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Nations’ water footprints and virtual water trade of wood products

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ABSTRACT

Several studies addressed the water footprint (WF) of countries and virtual water (VW) trade in agricultural and industrial products, but freshwater use associated with wood products has received little attention. Yet, international trade in wood products has been growing, and forestry competes with other forest ecosystem services over limited freshwater resources. Therefore, the objective of this paper is to assess nations’ WFs of consumption of wood products, the sustainability of these WFs, and the VW flows associated with international trade in wood products. We account nations’ WFs of and VW trade in wood products with a Multi-regional Input-Output model (MRIO-forest) that tracks wood flows along global supply chains (production, processing, trade, and final uses) for the period 1997-2017 and assess the sustainability of the green and blue WF of wood products in 2017. The WF of wood production increased from 8.37×10^{11} m^3/y in 1997 to 9.87×10^{11} m^3/y in 2017. About 38% (3.76×10^{11} m^3/y) of this WF relates to wood products for export (in 2017), which means that VW trade associated with wood products ranks in between agricultural and industrial products in absolute volumes. About 10% (9.9×10^{10} m^3/y) of the green WF and 11% (3.4×10^9 m^3/y) of the blue WF of wood products in 2017 are unsustainable, meaning that they are located in areas where the total green/blue WF exceeds the maximum sustainable green/blue WF. The unsustainable green WF occurs mainly in Germany, Indonesia, the Czech Republic and the UK, and mainly relates to coniferous sawnwood, paper and paperboard other than newsprint, fibreboard and non-coniferous sawnwood. The unsustainable blue WF, which is much smaller, occurs in the USA, Russia. Nigeria, Canada and India, and mainly relates to fuelwood, paper and paperboard other than newsprint, sawnwood and fibreboard. This study increases our understanding of how forest evaporation flows link to the final consumption of wood products and contributes to the wider debate on the allocation of freshwater resources in the global economy.

1. Introduction

Global sustainability challenges are closely intertwined, including air pollution, biodiversity loss, climate change, energy and food security, disease spread, species invasion, and water shortages and pollution (Liu et al., 2015). Today, humanity increasingly faces many of these challenges and is dependent on the goods and services provided by the planet (Deng et al., 2016; Moran, 2016; Motesharrei et al., 2016; Reid et al., 2005; Rockström et al., 2017; Stern et al., 2016; TEEB, 2010; Tietenberg and Lewis, 2016). In a connected world, goods and services consumed in one country are often produced in other countries and exchanged via international trade. Thus, local consumption is increasingly satisfied by global supply chains oftentimes involving large geographical distances and leading to global environmental change (Hubacek et al., 2014). This idea has been also reflected (e.g. in the special issue led by Yu et al., 2013) with the concept of teleconnections, to describe the remote (spatial) linkages between local consumption embedded in its local context and remote environmental impacts.

The rising world resource consumption is satisfied more and more through international trade (Giljum et al., 2014; Kastner et al., 2014; Plank et al., 2018; Schaffartzik et al., 2014; Warren Hertel and Villoria, 2011; Wiedmann et al., 2015; Yang et al., 2020). This also applies to the case of the consumption of wood products. International trade in primary and manufactured wood products more than doubled in the period of 1997 to 2014, according to the FAOSTAT database of the Food and Agriculture Organization (FAO). In science, a growing interest has

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emerged to analyse and quantify the virtual water (VW) and land embedded in final forest products (Furukawa et al., 2015; Kastner et al., 2011a, 2011b; Lambin and Meyfroidt, 2011; Liu, 2013; O'Brien and Bringezu, 2018; Schyns et al., 2017). Some of these works had used FAO data to assess the forest footprint of nations and forest land embodied in international trade, but have shortcomings in the tracing of global wood product supply chains regarding differentiating between intermediate and final consumption in Input-Output models and presenting multiple interrelations of inputs and outputs. Arto et al. (2022) developed a Multi-regional Input-Output (MRIO) framework that overcomes these shortcomings. In this study, we further develop this MRIO model to trace global wood product supply chains and apply it to the case of freshwater, to assess the water footprint (WF) of and VW flows of globally traded wood products. Nation's WFs of consumption of and VW trade in agricultural and industrial products has been studied (Hoekstra and Chapagain, 2007; Hoekstra and Mekonnen, 2012), but not for wood products. Assessing nations' WFs of globally traded wood products is a needed contribution to the wider debate on freshwater resources' allocation in the global economy, considering the importance of forests.

Forests play an important role in local hydrology (Bagley et al., 2014; Marhaento et al., 2018) and regional moisture recycling (Ellison et al., 2017; van der Ent et al., 2010). Forest evaporation is vital and unavoidable. However, annual forest evaporation is also limited, since it ultimately originates from annual precipitation over the forest. Hence it is relevant to address the question how forest evaporation is made productive for different competing consumption goods by means of WF accounting, in which the rate of moisture recycling is irrelevant (Schyns et al., 2019). The WF of forestry products indicates which fraction of forest evaporation is attributed to forestry products; the rest being attributed to other forest ecosystem services (Schyns et al., 2017). Van Oel and Hoekstra (2012, 2010) pointed towards the relevance of wood products in the freshwater debate by assessing the WF of paper. Schyns et al. (2017) presented estimates of global water use in the forestry sector related to roundwood production for lumber, pulp, paper, fuel and firewood in recent decades. In this study, we build upon the work of (Schyns et al.2017) by linking the WF of wood production to final consumption of wood products captured in a MRIO framework. By providing estimates of the WF of *consumption* of wood products for all nations, assessing their sustainability, and showing international VW flows related to trade in wood products, this article constitutes a novel contribution to our understanding of the WF of humanity.

The objective of this paper is to assess nations' WFs of consumption of wood products, the sustainability of these WFs, and the VW flows associated with international trade in wood products. We insert estimates on the WF per unit of roundwood production into the MRIO model to account the green and blue WF of wood products and the VW flows resulting from international trade in wood products. The framework covers 20 wood products types and 223 nations for the period 1997-2017. Finally, we assess the unsustainable part of the green and blue WF of wood products by analysing where the WF contributes to a situation in which the maximum sustainable WF is surpassed by the actual WF.

2. Materials and methods

We account nations' WFs of wood products by inserting estimates of the WF per unit of roundwood (Section 2.1) into the MRIO model (Sections 2.2 to 2.4). Section 2.2 describes the structure of I-O tables, Section 2.3 summarizes the methods for the construction of these I-O tables, and Section 2.4 describes how the nations' WFs and VW flows associated with wood products are estimated with the MRIO model. Section 2.5 described how we use structural decomposition analysis to understand the drivers of change of the WF of wood products over 1997-2017. Lastly, we assess the sustainability of the green and blue WF of wood products in 2017 (Section 2.6)

2.1. *The water footprint per unit of roundwood*

To assess the WF of traded forest products and national WFs associated with consumption of forest products, we couple the MRIO model to national-average estimates of the WF per unit of roundwood and roundwood-to-forest product conversion factors. We have estimated the national-average WF per unit of roundwood production for the period 1997-2015 according to the method by Schyns et al. (2017) but used updated wood harvest maps (LUH2, version v2h instead of v1.0h) from Hurtt et al. (2019a, 2019b, 2020). The LUH2 v2h update addresses known issues and further features, amongst others, a wood harvest reconstruction based on FAO and other sources and a spatial pattern of wood harvesting constrained by Landsat data (Hurt et al., 2016). First, annual forest evaporation (ET) from harvested wood areas is estimated on a 30 × 30 arc minute grid across the globe with separation between green water (direct ET of precipitation) and blue water (capillary uptake from shallow groundwater). Second, this ET flow is attributed to roundwood production based on ecosystem service values. Lastly, we divide total ET attributed to roundwood production by total roundwood produced per country over the period 1997-2015 to arrive at the WF in m^3 water per m^3 roundwood. The country-average values are presented in Table A1 and are provided, together with the underlying raster data, as a separate dataset (Schyns, 2022). We compared our updated estimates with those by Schyns et al. (2017) for the overlapping period 1997-2010. The global-average WF of roundwood (m^3/m^3 rw) is 2.8% smaller in our study. For the top-15 producers of roundwood, the relative changes are in the range of -24.6% (China) to +9.7% (Canada).

2.2. *Structure of input-output tables*

MRIO tables represent the flows of commodities among two or more countries/regions. Matrices[1] $\mathbf{Z}$ and mean the intermediate inputs and their element z_{ij} are the physical amount of domestically produced or imported commodity i (e.g. wood chips) used to produce commodity j (e.g. pulp). Similarly, $\mathbf{Y}$denote the matrices of final uses (wood products) and their element y_{if} indicates the final demand for commodity i to satisfy final use f. $\mathbf{x}$ denotes the column vector of the total output by commodity, and matrix of water use accounts $\mathbf{W}$ and its element w_{hj} is the physical amount of water footprint of production of type h in primary commodity i (roundwood).

Using bilateral trade data, we get the structure presented in Table 1. The scripts r, s, and t represent countries, showing bilateral trade matrices (origin for the first superscript, destination for the second) so, for a specific country r, we have total exports as $\mathbf{e}^{\mathbf{r}} = \mathbf{Z}^{\mathbf{rs}}\mathbf{u} + \mathbf{Z}^{\mathbf{rt}}\mathbf{u} + \mathbf{Y}^{\mathbf{rs}}\mathbf{v} + \mathbf{Y}^{\mathbf{rt}}\mathbf{v}$ and imports as $\mathbf{m}^{\mathbf{r}} = \mathbf{Z}^{\mathbf{sr}}\mathbf{u} + \mathbf{Z}^{\mathbf{rr}}\mathbf{u} + \mathbf{Y}^{\mathbf{sr}}\mathbf{v} + \mathbf{Y}^{\mathbf{tr}}\mathbf{v}$, being and $\mathbf{u}$ and $\mathbf{v}$ the summation vectors.

2.3. *Building global MRIO tables for forest*

FAOSTAT provides free access to historical data on food, agriculture, forestry and trade for over 200 countries. These data have been extensively used to analyse issues related to land use, production, consumption, and trade (Alexander et al., 2015; FAOSTAT, 2018a; Kastner et al., 2014, 2012, 2011b; Lambin and Meyfroidt, 2011; van Vliet et al., 2016; Weinzettel et al., 2013). In order to get full advantage of these datasets, we processed, reconciled, and assembled in a comprehensive accounting framework the following data: *i)* extraction and trade of wood fuel and roundwood, *ii)* the production of wood products by country, and *iii)*

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[1] Bold-faced lower-case letters are used to indicate vectors, bold-faced capital letters indicate matrices, and italic lower-case letters indicate scalars (including elements of a vector or matrix). Subscripts indicate industries and superscripts indicate countries. Vectors are columns by definition, row vectors are obtained by transposition, denoted by a prime (e.g.$\mathbf{x}'$). Diagonal matrices are denoted $\hat{}$(e.g. $\hat{\mathbf{x}}$).

Table 1
Simplified structure of a MRIO table for forest products.

		Intermediate use			Final use			Total
		Country *r*	Country *s*	Country *t*	Country *r*	Country *s*	Country *t*	
Intermediate input	Country *r*	$\mathbf{Z}^{rr}$	$\mathbf{Z}^{rs}$	$\mathbf{Z}^{rt}$	$\mathbf{Y}^{rr}$	$\mathbf{Y}^{rs}$	$\mathbf{Y}^{rt}$	$\mathbf{x}^{r}$
	Country *s*	$\mathbf{Z}^{sr}$	$\mathbf{Z}^{ss}$	$\mathbf{Z}^{st}$	$\mathbf{Y}^{sr}$	$\mathbf{Y}^{ss}$	$\mathbf{Y}^{st}$	$\mathbf{x}^{s}$
	Country *t*	$\mathbf{Z}^{tr}$	$\mathbf{Z}^{ts}$	$\mathbf{Z}^{tt}$	$\mathbf{Y}^{tr}$	$\mathbf{Y}^{ts}$	$\mathbf{Y}^{tt}$	$\mathbf{x}^{t}$
Water uses		$\mathbf{W}^{r}$	$\mathbf{W}^{s}$	$\mathbf{W}^{t}$				

Source: Adapted/reproduced from (Arto et al., 2022).

exports and imports by country and partner of wood products (primary and processed products). The accounting method departs from the I-O framework. I-O tables represent national economies and are reported in monetary terms, but a similar approach can be used to represent a sub-system of an economy, such as the extraction, the processing, and the consumption of forest products, e.g. in physical units (tonnes or cubic meters).

Representing data in physical units analogously to FAOSTAT structures, we obtain the physical MRIO of forest products (see Arto et al., 2022) making consistent the balances and classifications (notably of national and trade data), making compatible inconsistent data sources. In particular, firstly, we build national I-O tables for forest products from forest production and trade statistics. Secondly, detailed trade statistics are used to connect the national I-O tables of forest products to get the MRIO-forest table.

In the first procedure, the production and trade statistics of wood products come from FAO (FAOSTAT, 2018b), extraction rates and level of processing of the different wood products. Also, trade statistics are more aggregated than the production statistics, so we built classification with 20 wood products (see Fig. A1), although some are not explicitly shown anymore in bilateral trade data updates. It distinguishes between raw materials, intermediate products, and final products. Input requirements for production of intermediate and final products is obtained by the production of each commodity times the input factor, which is the. volume of roundwood per unit of product (Joint Forest Sector Questionnaire Conversion Factors, UNECE and FAO, 2010, UNECE and FAO, 2005). Finally, we did a reconciliation between input requirement available (for intermediate use) and estimated. Finally, a bi-proportional adjustment method (see Miller and Blair, 2009) served to match available supply and input requirements of the commodities, obtaining the set of 223 national I-O tables of forest products.

In the second procedure, we linked the national I-O tables with the unreconciled bilateral detailed trade FAO statistics, which we reconciled replacing the exports/imports by the maximum flow reported (after consulting experts, who agreed that underreporting is more likely to occur than overreporting, e.g. due to problems of reporting in certain countries or issues of underreported illegal harvesting) and obtaining shares among countries for splitting trade when partner countries are not specified[2].

