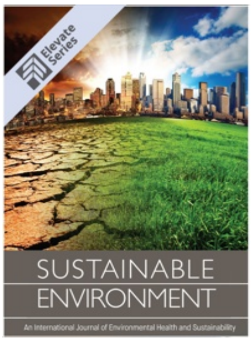

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Sustainable Environment

An international journal of environmental health and sustainability

ISSN: 2765-8511 (Online) Journal homepage: www.tandfonline.com/journals/oaes21

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To cite this article: Dario Caro & Fabio Sporchia (2026) Spatiotemporal patterns of water and land in the global production and consumption of tropical fruits, Sustainable Environment, 12:1, 2656546, DOI: 10.1080/27658511.2026.2656546

To link to this article: https://doi.org/10.1080/27658511.2026.2656546

Published online: 10 Apr 2026.

SUSTAINABLE ENVIRONMENT
2026, VOL. 12, NO. 1, 2656546
https://doi.org/10.1080/27658511.2026.2656546

SOCIETY AND THE ENVIRONMENT | RESEARCH ARTICLE

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Spatiotemporal patterns of water and land in the global production and consumption of tropical fruits

Dario Caro[a,b] and Fabio Sporchia[c]

[a]Ecodynamics Group, Department of Physical Sciences, Earth and Environment, University of Siena, Siena, Italy; [b]Department of Environmental Science, Aarhus University, Roskilde, Denmark; [c]Life Cycle Sustainability, Department of Sustainability and Planning, Aalborg University, Aalborg, Denmark

ABSTRACT

Tropical fruits, whose cultivation depends heavily on large amounts of water and land, are consumed globally but produced only in regions with specific climatic conditions. It follows that the environmental pressures caused by tropical fruit production are extremely concentrated and mostly driven by foreign demand. By assessing the water and land associated with global production and consumption of 10 tropical fruits in historical series (2000–2021), this study estimates the magnitude and direction of water and land embodied in international trade of tropical fruits. The global production of these fruits used approximately 296 Gm^3 of green water, 33 Gm^3 of blue water and 30 million hectares of land. In 2021, domestic consumption of coconuts had the highest water usage, both green (130 Gm^3) and blue (15 Gm^3), and required the most land (10 Mha). From 2000 to 2021, avocado showed the greatest increase in green and blue water embodied in trade, as well as in the land embodied in trade. The study highlights the largest international flows of water and land embodied in trade, revealing that generally, they flow from developing (especially South-Central America) to developed (especially U.S.) countries where tropical fruits have become staple foods. In some cases, these trade patterns could intensify water stress and pressure on land-use pressure in exporting regions. Despite this, developing countries remain the largest consumers of water and land associated with domestic consumption tropical fruits. This paper discusses the main drivers of these flows, identifying key consumers, their trade partners and potential mitigation strategies.

ARTICLE HISTORY
Received 4 December 2025
Accepted 2 April 2026

KEYWORDS
Food systems; water and land use; international trade; sustainable consumption; resource depletion; footprint analysis; food security

1 Introduction

Globally, agricultural land covers approximately five billion hectares, accounting for 38% of the Earth's land surface and is divided into 1.5 billion hectares of cropland and 3.4 billion hectares of pastures (Alexandratos & Bruinsma, 2012). The agricultural sector is also the largest global consumer of water, utilizing up to 70% of the world's freshwater (Kayatz et al., 2019; United Nations, 2024). As noted by the (FAO, 2016), agriculture's interaction with water and land is bidirectional: it both exacerbates and is affected by water and land scarcity. Currently, one-quarter of the global population experiences 'extremely high' water stress (Hofste et al., 2019) and the pressure on land, a finite resource, has also intensified over time. Between 1961 and 2022, global cropland area per capita steadily declined from approximately 0.43 hectares per person in 1961 to 0.19 hectares per person (FAOSTAT, 2024). These issues are expected to intensify due to population growth, increased incomes and shifting dietary preferences that will drive a 70–100% increase in food demand by 2050 (Falcon et al., 2022; FAO, 2018; Vermeulen et al., 2020).

In today's interconnected world, the international trade of agricultural goods redistributes food from regions of surplus to those in deficit, supplementing local production (Bahar et al., 2020; Osei-Owusu et al., 2019; Wang et al., 2023). However, this trade also transfers significant volumes of water and land between countries (Sporchia et al., 2021a, 2023a). Over the last 20 years, the trade of water- and land-intensive

CONTACT Dario Caro caro2@unisi.it Ecodynamics Group, Department of Physical Sciences, Earth and Environment, University of Siena, Siena, Italy

Supplemental data for this article can be accessed online at https://doi.org/10.1080/27658511.2026.2656546.

agricultural products has grown substantially (Kastner et al., 2021). Trade can therefore play a highly significant positive role in redistributing two essential resources: water and land. This is true when trade flows originate from regions with substantial resources and are directed toward areas affected by resource scarcity. Conversely, it can have a negative impact, exacerbating water and land stress. An expanding body of research has aimed to uncover the links between international trade and the environment, highlighting key drivers and strategies to enhance sustainability within agricultural supply chains (Caro et al., 2018; Osei-Owusu et al., 2021; Sporchia et al., 2023b). This evidence indicates that: (i) international markets significantly influence decisions related to agricultural production (Beghin et al., 2017; OECD/FAO, 2024); (ii) these market forces are responsible for a substantial share of the environmental impacts embedded in agricultural supply chains (Deconinck & Toyama, 2022; Galli et al., 2023; Wiedmann & Lenzen, 2018); and (iii) trade-related decisions represent a critical yet underexplored avenue for managing these impacts (Himics et al., 2018; Tamea et al., 2016; Yamaguchi, 2024).

This issue has increasingly drawn attention from governments and industries as policymakers become more aware of the risks associated with agricultural trade (Green et al., 2017; Komarek et al., 2020). However, a growing gap persists between the understanding of trade-related environmental impacts and the evidence required to address them effectively. Hence, a reinforcement of the science-policy interface is still required (Caro, 2023) as the complexity of globalized agricultural supply chains may obscure effective policy interventions. By mapping resource flows across agricultural trade networks, it becomes possible to better visualize and manage these challenges. In this context, the concept of virtual water trade (VWT) and virtual land trade (VLT), which were introduced to quantify the water and land embedded in traded goods (Hoekstra & Hung, 2002), have become essential frameworks for understanding resource flows associated with agricultural trade (Chapagain et al., 2005; Serrano et al., 2016; Sporchia et al., 2021b).

Tropical fruits are rich in essential nutrients and they are recognized as a source with high contents of bioactive compounds and health-promoting properties due to their nutritional composition, making them valuable for a balanced diet (Bvenura & Sivakumar, 2017). The global production of tropical fruits has consistently increased over the past decade, driven mainly by rising demand in major producing regions (FAO, 2024). This demand is not only driven by dietary preferences but also by the increasing popularity of plant-based diets. According to (FAOSTAT, 2024), over recent decades, tropical fruit-producing countries have significantly increased their exports to both established and emerging markets (Ali & Harun, 2021). While the production of many agricultural products is widespread globally, the production of tropical fruits is mostly located in regions with specific climatic conditions, yet they are still widely consumed worldwide. While the competitive market for major tropical fruits is rather concentrated, with few countries engaging in large-scale global trade, tropical fruits are crops heavily dependent on water and land requiring consistent rainfall or irrigation to thrive and significant land areas, often in regions with tropical climates and fertile soil (Altendorf, 2017). It follows that the environmental pressures caused by tropical fruit production are extremely concentrated geographically on the planet and mostly driven by foreign demand. Hence, the global trade in tropical fruits often implies substantial water use and land demand in producing regions, many of which already face water stress and limited arable land. As export-driven farming expands irrigation and plantation areas, it can intensify competition for water, strain ecosystems and reduce land available for local food systems, making sustainability a central concern.

