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The water footprint of wood for lumber, pulp, paper, fuel and firewood

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ABSTRACT

This paper presents the first estimate of global water use in the forestry sector related to roundwood production for lumber, pulp, paper, fuel and firewood. For the period 1961–2010, we estimate forest evaporation at a high spatial resolution level and attribute total water consumption to various forest products, including ecosystem services. Global water consumption for roundwood production increased by 25% over 50 years to 961×10^9 m³/y (96% green; 4% blue) in 2001–2010. The water footprint per m³ of wood is significantly smaller in (sub)tropical forests compared to temperate/boreal forests, because (sub)tropical forests host relatively more value next to wood production in the form of other ecosystem services. In terms of economic water productivity and energy yield from bio-ethanol per unit of water, roundwood is rather comparable with major food, feed and energy crops. Recycling of wood products could effectively reduce the water footprint of the forestry sector, thereby leaving more water available for the generation of other ecosystem services. Intensification of wood production can only reduce the water footprint per unit of wood value per ha outweighs the loss of value of other ecosystem services, which is often not the case in (sub)tropical forests. The results of this study contribute to a more complete picture of the human appropriation of water, thus feeding the debate on water for food or feed versus energy and wood.

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1. Introduction

Although precipitation is renewable, it is limited in time and space, and so are its subsequent pathways as green and blue water flows (Schyns et al., 2015; Hoekstra, 2013). There are alternative competing uses for these limited flows, which makes freshwater a scarce resource. This explains the interest in the human appropriation of water (Postel et al., 1996; Rockström et al., 1999; Rockström and Gordon, 2001; Hoekstra and Mekonnen, 2012) in relation to a maximum sustainable level (Hoekstra and Wiedmann, 2014) or planetary boundary (Steffen et al., 2015; Rockstrom et al., 2009). Freshwater sustains terrestrial and aquatic ecosystems and is used for the production of goods and services. Important water consuming sectors are agriculture, industries, municipalities and forestry. Multiple studies have quantified the global blue and green water consumption for producing crop and livestock products, and for fulfilling industrial and municipal demands (Hoekstra and Mekonnen, 2012; Rost et al., 2008; Hanasaki et al., 2010; Liu and Yang, 2010; Liu et al., 2009; Siebert and Döll, 2010; Mekonnen and Hoekstra, 2011; Wada et al., 2014; Döll et al., 2012).

* Corresponding author. E-mail address: j.f.schyns@utwente.nl (J.F. Schyns). As recently identified by Vanham (2016), we do not know how much water is used in the forestry sector for the production of wood products such as lumber, pulp and paper, firewood or bio-fuel.

Forest evaporation accounts for 45–58% of the total vapour flow from land to atmosphere (Rockström et al., 1999; Rockström and Gordon, 2001; Oki and Kanae, 2006). With the term evaporation we refer to the entire vapour flux from land to atmosphere, including evaporation through the process of plant transpiration (Savenije, 2004). Determining which part of the evaporation is appropriated for the production of roundwood (wood in the rough) is not as straightforward as it is for crops. For crops, all evaporation from the crop field during the growing season is usually attributed to crop production. This makes sense, since crop fields are generally used quite intensively for a distinct purpose (providing food, feed or fibre). Forests on the other hand provide numerous other ecosystem services next to the provision of wood (Costanza et al., 1997), depending on the intensity of forest exploitation. Therefore, forest evaporation is to be attributed to roundwood production based on the relative value of roundwood production compared to the value of other ecosystem services provided by the forest.

There are a few studies that have attributed forest evaporation to wood products. Van Oel and Hoekstra (2012) made a first es-

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timate of the water footprint of paper in the main pulp producing countries. Chiu and Wu (2013) estimated the water footprint of ethanol from wood residues from the southeast United States. Tian and Ke (2012) made estimates of the water footprint of lumber, panels, pulp and paper in China. However, these studies did not account for the value of wood production relative to other forest values (Van Oel and Hoekstra, 2012; Chiu and Wu, 2013; Tian and Ke, 2012). Launiainen et al. (2014) argue that one should not attribute forest evaporation of rain-fed managed forests to end products at all, based on the argument that the evaporation of these forests is not significantly different than that of natural forests (no net difference). However, for the purpose of measuring the amount of evaporation that is appropriated by roundwood production and therefore not available for other uses we should measure total (not net) water consumption (Hoekstra, 2017).