2.4. *Applying MRIO tables to estimate the water footprint of national consumption of wood products*

The MRIO database for forest products is used to study WFs of national consumption of wood products and VW flows resulting from international trade in wood products with a Leontief demand-driven model (see Leontief, 1936, 1937, Miller and Blair, 2009). From equation $\mathbf{x} = \mathbf{Zu} + \mathbf{Yv}$, where **x, Z,** and **Y** are the elements of the MRIO, and **u** and **v** are the summations vectors, we obtain $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Yv} = \mathbf{BYv}$. $\mathbf{A} = \mathbf{Z}(\widehat{\mathbf{x}})^{-1}$ represents the matrix of technical coefficients of the MRIO, being the element a_{ij}^{rs} of **A** the quantity of good *i* from country *r* needed to produce a unit of good *j* in country *s*. **B** the Leontief inverse matrix ($\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$) has as element b_{ij}^{rs} the total output of good *i* from country *r* needed to satisfy a unit of final demand of good *j* produced in country *s*.

The vector **w** represents the unitary water use coefficients of water use of wood product type *h* per unit of output. The elements of **w** are the WF in country *s* needed to get one unit of good *j*: $w_j^s = w_{hj}^s / x_j^s$.

We represent the vector of WF as: $= \widehat{\mathbf{w}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Yv} = \mathbf{MYv}$, with element m_{ij}^{rs} of **M** denoting the water used in country *r* to produce the quantity of good *i* needed to satisfy a unit of final demand of good *j* produced in country *s*. The WF of consumption can be shown at various levels of aggregation, e.g. the forest water uses in Canadian roundwood that ends up in the newsprint consumption of the USA, or the worldwide forest water needed in the total demand of wood products of USA. The water in region *t* to satisfy the final uses of country *s* (water footprint of country *t* in country *r*) is obtained from $^{\mathbf{r(t)}} = \sum_{\mathbf{s}} \mathbf{M}^{\mathbf{rs}}\mathbf{Y}^{\mathbf{st}}\mathbf{v}$. Furthermore, we can differentiate between, the internal or domestic part of the WF of consumption (i.e. USA forest water needed for USA consumption, when $t = r$) and the external part (i.e. foreign forest water needed for USA consumption, when $t \neq r$).

2.5. *Structural Decomposition Analysis (SDA) to understand drivers of change*

Finally, in order to understand the drivers of change, we perform a Structural Decomposition Analysis (SDA) following the method proposed by Dietzenbacher and Los (1998, 1997) (see also a similar decomposition into components of emissions over time in Arto and Dietzenbacher, 2014). As fully developed in Appendix B, we decompose the forest WF of consumption in country *r* into the following 7 components (by assumption the average water per unit of output for each product in country *r* is the same along years): the change in input structure in country *t*; the change in the intermediate trade structure in country *t*; the change in the final trade structure in country *t*; the change in the composition of the final demand in country *t*; the change in the consumption propensity in country *t*; the change in the affluence in country *t*; and the change in population in country *t*. We can also distinguish the forest WF of consumption in country *r* that are driven by changes in domestic factors (when $t = r$) or foreign factors ($t \neq r$).

2.6. *Assessing the sustainability of the water footprint of wood products*

After the appearance of many studies on WFs, recently other considerations such as sustainability of the uses are being associated in some recent studies of this type, as e.g. on global crop production in Mekonnen and Hoekstra (2020). Here we assess the sustainability of the green and blue WF of wood products – in accordance with the global standard for WF assessment (Hoekstra et al., 2011) – separately, by overlaying them with green (Schyns et al., 2019a) and blue (Mekonnen and Hoekstra, 2016) water scarcity statistics. The green water scarcity index

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[2] Still additional adjustments were needed, such as 1) modifying the "Country trade" figures when there are zeroes in the "Country trade" for a product, but there is a value reported in the "Detailed trade" statistics; 2) replacing those flows with zero total exports/imports in the "Detailed trade" and non-zero values in the "Country trade" by the weighted average World bilateral trade patterns of the "Detailed trade"; 3) allocating (to "Statistical Difference") the differences between the total "Country trade" and the World totals; 4) applying a bi-proportional adjustment method for the final reconciliation.

by Schyns et al. (2019a) is defined as the ratio of the actual to the maximum sustainable green WF. Similarly, the blue water scarcity index by Mekonnen and Hoekstra (2016) is defined as the ratio of the actual to the maximum sustainable blue WF. For both indices, the maximum sustainable WF has been estimated by subtracting environmental green/blue water requirements from the total green/blue flow. Also for both indices, when the ratio exceeds 1 this indicates a situation in which the WF exceeds the maximum sustainable level. We assess which part of the green and blue WF of wood products is located in areas where the total green/blue WF of all activities in the area exceeds the maximum sustainable green/blue WF (i.e. where the green/blue water scarcity ratio exceeds 1), which we label as 'unsustainable'.

For green water, we make the overlay at the level of nations, following Schyns and Vanham (2019) who made a similar assessment for the case of the WF of wood for energy in the EU. When the green water scarcity index for a nation is >1, we label the green WF in that nation as unsustainable. For blue water, we use the gridded (30 × 30 arc minutes) average (1997-2015) blue WF of wood production (section 2.1), which we overlay with the gridded (30 × 30 arc minutes) blue water scarcity index map. We then calculate the fraction of the blue WF of wood products in a nation that is unsustainable as the ratio of the blue WF of wood production in the nation in grid cells where the blue water scarcity index is >1 to the total blue WF of wood production in the nation.

3. Results

First, we analyse the WF of wood products from the production (Section 3.1) and consumption (Section 3.2) perspective. Then, we analyse patterns of VW flows resulting from international trade in wood products (section 3.3). Lastly, we assess the sustainability of the wood products WFs (Section 3.4).

3.1. The water footprint of global and national production of wood products

The WF of production of wood products increased from 8.37×10^{11} m^3/y in 1997 to 9.87×10^{11} m^3/y (97% green; 3.1% blue) in 2017, with a mean value of 9.06×10^{11} m^3/y and a median value of 9.45×10^{11} m^3/y (Fig. 1).

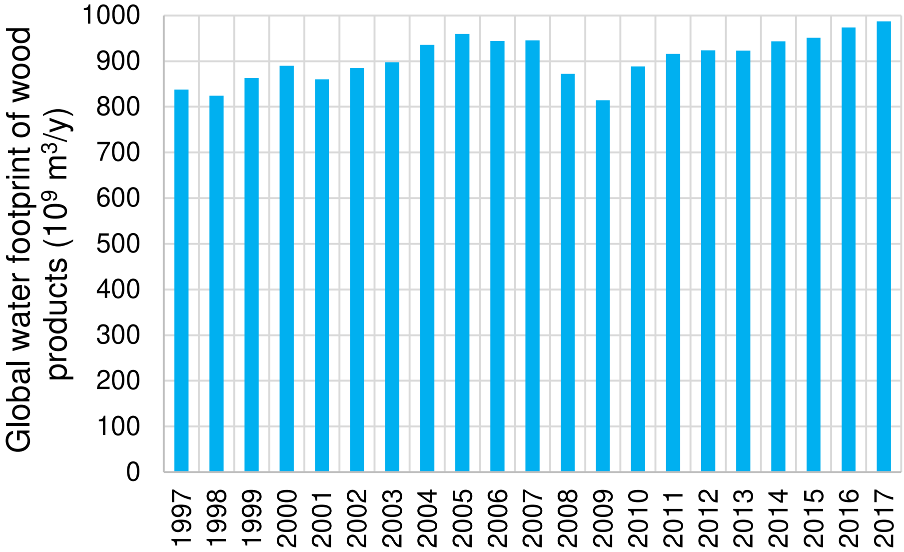

Fig. 1. Global green plus blue water footprint of wood products from 1997 to 2017.

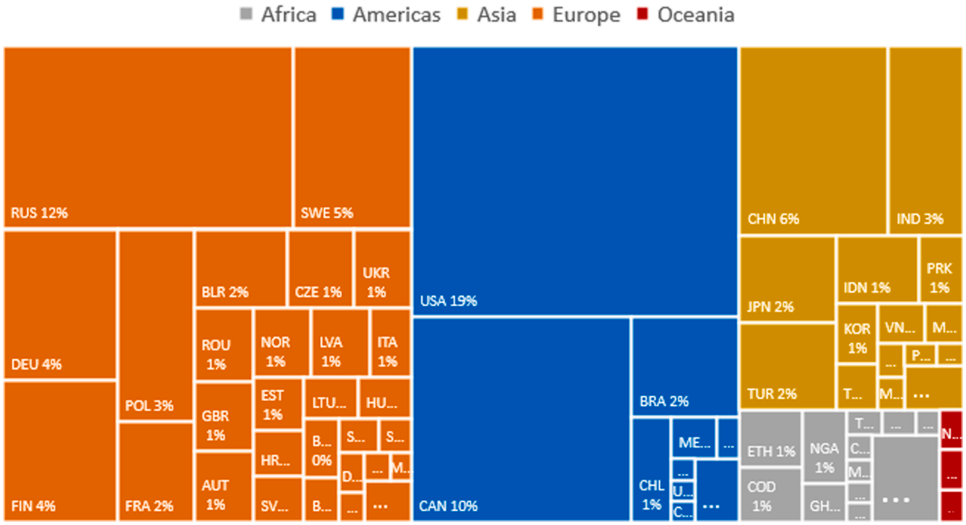

Fig. 2. Contribution (%) of nations to the world total water footprint (green plus blue) of production of wood products (volume/year) in the year 2017. Areas represent the contribution of (ISO3 coded) countries and colours indicate the continents.

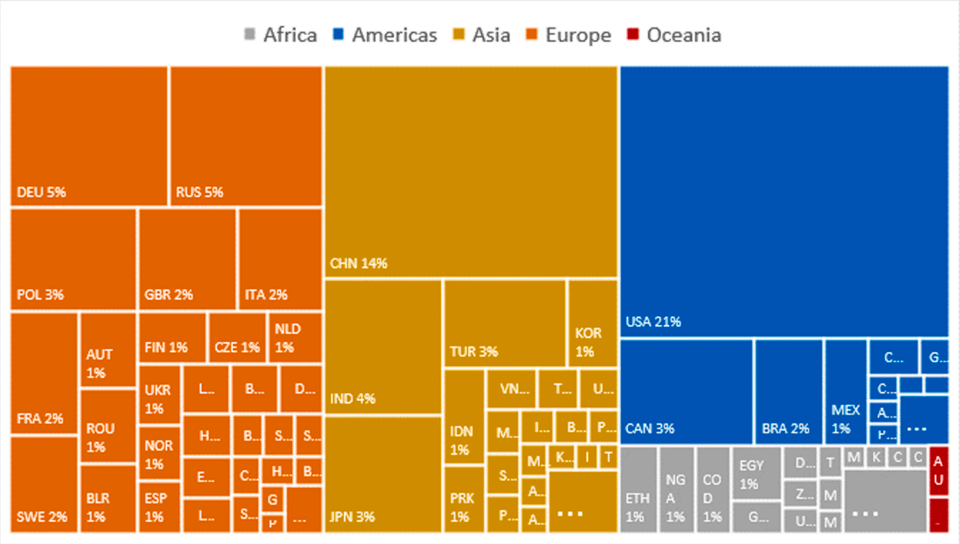

Fig. 3. Contribution (%) of nations to the world total water footprint (green plus blue) of consumption of wood products (volume/year) in the year 2017. Areas represent the contribution of (ISO3 coded) countries and colours indicate the continents.

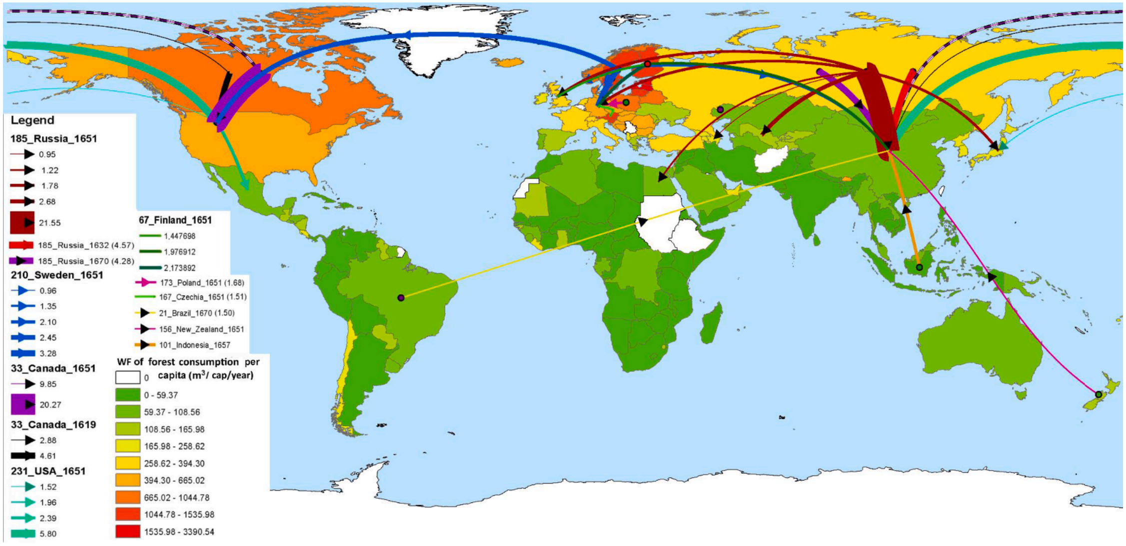

Fig. 4. Main VW flows from 10 main origins by product and trading nations in 2017. The country code precedes the name of the VW exporting country. Product codes: 1619 Wood chips and particles; 1632 Sawnwood, coniferous; 1651 Industrial roundwood, coniferous (export/import); 1657 Industrial roundwood, non-coniferous tropical; 1670 Industrial roundwood, non-coniferous non-tropical (export/import). The background colour of countries is given by their global WF of forest consumption per capita (m^3/cap/year), i.e. the global pressure per capita from the consumption side.

In 2008/2009 the WF of wood production decreased as a consequence of reduced demand for wood during the real estate crisis. Using SDA, we aim to identify the main drivers behind year-to-year changes in the global WF of wood products (Appendix C). Globally the main drivers of increased WFs were affluence, and to a lesser extent population changes (also minimally the demand structure), while those lowering the WFs "ceteris paribus" from the initial to the end point of the period were technology, trade structure, and especially from the mid-2000s onwards the propensity to consume effect.