For this purpose, this study estimates the magnitude and direction of water and land associated with international trade of tropical fruits, thus providing a first global overview upon which interventions and policy actions may be based. Specifically, this study estimates the VWT and VLT linked to 10 tropical fruits namely avocado, banana, coconut, fig, kiwi fruit, lemon, mango, papaya, pineapple and watermelon at the global level. The ten tropical fruits were selected based on the availability of both production (FAOSTAT, 2024) and international bilateral trade data (UN Statistics Division, 2024). To date, this is the first global study that assesses the flows of water and land derived from the consumption and production of tropical fruits. Employing a physical trade analysis approach, it examines export and import data from major trading countries and evaluates resource use information from 254 territories over the period 2000–2021. The main drivers of water and land flows are discussed highlighting key consumers, their trade partners and potential mitigation strategies.

2 Materials and methods

Our analysis covers the period 2000–2021, focuses on the production, trade and consumption of 10 commodities (avocado, banana, coconut, fig, kiwi fruit, lemon, mango, papaya, pineapple and watermelon), and on the related natural resources use (water use and land use). Despite borrowing the name from the different climate classification, tropical and subtropical fruit are often grouped together due to the lack of a net distinction (e.g. suitable latitude, temperature and humidity ranges) with known overlaps between tropical and subtropical fruits and due to the intrinsic large diversity across the included species and their varieties or subspecies (Galàn Saucò et al., 2014). This is reflected in the commercial classifications. For instance, according to the United Nation Central Product Classification (CPC), 0131 '*Tropical and subtropical fruits*' include a broad range of fruits without clear distinction between the tropical and sub-tropical (UN Statistics Division, 2024). The case of citrus fruits is notable because despite fitting the common definition of tropical and subtropical fruits, they are commonly grouped separately (Galàn Saucò et al., 2014). The commercial value of the various species affects the existence of dedicated statistics and data, resulting in the most internationally traded fruit having a separate classification and the less internationally traded fruit being grouped in a single undistinguished class, or even without international statistics at all. The selected commodities are among the '*Tropical and subtropical fruits*' and were selected based on the availability of both production (FAOSTAT, 2024) and international bilateral trade data (UN Statistics Division, 2024).

2.1 Water use for tropical fruit cultivation

The Water Footprint Network (WFN) (Mekonnen & Hoekstra, 2010) divides water use—the volume of water required for crop cultivation—into green water, blue water and gray water.

Green water is defined as the residual rainwater that remains in soil, whereas blue water is defined as the groundwater or surface water that is provided to agricultural soils after abstraction (Hoekstra et al., 2011). Finally, the volume of water that is necessary to reduce the concentration of the pollutants in effluent water to a level that complies with legal limits is termed gray water, and it requires high-resolution spatial data in terms of both regulation and effluent characteristics to be estimated (Hoekstra et al., 2011).

In order to calculate the water used for the cultivation of tropical fruits across the globe, we used the approach proposed by Chapagain and Hoekstra (2004) (Mekonnen & Hoekstra, 2011). Accordingly, for each producing country and for each fruit, and each year, we derived the specific water demand (SWD, m^3 t^{-1}), starting from the crop water requirement (CWR, m^3 ha^{-1}) and the yield (Y, t ha^{-1}) values as detailed in Equation 1:

$$SWD_{f,n,y} = CWR_{f,n}/Y_{f,n,y} \tag{1}$$

$SWD_{f,n,y}$ indicates the specific water demand—i.e. the water required to produce one unit of fruit—for every combination of country n, year y and fruit f. $CWR_{f,n}$ indicates instead the water requirement—i.e. the unit of water utilizer per unit of surface of agricultural field—for every combination of fruit f and country n. Finally, $Y_{f,n,y}$ indicates the yield for every combination of fruit f, country n and year y. The underlying assumption is that CWR values are considered constant over the accounted period of time, since they are directly linked to climate conditions. This assumption is common in studies of this kind (Sporchiaet al., 2021a, 2021b, 2023b; Tuninetti et al., 2017), justified by the rather short time span covered. For analyzes spanning across several decades a more detailed modeling would be required to capture the effect of anthropogenic climate change. The CWR value for every fruit was estimated as the product of the average yield and the average SWD over the same period considered by Mekonnen and Hoekstra (2011) as detailed in Equation 2:

$$CWR_{f,n} = SWD_{f,n,96-05} \cdot Y_{f,n,96-05} \tag{2}$$

$SWD_{f,n,96-05}$ stands for the specific water demand (m^3 t^{-1}) in country n for the fruit f sourced from Mekonnen and Hoekstra (2011). $Y_{f,n,96-05}$ indicates to the yield of country n averaged over the years 1996–2005 for the fruit f. Yield average were estimated by averaging annual yield data obtained from FAOSTAT (FAOSTAT, 2024). The procedure illustrated above is well-established and commonly applied for both food and feed, see for instance (Sporchia et al., 2021a, 2021c, 2023b). SWD and CWR can differentiate between green, blue and gray water. Despite the availability of SWD for gray water, we decided to exclude gray water use from the assessment its estimation relies on parameters that are subject to extreme spatiotemporal variability affecting the accuracy of the estimation. It would require specific data about the water body receiving the load of contaminants deriving from field run-off and local regulation, normally drawn on the basis of the local ecosystem vulnerability (Hoekstra et al., 2011). Both are highly variable with variations even within a municipality. To overcome this high-resolution data requirement, previous studies opted for single fixed global or regional run-off rates and a single fixed global acceptable value as threshold for the concentration of contaminants. We believe that this kind of approximation would be detrimental for the current study as one of the key features that distinguishes the analysis is the country-specificity. Accordingly, we exclude gray water from the scope of this study. Nevertheless, gray water covers the lowest part of the total water use, and only for a few countries and fruits it goes above 20% of the total water use (i.e. green, blue and gray) (Mekonnen & Hoekstra, 2011). SWD for green and blue water is here used as an indicator of efficiency, namely green water use intensity, and blue water use intensity.

2.2 Land use for fruit production

Agricultural land is classified in categories according to the specific type of exploitation it undergoes. It includes arable land and land for permanent or temporary crops, and pastures (FAOSTAT, 2024).

Following the approach of previous studies (Caro et al., 2021; Sporchia et al., 2021a, 2021c) we considered the land use directly linked to the cultivation the considered tropical fruit. For each fruit, we estimated the land use by considering the data on harvested area from (FAOSTAT, 2024). Land use is therefore measured in terms of surface of agricultural land occupied by the fruit plantation, normally expressed in hectares (ha). The analysis captures the existing global diversity in terms of land use efficiency by using country-scale crop-specific yield data for 254 territories (Table S1) and for each year considered. As an indicator of efficiency in the exploitation of agricultural land, we utilized the reciprocal of the yield, thereby expressing land use intensity (LUI), measured in terms of ha m^3 t^{-1}. It should be noted that the use of national average yield data might overlook the potential sub-national variety that could characterize cultivation, due For instance to climate, infrastructure, especially in large countries. Therefore, the use of national averages introduces uncertainty in the results. This uncertainty could be mitigated by using sub-national yield which, however, are not yet available. Due to this unavailability, it is also not possible to estimate the potential range of uncertainty itself. Hereafter, we refer to LUI and SWD with the general terms of resource use intensities.

2.3 Mapping the origin of fruit

Tropical fruits are consumed worldwide while originating from few countries. Consequently, the present analysis is designed to capture and reveal the global dependencies that underpin such consumption patterns. Accordingly, we ensured that the origin of each fruit included in the analysis was traced, following the international trade pathways across 254 territories (Table S1). We used (FAOSTAT, 2024) crop production data, trade data from (UN Statistics Division, 2024) and applied (Kastner et al., 2011) data treatment approach to link producers to final consumers, avoiding double counting of re-export. Production and consumption data had to be harmonized and balanced beforehand. The harmonization was carried out by integrating import flows data with export flows data, e.g. by using mirror data. Thanks to this data, treatment trade flows are linked with country-specific resource use intensities based on their origin. Since the aim of this operation was to trace the origin of each feed item, we applied mass equivalence factors to convert processed products (such as pineapple juice) into primary crops equivalents. By doing so we ensure respect of the mass balance throughout the calculation. Nevertheless, if this kind of conversion is performed purely on mass basis the calculation can incur double counting. For example, producing 0.24 kg of coconut oil requires 1 kg of copra, and producing 0.76 kg of coconut oil cake requires 1 kg of copra. Converting 0.24 kg of coconut oil and 0.76 kg of coconut cake back into copra would result in 2 kg of copra, but 1 kg of copra yields both 0.24 kg of coconut oil and 0.76 kg of coconut oil cake. This clearly exemplifies the double counting issue that would arise from a direct conversion. We apply an economic allocation to safeguard the conversion consistency on the basis of a distribution proportional to the economic value of the different fruit-derived products (Sporchia et al., 2023). Following the previous example, if the value obtained from oil and cake are 80% and 20%, respectively, of the total value obtained from 1 kg of copra, then these factors are utilized to distribute the initial mass of copra. Accordingly producing 0.24 kg of coconut oil will be linked to 0.80 kg of copra, and producing 0.76 kg of coconut oil cake will be linked to 0.20 kg of copra, ensuring the correct mass balance. While economic conversions are necessary, they might introduce some uncertainty due to potential price fluctuations across years. However, this method is commonly utilized not only in environmental footprint studies but also in other life cycle thinking approaches (Kastner et al., 2011).