The objective of this paper is to provide the first estimate of the global water consumption related to roundwood production and to subsequently attribute this to various end-uses of wood. Our analysis is at high spatial resolution $(30 \times 30')$ for the period 1961–2010 and includes a number of innovations:

- Global high-resolution estimates of actual evaporation from production forests, distinguishing the contribution of green water (precipitation) and blue water (groundwater through capillary rise).
- Attribution of forest evaporation to roundwood production based on the relative value of roundwood production compared to the value of other ecosystem services provided by the forest.
- Estimates of the green and blue water footprints of wood products, including sawnwood, wood-based panels, wood pulp, paper and wood-based energy carriers.

2. Method and data

2.1. Method

We follow the method of water footprint assessment to estimate the water consumption associated with roundwood production for lumber, pulp, paper, fuel and firewood (Hoekstra et al., 2011). Firstly, we estimate the volume of water consumed that can be attributed to roundwood production per $30 \times 30'$ grid cell per year over the period 1961–2010 (Section 2.1.1). Secondly, we estimate the period-average water footprint per unit of roundwood produced (Section 2.1.2). Finally, we attribute the water footprint of roundwood production to various end-uses of wood (Section 2.1.3). Throughout this paper we use the term water footprint to refer to the consumptive part only (green plus blue) and exclude the grey component that expresses water pollution.

2.1.1. Water consumption attributed to roundwood production

The volume of water consumed that can be attributed to roundwood production (*WU*, in m^3/y) in grid cell *x* in year *t* is estimated as:

$$WU[x, t] = (E_{act}[x, t] \times A_{rw}[x, t] + P_{act}[x, t] \times f_{water}[x])$$
$$\times f_{value, rw}[x, t]$$
(1)

in which E_{act} is the actual forest evaporation (m/y), A_{rw} the area used for roundwood production (m²), P_{act} the actual roundwood harvested (m³/y), f_{water} the volumetric moisture content of freshly harvested wood (m³ water/m³ wood), and $f_{value,rw}$ a dimensionless fraction that represents the relative value of roundwood production compared to the value of other ecosystem services provided by the forest. Annual actual forest evaporation

 E_{act} (m/y) is estimated using the method of Zhang et al. (2001):

$$E_{act}[x,t] = Pr[x,t] \left(\frac{1 + w \frac{E_0[x,t]}{Pr[x,t]}}{1 + w \frac{E_0[x,t]}{Pr[x,t]} + \frac{Pr[x,t]}{E_0[x,t]}} \right)$$
(2)

in which Pr is the annual precipitation (m/y), w a dimensionless coefficient representing plant water availability, and E_0 the annual potential forest evaporation (m/y). We apply w=2, which is the best fit value for forests based on a study that includes 56 forest catchments around the world (Zhang et al., 1999). We determine E_0 based on the mean annual temperature (T, in ⁰C) using the empirical equation derived by Komatsu et al. (2012), which they derived for Zhang's equation by regressing 829 forest E_{act} data points:

$$E_0[x,t] = (0.488T^2[x,t] + 27.5T[x,t] + 412) \times 10^{-3}$$
(3)

The factor 10^{-3} is to convert mm to m.

Distinction between green and blue water use

The distinction between green and blue water use is made by applying a fraction that represents the part of water use that originates from capillary rise (f_{blue}):

$$WU_{\text{green}}[x,t] = WU[x,t] \times (1 - f_{\text{blue}}[x,t])$$
(4)

$$WU_{\text{blue}}[x, t] = WU[x, t] \times f_{\text{blue}}[x, t]$$

We estimate f_{blue} based on two main assumptions:

- Capillary rise is at its maximum in a very dry year ($E_{act}/Pr = 1$) and moves linearly to zero in an extremely wet year ($E_{act}/Pr = 0$). A water potential gradient is required to move water upward from the groundwater table. When the soil is dry this gradient is strong. If the soil is saturated this gradient is absent and there will be no capillary rise.
- The distance that needs to be bridged by capillary rise (d_{cap} , in m) is defined as the difference between the groundwater table depth (z_g) and the root depth of the forest type (z_r), both in m below a certain reference level. The maximum height of capillary rise ($d_{cap,max}$, in m) depends on the soil type. When d_{cap} is non-limiting (\leq 0), the roots take up a share $d_{cap,max}$ of z_r through capillary rise under very dry conditions. This share decreases linearly to zero when d_{cap} approaches $d_{cap,max}$ (beyond, there is no capillary uptake at all).