The largest part of the WF of production of wood products is located in Europe (incl. Russia) (42.5%), followed by America (34%) and Asia (17.9%) (Fig. 2; Table A2).

In terms of forestland harvested, Arto et al. (2020) have found the largest contributors to be in a different order: America (32%), followed by Asia (29%) and Europe (28%). This has to do with the fact that South America and Asia have large areas of tropical forests (see Schyns et al., 2017), which a smaller share of total forest ET attributed to roundwood production (but a higher share of forest ET attributed to other ecosystem services) compared to the predominantly temporal and boreal forests in Europe. The top five individual countries with a large share in the global WF of forest production are the USA (19%), Russia (12%), Canada (10%), China (6%) and Sweden (5%).

The WF of global production/consumption of wood products relates for 99% to nine types of products: paper and paperboard (27%), coniferous sawnwood (25%), wood fuel (20%), fibreboard (9%), non-coniferous sawnwood (5%), plywood (4%), wood pellets (4%), wood charcoal (3%) and newsprint paper (2%) (Table A3). The first three listed products together account for 72% of the global WF of wood products.

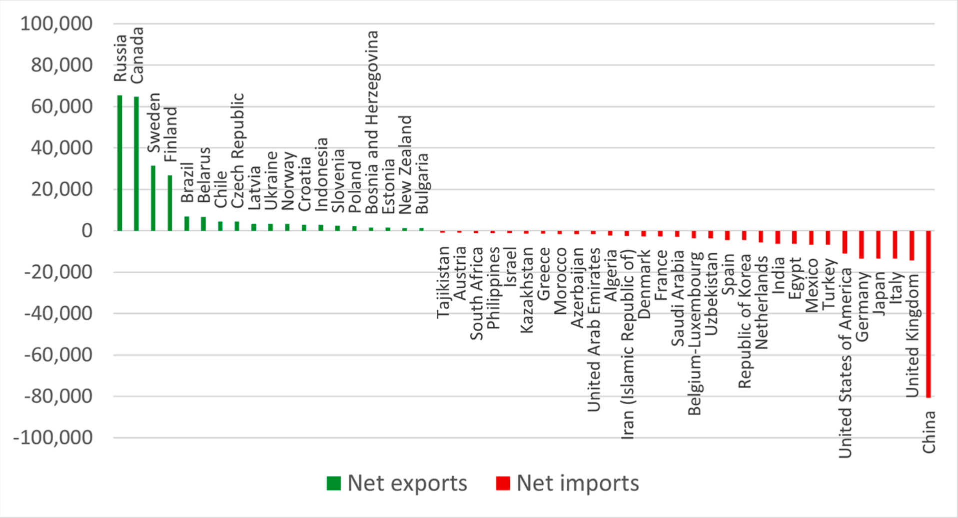

Fig. 5. Top net VW exporting (green) and importing (red) countries, 2017 (10^6 m^3/y). Only countries with absolute net VW flows larger than one billion m^3/y are shown.

3.2. *The water footprint of national consumption of wood products*

A nation's WF of consumption of wood products (Fig. 3; Table A2) reflects the water use (both within the nation and in other nations) associated with all wood products consumed within the nation.

We observe a different picture compared to the WF of production (Fig. 2). The largest part of the WF of consumption is located in Europe (incl. Russia) (33.3%), followed by Asia (31.4%) and America (28.6%). Notable countries with a smaller WF of consumption vs. WF of production are Russia (5% vs. 12%), Canada (3% vs. 10%) and Sweden (2% vs. 5%). Vice versa, countries with a larger WF of consumption vs. WF of production are, for example, China (14% vs. 6%) USA (21% vs. 19%) and Germany (5% vs. 4%).

3.3. *Virtual water flows resulting from international trade in wood products*

The displacement between production and consumption of wood products is associated with international trade in wood products which results in VW flows. In the year 2017, more than 3.76×10^{11} m^3/y of water – i.e. 38% of the WF of global production of wood products – is used to produce wood products for export. International trade in wood products ranks in between trade in agricultural and industrial products in terms of volumes of green and blue embedded in these trade flows, as we can see by comparing our results with those from Hoekstra and Mekonnen (2012). They estimated that in 1996-2005, the total volume of international VW flows (incl. grey water) related to trade in agricultural and industrial products amounted to 2.03×10^{12} and 2.82×10^{11}, respectively. We find that the total volume of international virtual (green plus blue) water flows related to trade in wood products was 3.30×10^{11} m^3/y in 1997-2005.

International VW flows are associated with certain wood products (Table A4). In 2017, about 90% of the VW flows were related to trade in six wood products: raw industrial roundwood from coniferous (1.9×10^{11} m^3/y), and non-coniferous non-tropical (5.3×10^{10} m^3/y) sources, wood chips and particles (4.3×10^{10} m^3/y), coniferous sawnwood (2.6×10^{10} m^3/y), wood residues (1.3×10^{10} m^3/y), and industrial roundwood from non-coniferous tropical sources (1.0×10^{10} m^3/y).

Fig. 4 shows the main VW flows by product and trading nations in 2017 highlighting the 10 main origins. The main VW flows are concentrated on the northern hemisphere. The largest virtual forest water flows relate to export from Russia to China, and from Canada to the USA and China

Fig. 5 shows that some countries are net exporters of virtual forest water, while others are net importers of virtual forest water. There is a minority of net exporters of VW (53 in 2007, 46 in 2017) compared to net importers of VW (143 in 2007, 121 in 2017). Furthermore, in 2017, only 19 countries had net exports of VW in wood products larger than one billion m^3/y and 30 countries had net imports of VW in wood products larger than one billion m^3/y. The main net VW exporters are countries with a large forest production sector like Russia, Canada, Sweden and Finland. The largest net virtual forest water importer is China, at a distance followed by UK, Italy, Japan, Germany and the USA.

Fig. 6 shows a larger number of flows, but still it is limited to the VW flows for countries with total imports or exports below 5.0×10^9 m^3/y (this leaves with 17 exporting and 18 importing regions plus the "All other" group, showing flows only interacting with the former). Hence the graph highlights the most important origins, destinations and VW flows. The explanation is given at the bottom of the figure on the items (ribbons) A–F, and the country codes in Table A1(also some below). Fig. 5 indicates that some countries with are large net VW importers, like the USA (Fig. 5), also have some large VW export flows, for example to Mexico in the case of the USA.

3.4. *The sustainability of the water footprint of wood products*

About 10% (9.9×10^{10} m^3/y) of the green WF of wood products in 2017 is labelled as 'unsustainable', meaning that it is located in countries where the total green WF (i.e. of all activities, incl. wood production) exceeds the maximum sustainable green WF, which implies that al large share of the green WF taps into environmental green water requirement and indicates fierce competition over limited available green water flows between human society and nature. This unsustainable green WF is mainly in Germany (37.5%), Indonesia (12.3%), the Czech Republic (11.5%) and the UK (9.1%). Another 16% (1.56×10^{11} m^3/y) of the green WF of wood products in 2017 is located in countries where the total green WF is 75-100% of the maximum sustainable green WF, indicating significant pressure on green water resources. This part of the green WF is mainly in Poland (~20%), India (~19%), France (11%), Ukraine (~6%), Romania (~6%) and Latvia (~6%). Out of the total unsustainable green WF, ~40% (3.9×10^{10} m^3/y) relates to wood products for export, while 60% (6.0×10^{10} m^3/y) relates to domestic wood supply. In terms of product types, ~68% (6.7×10^{10} m^3/y) of the unsustainable green WF relates to roundwood products and ~32% (3.1×10^{10} m^3/y) to fuelwood. Within the unsustainable green WF of

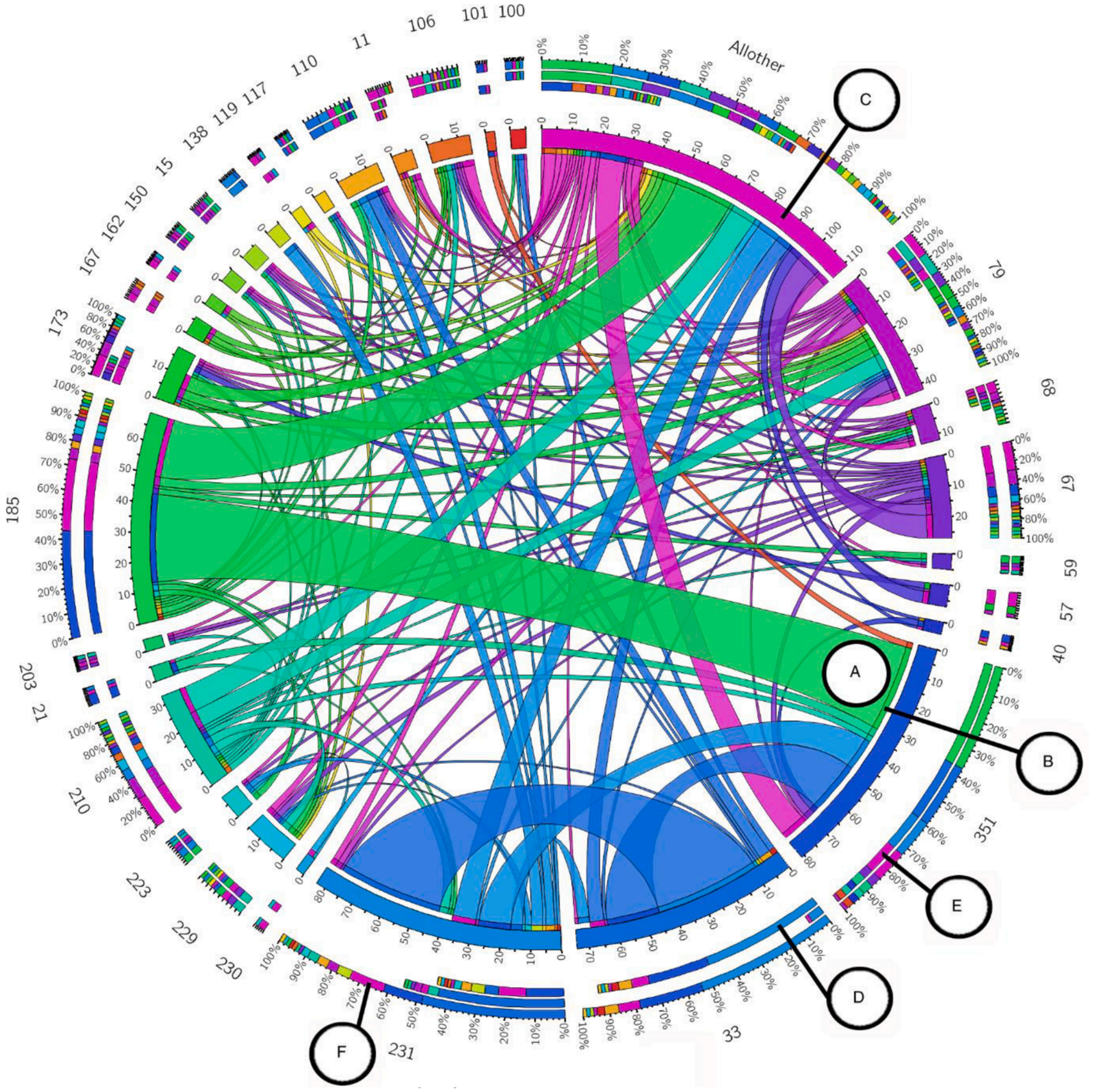

Fig. 6. VW flows larger than 5.0×10^9 m^3/y by trading nations (see all country codes in Table A1) in 2017. Ribbons: A: VW export (30×10^9 m^3/y) from Russia (185) (the green country given by ribbon) to China (351) (the dark blue region, shown by the second ribbon). B: The inner most ribbon gives the color of the origin (exporting) country, for example green because Russia (185) is the origin shown in green (given by the second ribbon). C: The second ribbon gives the color associated to the FAO code number. All flows that depart from it have this colour (as exporter; in the example, pink of "all other", while it also covers the space of imports, in the example, many flows from other origins). D: The third ribbon also gives the VW exports split according to destination countries/regions (e.g. in the example the export from Canada (33) to USA (231) of 36×10^9 m^3/y, which is the largest flow). E: The fourth ribbon gives the imports split according to origin (e.g. in the example VW import of China (351) from "all other" countries). F: The outer ribbon gives the share of the total VW trade (export or import) by partner, i.e., it reflects which ones are the main VW trade partners for each country.

roundwood products, products of particular relevance are coniferous sawnwood (38%, with Germany and the UK as main final destinations), paper and paperboard other than newsprint (30%, with China and the UK as main final destinations), fibreboard (16%, with Germany, the UK and China as main final destinations) and non-coniferous sawnwood (8%, with China, Indonesia and Vietnam as main final destinations).

About 11% (3.4×10^9 m^3/y) of the blue WF of wood products in 2017 is labelled as 'unsustainable', meaning that it is located in places where the average monthly total blue WF (i.e. of all activities, incl. wood production) exceeds blue water availability indicating significant-severe alteration of runoff and violation of environmental flow requirements. Note that share of blue (3.1%) is much smaller than the share of green (97%) in the WF of wood production (Section 3.1), and so the volume of the unsustainable blue WF is much smaller than of the green WF. The unsustainable blue WF is mainly in the United States of America (23.8%), Russia (9.7%), Nigeria (9.4%). Canada (8.6%), India (6.5%), Hungary (4.1%), Bangladesh (4.0%), Democratic Republic of the Congo (3.8%), Netherlands (3.5%) and Somalia (2.7%). This list reflects areas where blue water contributes significantly to forest water use through capillary rise as depicted in Schyns et al. (2017). Out of the total unsustainable blue WF, 77% (2.6×10^9 m^3/y) relates to wood products for export, while ~23% (0.79×10^9 m^3/y) relates to domestic wood supply. About half of the unsustainable blue WF relates to fuelwood – mainly in Nigeria (~16%), India (~11%), Bangladesh (~8%), Democratic Republic of the Congo (~7%), USA (~7%) and Somalia (~5%) – and the other half to roundwood products, in particular: paper and paperboard other than newsprint (~32%, with the USA and China as main final destinations), coniferous sawnwood (~25%, with the USA and China as main final destinations), non-coniferous sawnwood (~23%, with the USA, Nigeria and China as main final destinations) and fibreboard (~10%, with the USA, Russia and China as main final destinations).