We retrieved both value and mass conversion factors from FAO (1997), the water footprint network (Mekonnen & Hoekstra, 2011). Details on each commodity trade flow and the related conversion factors applied can be found in the supplementary material, together with the respective sources (see Table S2).

Thanks to the data treatment illustrated above, our calculation captures the diversity among the resource use intensities of each country that was produced in the world along the considered period of time. Note however, that the data treatment and the linked results might be affected by unreported data. Regardless, it is not possible to verify the existence of unreported data, nor to quantify the extent to which they could affect the results and any hypothesis would be rather speculative, and not based on a scientifically sound method. In any case, potential revision might be necessary in case new or revised data becomes available.

For each tropical fruit, we compiled a detailed bilateral trade matrix showing import and export quantities between 254 countries/territories, as described in detail in the supplementary material (Table S1).

2.4 Estimation of virtual resource use trade

The virtual resource use trade (VRUT) indicates the crop-specific resource use necessary the export-oriented fruit production. We calculate the VRUT of country *n* as the multiplication of the traded fruit (TF) by its RI. The calculation is illustrated Equation (3):

$$VRUT_{f,ne,ni} = TF_{f,ne,ni} \times RI_{f,ne} \tag{3}$$

$VRUT_{f,ne,ni}$ indicates the resource use for every combination of exporting (and origin) country *ne*, importing country *ni*, and fruit *f*. $TF_{f,ne,ni}$ indicates the quantity of fruit exported by exporting country *ne* to the importing country *ni*. Trade data were retrieved from UN Statistics Division (2024). RI corresponds to the resource use intensities, as detailed in Sections 2.1 and 2.2.

The application of the data treatment introduced by Kastner et al. (2011), ensures that every producer is directly linked to the final consumer. In this way, re-export flows included in raw trade data are filtered out and the related issues avoided. In this way, the virtual resource use trade balance is respected and the correspondence of the final consumption with the sum of the total production plus the imports minus the exports is ensured.

In a few instances, production data was missing from FAOSTAT (2024). In such cases, data gaps were filled by using official national statistics, and other sources, which are anyway the common sources utilized by FAO to compile FAOSTAT datasets. See Table S3 in the supplementary material for details. In other cases, while the CWR was available, yield data was missing. In such cases, area average yields were used to fill the data gaps. For instance, the yield for 'Southern Europe' area provided by FAOSTAT was utilized to fill the gap for lemon production in 'Albania'. See Table S4 in the supplementary material for details.

All data utilized in this work was retrieved from openly available sources such as international databases (e.g. FAOSTAT) or official national reports (see Tables S3–S4). Modeling variables were also calculated from openly available publications, and the derived values are provided in the supplementary material.

3 Results

We find that in 2021, the global production of the ten tropical fruits analyzed (added together) involved about 296 Gm^3 of green water, 33 Gm^3 of blue water and 30 Mha of land. These three values increased by 50%, 20% and 24% with respect to 2000. Global green and blue water associated with domestic consumption of the ten tropical fruits analyzed increased by 17% and 45%, respectively. A significant increase is recorded for the virtual water embodied in trade (+55% for green and +143% for blue water). The global land associated with domestic consumption and the virtual land trade also increased over the period analyzed but less significantly (+21% and +65%, respectively).

Figure 1a and b show that the green and blue water associated with domestic consumption of coconuts (130 and 15 Gm^3, respectively, in 2021) is the highest in absolute terms. Over the period 2000–2021 the related green water showed no significant change (+2%) while blue water recorded an increase (+23%). This increase in blue water use is partially attributable to technological limitations in irrigation efficiency and the expansion of irrigated cultivation in specific regions. The international trade in 2021 has represented 1% (green water) and less than 1% (blue water) of the total production of coconuts. Concerning green water, domestic consumption of bananas in 2021 is also relevant (51 Gm^3) and an increase by 21% of this value with respect to 2000, is recorded. The contribution of blue water to bananas is relevant as well, reaching 8 Gm^3 in 2021 after increasing by 57% with respect to 2000. Rising blue water consumption can be linked to policy-driven expansion of high-yield banana plantations and the growing international demand for bananas in developed markets. The tropical fruits mostly dependent on trade in relative terms are kiwi fruits as their international trade in 2021 represented 53% (green water) and 47% (blue water) of its total production. Figure 1b reveals that coconuts are mostly cultivated without irrigation, and pineapples and papayas are only marginally dependent on irrigation, these tropical fruits adapt very well to arid soils. Instead, Figure 1c shows that in 2021, the land associated with domestic consumption of coconuts (10.0 Mha) is the highest in absolute terms, representing 90% of total production of this fruit with the remaining 10% due to international trade. Unlike coconuts, the land associated with domestic consumption of mangoes substantially increased over the period 2000–2021 (+234%); for this fruit an evident increase of international trade (+203%) is also recorded. This expansion in mango cultivation is influenced by both global market incentives and national agricultural policies favoring export-oriented fruit production. The land used to domestically consume watermelons decreased by 6% from 200 to 2021, a trend that is not confirmed with regards to the green and blue water of this tropical fruit. Therefore, it suggests a general increase in efficiency in the use of land to grow this fruit.

Figure 2 provides a general overview of the trend of virtual green and blue water and land used to grow the tropical fruits analyzed, namely involved in international trade. The 2008 economic crisis led to a slight reduction in growth during the period 2008–2010. Starting from the post-economic crisis period, the curves resume the growing trend again and for some fruits they increase substantially. Figure 3 reveals that the COVID crisis did not affect the trend of VWT and VLT and this is in line with the fact that the food sector was only relatively compromised by this crisis (Béné et al., 2021; OECD, 2021). Concerning green water, Figure 2a shows a general increase of VWT associated with tropical fruits during the period 2000–2021. In particular, the VWT of avocados remarkably increased, especially starting from 2010 to 2021 (+185% for green water and +101% for blue water). This happens mainly because in recent years this fruit has been associated with several health benefits (Dreher & Davenport, 2013; Weschenfelder et al., 2015) and has forcefully become part of many diets, especially those that try to reduce meat consumption (Ohlau et al., 2023; Skelly & Ditlevsen, 2024). Another significant increase of virtual green water trade is recorded for mangoes and lemons. Concerning blue water, Figure 2b shows a general increase of VWT associated with tropical fruits during the period 2000–2021. In particular, the VWT of avocados and mangoes represents the highest increase over the years analyzed (+325% and +314%, respectively, between 2000 and 2021). also show a relevant increase. Concerning land, Figure 2c shows that the increase is limited to specific fruits such as avocados, mangoes and lemons whereas the remaining fruits record a moderate and low increase.

