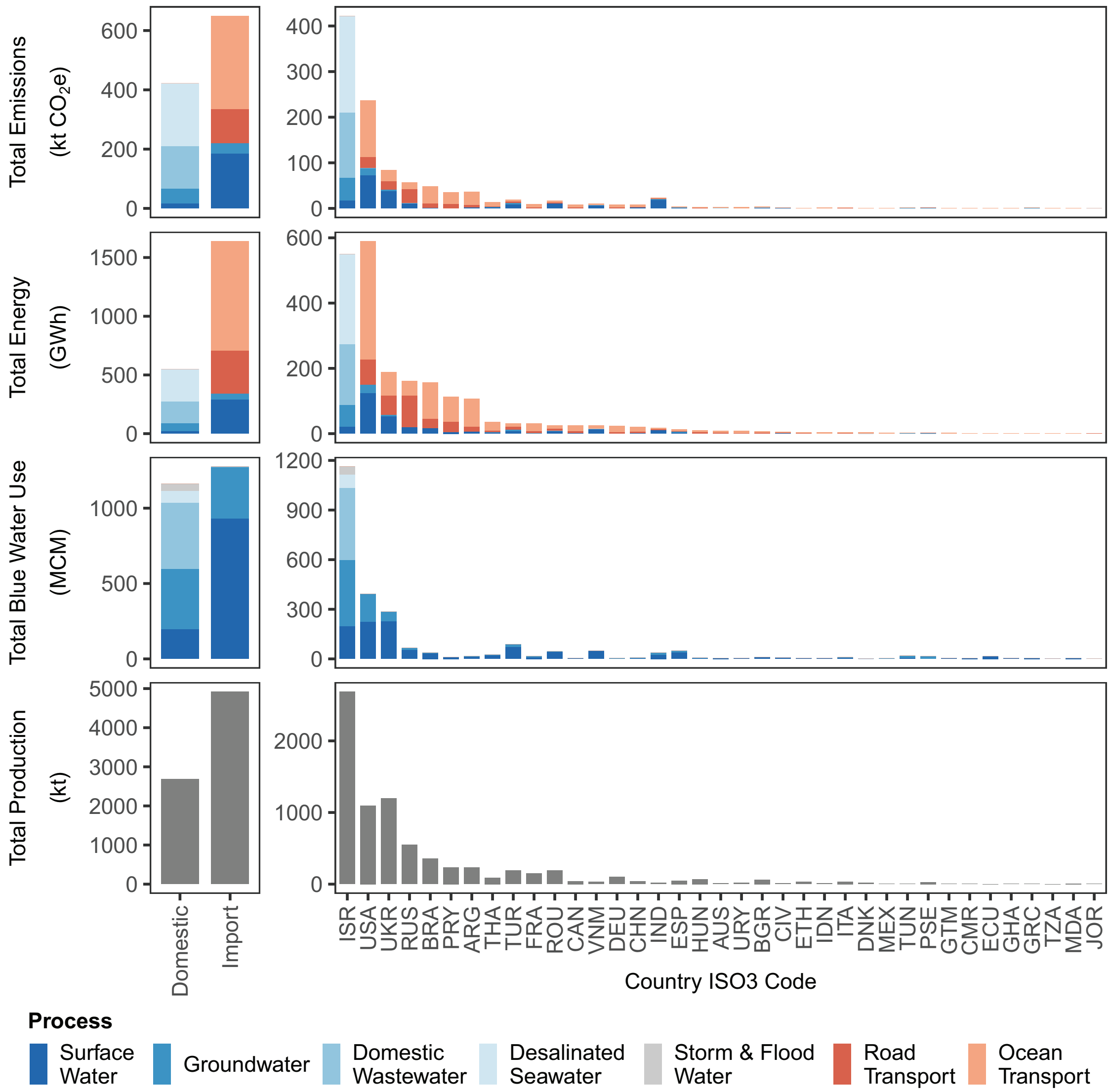

FIGURE 5 Total greenhouse gas emissions (kt CO_2e) and energy consumption (GWh) of domestic and imported virtual blue water for agricultural production as well as the corresponding total blue water use (MCM) and production quantities (kt) to satisfy Israel's consumption. Energy and emissions are differentiated by the respective energy-consuming process for water supply and transport. Blue water use is to be understood as irrigation water use and therefore also includes artificial water sources. It is differentiated by water source. Full country names corresponding to the ISO3 codes are provided in Section S3 of Supporting Information S1. The underlying data for this figure can be found in Supporting Information S3.

Information 1). It also exports around 260 MCM of virtual blue water per year, primarily embedded into high-value crops of these two crop groups (Shtull-Trauring & Bernstein, 2018) out of economic reasons.