From the consumption perspective, the top-30 nations with a large

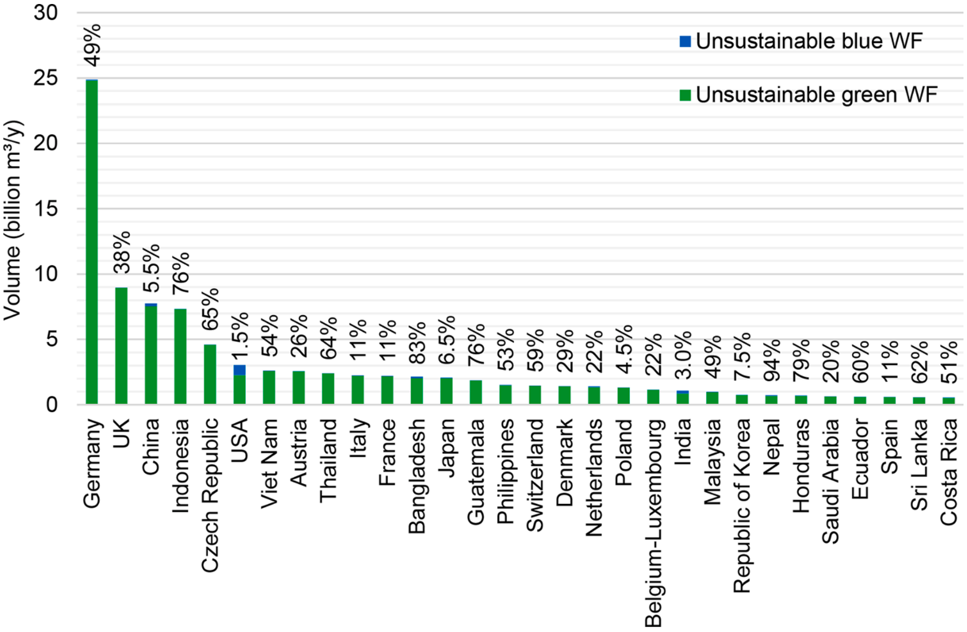

Fig. 7. The unsustainable water footprint (WF) of consumption of wood products in absolute volumes and as a fraction of the total WF of consumption of wood products (% shown on each bar). Only the top-30 nations in terms of volume are shown. Year: 2017.

unsustainable WF related to the use of wood products are shown in Fig. 7 (and in Table A2, also for other nations). Top of this list are Germany, the United Kingdom, China, Indonesia and Czech Republic. For these countries, except for China, the unsustainable fraction is close to the internal fraction of the WF of consumption of wood products (data not shown). I.e., the unsustainable WF is in the consuming country itself. Countries for which the unsustainable fraction of the WF of consumption of wood products exceeds 50% are shown in Fig. 8. All these nations rely for a large share on wood from areas in which green or blue WF is unsustainable, which may form a risk to their future wood supply. In absolute volumetric terms, the list is led by Indonesia, Czech Republic, Vietnam, Thailand, Bangladesh, Guatemala, the Philippines and Switzerland. Further, several small (island) states appear in Fig. 8.

4. Discussion

4.1. Limitations of this study

The framework we have applied has some limitations that are worth noting. One is the limitation of not being able to fully capture the forest final products transformations and destinations (due to FAOSTAT and trade data limitations to register all these), such as the final processing of furniture, for which we find some attempts of better capturing this (see Schütz et al., 2003) with economy-wide material flow analysis and

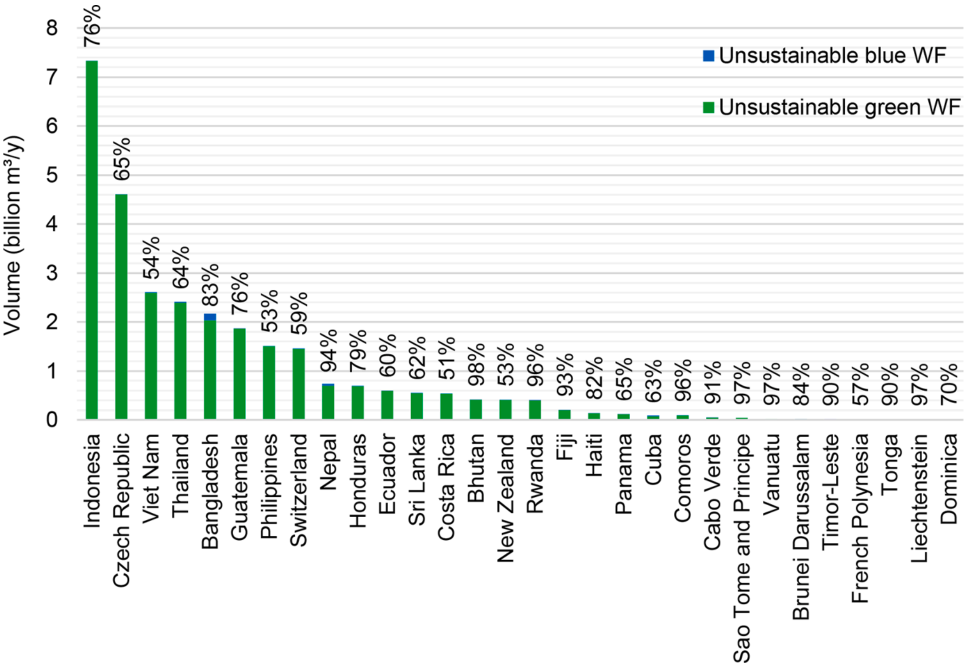

Fig. 8. The unsustainable water footprint (WF) of consumption of wood products in absolute volumes and as a fraction of the total WF of consumption of wood products (% shown on each bar). Only the nations for which the latter fraction >50% are shown. Ordered left-right from largest-smallest volume. Year: 2017.

conversions of volumes of processed products to primary equivalent. Also, despite the attempt made to capture most of the best features of process analysis type of studies and MRIO modelling distinction of intermediates and final goods to avoid usual results disparities (see Feng et al., 2011), further integration of the MRIO-forest with other global databases. E.g. detailed trade statistics and economy-wide MRIO databases (e.g. EXIOBASE or Eora) could be applied to expand system boundaries, to cover upstream and downstream chains and VW flows related to wood products, such as final furniture products, inputs used in the activity such as machinery, energy, transportation, etc.

We coupled the physical MRIO-forest model with national average estimates of the WF of roundwood. Ideally, if we had information on which specific areas are used to harvest wood for export vs. domestic use, we could have used subnational averages. This lack of spatially-explicit information on the end-purposes of harvested goods is also playing a role in previous studies that looked agricultural products and related VW trade (Hoekstra and Mekonnen, 2012). In general, it would be desirable to refine the estimates of wood products (and VW) trade among subnational regions, but data is lacking for this. This relates to the issue of limitations on roundwood data reported to FAO, since it would be desirable to find ways to deal with illegal harvest, which might be substantial in some countries (see e.g. Dieter, 2009; Haore, 2015; Lee et al., 2009; MCPFE Liaison Unit Warsaw, 2005; Ottitsch et al., n.d.; WWF, 2008; Zhang et al., 2016).

On another technical note, based on the updated accounts from Schyns et al. (2017), we were able to differentiate between the WF of coniferous and non-coniferous roundwood. However, we were not able to track this difference further along the wood supply chains, since it is only in the first transformations where this distinction is documented in production statistics.

4.2. Comparison with methods of other studies

Despite the mentioned limitations, this study includes a number of methodological advances. Our framework allows for examining wood and associated VW flows looking at the multilateral supply chains by connecting primary, intermediate and final products. This distinction results in detailed information on the production, transformation, trade and final use of 20 wood products and 252 FAO country codes (leading to 223 countries with non-zero values for WFs). It is also the main advantage with respect to the previous literature. For the analysis of land use changes, the work of Kastner et al. (2011a, 2011b) with a “process analysis” perspective followed a similar method (but without this distinction as acknowledged and hinted as possible future research), while O’Brien and Bringezu (2018) accounted for timber flows and footprints, also converting processed products into volume of primary equivalent.

Our analysis of the decomposition of drivers of change in the WF of wood products also fits within similar exercises of decompositions of energy and emission pressures (Arto and Dietzenbacher, 2014; Cao et al., 2019; Lan et al., 2016; Wang et al., 2017, 2019) and can also feed into future scenario assessments by showing how e.g. a change in one place (e.g. increased final demand, or a change in some of the drivers, i.e., population, affluence, etc.) affects the forest WF of production in another place (country).

4.3. Policy implications

In the article we have shown that consumption and import of forestry products puts a claim on foreign water resources. As water scarcity and drought occurrence intensify, this may disrupt forest production and wood supply chains in the future which could have cascading effects on wood-dependent sectors such as energy and construction. This is relevant for policy-makers to realize, especially for those in the large net virtual water importing countries, which are to some degree dependent on how the wood-producing countries respond to such disruptions (e.g. restrain wood export and focus on domestic supply).

Our results are intended to show the links between forest product consumption in one place and water use elsewhere, such that they can feed discussions on the sustainability and reliability of future wood supplies of nations. We stress that such discussions cannot focus on water alone, but should also include other environmental (e.g. deforestation, forest fires), economic (e.g. comparative advantages, transport routes, trade agreements) and social (e.g. provision of labour) considerations associated with forest production. In this context, future research could focus on VW displaced by trade from areas where forest water use contributes to the climate system tipping points – for example in (semi-)natural or forests in the Amazon, Congo or Mekong basins (Eisenhammer, 2021; Lenton et al., 2009; Welch, 2021), which could contribute to disruptions of the regional climate system and associated risks.

5. Conclusions

We have estimated nations’ green and blue WFs and VW flows of globally traded wood products with a MRIO framework for the period 1997-2017 and assessed the sustainability of these WFs for the year 2017. We find that over the study period the global WF of wood production and consumption increased and mostly refers to green water use (97% in 2017). The WF of production and consumption of wood products can vary strongly per nation, depending on their character as net exporters of importers of virtual forest water. We find there are relatively few net exporters (53 in 2007, 46 in 2017) compared to net importers (143 in 2007, 121 in 2017) of virtual forest water. The main net exporters are Russia, Canada, Sweden, and Finland. The main net importers are China, at a large distance followed by the UK, Italy, Japan, Germany, and the USA. The sum of international VW flows resulting from trade in wood products ranks in between the VW volumes associated with trade in agricultural and industrial products as estimated by others. About 10% (9.9×10^{10} m^3/y) of the green WF and 11% (3.4×10^9 m^3/y) of the blue WF of wood products in 2017 are unsustainable, meaning that they are located in areas where the total green/blue WF exceeds the maximum sustainable green/blue WF. The unsustainable green WF is mainly in Germany, Indonesia, the Czech Republic and the UK, and mainly relates to coniferous sawnwood, paper and paperboard other than newsprint, fibreboard and non-coniferous sawnwood. The unsustainable blue WF, which is much smaller, is mainly in the USA, Russia. Nigeria, Canada and India, and mainly relates to fuelwood, paper and paperboard other than newsprint, sawnwood and fibreboard.

The application of MRIO-forest to the case of freshwater resources represents a powerful toolkit to better understand past, present, and future forest uses and WFs at multiple levels (i.e. global, regional, national and product/commodity). This study has increased our understanding of how forest evaporation flows link to the final consumption of wood products and contributes to the wider debate on the allocation of freshwater resources in the global economy.

CRediT author statement

Ignacio Cazcarro: Conceptualization, Methodology, Data curation, Resources, Investigation, Validation, Formal analysis, Software, Visualization, Writing- Original draft preparation, Reviewing and Editing, Funding acquisition, **Joep F. Schyns**: Conceptualization, Methodology, Data curation, Resources, Investigation, Validation, Formal analysis, Software, Visualization, Writing- Original draft preparation, Reviewing and Editing, Funding acquisition, **Iñaki Arto**: Conceptualization, Methodology, Data curation, Resources, Investigation, Validation, Formal analysis, Software, Writing- Original draft preparation, Reviewing and Editing, Funding acquisition. ***María José Sanz:*** Conceptualization, Resources, Investigation, Validation, Writing- Original draft preparation, Reviewing and Editing, Supervision, Project administration, Funding acquisition.

CRediT authorship contribution statement

Ignacio CAZCARRO: Conceptualization, Methodology, Data curation, Resources, Investigation, Validation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Joep F. SCHYNS:** Conceptualization, Methodology, Data curation, Resources, Investigation, Validation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Iñaki ARTO:** Conceptualization, Methodology, Data curation, Resources, Investigation, Validation, Formal analysis, Software, Writing – original draft, Writing – review & editing, Funding acquisition. **M. Jose SANZ:** Conceptualization, Resources, Investigation, Validation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A: Extra tables and figures

Tables A1 to A5 and Fig. A1

Table A1
Green plus blue water footprint (WF) per unit of roundwood produced for each country in MRIO-forest.