Looking at the global top consumers, Figure 3a shows that in 2021, Indonesia was the largest consumer of green water associated with bananas (9.5 Gm^3) followed by India and China (8.3 and 5.3 Gm^3, respectively). Over the analyzed years, Indonesia and India also recorded the largest increase of green

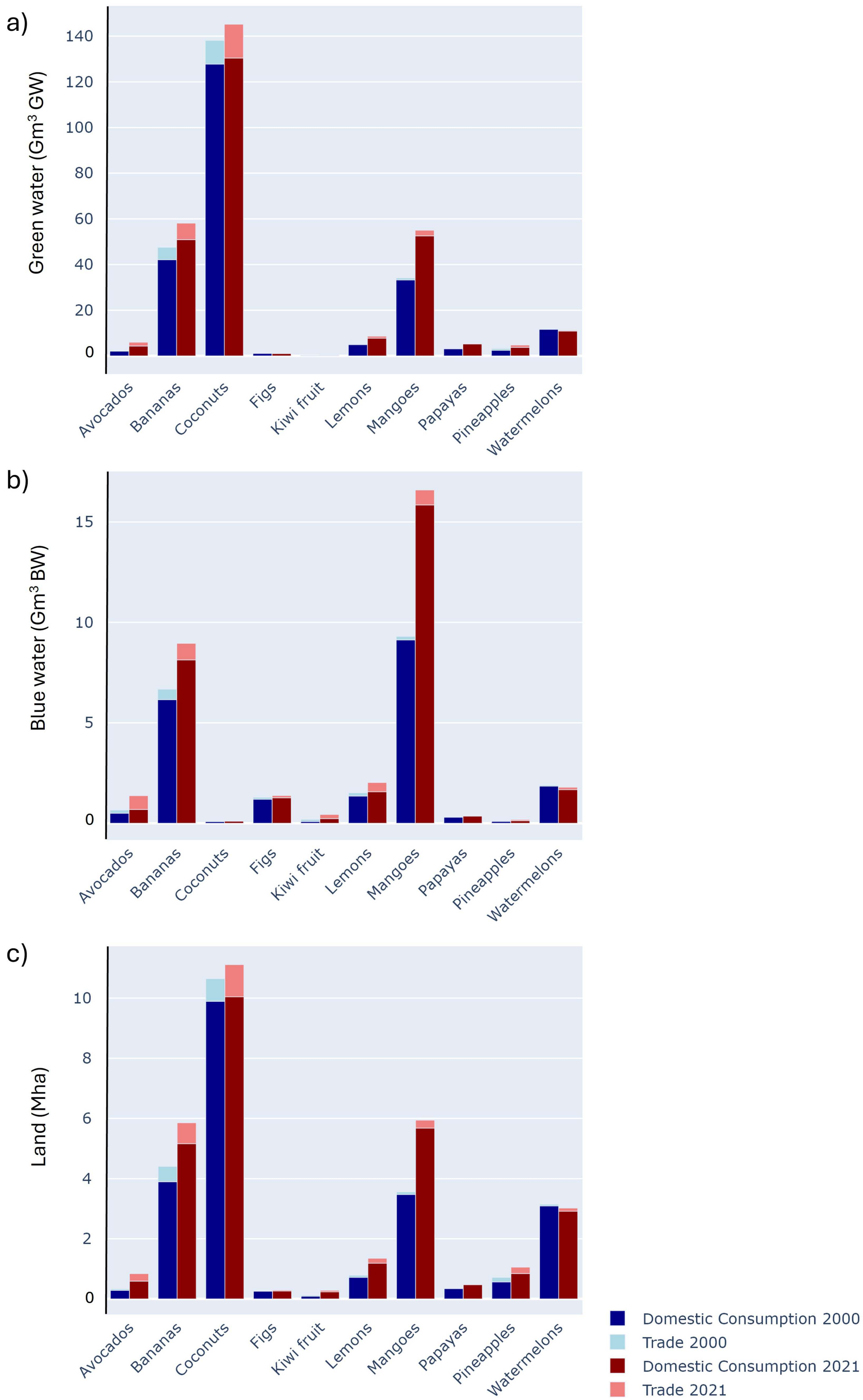

Figure 1. Green water (a), blue water (b) and land (c) associated with domestic consumption and trade of 10 tropical fruits at the global level in 2000 and 2021. Green and blue water are expressed as Gm^3. Land is expressed as Mha.

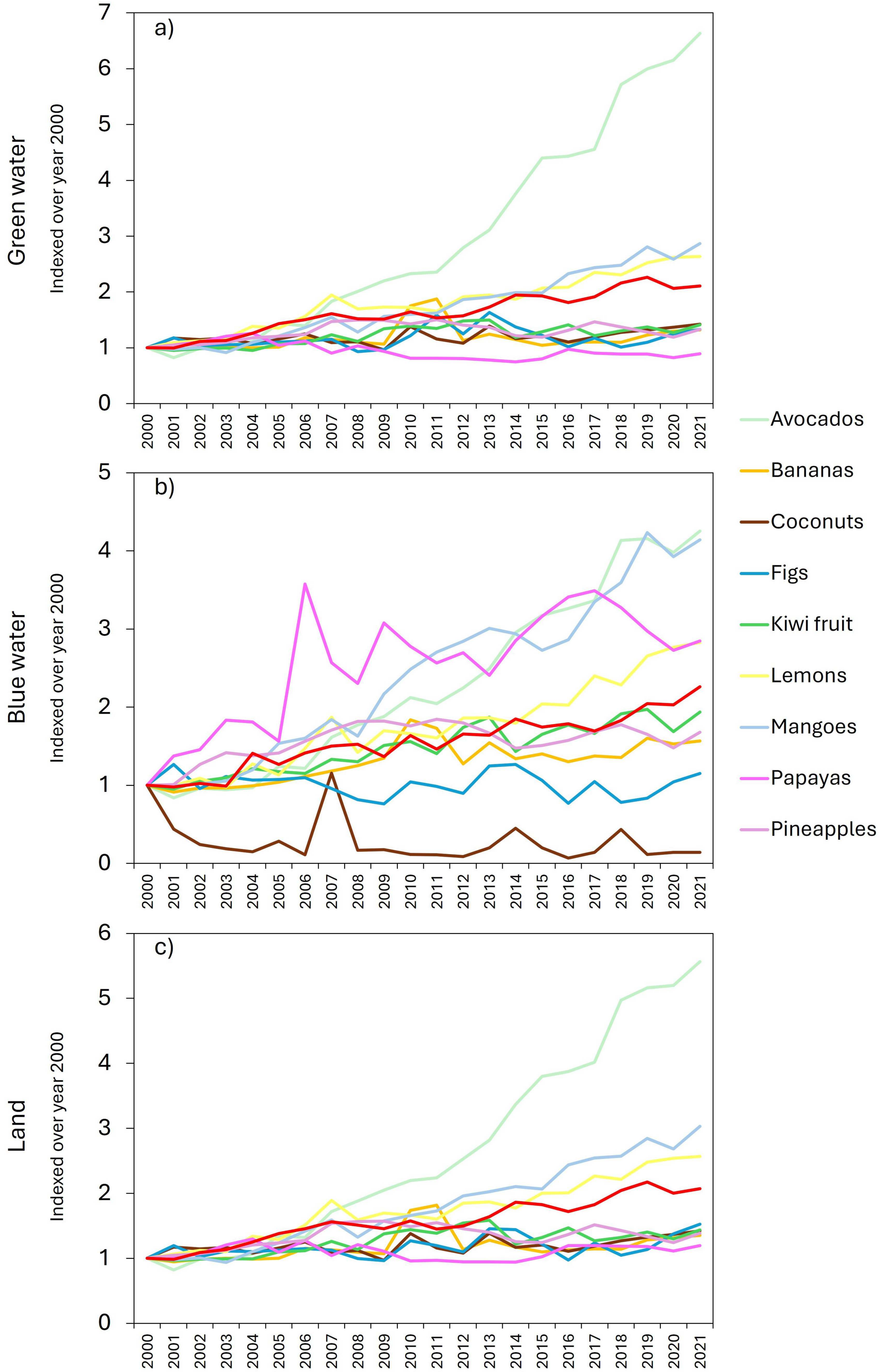

Figure 2. Trend of virtual green water (a), blue water (b) and land (c) used to grow 10 tropical fruits over the period 2000–2021. The dimensionless index is obtained by normalizing all the fruits to a value of 1 in the year 2000. The values of the index in the following years are derived from the variation compared to the year 2000.