These assumptions can be combined into a single equation that applies when $0 \le d_{cap} < d_{cap,max}$:

$$f_{\text{blue}}[x,t] = \frac{d_{\text{cap},\max}[x]}{z_{\text{r}}[x]} \frac{E_{\text{act}}[x,t]}{Pr[x,t]} \left(1 - \frac{z_{\text{g}}[x] - z_{\text{r}}[x]}{d_{\text{cap},\max}[x]}\right)$$
(6)

2.1.2. Water footprint per unit of roundwood production

Since wood production cycles are commonly multi-decadal (Bauhus et al., 2009), we calculate the water footprint per unit of production as a period-average. The water footprint of roundwood production (WF_{rw} , in m³ water/m³ roundwood) for the period of *m* years is defined as:

$$WF_{\rm rw}[x] = \frac{\sum_{t=1}^{m} WU[x]}{\sum_{t=1}^{m} P_{\rm act}[x]}$$
(7)

2.1.3. Water footprint per unit of end product

The water footprint per unit of end product *p* produced with roundwood from grid cell *x* is estimated by multiplying WF_{rw} with a conversion factor ($f_{conversion}$, in m³ roundwood/unit of end product):

$$WF_{p}[p, x] = WF_{rw}[x] \times f_{conversion}[p]$$
(8)

(5)

2.2. Data

2.2.1. Wood harvested area

We obtained wood harvested area maps (as fraction of a grid cell) at $30 \times 30'$ resolution for each year in the period 1961–2004 from Chini et al. (2014). For 2005–2010, we keep the pattern from 2004. Hurtt et al. (2011) estimated the wood harvest pattern with a global land-use model that takes, among others, national wood harvest data as input, constrains wood harvesting by the presence of forests, and gives preference to wood harvesting near existing land-use (proximity to infrastructure or local markets). We took the sum of the five different land types from which wood can be harvested as distinguished by Hurtt et al. (2011).

We apply three restrictions to these maps. Firstly, we assumed that roundwood production only takes place in those grid cells that have a forest cover according to the IGBP DISCover land cover database (Loveland et al., 2009). Secondly, we consider grid cells with an average E_{act} over the study period of less than 100 mm/y to be unsuitable for forest growth that enables wood harvesting and hence remove those grid cells from our final map. This threshold is derived from Komatsu et al. (2012), who collected 829 forest E_{act} data points at locations spread over the world, of which only three (0.4%) have an E_{act} smaller than 100 mm/y. Thirdly, we assumed that no wood is harvested from grid cells that are entirely located within a protected area of IUCN category Ia (strict nature reserves), Ib (wilderness areas) or II (national parks) from the year that these areas received this status. The data on protected areas have been obtained from IUCN and UNEP-WCMC (2016).

We made one exception to the above procedure. The People's Democratic Republic of Ethiopia (1961–1992) had a significant contribution to world roundwood production according to national statistics (FAOSTAT, 2016a). However, the cells where wood harvesting took place in this country according to the map by Chini et al. (2014) have no forest cover according to the IGBP DIS-Cover dataset. To avoid neglect of this roundwood production, we assigned the most common forest type in the region to the cells where wood was harvested: tropical evergreen broadleaf forest. Finally, we scale the wood harvested area maps on the national level to the area used for roundwood production estimated based on the Global Forest Resources Assessment 2015 (Köhl et al., 2015) (see SI).