Due to the large variability of specific energy and emissions across watersheds, the differences between domestic and imported crop production were often not statistically significant. This is well reflected in a country comparison of energy and emissions related to wheat (see Figures 3 and 4), which was likely due to the high variability between Israeli watersheds. The weighted average, however, includes information on the actual quantitative distribution of production. It is therefore seen as a meaningful reflection of actual differences. In this context, the high amount of wheat imports from these countries is not only connected to domestic water savings, but also to comparatively high energy and related GHG emission savings. Considering only the water- and transport-related energy consumption and GHG emissions assessed here, they should be preferred against wheat imports from the United States, which show much larger average energy consumption (Figure 3), mainly due to the large contribution of transport energy (Figure 4). This finding was in line with previous findings of Kissinger and Gottlieb (2010). They found a particularly large energy land footprint for grains imported from North America to Israel, which was to a large extent connected to long transport distances. However, they used another measure (energy land footprint) and their results were based on energy consumption connected to fertilizer and machinery use as well as ocean transport. Apart from that, even for wheat imports from the United States, the energy consumption (and GHG emissions) could be substantially reduced by preferring watersheds with low irrigation energy consumption.

The analysis presented in this manuscript also has several potential implications for domestic and international policy. As energy availability and costs are becoming important components of any commodity value chain, the analysis illustrated here can signal the need for domestic policies that increase local food production and economic accessibility as part of a national food security policy. As long as energy costs are negligible, significant reliance on imported food as illustrated in this case makes sense. However, as energy prices rise, the analysis can signal points of intervention to minimize the costs of that component.

Another relevant policy-related aspect is connected to embedded GHG emissions along the studied commodity chain. Most GHG mitigation policies are still considering emissions within national boundaries. However, as our analysis shows, a part of the emissions is also related to production activities abroad. An emerging policy direction which embraces a consumption perspective should and perhaps will consider those emissions in the importing nations GHG accounting and will be accountable for their mitigation.

The integration of the food–energy–water dimensions of Israel's water supply, as suggested here can support sustainable food system policy-making in Israel. This includes, for example, the Israeli Ministry of Agriculture and rural development strategic plan which aspires to dramatically increase the share of locally supplied fresh fruit and vegetables, while considering the environmental and economic implications of local production versus food imports (Kahal, 2019). It can also be relevant to the emerging Israeli government's cross ministries discussions on food system sustainability and related GHG mitigation strategies and policies (The Israeli Ministry of Environmental Protection, 2021).

4.2 | Irrigation water provision versus transport

Water-related processes were found to account for a large share of specific energy consumption and particularly specific GHG emissions within watersheds of major wheat producing countries (Figure 4 and Figure S11 of Supporting Information 1). Water-related specific GHG emissions even exceeded transport-related emissions in some watersheds of the distant United States. These findings strongly point to the relevance of including water-related GHG emissions into environmental impact assessments of food production and supply. This argument is additionally supported by the earlier discussed finding of higher domestic versus import specific energy and emissions for several crops, which was partially related to the high level of artificial water supply. Moreover, energy-intense desalination techniques are becoming increasingly feasible for irrigation purposes, particularly for high-value crops (Kaner et al., 2017). Increasing the use of renewable energy sources in powering artificial water sources could strongly contribute to reducing related GHG emissions. This particularly applies to Israel, regarding the country's plans to further expand desalination capacity in the context of the low share of renewables in its grid electricity (Tal, 2018).

4.3 | Limitations and uncertainty

The approach taken by this study was subject to several limitations related to the availability of input data as well as to the necessity of simplifying assumptions. Closing the data gaps could significantly increase the accuracy of future assessments. One source of uncertainty was the difference in temporal coverage and spatial resolution of input datasets. The BWC dataset was representative for crop production in the year 2000 (Pfister & Bayer, 2014). The crop production dataset and Israel's irrigation mix data were instead obtained for the year 2010 to better account for the dominance of artificial water supply in the country. While the specific BWC per watershed may not have significantly changed in these 10 years, crop production patterns have. Three percent of total crop production had to be excluded from the analysis because of missing BWC data, likely resulting in an underestimation of total BWC. Our results were therefore compared to the findings of a recent study on Israel's crop virtual water flows based on production data from 2007 to 2012 and on high-resolution local blue water datasets (Shtull-Trauring & Bernstein, 2018). Our results showed a 10% lower total BWC of imports (892 vs. 991 MCM), but total BWC of domestic production minus exports was 24% higher (1047 vs. 847 MCM). These differences may have been partially caused by the different input datasets. Particularly the use of a global BWC dataset in our study may have been responsible for a slight overestimation of domestic total BWC.

Regarding the spatial resolution, the raster resolution of 5 arc minutes (ca. 9.26 km at equator) may have caused inaccuracy in production, particularly in small watersheds (e.g., overestimation of wheat in the south of Israel, see Figure 4). Blue water data was only available on the watershed scale. This could have particularly affected the accuracy of results of large watersheds where variability within the watershed is higher. Irrigation mix data was instead obtained on a country level (Leão et al., 2018). Regional characteristics of water supply could therefore not be accounted for. In Israel, for example, desalinated seawater has been reported to be used for irrigation mainly in the coastal regions (Yermiyahu et al., 2007), water supply in Northern Negev relies to a large extent on the Shafdan wastewater treatment facility, and many farmers in the Arava desert irrigate their crops directly with deep saline (not desalinated) groundwater (Fridman et al., 2021). These data may significantly change the domestic specific energy and emission for some crops.