Codes	Country Codes	WF (m^3 water /m^3 wood)	Codes	Country Codes	WF (m^3 water /m^3 wood)	Codes	Country Codes	WF (m^3 water /m^3 wood)
1	Armenia	302	90	Guinea	80	178	Eritrea	269
2	Afghanistan	42	91	Guyana	104	179	Qatar	269
3	Albania	210	93	Haiti	61	180	Palau	269
4	Algeria	35	94	Holy See	269	181	Zimbabwe	55
5	American Samoa	269	95	Honduras	85	182	Réunion	269
6	Andorra	269	96	China, Hong Kong SAR	269	183	Romania	627
7	Angola	4	97	Hungary	775	184	Rwanda	68
8	Antigua and Barbuda	269	98	Croatia	896	185	Russian Federation	559
9	Argentina	69	99	Iceland	819	186	Serbia and Montenegro	784
10	Australia	59	100	India	91	187	Saint Helena, Ascension and Tristan da Cunha	269
11	Austria	545	101	Indonesia	109	188	Saint Kitts and Nevis	269
12	Bahamas	80	102	Iran (Islamic Republic of)	113	189	Saint Lucia	269
13	Bahrain	269	103	Iraq	28	190	Saint Pierre and Miquelon	269
14	Barbados	269	104	Ireland	190	191	Saint Vincent and the Grenadines	269
15	Belgium-Luxembourg	297	105	Israel	37	192	San Marino	269
16	Bangladesh	81	106	Italy	620	193	Sao Tome and Principe	269
17	Bermuda	269	107	Côte d'Ivoire	85	194	Saudi Arabia	269
18	Bhutan	82	108	Kazakhstan	405	195	Senegal	64
19	Bolivia (Plurinational State of)	68	109	Jamaica	92	196	Seychelles	269
20	Botswana	36	110	Japan	924	197	Sierra Leone	99
21	Brazil	91	112	Jordan	30	198	Slovenia	1061
22	Aruba	269	113	Kyrgyzstan	269	199	Slovakia	342

(continued on next page)

Table A1 (*continued*)

23	Belize	100	114	Kenya	28	200	Singapore	269
24	British Indian Ocean Territory	269	115	Cambodia	107	201	Somalia	30
25	Solomon Islands	119	116	Democratic People's Republic of Korea	926	202	South Africa	42
26	Brunei Darussalam	116	117	Republic of Korea	1228	203	Spain	53
27	Bulgaria	682	118	Kuwait	269	205	Western Sahara	269
28	Myanmar	82	119	Latvia	680	206	Sudan (former)	43
29	Burundi	46	120	Lao People's Democratic Republic	91	207	Suriname	104
30	Antarctica	-	121	Lebanon	40	208	Tajikistan	23
32	Cameroon	94	122	Lesotho	32	209	Swaziland	53
33	Canada	744	123	Liberia	104	210	Sweden	668
35	Cabo Verde	269	124	Libya	24	211	Switzerland	372
36	Cayman Islands	269	125	Liechtenstein	269	212	Syrian Arab Republic	34
37	Central African Republic	83	126	Lithuania	735	213	Turkmenistan	461
38	Sri Lanka	106	127	Marshall Islands	269	214	China, Taiwan Province of	269
39	Chad	31	128	China, Macao SAR	269	215	United Republic of Tanzania	75
40	Chile	150	129	Madagascar	85	216	Thailand	111
41	China, mainland	143	130	Malawi	67	217	Togo	79
42	Christmas Island	269	131	Malaysia	113	218	Tokelau	269
43	Cocos (Keeling) Islands	269	132	Maldives	269	219	Tonga	269
44	Colombia	104	133	Mali	20	220	Trinidad and Tobago	94
45	Comoros	269	134	Malta	269	221	Oman	269
46	Congo	86	135	Martinique	269	222	Tunisia	38
47	Cook Islands	269	136	Mauritania	269	223	Turkey	746
48	Costa Rica	112	137	Mauritius	269	224	Turks and Caicos Islands	269
49	Cuba	77	138	Mexico	89	225	United Arab Emirates	269
50	Cyprus	32	140	Monaco	269	226	Uganda	41
51	Czechoslovakia	269	141	Mongolia	446	227	Tuvalu	269
52	Azerbaijan	545	142	Montserrat	269	228	USSR	269
53	Benin	74	143	Morocco	33	229	United Kingdom	928
54	Denmark	729	144	Mozambique	72	230	Ukraine	512
55	Dominica	269	145	Micronesia (Federated States of)	269	231	United States of America	487
56	Dominican Republic	71	146	Republic of Moldova	269	233	Burkina Faso	70
57	Belarus	682	147	Namibia	43	234	Uruguay	72
58	Ecuador	101	148	Nauru	269	235	Uzbekistan	269
59	Egypt	1	149	Nepal	57	236	Venezuela (Bolivarian Republic of)	99
60	El Salvador	75	150	Netherlands	447	237	Viet Nam	99
61	Equatorial Guinea	101	151	Netherlands Antilles (former)	269	238	Ethiopia	73
62	Ethiopia PDR	269	153	New Caledonia	269	239	British Virgin Islands	269
63	Estonia	657	154	The former Yugoslav Republic of Macedonia	958	240	United States Virgin Islands	269
64	Faroe Islands	269	155	Vanuatu	96	242	Wake Island	269
65	Falkland Islands (Malvinas)	269	156	New Zealand	80	243	Wallis and Futuna Islands	269
66	Fiji	269	157	Nicaragua	106	244	Samoa	269
67	Finland	611	158	Niger	21	248	Yugoslav SFR	269
68	France	352	159	Nigeria	100	249	Yemen	53
69	French Guiana	111	160	Niue	269	250	Democratic Republic of the Congo	86
70	French Polynesia	269	161	Norfolk Island	269	251	Zambia	66
71	French Southern and Antarctic Territories	-	162	Norway	828	255	Belgium	-
72	Djibouti	12	163	Northern Mariana Islands	269	256	Luxembourg	-
73	Georgia	817	164	Pacific Islands Trust Territory	269	258	Anguilla	269
74	Gabon	94	165	Pakistan	41	259	Channel Islands	269
75	Gambia	52	166	Panama	103	260	Svalbard and Jan Mayen Islands	269
79	Germany	598	167	Czechia	654	264	Isle of Man	269
80	Bosnia and Herzegovina	686	168	Papua New Guinea	108	270	Mayotte	269
81	Ghana	81	169	Paraguay	82	272	Serbia	269
82	Gibraltar	269	170	Peru	98	273	Montenegro	784
83	Kiribati	269	171	Philippines	109	276	Sudan	29
84	Greece	73	172	Pitcairn Islands	269	277	South Sudan	71
85	Greenland	269	173	Poland	699	279	Curaçao	269
86	Grenada	269	174	Portugal	60	281	Saint-Martin (French Part)	269
87	Guadeloupe	269	175	Guinea-Bissau	95	299	Occupied Palestinian Territory	269
88	Guam	269	176	Timor-Leste	67	254	Others (adjustment)	-
89	Guatemala	91	177	Puerto Rico	269	351	China	143

Note: For countries in MRIO-forest for which we have no data on the WF per unit of roundwood we inserted the global-average value of 269 m^3 water/m^3 wood. In general, the roundwood production of these countries is small.

Table A2

Nations' water footprints of wood products in 2017 (10^6 m^3 y^{-1}).

Codes	Country Codes	WF of production	WF of consumption				
			Total	Unsustainable, green	Unsustainable, blue	Unsustainable, total	Unsustainable, total (%)
1	Armenia	438	582	2	0	3	0.4%
2	Afghanistan	142	395	1	1	1	0.3%
3	Albania	217	510	210	1	211	41.3%
4	Algeria	289	2691	235	1	237	8.8%
5	American Samoa	0	1	0	0	0	8.3%
6	Andorra	0	14	1	0	1	9.7%
7	Angola	24	41	4	0	4	9.1%
8	Antigua and Barbuda	0	10	1	0	1	10.3%
9	Argentina	1118	1488	29	3	32	2.2%
10	Australia	2065	2476	320	3	322	13.0%
11	Austria	8994	10055	2566	12	2579	25.6%
12	Bahamas	4	20	0	1	1	4.6%
13	Bahrain	7	135	26	0	26	19.4%
14	Barbados	3	13	1	0	1	4.8%
15	Belgium-Luxembourg	1598	5307	1133	12	1145	21.6%
16	Bangladesh	2029	2627	2033	137	2169	82.6%
17	Bermuda	0	0	0	0	0	0.0%
18	Bhutan	412	420	413	0	413	98.3%
19	Bolivia (Plurinational State of)	221	272	4	0	4	1.5%
20	Botswana	27	91	6	1	7	7.6%
21	Brazil	23607	16743	45	2	48	0.3%
22	Aruba	1	5	1	0	1	10.3%
23	Belize	15	38	2	0	2	5.4%
24	British Indian Ocean Territory	0	0	0	0	0	10.2%
25	Solomon Islands	374	21	0	0	0	2.4%
26	Brunei Darussalam	10	13	11	0	11	84.4%
27	Bulgaria	4386	3119	59	1	60	1.9%
28	Myanmar	3309	3370	41	3	43	1.3%
29	Burundi	290	293	0	0	0	0.1%
30	Antarctica	-	-	0	0	0	0.0%
32	Cameroon	1271	1108	9	0	10	0.9%
33	Canada	97566	32810	397	102	500	1.5%
35	Cabo Verde	50	54	49	0	49	91.2%
36	Cayman Islands	0	17	2	0	2	9.6%
37	Central African Republic	223	186	0	1	1	0.7%
38	Sri Lanka	549	897	550	4	554	61.8%
39	Chad	255	258	0	52	52	20.1%
40	Chile	8853	4362	53	3	56	1.3%
41	China, mainland	-	-	0	0	0	0.0%
42	Christmas Island	0	0	0	0	0	8.4%
43	Cocos (Keeling) Islands	0	0	0	0	0	10.2%
44	Colombia	1020	1627	34	44	78	4.8%
45	Comoros	94	94	90	0	90	96.2%
46	Congo	309	196	1	1	2	1.2%
47	Cook Islands	1	6	2	0	2	26.9%
48	Costa Rica	569	1053	540	2	542	51.4%
49	Cuba	129	144	78	13	91	63.3%
50	Cyprus	1	129	12	0	12	9.6%
51	Czechoslovakia	-	-	0	0	0	0.0%
52	Azerbaijan	203	1779	1	4	5	0.3%
53	Benin	487	486	2	0	2	0.3%
54	Denmark	2128	4866	1425	2	1427	29.3%
55	Dominica	2	3	2	0	2	69.6%
56	Dominican Republic	68	512	74	2	76	14.9%
57	Belarus	15783	9058	22	2	24	0.3%
58	Ecuador	705	1001	595	1	596	59.5%
59	Egypt	17	6396	340	10	350	5.5%
60	El Salvador	346	580	16	1	17	2.9%
61	Equatorial Guinea	145	45	0	0	0	0.1%
62	Ethiopia PDR	0	0	0	0	0	0.0%
63	Estonia	5890	4431	71	2	73	1.7%
64	Faroe Islands	0	5	0	0	0	9.0%

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Table A2 (*continued*)

Codes	Country Codes	WF of production	WF of consumption				
			Total	Unsustainable, green	Unsustainable, blue	Unsustainable, total	Unsustainable, total (%)
65	Falkland Islands (Malvinas)	0	1	0	0	0	6.3%
66	Fiji	303	215	200	0	200	92.8%
67	Finland	34868	8209	110	4	113	1.4%
68	France	16439	19216	2178	18	2195	11.4%
69	French Guiana	25	25	0	0	0	1.2%
70	French Polynesia	2	7	4	0	4	57.3%
71	French Southern and Antarctic Territories	0	0	0	0	0	0.0%
72	Djibouti	4	26	6	0	6	24.7%
73	Georgia	493	682	10	0	11	1.6%
74	Gabon	326	155	0	0	0	0.1%
75	Gambia	47	46	1	10	12	25.1%
79	Germany	37372	50736	24819	53	24872	49.0%
80	Bosnia and Herzegovina	3331	1845	26	1	27	1.5%
81	Ghana	3748	3775	13	8	21	0.6%
82	Gibraltar	0	1	0	0	0	10.5%
83	Kiribati	1	3	0	0	0	6.5%
84	Greece	101	1576	199	3	202	12.8%
85	Greenland	0	12	1	0	1	9.5%
86	Grenada	0	4	0	0	0	10.4%
87	Guadeloupe	4	61	10	0	10	16.2%
88	Guam	0	0	0	0	0	0.0%
89	Guatemala	1884	2463	1863	2	1865	75.7%
90	Guinea	989	989	1	10	11	1.1%
91	Guyana	149	125	0	0	0	0.4%
93	Haiti	136	166	137	0	137	82.3%
94	Holy See	0	0	0	0	0	0.0%
95	Honduras	720	878	688	1	689	78.5%
96	China, Hong Kong SAR	0	0	0	0	0	0.0%
97	Hungary	4751	4777	287	76	363	7.6%
98	Croatia	5079	2205	99	2	100	4.5%
99	Iceland	2	153	24	0	24	15.8%
100	India	30550	36779	866	236	1101	3.0%
101	Indonesia	12357	9614	7328	7	7334	76.3%
102	Iran (Islamic Republic of)	112	2671	297	6	303	11.4%
103	Iraq	6	380	37	1	38	10.1%
104	Ireland	554	977	317	1	318	32.6%
105	Israel	2	1291	126	2	128	9.9%
106	Italy	6315	19731	2213	29	2243	11.4%
107	Côte d’Ivoire	942	1010	10	59	69	6.9%
108	Kazakhstan	155	1580	7	4	11	0.7%
109	Jamaica	59	139	62	0	62	44.8%
110	Japan	18398	31771	2035	35	2069	6.5%
112	Jordan	10	340	73	1	74	21.7%
113	Kyrgyzstan	32	749	2	2	4	0.5%
114	Kenya	737	1129	22	8	30	2.6%
115	Cambodia	805	854	12	48	61	7.1%
116	Democratic People’s Re of Korea	6745	6623	1	0	1	0.0%
117	Republic of Korea	5419	9977	733	13	746	7.5%
118	Kuwait	17	318	76	1	77	24.1%
119	Latvia	8781	5391	36	2	38	0.7%
120	Lao People’s Democratic Republic	866	721	0	1	1	0.1%
121	Lebanon	1	429	48	1	49	11.3%
122	Lesotho	66	78	1	0	1	1.6%
123	Liberia	919	909	0	51	51	5.6%
124	Libya	27	83	2	0	2	2.3%
125	Liechtenstein	2	2	2	0	2	96.7%
126	Lithuania	4814	3930	71	2	72	1.8%
127	Marshall Islands	0	7	1	0	1	9.6%
128	China, Macao SAR	-	-	0	0	0	0.0%
129	Madagascar	1183	1189	3	0	3	0.2%
130	Malawi	464	455	0	0	0	0.1%
131	Malaysia	1899	2000	972	3	975	48.8%

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Table A2 (*continued*)