2.2.2. Actual roundwood production on the grid level

National annual statistics on actual roundwood production from coniferous (C) and non-coniferous (NC) forest covering the study period have been obtained from FAOSTAT, 2016a). We downscale these data to the grid level in two steps. Firstly, we estimate the maximum sustainable production in a grid cell by multiplying the wood harvested area with a long-term maximum sustainable wood yield (Section 2.2.3). Therein, we distinguish between C and NC production by assuming that C wood is produced in needleleaf forests and NC wood in broadleaf forests and that mixed forest contributes to both C and NC production (fifty-fifty). For a small number of countries, in some years, reported production concerns C and/or NC wood, while our maps contain no grid cells yielding that type of wood (e.g. only NC production is reported, but all grid cells in the wood harvest map are of the needleleaf type). In these cases, we overwrite the dominant forest type in all affected grid cells for that year to mixed forest. Secondly, we distribute the national annual statistics over all grid cells used for roundwood production in that year, according to the estimated maximum sustainable production for that roundwood type (C or NC).

2.2.3. Long-term maximum sustainable wood yield

The rate of wood production varies over the age of the forest stand following an s-shaped curve that is different for each species, location and type of management (Lutz, 2011). The mean annual increment is the average production rate at any particular age of the forest, calculated as the total growing stock volume divided by the age of the forest stand (Lutz, 2011; Jürgensen et al., 2014; Blanchez, 1997). We obtained minimum and maximum forest plantation yields (in m³/ha/y) for different tree species in various countries around the world from Brown (2000). These yields represent the mean annual increment for the likely rotation length of the forest stand. We assume that forests are of a mixed age, that trees are harvested at their likely rotation length and that natural losses are minimal. Under these circumstances, we consider the yields by Brown (2000) to be a good proxy of the long-term maximum sustainable wood yield (Y_{sus}).

Ultimately, we need an estimate of Y_{sus} for each grid cell in our roundwood production maps. To arrive there, (i) we determine the dominant forest type and climate zone of each grid cell; (ii) we assume characteristic tree species for each forest type; (iii) we determine the dominant climate zone in each country in the dataset by Brown (2000); (iv) from this dataset we calculate the average Y_{sus} of a tree species per climate zone and (v) we assign those Y_{sus} estimates to the grid cells. Details are described in the SI. The following assumptions are made under (ii), which are loosely based on the forest type descriptions of Matthews et al. (2000):

- Evergreen needleleaf forest yields pine (*Pinus species*) in all climate zones.
- Evergreen broadleaf forest yields eucalyptus (*Eucalyptus species*) in all climate zones.
- Deciduous needleleaf forest yields larch (*Larix species*) in all climate zones.
- Deciduous broadleaf forest yields oak (Quercus species) in all climate zones.
- Mixed forest in the tropical and subtropical zone yields a 50–50 mix of pine and eucalyptus.
- Mixed forest in the temperate zone yields a 50–50 mix of pine and oak.
- Mixed forest in the boreal zone yields a 50–50 mix of pine and larch.

The resulting Y_{sus} estimates per forest type and climate zone are presented in Table 1. The climate zones and forest types are mapped in Fig. 1.

2.2.4. Meteorological data

For each $30 \times 30'$ grid cell and each year in our study period, we estimated the annual precipitation (*Pr*) and annual mean temperature (*T*) based on daily data obtained from de Graaf et al. (2014).

2.2.5. Fraction of water use originating from capillary rise

Rooting depths were derived from Canadell et al. (1996) (Table 2). The groundwater table depth per $30 \times 30'$ grid cell has been estimated by averaging over the $30 \times 30'$ map by Fan et al. (2013). The maximum height of capillary rise is estimated using an empirical relation based on the soil's grain size and void ratio (details in SI).

2.2.6. Volumetric moisture content of freshly harvested wood

The fraction f_{water} is estimated by multiplying a species wood density with the equilibrium moisture content (t water/t oven dried wood) (derivation in the SI). The wood density for each of the characteristic tree species considered in this study has been estimated from Zanne et al. (2009) (Table 3). The equilibrium moisture content is estimated per grid cell for each year with



Fig. 1. Forest types and climate zones for the grid cells where roundwood is produced. Data obtained from Loveland et al. (2009) and Van Velthuizen et al. (2007) as described in the SI.