Despite the application of the 99% filter of total BWC to reduce data gaps, assumptions (100% surface water supply) had to be made for eight countries without water supply. The related effect on the results is expected to be low due to the low relative contribution of these countries to total BWC (1.5%). The country filter itself may, however, have particularly impacted specific energy and emissions. These were biased towards countries with higher total BWC. On the other hand, these data gaps also point to the importance of improving the availability of water supply mix data to achieve higher accuracy in future assessments.

"Energy for water" includes the energy for water abstraction, treatment, distribution, and post-use wastewater (Kyle et al., 2016). For reasons of simplicity only some of these factors were implemented in the analysis depending on the water source. Water distribution for desalinated seawater and domestic wastewater was excluded because it was expected to be low compared to the treatment energy and would have required knowledge on the location of the respective plants. It could be generally questioned whether it makes sense to fully attribute wastewater treatment energy to the end user of the domestic wastewater (here: agriculture) instead of the perpetrator (households). We chose this approach as the wastewater does not represent a classical "waste," which needs to be handled by the first user, but also a "raw material" for a second use phase. Hence, in the same way that the energy required for the water's "primary production" (pumping, purification, and distribution) has been allocated to the "primary" domestic users, the energy required for its "secondary production" (wastewater treatment) has been allocated to the "secondary" agricultural user. Future assessments could potentially only account for the additional treatment energy needed to process wastewater from the state of meeting environmental standards to the state of meeting irrigation water standards.

Lacking reliable data on pumping energy sources, pumping energy was for simplicity assumed to be provided by electricity, even though diesel pumps are presumably more common in rural areas. This may have resulted in a slight underestimation of "energy for water" related to surface water and groundwater irrigation. On the other hand, the "energy for water" of surface water is likely to be overestimated particularly in regions, where surface water is primarily supplied gravitationally. Coherent country-specific data on that topic was not available. To still partially account for the expected overestimation a fraction of only 65% of surface water was assumed to be pumped—based on data from the United States as one of the most important countries Israel imports crops from. The surface water pumping energy consumption factor was derived from data on large-distance water transport systems as documented in Plappally and Lienhard (2012), potentially overestimating pumping energy requirements due to larger pipe diameters of such systems. The assumption of surface water being sourced from the geographic centroid of a watershed was simplified, but it provided a rough estimation of the location of a river as potential surface water source. In future studies, surface water supply distance could potentially be better modeled by using explicit surface water body datasets. Particularly in Israel, surface water is primarily sourced from the Sea of Galilee located in the far North of the country and fed into the National Carrier to allocate it across the country (Oziransky et al., 2014). Consistent data for the amount of such interbasin transfer water is however not yet available and could therefore not be considered in our global analysis.

The most important limitation of the transport model was related to the use of crop primary equivalent production data in the methodology of Fridman and Kissinger (2019). The dataset accounted for all crop consumption in Israel, direct and indirect (in the form of processed food products as well as feed embedded in imported animal products). Our model only considered direct crop transport from the agricultural origin to Israel even though processed food products are often transported to other places for processing before reaching the final destination (Kastner et al., 2011). The detailed backtracking of each individual food product's "real" transport distances was out of the scope of this analysis. The same applies for food processing energy. Long-distance transport was assumed to be entirely covered by ship transport. Ship transport is by far the most common means of long-distance transport, even for perishables (Seabury, 2014). But particularly high-value fresh products (e.g., tropical fruits) are often transported by plane causing much higher emissions than ship transport (Marriott, 2005). Regarding land transport, we acknowledge that particularly cereals are more likely transported by train in some countries. Lacking consistent data and for the reason of model simplicity, the conservative approach of assuming all land transport to be done by lorry was chosen.

5 | CONCLUSION

Our results suggest that domestic food system policy should consider all aspects of the water–energy–food nexus. It may make sense for a country's food sovereignty or export economy to produce domestically, it may be favorable in terms of water use, energy use, and GHG emissions to import certain crops. Nevertheless, this environmental burden of imported commodities should also be considered in national policy (e.g., GHG mitigation policy) and weighed against options to reduce the impact of domestic production (e.g., by expanding renewable energy supply). Considering the increasing global importance and feasibility of energy-intensive artificial water sources, our results highlight the importance of including the energy consumption and GHG emissions related to agricultural irrigation water supply into environmental assessments. We hope this to be facilitated by the approach presented here. Nevertheless, our approach was also limited by the availability of spatially and temporally consistent datasets of BWC and irrigation water supply. Closing these data gaps could significantly increase the accuracy of future pertinent assessments.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the Supporting Information of this article.

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