Codes	Country Codes	WF of production	WF of consumption				
			Total	Unsustainable, green	Unsustainable, blue	Unsustainable, total	Unsustainable, total (%)
132	Maldives	4	53	7	0	7	12.6%
133	Mali	137	144	1	0	1	0.6%
134	Malta	1	55	7	0	7	11.9%
135	Martinique	3	37	6	0	6	17.1%
136	Mauritania	594	601	1	0	1	0.1%
137	Mauritius	2	30	8	0	8	28.0%
138	Mexico	4032	10803	189	37	225	2.1%
140	Monaco	0	0	0	0	0	0.0%
141	Mongolia	283	329	2	0	2	0.6%
142	Montserrat	0	0	0	0	0	12.1%
143	Morocco	218	1774	139	1	141	7.9%
144	Mozambique	1281	1204	1	1	2	0.2%
145	Micronesia (Federated States of)	1	4	1	0	1	23.9%
146	Republic of Moldova	343	671	5	0	5	0.7%
147	Namibia	61	111	7	1	8	7.1%
148	Nauru	0	0	0	0	0	9.1%
149	Nepal	724	783	694	43	736	94.0%
150	Netherlands	720	6434	1356	67	1423	22.1%
151	Netherlands Antilles (former)	-	-	0	0	0	0.0%
153	New Caledonia	8	15	3	0	3	19.9%
154	The former Yugoslav Republic of Macedonia	731	822	27	0	27	3.3%
155	Vanuatu	12	13	13	0	13	97.1%
156	New Zealand	2127	776	407	1	408	52.5%
157	Nicaragua	629	690	7	0	7	1.1%
158	Niger	241	256	1	51	52	20.3%
159	Nigeria	7202	7314	37	313	350	4.8%
160	Niue	0	0	0	0	0	12.3%
161	Norfolk Island	0	1	0	0	0	9.2%
162	Norway	8830	5593	208	2	210	3.7%
163	Northern Mariana Islands	0	0	0	0	0	9.3%
164	Pacific Islands Trust Territory	-	-	0	0	0	0.0%
165	Pakistan	1276	2259	130	5	135	6.0%
166	Panama	126	179	117	0	117	65.3%
167	Czechia	11390	7066	4607	5	4612	65.3%
168	Papua New Guinea	998	667	1	0	1	0.1%
169	Paraguay	886	887	2	0	2	0.3%
170	Peru	782	1376	29	1	30	2.2%
171	Philippines	1582	2860	1507	3	1509	52.8%
172	Pitcairn Islands	0	0	0	0	0	9.5%
173	Poland	31841	29676	1318	10	1328	4.5%
174	Portugal	731	1071	305	1	307	28.6%
175	Guinea-Bissau	269	269	0	48	48	17.8%
176	Timor-Leste	6	7	6	0	6	90.2%
177	Puerto Rico	-	-	0	0	0	0.0%
178	Eritrea	282	282	0	0	0	0.0%
179	Qatar	2	152	31	0	31	20.7%
180	Palau	0	3	0	0	0	9.7%
181	Zimbabwe	506	517	1	2	2	0.5%
182	Réunion	30	118	39	0	39	33.2%
183	Romania	9463	9811	293	8	301	3.1%
184	Rwanda	398	416	399	0	399	95.8%
185	Russian Federation	114559	49163	158	137	295	0.6%
186	Serbia and Montenegro	-	-	0	0	0	0.0%
187	Saint Helena, Ascension a& Tristan da Cunha	0	0	0	0	0	11.1%
188	Saint Kitts and Nevis	0	10	1	0	1	9.8%
189	Saint Lucia	3	28	2	0	2	8.7%
190	Saint Pierre and Miquelon	0	2	0	0	0	16.2%
191	Saint Vincent and the Grenadines	2	5	0	0	0	1.2%
192	San Marino	0	0	0	0	0	0.0%
193	Sao Tome and Principe	40	40	39	0	39	96.6%

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Table A2 (*continued*)

Codes	Country Codes	WF of production	WF of consumption				
			Total	Unsustainable, green	Unsustainable, blue	Unsustainable, total	Unsustainable, total (%)
194	Saudi Arabia	226	3123	627	4	631	20.2%
195	Senegal	389	487	10	55	65	13.4%
196	Seychelles	4	35	6	0	6	18.2%
197	Sierra Leone	564	557	1	24	25	4.5%
198	Slovenia	4897	2470	246	2	248	10.0%
199	Slovakia	2961	2709	417	4	420	15.5%
200	Singapore	96	502	147	1	148	29.5%
201	Somalia	436	509	41	92	133	26.0%
202	South Africa	999	2183	184	4	188	8.6%
203	Spain	849	5399	576	7	582	10.8%
205	Western Sahara	0	0	0	0	0	0.0%
206	Sudan (former)	0	0	0	0	0	0.0%
207	Suriname	82	48	0	0	0	0.9%
208	Tajikistan	45	1070	0	3	3	0.3%
209	Swaziland	75	189	14	1	15	7.9%
210	Sweden	46718	15333	390	3	393	2.6%
211	Switzerland	1565	2491	1456	2	1458	58.5%
212	Syrian Arab Republic	2	195	13	0	13	6.6%
213	Turkmenistan	0	572	1	1	2	0.4%
214	China, Taiwan Province of	-	-	0	0	0	0.0%
215	United Republic of Tanzania	1941	1805	5	0	6	0.3%
216	Thailand	4065	3794	2396	14	2410	63.5%
217	Togo	350	356	1	0	1	0.4%
218	Tokelau	0	0	0	0	0	9.2%
219	Tonga	1	3	3	0	3	90.1%
220	Trinidad and Tobago	16	97	21	0	21	21.3%
221	Oman	17	299	82	0	82	27.5%
222	Tunisia	141	844	46	1	47	5.5%
223	Turkey	18020	24895	308	15	323	1.3%
224	Turks and Caicos Islands	0	6	1	0	1	10.0%
225	United Arab Emirates	49	1675	315	2	317	18.9%
226	Uganda	1883	2005	5	11	17	0.8%
227	Tuvalu	0	1	0	0	0	11.1%
228	USSR	-	-	0	0	0	0.0%
229	United Kingdom	9012	23413	8955	20	8975	38.3%
230	Ukraine	9583	6248	77	2	79	1.3%
231	United States of America	191383	202410	2273	772	3045	1.5%
233	Burkina Faso	1002	1005	1	0	1	0.1%
234	Uruguay	1034	258	5	3	8	3.1%
235	Uzbekistan	17	3732	3	10	13	0.3%
236	Venezuela (Bolivarian Republic of)	532	572	1	16	17	3.0%
237	Viet Nam	3985	4794	2592	20	2612	54.5%
238	Ethiopia	7909	8050	8	3	11	0.1%
239	British Virgin Islands	0	7	1	0	1	13.7%
240	United States Virgin Islands	0	0	0	0	0	0.0%
242	Wake Island	0	0	0	0	0	4.8%
243	Wallis and Futuna Islands	0	1	0	0	0	19.4%
244	Samoa	21	23	2	0	2	6.6%
248	Yugoslav SFR	-	-	0	0	0	0.0%
249	Yemen	28	260	56	1	56	21.6%
250	Democratic Republic of the Congo	7240	7168	1	129	130	1.8%
251	Zambia	811	826	1	0	1	0.1%
254	Others (adjustment)	0	332	30	1	31	9.3%
255	Belgium	-	-	0	0	0	0.0%
256	Luxembourg	-	-	0	0	0	0.0%
258	Anguilla	0	0	0	0	0	0.0%
259	Channel Islands	0	0	0	0	0	0.0%
260	Svalbard and Jan Mayen Islands	0	0	0	0	0	0.0%
264	Isle of Man	0	0	0	0	0	0.0%
270	Mayotte	7	7	0	0	0	0.0%
272	Serbia	2391	2964	93	2	95	3.2%
273	Montenegro	1224	853	4	0	4	0.5%
276	Sudan	505	762	32	46	79	10.3%

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Table A2 (*continued*)

Codes	Country Codes	WF of production	WF of consumption Total	Unsustainable, green	Unsustainable, blue	Unsustainable, total	Unsustainable, total (%)
277	South Sudan	350	350	0	13	13	3.8%
279	Curaçao	0	26	3	0	3	10.4%
281	Saint-Martin (French Part)	0	6	1	0	1	9.5%
299	Occupied Palestinian Territory	-	-	0	0	0	0.0%
351	China	60854	141466	7517	253	7770	5.5%

Table A3
The water footprint (WF) of consumption of wood products in 2017 by product type.

Code	Product	Processing stage	Sum of WF of consumption (billion m^3/y)	% of total	Cumulative %
1860	Paper and paperboard other than newsprint	Final	268	27%	27%
1632	Sawnwood, coniferous	Final	251	25%	53%
1864	Wood Fuel	Raw material/Final	193	20%	72%
1874	Fibreboard	Final	85	9%	81%
1633	Sawnwood, non-coniferous all	Final	53	5%	86%
1640	Plywood	Final	40	4%	90%
1693	Wood pellets	Final	37	4%	94%
1630	Wood charcoal	Final	26	3%	97%
1671	Newsprint	Final	21	2%	99%
1634	Veneer sheets	Final	6	1%	99%
1694	Other agglomerates	Final	6	1%	100%
1619	Wood chips and particles	Intermediate	1	0.12%	100%
1620	Wood residues	Intermediate	0.35	0.04%	100%
1875	Wood Pulp	Intermediate	0.08	0.01%	100%
1651	Industrial roundwood, coniferous (export/import)	Raw material	0.06	0.01%	100%
1670	Industrial roundwood, non-coniferous non-tropical (export/import)	Intermediate	0.03	0.00%	100%
1657	Industrial roundwood, non-coniferous tropical (export/import)	Raw material	0.01	0.00%	100%
1669	Recovered paper	Intermediate	0.000	0.00%	100%
1668	Pulp from fibres other than wood	Raw material	0.00	0.00%	100%
	Total		987	100.0%	

Note: In the first downloads from FAOSTAT we had categories such as Particle board and OSB, Wood pellets, Other agglomerates; which then were removed in more recent updates. Furthermore, when bilateral data is not present, world totals structures are used.

Table A4
International virtual water flows (VW) by wood product in 2017.

Product	Processing stage	Sum of international VW flows (billion m^3/y)	% of total	Cumulative %
Industrial roundwood, coniferous	Raw material	191	50.9%	50.9%
Industrial roundwood, non-coniferous non-tropical	Raw material	53.3	14.2%	65.1%
Wood chips and particles	Intermediate	42.7	11.4%	76.4%
Sawnwood, coniferous	Final	26.2	7.0%	83.4%
Wood residues	Intermediate	12.9	3.4%	86.8%
Industrial roundwood, non-coniferous tropical	Raw material	10.3	2.7%	89.6%
Paper+-Board Ex Newsprint	Final	8.95	2.4%	91.9%
Wood Pulp	Intermediate	8.37	2.2%	94.2%
Wood Fuel	Raw material/ Final	5.55	1.5%	95.7%
Recovered paper	Intermediate	4.68	1.2%	96.9%
Fibreboard	Final	3.93	1.0%	98.0%
Sawnwood, non-coniferous all	Final	3.42	0.9%	98.9%
Plywood	Final	2.42	0.6%	99.5%
Newsprint	Final	1.21	0.3%	99.8%
Veneer sheets	Final	0.55	0.1%	100.0%
Wood charcoal	Final	0.06	0.0%	100.0%
Pulp from fibres other than wood	Intermediate	0.04	0.0%	100.0%
Total		**376**	**100.0%**	

Note: In the first downloads from FAOSTAT we had categories such as Particle board and OSB, Wood pellets, Other agglomerates; which then were removed in more recent updates. Furthermore, when bilateral data is not present, world totals structures are used.

Table A5
Top 10 largest virtual water (VW) flows by product and trading nations in 2017.

Rank	Product	From	To	VW flow (10^9 m^3/y)
1	Industrial roundwood, coniferous	Russian Federation	China	21.6
2	Industrial roundwood, coniferous	Canada	USA	20.3
3	Industrial roundwood, coniferous	Canada	China	9.9
4	Industrial roundwood, coniferous	USA	China	5.8
5	Wood chips and particles	Canada	USA	4.6
6	Sawnwood, coniferous	Canada	USA	4.6
7	Industrial roundwood, non-coniferous non-tropical	Russian Federation	China	4.3
8	Industrial roundwood, non-coniferous non-tropical	Canada	USA	4.2
9	Sawnwood, coniferous	Russian Federation	China	3.5
10	Industrial roundwood, coniferous	Sweden	Germany	3.3

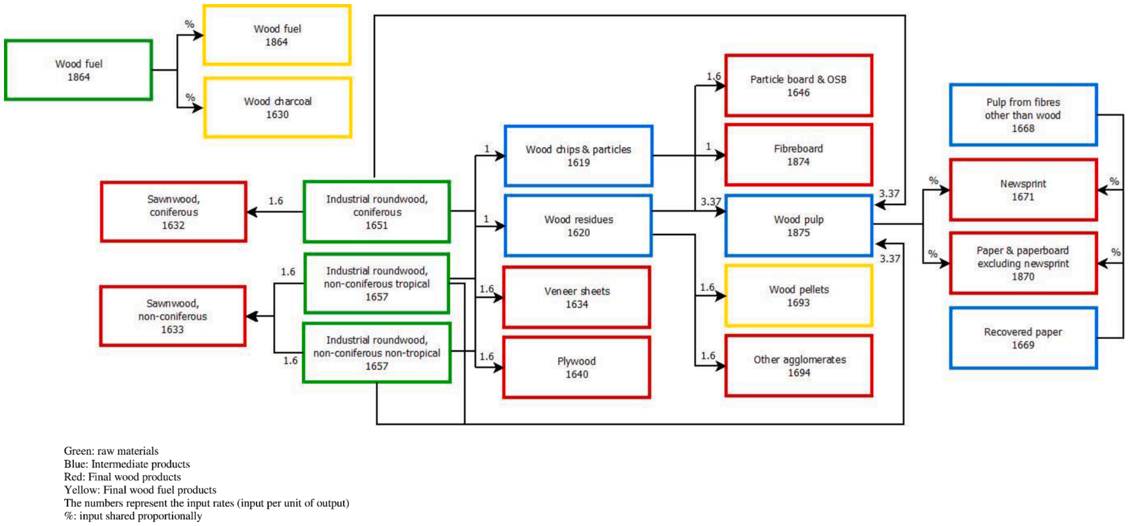

Fig. A1. Supply-Use structure of the supply chain of forest products and input rates
Green: raw materials
Blue: Intermediate products
Red: Final wood products
Yellow: Final wood fuel products
The numbers represent the input rates (input per unit of output)
%: input shared proportionally
Note: The code 1864 is finally used as in the yellow box, as a separate entity of Wood charcoal (1630), hence being 20 forest products with code.
Source: Initial estimates applied (before balancing). Own elaboration from FAOSTAT statistics, see also (Arto et al., 2022). In the first downloads from FAOSTAT we had categories such as Particle board and OSB, Wood pellets, Other agglomerates; which then were removed in more recent updates. Furthermore, when bilateral data is not present, world totals structures are used.