Fig. 2. The relative value of ecosystems services for tropical (left) and temperate/boreal forests (right). Data source: Costanza et al. (2014). Descriptions of the ecosystem services can be found in Costanza et al. (1997).

the function of Simpson (1998) that takes temperature and relative humidity as inputs. We applied the mean annual temperature (Section 2.2.4) and a climate-average relative humidity per grid cell. The latter is estimated based on the 10 \times 10' gridded monthly mean relative humidity data for 1961–1990 from New et al. (2002). We took the average of all months and subsequently the average of all 10 \times 10' grid cells within a 30 \times 30' grid cell.

2.2.7. Value fraction of roundwood production

We base our estimate of the value fraction of roundwood production ($f_{value,rw}$) on Costanza et al. (2014), who estimated the value of 17 ecosystems services (in monetary units/ha) around the year 2011 for (sub)tropical forests and temperate/boreal forests, separately (Fig. 2). We assume that the service labelled 'raw materials' by Costanza et al. (2014) primarily refers to roundwood production. Non-wood forest products that are not of interest for this study are included under other services, e.g. food and food additives ('food production') and plant and animal parts for pharmaceutical products ('genetic resources').

The data in Fig. 2 refer to the entire forest biomes, while we are interested in production forests specifically. Therefore, we first distribute the monetary values per hectare of the services over production and non-production forests for the reference year 2010

(which lies closest to the reporting year by Costanza et al. (2014)). Secondly, we scale the values back in time and disaggregate them spatially over the grid cells. Therein, we distinguish three categories of ecosystem service values:

- The value of roundwood production that varies with the volume of roundwood produced.
- The value of the services pollination, biological control, habitat/refugia, recreation and culture that are inversely proportional to the intensity of forest exploitation, which is defined as the actual wood production over the maximum sustainable wood production.
- The value of the other services given in Fig. 2 that are invariable with the intensity of forest exploitation.

For the year 2010, and averaged per biome, the resulting ecosystem service values are consistent with those reported in Fig. 2. Details and assumptions are described in the SI. Ultimately, we calculate $f_{\text{value,rw}}$ per grid cell per year using Eq. (SI.10).

2.2.8. Wood to end product conversion factors

Conversion factors for sawnwood, panels, pulp, paper and energy wood products are obtained from UNECE/FAO (2010) and represent averages of reported values by countries in the UNECE region. The energy values represent higher heating values (HHV).

Table 2

Rooting depth (m). Data derived from Canadell et al. (1996).

Climate zone	Evergreen	Deciduous	Mixed
Tropics & subtropics, summer rainfall	7	4	5.5
Subtropics, winter rainfall ^a	5	5	5
Temperate	4	3	3.5
Boreal & arctic	2	2	2

^a Values for sclerophyllous forest

Species	Wood density (t/m^3)
Pinus (Pine)	0.4
Eucalyptus (Eucalyptus)	0.8
Larix (Larch)	0.5
Quercus (Oak)	0.7

Some additional data on the HHV of softwood, hardwood, ethanol and charcoal are obtained from Speight (2010). The water footprint of an A4 ($=1/16 \text{ m}^2$) sheet of paper of 80 g/m^2 in l/sheet is estimated by multiplying the water footprint of paper in m^3/t with a factor 0.005 (=80/16/1000).

3. Results

3.1. Water consumption attributed to roundwood production

The global water consumption attributed to roundwood production increased by 25% over 50 years, from 768 \times 10⁹ m³/y in 1961–1970 to 961 \times 10⁹ m³/y in 2001–2010 (for both decades: 96% green; 4% blue). The water consumption equals the evaporated volume attributed to roundwood production, since the share of the water incorporated in the harvested wood is negligible (0.01% on average). Fig. 3 shows the water consumption attributed to roundwood production (WU) and the value fraction of roundwood production $(f_{value,rw})$ in the biomes (sub)tropical forests and temperate and boreal forests, separately. WU is significantly smaller in the former compared to the latter caused by the difference in $f_{value,rw}$ for those biomes (Fig. 2 and SI). For (sub)tropical forests, an increasing trend in WU is observed, driven by increases in the area used for roundwood production and the volume of roundwood produced (see Fig. SI.2). For temperate and boreal forests, a moderate increasing trend in WU is visible due to an increased area used for roundwood production. Inter-annual variation is larger in this case. Variation in WU is caused by variation in $f_{\text{value,rw}}$, which in turn is mainly driven by variation in the volume of roundwood produced (Fig. SI.2). The latter explains the sudden decline in $f_{\text{value,rw}}$ and WU after 1990 when the statistics (FAOSTAT, 2016a) show a drop in roundwood production (in the former USSR). In both forest biomes, varying forest evaporation rates add to the temporal variation in WU (Fig. SI.2).