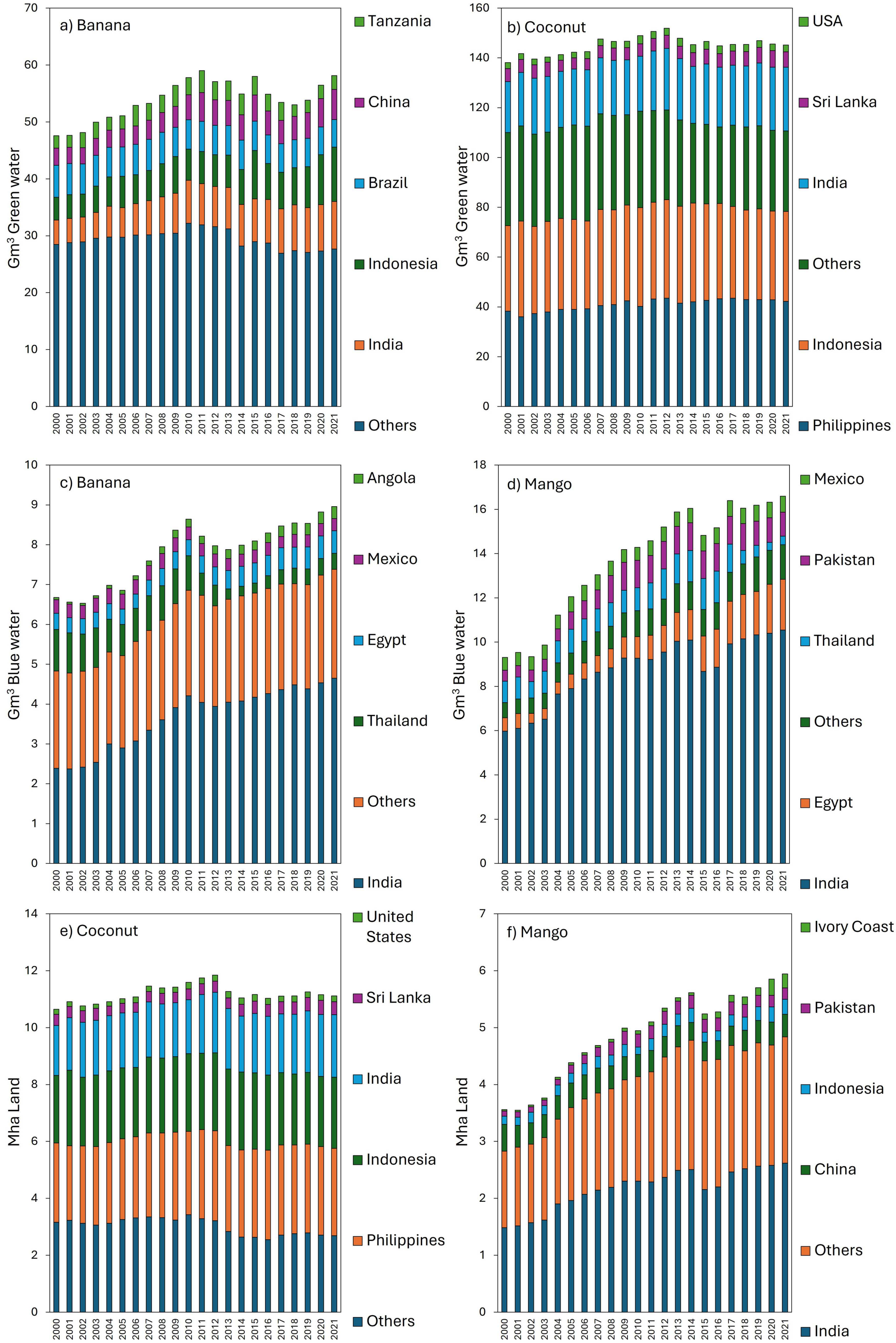

Figure 3. Global top 5 consumers of green water (a and b), blue water (c and d) and land (e and f) associated with the two tropical fruits associated with the highest resource use, for each resource use, in 2021, as shown in Figure 1. Green and blue water are expressed as Gm^3. Land is expressed as Mha.

water (+140% and +95%, respectively). However, concerning blue water associated with bananas (Figure 3c), the largest consumers were different with India (4.7 Gm^3) covering about 52% of global consumption of blue water associated with bananas. For coconut, Philippines is clearly the largest consumer, covering 30% of global consumption of green water associated with this tropical fruit (Figure 3b). However, the highest increase from 2000 to 2021 was recorded for India (+25%). Concerning mangoes, the greatest consumer of blue water in 2021 was India (10.5 Gm^3) covering about 63% of global consumption (Figure 3d). Figure 3e shows that for coconuts, in 2021, Philippines was the largest consumer of land associated with this tropical fruit (3.1 Mha) followed by Indonesia and India (2.5 and 2.2 Mha, respectively). Over the years analyzed, there was no significant increase and the global trend was quite steady. Instead, global consumption of mangoes led to an increase of hectares of land used (+76%) during the period 2000–2021 (Figure 3f). In particular, India was the largest consumer (2.6 Mha) covering about 44% of global consumption. These patterns indicate that both domestic policies supporting crop expansion and shifting dietary preferences significantly influence regional water and land demand.

Figures 4–6 highlight the largest international flows of tropical fruits-related virtual water (green and blue) and land, respectively. In general, we observe that the largest fluxes flow from developing to developed countries. Despite this, developing countries generally remain the largest consumers of water and land associated with consumption of tropical fruits (Figure 3). For some tropical fruits the results are characterized by a single large flow. This is the case of avocados, where the dominant global flux is the gross virtual green water export from Mexico to U.S. (0.7 Gm^3), bananas (from Guatemala to U.S., 0.6 Gm^3), mangos from Thailand to China (0.3 Gm^3) and lemons and mangoes from Mexico to U.S. (0.3 and 0.3 Gm^3, respectively). For coconut, Philippines and Indonesia cover most of the export to the rest of the world. Two countries lead the export of pineapples (Thailand and Costa Rica) and watermelons (Mexico and Iran). The same happens for single exporter countries in other tropical fruits: Turkey (figs), New Zealand (kiwi fruit) and Mexico (papayas). Concerning blue water, for avocados, the dominant global flux remains the one from Mexico to U.S. (0.26 Gm^3, Figure 5). The same flux is also determining for lemons (0.1 Gm^3), mangoes (0.2 Gm^3) and bananas (0.1 Gm^3). We observe that fluxes of blue water (Figure 5) for coconuts are completely different than the ones for green water (Figure 4). These trade patterns reflect both historical trade agreements and global market demand, demonstrating the critical role of international trade policies in driving resource flows.

In particular, for blue water, Brazil becomes the most important exporter to the rest of the world. However, Brazil is not a relevant exporter of coconuts in terms of volume: this is because Brazil is one of the few countries using irrigation to grow this specific tropical fruit (Sousa Santos et al., 2020). Instead, for pineapples Thailand and Costa Rica, the largest exporters of green water (Figure 4), become less relevant for blue water (Figure 5), while South Africa becomes a significant exporter, suggesting that irrigation heavily implied in there for this specific tropical fruit.

For land, Figure 6 shows that the relevant flux from Mexico to U.S. is confirmed for avocados (0.09 Mha), lemons (0.04 Mha), mangoes (0.03 Mha) and watermelons (0.02 Mha). For coconuts, the flux from Philippine to U.S. is remarkable (0.03 Mha) as well as the one for pineapples from Thailand to U.S. (0.04 Mha). For figs and kiwi fruit, Turkey and New Zealand are the largest exporters, respectively (Figure 6). Concerning pineapples, unlike green (Figure 4) and blue water (Figure 5), virtual land flows are close to (Figure 6).