Appendix B: Analysis of drivers of forest water footprint of consumption changes

The time series of MRIO can also be used in combination with decomposition techniques to analyse the drivers of change in water footprint of consumption. There is a considerable body of literature on how to decompose the effects of different factors in the evolution of a variable. There are basically 2 techniques for such decompositions: Index Decomposition Analysis (IDA) and Structural Decomposition Analysis (SDA). IDA is usually adopted when the scope of the study is to have a better understanding of the drivers of the changes of emissions of a specific sector. SDA is based on I-O analysis and is used to analyse the changes of the whole economy. Su and Ang (2012) offer a detailed review of the literature on the application of SDA. The SDA is based on Leontief's demand-driven model as describe in expression $= \widehat{\mathbf{w}}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{Yv}$. The elements of the vector of forest water footprint by commodity can expressed as:

$$ {}_i^r = \sum_j \sum_{s,t} w_i^r b_{ij}^{rs} y_j^{st} \tag{B1} $$

Furthermore, the elements of the matrix of final demand can expressed as the product of different components as follows:

$$ y_j^{st} = \frac{y_j^{st}}{\sum_s y_j^{st}} \frac{\sum_s y_j^{st}}{\sum_j \sum_s y_j^{st}} \frac{\sum_j \sum_s y_j^{st}}{GDP^t} \frac{GDP^t}{p^t} p^t = t_j^{st} s_j^t c^t a^t p^t \tag{B2} $$

Where $p^t$is the population of country *t; a^t* is the affluence or GDP per capita of region *t; c^t* is the propensity to consume (wood products) measured as the total consumption of commodities (wood products) per unit of GDP in country *t; s^t* is the share of each commodity *i* in the total final demand of country *t; t_j^{st}* is the fraction of the total final demand of commodity *i* that is imported from country *s* (if $s \neq t$) or is produced domestically (if $s = t$).

From expression (B1) the total forest water footprint of production in country *r* can be expressed:

$$ {}_i^r = \sum_j \sum_{s,t} w_i^r b_{ij}^{rs} t_j^{st} s_j^t c^t a^t p^t \tag{B3}$$

Expression (B3) shows the forest water footprint as the product of a series of factors. As we have pointed before, from a policy perspective it results interesting to quantify the effect of each of these factors.

There are several ways to decompose expression (B3) with an SDA (see Su and Ang, 2012) for the different methods). We follow the simplified method proposed by (Dietzenbacher and Los, 1998, 1997).

The changes in the water footprint between 2 points in time (indicated by the subscripts 0 and 1) are $\Delta\varpi = \varpi_1^r - \varpi_0^r$, where subscripts indicate the years. The 2 polar decompositions ($\Delta\varpi_a^r$ and$\Delta\varpi_b^r$) are:

$$\begin{aligned}\Delta\varpi_a^r &= \sum_{i,j}\sum_{s,t}\Delta w_i^r b_{ij1}^{rs} t_{j1}^{st} s_{j1}^t c_1^t a_1^t p_1^t + \sum_{i,j}\sum_{s,t} w_{i0}^r \Delta b_{ij}^{rs} t_{j1}^{st} s_{j1}^t c_1^t a_1^t p_1^t \\ &+ \sum_{i,j}\sum_{s,t} w_{i0}^r b_{ij0}^{rs} \Delta t_j^{st} s_{j1}^t c_1^t a_1^t p_1^t + \sum_{i,j}\sum_{s,t} w_{i0}^r b_{ij0}^{rs} t_{j0}^{st} \Delta s_j^t c_1^t a_1^t p_1^t \\ &+ \sum_{i,j}\sum_{s,t} w_{i0}^r b_{ij0}^{rs} t_{j0}^{st} s_{j0}^t \Delta c^t a_1^t p_1^t + \sum_{i,j}\sum_{s,t} w_{i0}^r b_{ij0}^{rs} t_{j0}^{st} s_{j0}^t c_0^t \Delta a^t p_1^t \\ &+ \sum_{i,j}\sum_{s,t} w_{i0}^r b_{ij0}^{rs} t_{j0}^{st} s_{j0}^t c_0^t a_0^t \Delta p^t\end{aligned} \tag{B4}$$

$$\begin{aligned}\Delta\varpi_b^r &= \sum_{i,j}\sum_{s,t}\Delta w_i^r b_{ij0}^{rs} t_{j0}^{st} s_{j0}^t c_0^t a_0^t p_0^t + \sum_{i,j}\sum_{s,t} w_{i1}^r \Delta b_{ij}^{rs} t_{j0}^{st} s_{j0}^t c_0^t a_0^t p_0^t \\ &+ \sum_{i,j}\sum_{s,t} w_{i1}^r b_{ij1}^{rs} \Delta t_j^{st} s_{j0}^t c_0^t a_0^t p_0^t + \sum_{i,j}\sum_{s,t} w_{i1}^r b_{ij1}^{rs} t_{j1}^{st} \Delta s_j^t c_0^t a_0^t p_0^t \\ &+ \sum_{i,j}\sum_{s,t} w_{i1}^r b_{ij1}^{rs} t_{j1}^{st} s_{j1}^t \Delta c^t a_0^t p_0^t + \sum_{i,j}\sum_{s,t} w_{i1}^r b_{ij1}^{rs} t_{j1}^{st} s_{j1}^t c_1^t \Delta a^t p_0^t \\ &+ \sum_{i,j}\sum_{s,t} w_{i1}^r b_{ij1}^{rs} t_{j1}^{st} s_{j1}^t c_1^t a_1^t \Delta p^t\end{aligned} \tag{B5}$$

And the average of the polar decompositions

$$\Delta\varpi^r = \frac{1}{2}\left(\Delta w_a^r + \Delta w_b^r\right) \tag{B6}$$

The 2nd element of (B4) and (B5) can further be decomposed to distinguish between changes in the total intermediate input structure and changes in the trade structure of intermediate consumption. Since $\mathbf{x} = \mathbf{BYv}$, and $\Delta\mathbf{B} = \mathbf{B}_1(\Delta\mathbf{A})\mathbf{B}_0 = \mathbf{B}_0(\Delta\mathbf{A})\mathbf{B}_1$, we have then that the 2nd element of (B4) and (B5) can be:

$$\sum_{i,j}\sum_{s,t} w_{i0}^r \Delta b_{ij}^{rs} t_{j1}^{st} s_{j1}^t c_1^t a_1^t p_1^t = \sum_{i,j,h}\sum_{s,t} w_{i0}^r b_{ij0}^{rs} \Delta a_{jh}^{st} x_{h1}^t \tag{B7}$$

$$\sum_{i,j}\sum_{s,t} w_{i1}^r \Delta b_{ij}^{rs} t_{j0}^{st} s_{j0}^t c_0^t a_0^t p_0^t = \sum_{i,j,h}\sum_{s,t} w_{i1}^r b_{ij1}^{rs} \Delta a_{jh}^{st} x_{h0}^t \tag{B8}$$

The following step is to split the change in the input coefficients in Eqs. (B7) and (B8) into the change in the total intermediate input structure and the change in the trade coefficients. We define the country-specific input coefficients $d_{ij}^r = \sum_s a_{ij}^{sr}$, and country trade coefficients $\tau_{ij}^{sr} = a_{ij}^{sr} / d_{ij}^r$. For each intermediate input *i* and output *j*, the corresponding τ_{ij}^{sr} indicates the fraction that is imported from country *s* (if $s \neq r$) or is produced domestically (if $s = r$). Hence, we may write the change in Δa_{ji}^{st}

$$\Delta a_{ji}^{st} = \frac{1}{2}\left(\tau_{ji0}^{st} + \tau_{ji1}^{st}\right)\Delta d_{ji}^t + \frac{1}{2}\Delta\tau_{ji}^{st}\left(d_{ji0}^t + d_{ji1}^t\right) \tag{B9}$$

From expressions (B4) to (B8), we may also obtain how much of the change in water footprint of consumption in country *s* is driven by the changes in the socio-economic structure in each other country:

$$\Delta\varpi^r = \frac{1}{2}\sum_{i,j}\sum_{s,t}\Delta w_i^r\left(x_{i1}^r + x_{i0}^r\right) \tag{B10}$$

$$+\frac{1}{4}\sum_{i,j,h}\sum_{s,t}\left[w_{i0}^r b_{ij0}^{rs}\left(\tau_{jh0}^{st} + \tau_{jh1}^{st}\right)\Delta d_{jh}^t x_{h1}^t + w_{i1}^r b_{ij1}^{rs}\left(\tau_{jh0}^{st} + \tau_{jh1}^{st}\right)\Delta d_{jh}^t x_{h0}^t\right] \tag{B11}$$

$$+\frac{1}{4}\sum_{i,j,h}\sum_{s,t}\left[w_{i0}^r b_{ij0}^{rs}\Delta\tau_{jh}^{st}\left(d_{jh0}^t + \Delta d_{jh1}^t\right)x_{h1}^t + w_{i1}^r b_{ij1}^{rs}\Delta\tau_{jh}^{st}\left(d_{jh0}^t + \Delta d_{jh1}^t\right)x_{h0}^t\right] \tag{B12}$$

$$+\frac{1}{2}\sum_{i,j}\sum_{s,t}\left[w_{i0}^{r}b_{ij0}^{rs}\Delta t_{j}^{st}s_{j1}^{t}c_{1}^{t}a_{1}^{t}p_{1}^{t}+w_{i1}^{r}b_{ij1}^{rs}\Delta t_{j}^{st}s_{j0}^{t}c_{0}^{t}a_{0}^{t}p_{0}^{t}\right] \tag{B13}$$

$$+\frac{1}{2}\sum_{i,j}\sum_{s,t}\left[w_{i0}^{r}b_{ij0}^{rs}t_{j0}^{st}\Delta s_{j}^{t}c_{1}^{t}a_{1}^{t}p_{1}^{t}+w_{i1}^{r}b_{ij1}^{rs}t_{j1}^{st}\Delta s_{j}^{t}c_{0}^{t}a_{0}^{t}p_{0}^{t}\right] \tag{B14}$$

$$+\frac{1}{2}\sum_{i,j}\sum_{s,t}\left[w_{i0}^{r}b_{ij0}^{rs}t_{j0}^{st}s_{j0}^{t}\Delta c^{t}a_{1}^{t}p_{1}^{t}+w_{i1}^{r}b_{ij1}^{rs}t_{j1}^{st}s_{j1}^{t}\Delta c^{t}a_{0}^{t}p_{0}^{t}\right] \tag{B15}$$

$$+\frac{1}{2}\sum_{i,j}\sum_{s,t}\left[w_{i0}^{r}b_{ij0}^{rs}t_{j0}^{st}s_{j0}^{t}c_{0}^{t}\Delta a^{t}p_{1}^{t}+w_{i1}^{r}b_{ij1}^{rs}t_{j1}^{st}s_{j1}^{t}c_{1}^{t}\Delta a^{t}p_{0}^{t}\right] \tag{B16}$$

$$+\frac{1}{2}\sum_{i,j}\sum_{s,t}\left[w_{i0}^{r}b_{ij0}^{rs}t_{j0}^{st}s_{j0}^{t}c_{0}^{t}a_{0}^{t}\Delta p^{t}+w_{i1}^{r}b_{ij1}^{rs}t_{j1}^{st}s_{j1}^{t}c_{1}^{t}a_{1}^{t}\Delta p^{t}\right] \tag{B17}$$

Expressions (B10-B17), decompose the forest WF of consumption in country r into the following 8 components: the change in the yield in country r (B10, which is zero due to using an average one over the years); the change in input structure in country t (B11); the change in the intermediate trade structure in country t (B12); the change in the final trade structure in country t (B13); the change in the composition of the final demand in country t (B14); the change in the consumption propensity in country t (B15); the change in the affluence in country t (B16); and the change in population in country t (B17). Note that we can also distinguish the forest WF of consumption in country r that are driven by changes in domestic factors (when $t = r$) or foreign factors ($t \neq r$).

Appendix C: Drivers of change in the water footprint of wood products

Using structural decomposition analysis (SDA) we decomposed drivers of change in the WF of wood products into 7 components (Fig. C1). Globally, we see how affluence (higher GDP per capita) tends to drive the total changes, showing also the shape of decrease in the years 2008-2009. To a much smaller extent (typically representing about a third of the change due to affluence), population also drove part of the increases in global WF. The propensity effect, i.e., the tendency to consume wood products measured as the total consumption of wood products per unit of GDP, was clearly negative, showing the opposite trend to affluence. The trade structure, i.e. the composition of trade, shows in general negative values, revealing that from 1997 onwards there were slight changes favouring a reduction in WFs of consumption. The technological effect also played an important role in buffering the general changes of increased WFs.