4 Discussion

The findings of this study have underscored the significant variation in the virtual water and land used in the production and trade of ten tropical fruits, driven by multiple factors including climatic conditions, agricultural practices and regional trade patterns. The study has shown how the water and land associated with the domestic consumption and trade of these fruits vary considerably across the different fruits (Figure 1). Coconuts, for example, have the highest green water use mainly due to the volume of this fruit globally consumed, but also to the almost exclusive reliance of their cultivation on green water which leads to high average SWD for green water. However, bananas are also characterized by a high average SWD for green water—second only to papaya—and for blue water—preceded only by kiwi fruit and lemons only, highlighting also a comparatively low water-use efficiency, possibly linked with a yield value that ranks

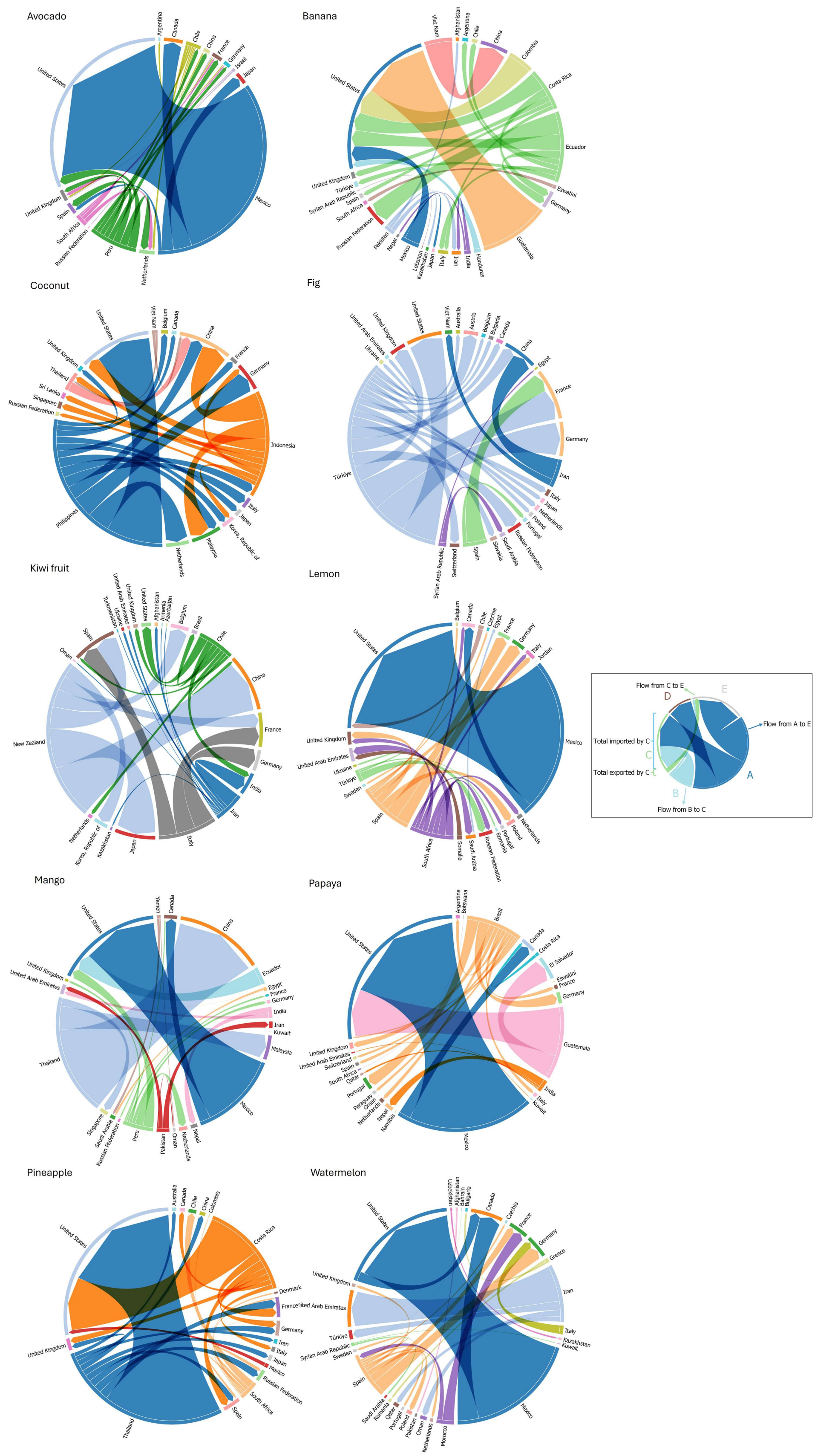

Figure 4. Largest international flows of virtual green water associated with 10 tropical fruits in 2021.

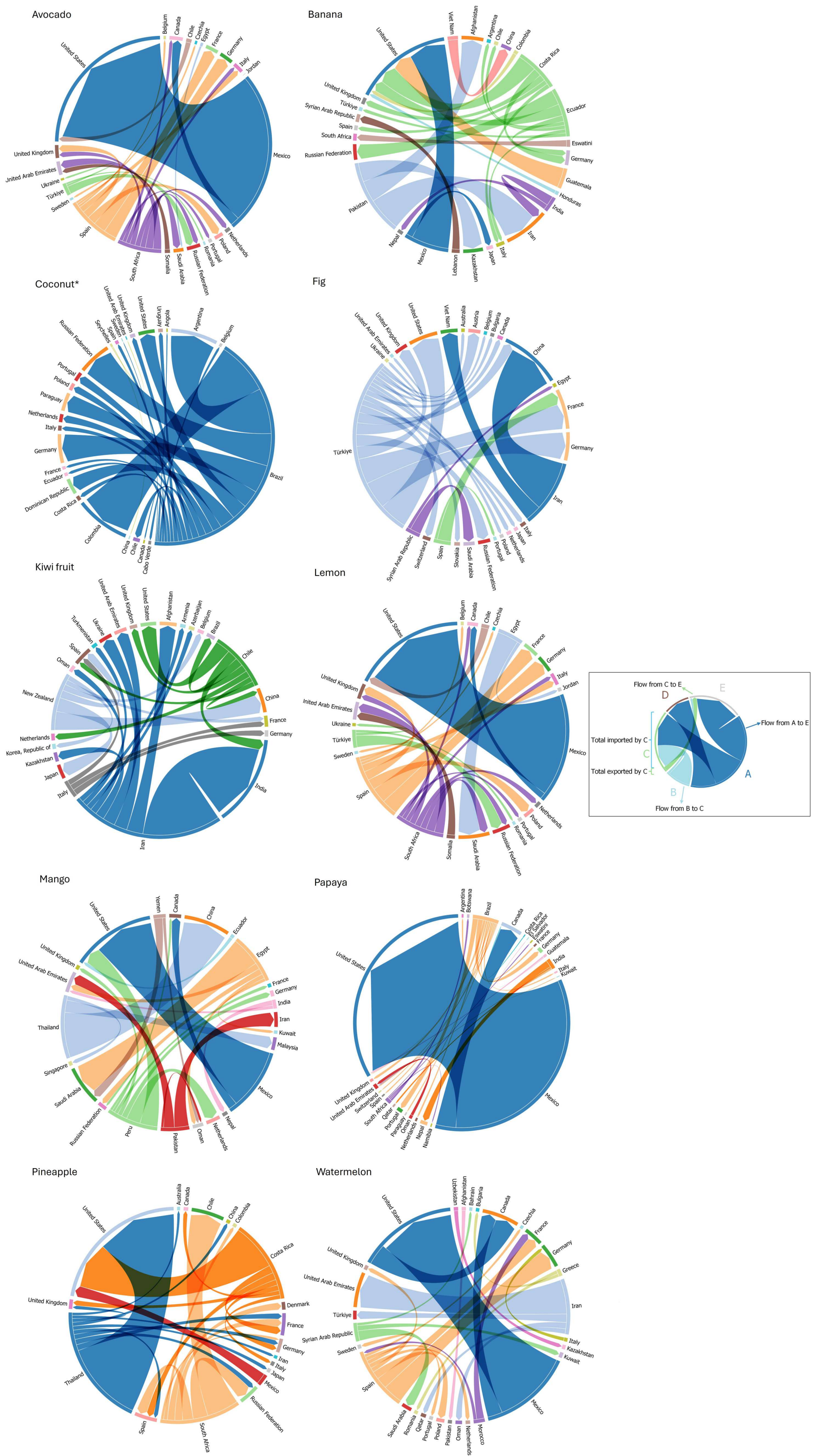

Figure 5. Largest international flows of virtual blue water associated with 10 tropical fruits in 2021.

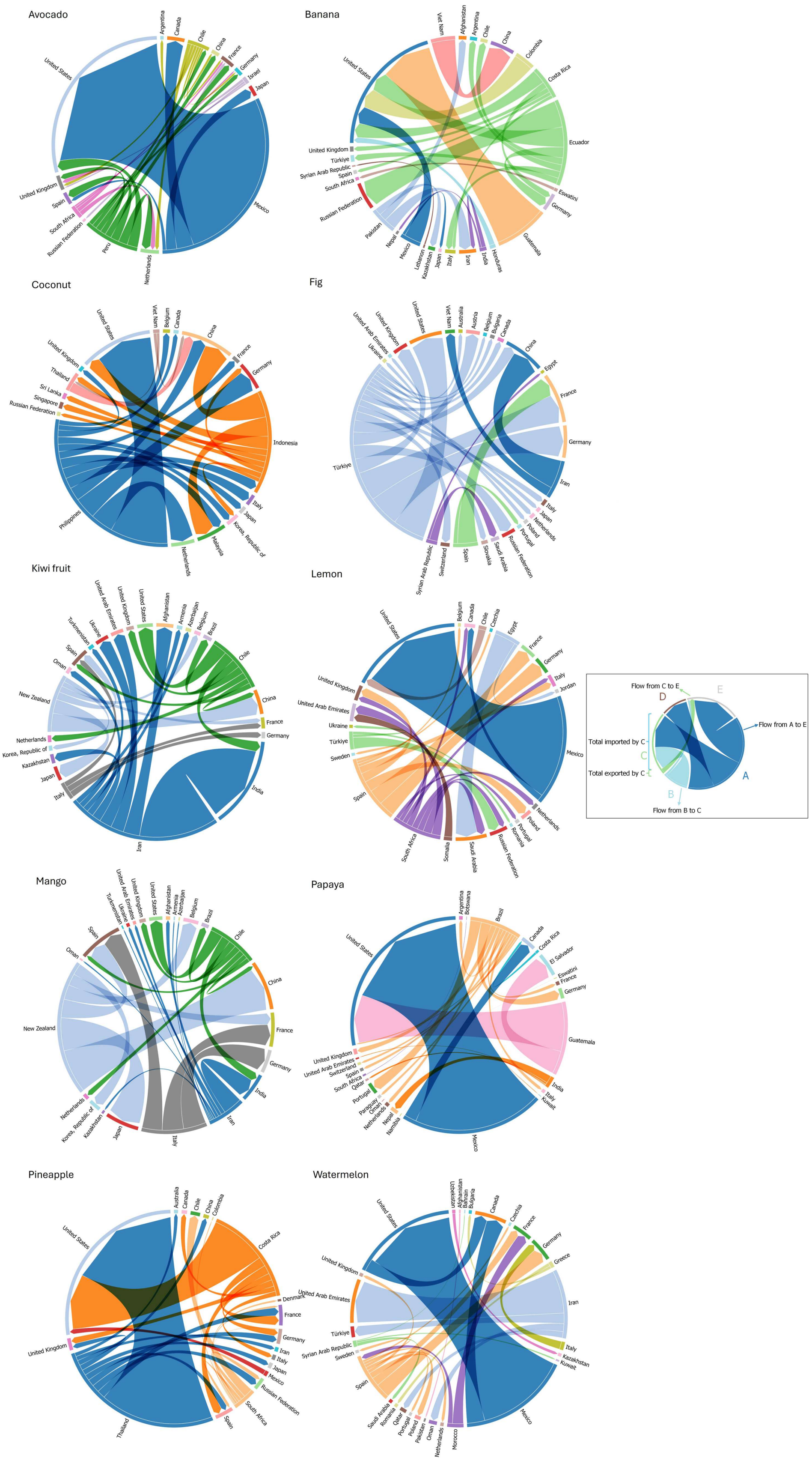

Figure 6. Largest international flows of virtual land associated with 10 tropical fruits in 2021.

mid-range compared to the other tropical fruits considered (Benavides et al., 2021). Thus, crops like bananas require significant amounts of water, which can strain local water supplies (Roibás et al., 2015), especially when these crops are grown in water-stressed regions. Indeed, the VWT of bananas is significant for green and blue water, showing how this fruit is largely consumed at the global level, but also significantly traded (Figure 1).

The largest fluxes are shown from Central-South American countries to the U.S. (Figures 4–6). In particular, the flux from Mexico to the U.S. is observed, for green (Figure 4) and blue water (Figure 5), for many tropical fruits such as avocado, lemon, mango, papaya and watermelon. While some other exporters are irrigation-oriented such as Costa Rica, others are not strictly dependent on this technique for producing and exporting bananas (e.g. Guatemala). Bananas, in absolute terms, are also among the most land-requiring fruits, being preceded only by coconuts which are extremely land-intensive (Kumar & Kunhamu, 2022). About half of the global land exported for coconut consumption comes from the Philippines and Indonesia (Figure 3). This contrasts with fruits like papaya, which require comparatively lower land inputs but a substantial amount of water due to their cultivation in tropical regions with more abundant rainfall (Carr, 2014). Since tropical fruits are, by nature, all produced in very similar climatic regions, the water needed for each fruit is largely determined by the crop's water requirements in the producing country. The findings suggest that, although some fruits may require large quantities of water, their blue water can be mitigated if grown in regions where water resources are more readily available or efficiently managed (Hoekstra, 2008). These regions can be identified by comparing the SWD for both green and blue water, while also ensuring land availability and suitability.

The land associated with domestic consumption and trade of these tropical fruits varies widely. Fruits like coconuts and mangoes are land-intensive, requiring substantial agricultural land area per unit of fruit produced (Figure 1). This is partly because these crops have long growing seasons and large growth cycles (Sthapit et al., 2012). In contrast, fruits like kiwi fruit, figs and papayas, which have faster growth cycles, require less land per unit produced even if they are also affected by environmental and soil conditions (Khan et al., 2023; Pittaro et al., 2024; Salinas et al., 2019). The land use associated with these fruits is also influenced by regional agricultural policies and land availability. For instance, countries with large areas of suitable agricultural land, such as Brazil and Thailand, tend to have lower agricultural land-use intensities (Dietrich et al., 2012). However, it is important to note that coconut production almost exclusively relies on green water in major producing countries, where irrigation is not commonly used (Khaidir et al. 2022) or water with high salinity is used for irrigation, despite its detrimental effect (Thai et al., 2024).

We observe that countries that specialize in the production and export-oriented production of these tropical fruits are those with favorable climatic conditions but may also, sometimes, face challenges in terms of water scarcity and land use sustainability (Hofste et al., 2019; United Nations, 2024). As water scarcity becomes an increasingly critical issue in many regions, particularly in arid and semi-arid climates where tropical fruits are often cultivated (Caro et al., 2021), it is essential to adopt agricultural techniques that maximize water efficiency (Morante-Carballo et al., 2022). These pressures are likely to be exacerbated by climate change, as shifts in precipitation patterns, increasing temperatures and the growing frequency of extreme events may alter water availability, reduce crop yields and intensify competition for land and water resources in key producing regions. For vulnerable exporting countries, this implies a disproportionate exposure to environmental degradation and resource depletion, as their water and land resources are increasingly embedded in export flows driven by external demand, potentially undermining local resource security and long-term sustainability.

In this context, the discussion about avocado production is central: indeed, 72% of the avocado edible fruit consists of water (Dreher & Davenport, 2013) and avocado production is mostly located in a few Latin American countries such as Mexico, Chile and Peru but is still widely consumed globally. The avocado industry has brought some economic benefits, namely increased employment and reductions in poverty and out-migration, but impacts on hydrological systems have limited the positive socioeconomic impacts. Therefore, steps should be taken at all levels of the commodity chain to improve sustainability, including improved farming practices, policies protecting smallholders and local capital and increased consumer awareness (Denvir et al., 2022). One of the most promising practices for reducing water consumption is the adoption of drip irrigation systems (Andrews et al., 2022). Unlike conventional flood irrigation, drip irrigation delivers water directly to the plant's root zone, minimizing evaporation and runoff. Studies have shown that this method can reduce water usage by up to 50% (Maisiri et al., 2005) while also improving agricultural product quality and reducing the risk of disease caused by excessive moisture on the product's surface (Li et al., 2021).