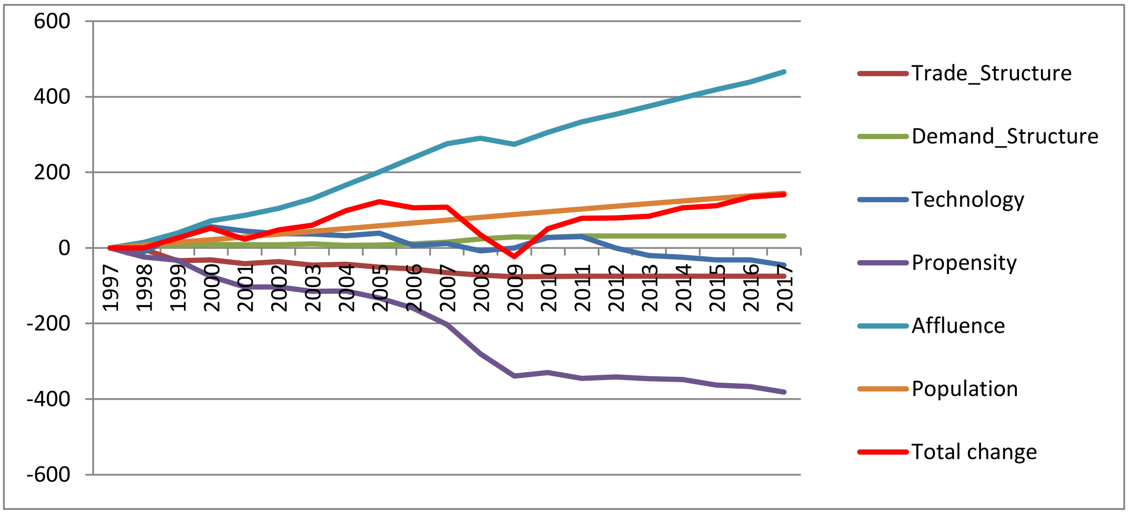

Fig. C1. Drivers of change in the global WF of wood products (10^9 m^3/y). Period: 1997-2017.

Note: The “Trade_Structure” here joins the change in the intermediate trade structure in country t (B12 in the Appendix B) and the change in the final trade structure in country t (B13). The “Trade_Structure” and “Demand_Structure” effects get unreasonably extreme values (but which compensate each other) which compensate to each other due to sharp changes in the original FAOSTAT accounting and classifications (appearance/disappearance of products, regions, etc.). Being in general the smallest absolute effects (together with “technology”) we have kept the former two constants from 2012-2017.

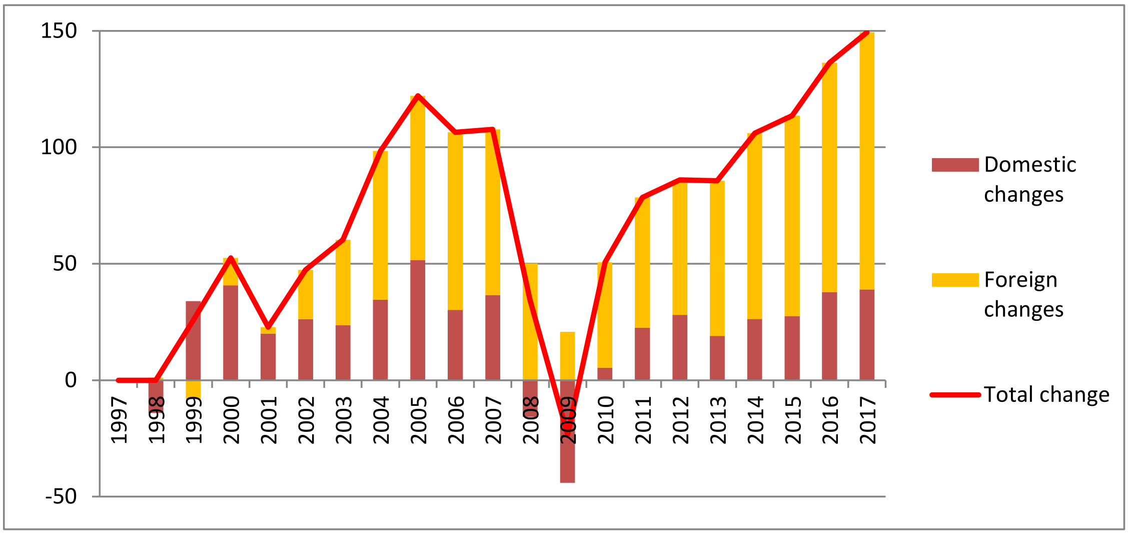

Fig. C2. Domestic vs. foreign drivers of change in the global WF of wood products (10^9 m^3/y). 1997-2017.

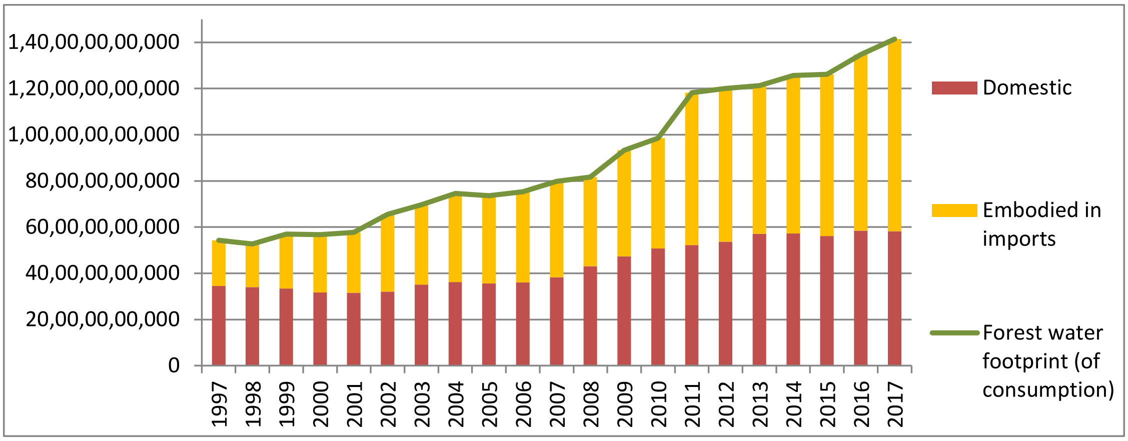

Fig. C3. Water footprint of national consumption of wood products (m^3/y) of China. Period: 1997-2017.

Fig. C2 shows the attribution of changes in the global WF of wood products to domestic vs. foreign factors. In the beginning of the study period these changes are mostly driven by domestic changes, i.e. changes in a nation's demand for wood products. In later years, the role of trade becomes increasingly important with foreign changes explaining the largest part (around 75%) of annual changes in the global WF of wood products.

In contrast to the temporal development of the global WF of wood products and underlying drivers at the global scale, the picture looks different for two important countries on the global market of forest products: China and the USA. Several studies have addressed the specifics of the general water footprints (mainly from food products, in relation to other sectors, etc.), e.g. for China (among many others, Chen et al., 2017; Guan and Hubacek, 2007; Hubacek et al., 2009; Liqiang et al., 2016; Ma et al., 2006;Wang et al., 2013; Zhao et al., 2015, 2009; Zhuo et al., 2020), and for the USA (among others, Chini et al., 2020, 2017; Konar and Marston, 2020; Marston et al., 2018).

In China, the WF of consumption of wood products increased by roughly a factor 2.5 while the external component of the WF (related to imported wood products) increased from ~35% to nearly 60% during the study period (Fig. C3). No effect of the real estate crisis in 2008 and 2009 is visible. In terms of drivers behind annual changes (Fig. C4), we see that affluence as key driver has also a more upward and continuous trend compared to the global picture (Fig. C1). It is quite interesting to observe how this effect seems to hide (capturing most of the positive effects) the role of growing population. The propensity effect is less negative in China than globally (this relates to the fact that there is not such a clear-cut reduction in the share of demand of wood products when becoming richer), while technology played an important role in compensating partially the upward trend of WFs of consumption.

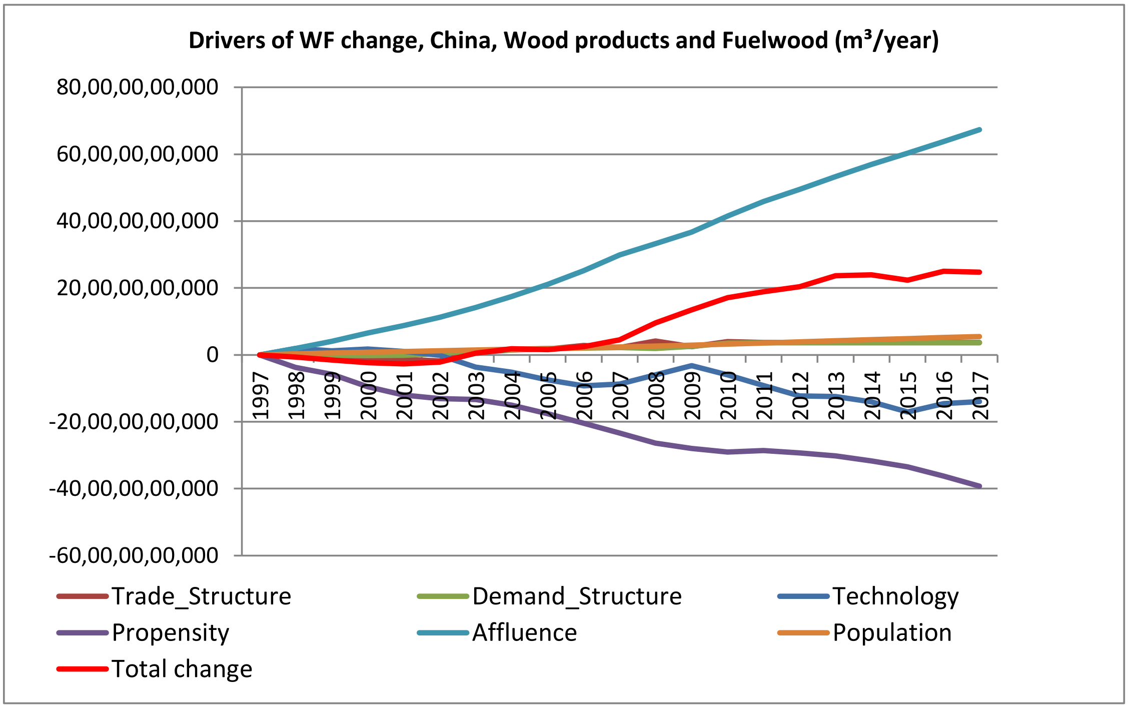

Fig. C4. Drivers of change in the water footprint of national consumption of wood products (m^3/y) of China. Period: 1997-2017.
Note: The "Trade_Structure" here joins the change in the intermediate trade structure in country *t* (B12 in the Appendix B) and the change in the final trade structure in country *t* (B13). The "Trade_Structure" and "Demand_Structure" effects get unreasonably extreme values (but which compensate each other) which compensate to each other due to sharp changes in the original FAOSTAT accounting and classifications (appearance/disappearance of products, regions, etc.). Being in general the smallest absolute effects (together with "population") we have kept the former two constants from 2012-2017.

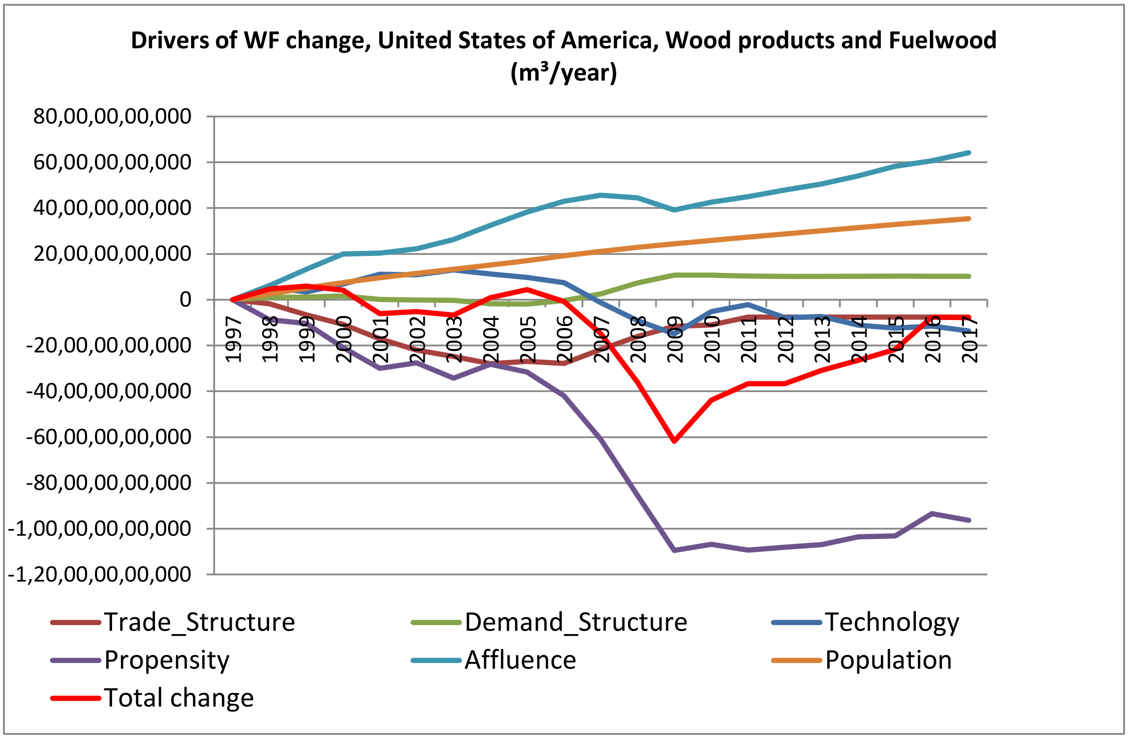

Fig. C5. Drivers of change in the water footprint of national consumption of wood products (m^3/y) of the USA. Period: 1997-2017.
Note: The "Trade_Structure" here joins the change in the intermediate trade structure in country *t* (B12 in the Appendix B) and the change in the final trade structure in country *t* (B13). The "Trade_Structure" and "Demand_Structure" effects get unreasonably extreme values which compensate to each other due to sharp changes in the original FAOSTAT accounting and classifications (appearance/disappearance of products, regions, etc.). Being in general the smallest absolute effects (together with "technology") we have kept the former two constants from 2012-2017.

In the case of the WF of national consumption of wood products of the USA, we observe affluence and population (and to a lesser degree, the demand structure) as clear drivers of the increase in the WF (Fig. C5). From 2006 onwards the total change becomes negative, strongly driven by the propensity effect. Closely linked to the financial crisis and, in particular, with the slowdown of the building sector (years 2007-2009), it is remarkable how the reduction in building, but also the move in demand in housing towards other materials than wood (typically also more expensive), have reduced the WF of wood products consumed in the USA.

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