While the economic benefits of tropical fruits trade are well documented (Gibba, 2017; Mohamed et al., 2011; Mukametzyanov et al., 2023), the environmental costs should be weighed carefully. This study shows that the virtual water and land embodied in trade of these products are not uniformly distributed across international flows, with some countries acting as major exporters while others import significant quantities to meet domestic demand. This discrepancy highlights the need for greater transparency in food supply chains, encouraging sustainable practices both at the production and consumption stages. Trade patterns are mainly influenced by global demand for these fruits, particularly in developed markets where tropical fruits have become a staple of healthy diets (Vermeulen et al., 2020). However, the environmental impact of such imports may not always be transparent, as the water and land used to produce these fruits are often externalized from the importing countries. This implies that importing countries bear a significant responsibility to promote sustainable supply chains, as their consumption patterns directly drive resource use and environmental pressures in exporting regions, calling for stronger accountability, transparency and support for sustainable production practices.

The study has revealed that the largest volumes of water and land embodied in trade flows from developing to developed countries. In some cases, these trade patterns could intensify water stress and pressure on land in exporting regions. However, stress on water and land is not strictly linked with to the level of development of nations nor to their geographical distribution (OECD, 2017). The analysis of flows and their consequences in terms of water and land at the national level must therefore be considered on a case-by-case basis. As global trade continues to expand and the demand for tropical fruits grows (Figure 2), it is imperative that both producers and consumers recognize the environmental costs embedded in these products. In the long term, providing consumers and the public with a deeper understanding of the links between global environmental issues and the social and economic challenges tied to production and trade can make ethical purchasing decisions more consistent and sustainable (Hejkrlik et al., 2024). This underscores the need for policy frameworks that integrate environmental accountability and ethical responsibility across the entire supply chain, ensuring that economic benefits do not come at the expense of resource depletion, social inequities, or environmental degradation in producing regions. Therefore, future advancements should focus on disseminating the results at every level, from the end consumer to the large-scale producers.

This study reveals the environmental disparity between the tropical fruit-growing regions and the importing countries. For instance, while countries like the U.S. and the European Union import large quantities of tropical fruits, the virtual water and land of these imports remain hidden from consumers. Consumers are increasingly looking for healthier food choices to preserve the nutritional value of their diets and optimize health benefits, which has led to a rise in demand for new fruits and a greater exploration of existing varieties (Alsubhi et al., 2023). However, despite this growing curiosity, there is still a lack of comprehensive knowledge about the full potential and variety of these fruits, making it difficult for key stakeholders to balance sustainable production with the promotion of healthier diets on a global scale. From this point of view, a study of this sort provides an important overview to support policymakers and stakeholders in developing strategies that balance the increasing global demand for tropical fruits with the pressing need to conserve water and land resources. Environmental policy is needed to ensure that trade practices benefit not only the global market but also the local economies and communities involved in fruit production. Policies could promote fair trade, which supports environmentally sustainable farming practices and better working conditions for farm workers. Furthermore, tropical fruit farming is highly susceptible to environmental degradation and climate change effects, such as droughts, floods and shifts in temperature (Pathmeswaran et al., 2018). Such disruptions can affect both the quantity and quality of produce, threatening the livelihood of farmers. Environmental policies need to support environmental adaptation strategies, such as the development of resilient farming systems, better infrastructure to cope with extreme weather events and financial support for transitioning farmers to more sustainable practices.

A study of this sort is particularly relevant when aligned with public policy instruments. Without harmonized global data, sustainability standards, trade rules and water governance often rely on fragmented or country-specific information, which limits their effectiveness. First, global assessments create comparable metrics. Sustainability certification bodies such as Rainforest Alliance (CGIAR, 2018) and Fairtrade International (Ruggeri et al., 2019) increasingly require measurable environmental indicators. A worldwide dataset can provide standardized benchmarks for water footprints, irrigation efficiency and land-use intensity across producing regions. This allows certification schemes to move beyond generic sustainability requirements toward crop- and region-specific thresholds (Podhorsky, 2015). Second, global evidence strengthens trade policy design and negotiation. Institutions such as the World Trade Organization and trade agreements negotiated by the European Union must balance environmental protection with nondiscrimination in trade (Bazerkoska, 2011). Finally, our study enables shared responsibility across supply chains. Virtual water and land flows connect consumers, retailers and producers across continents. By quantifying these flows, the study supports collaborative policy instruments—such as sustainability partnerships, climate finance, or water stewardship initiatives—because it shows how impacts are distributed along the value chain.

5 Conclusions

The growth in the global demand for tropical fruit has led to increased exploiatation of natural resources being exploited, not only to satisfy domestic consumption, but also and increasingly, foreign consumption, mediated through international trade. This study quantified the amounts of agricultural land, green water and blue water required over the last two decades highlighting the associated growing trends, driven not only by population growth, but also by a shift in consumption patterns, with diets richer in fruit, in some global regions. The underlying dynamics and drivers were unveiled and mapped at the global level in a spatiotemporally explicit manner, highlighting area-specific trends thus providing relevant information for decision-makers to support actions aimed at ensuring a more sustainable resource use, especially for countries with a strong reliance on imports, but also for producing, and export-oriented countries. Policymakers can identify 'hotspot' supply chains with high water stress or land pressure, design incentive mechanisms (tariff preferences, technical assistance, sustainability funds) and avoid blanket restrictions by targeting the most critical production systems. In practical terms, this could translate into the implementation of sustainability-based import standards, targeted subsidies for water-efficient technologies (e.g. drip irrigation), mandatory supply chain disclosure requirements and bilateral agreements that link market access to compliance with environmental performance indicators.

These findings also carry clear practical implications for stakeholders: producers can optimize water and land efficiency; consumers can make more informed and ethical choices; and governments can design policies that align trade, environmental sustainability and food security objectives.This study also helps align water governance and agricultural policy in producing countries. Governments often lack a clear picture of how much of their water and land resources are effectively exported through tropical fruit supply chains.

This study presents some limitations, mainly due to data quality and granularity. Most tropical fruits were tracked as fresh fruit only, although they might have been processed in the country now classified as consumer but ultimately imported and consumed elsewhere. Furthermore, this becomes even more relevant considering that juices might be made from a mix of different fruits, potentially with different origins. However, trade data cannot distinguish between different fruits used in processed products such as fruit juice. Therefore, for the sake of accuracy, the few processed fruit-related trade flows were excluded, unless they contained a single fruit (see Table S2 in the supplementary material). Moreover, the study assumed constant climate conditions across the producing areas. While this is justified by the short length of the time series analysis, more accurate temporally explicit data would support further refinement of the results. However, to the knowledge of the authors, a comprehensive database with a homogeneous methodological approach for the global production of the analyzed commodities is not available. The data was also limited to the national scale in terms of spatial granularity for both production and trade values, while SWD information is available at the sub-national level. However, for consistency, national average SWD values were used to match the granularity of production and trade data. More detailed information could allow further refinement of the assessment. It must be added that the exclusion of gray water from the assessment might underestimate blue water use results from both the production and consumption viewpoints. Average global estimates suggest that gray water footprint might be around 10%

of the total water footprint (Mekonnen & Hoekstra, 2011). However, as detailed in the methods, accurate information for including gray water is missing.

Future research could address these limitations by prioritizing greater spatial and temporal data disaggregation along tropical fruit supply chains. Improved trade statistics capable of distinguishing between fresh and processed products, particularly mixed-fruit derivatives such as juices and concentrates, would enable a more comprehensive representation of global commodity flows and reduce uncertainty in the allocation of production origins. In parallel, the integration of sub-national production, trade and water demand datasets would allow the identification of basin-level hotspots and improve the representation of regional heterogeneity in water availability, irrigation practices and land use.

Notes on contributors

Dario Caro is an environmental scientist at the University of Siena. Dario consults, works and teaches sustainability indicators with a special emphasis on waste and agricultural sectors.

Fabio Sporchia is an environmental scientist at the Aalborg University. He works on the identification and quantification of the trade-off deriving from the transition from fossil-based economy to bio-based economy due to the competition for biomass sources.

Author contributions

CRediT: **Dario Caro:** Conceptualization, Formal analysis, Supervision, Validation, Writing – original draft; **Fabio Sporchia:** Data curation, Formal analysis, Methodology, Writing – review & editing.

Disclosure statement

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.

Funding

The author(s) received no specific funding for this work.

ORCID

Dario Caro 0000-0001-7334-4857

Data availability statement

The data that support the findings of this study are available from the corresponding author, D.C., upon reasonable request.

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