3.2. Water footprint per unit of roundwood production

The study period average water footprint per unit of roundwood production (WF_{rw}) is presented in Fig. 4. Besides the differences between the (sub)tropical and temperate/boreal zones (Section 3.1), spatial variation in WF_{rw} is mostly explained by varying forest evaporation rates (Table SI.2). The decade average WF_{rw} increased with about ten percent over the study period in temperate and boreal zones, while it varied within five percent in the (sub)tropics.

usig-term maximum sustainance yre as indicated with a hyphen.	ום או וחופא נאאב מום בחווומנב בט	טוור (ווו ווו־/וומלץ). שמנמ באנוווומוכט שמאכ	כנו טון פוטאוו (בטטט). ואטר במרוו וט	ובאו ואשב וא מובאבווו ווו במרוו רוו	
Climate zone	Evergreen needleleaf (pine)	Evergreen broadleaf (eucalyptus)	Deciduous needleleaf (larch)	Deciduous broadleaf (oak)	Mixed
Tropics	13.5	6	-	6	11.5
Subtropics, summer rainfall	13.5	11.5	12	11.5	12.5
Subtropics, winter rainfall	8	10	12	5	6
Temperate	7	1	8	5	9
Boreal, oceanic & sub-continental	6	1	4	I	5
Boreal, continental & arctic	3	I	4	1	3.5

Table 1



Fig. 4. The water footprint per unit of roundwood production (m³ water/m³ roundwood) at 30 × 30' resolution. The table next to the legend shows the average (production-weighted) water footprint per climate zone: boreal, continental & arctic (Bca); boreal, oceanic & sub-continental (Bsc); temperate (Tmp); subtropics, winter rainfall (Swr); subtropics, summer rainfall (Ssr); tropics (Tro). Period: 1961–2010. Note that not all grid cells were necessarily used for roundwood production in each year.

The average capillary rise contribution to WF_{rw} is mapped in Fig. 5. The areas with a capillary rise contribution of more than 50% are mostly found in Russia and Canada. Blue water constitutes a significant part of the total water consumption attributed to roundwood production in countries like the Bahamas (32%), Gambia (28%), the Netherlands (24%) and Somalia (23%). Variations in the capillary rise contribution are mainly explained by the groundwater depth. Miller et al. (2010) found for a semi-arid oak savanna

Swr

Ssr

Tro

1000 - 1200

1200 - 1631

57 (2)

65 (2)

93 (4)

in the period 2005–2008 (average $E_{\rm act}/Pr$ ratio of 0.7), that the average contribution of capillary rise to the evaporation over the year was about 22%. For grid cells with a capillary rise contribution to evaporation and an $E_{\rm act}/Pr$ ratio of at least 0.7, we found this contribution to be 18% on average.

Fig. 6 shows the average WF_{rw} for each of the main roundwood producing countries. There is a clear distinction between countries with production forests in mainly (sub)tropical versus temper-



Fig. 5. The average capillary rise contribution as a fraction of the forest water consumption (f_{blue}). Resolution: 30 \times 30'. Period: 1961–2010.



Fig. 6. The average (production-weighted) water footprint per unit of roundwood production (m³ water/m³ roundwood) for the main roundwood producing countries. Period: 1961–2010.

ate/boreal zones. Among the main roundwood producing countries, Japan has on average the largest WF_{rw} , resulting from a combination of a relatively high forest evaporation rate with a relatively low wood yield.

tive uses of the same water to produce more or different goods and services in the same area (see Section 4.3).

3.3. Water footprint per unit of end product

Although pronounced spatial variations in WF_{rw} occur, one should be cautious in evaluating these differences in terms of better or worse. The relevance of the data presented rather lies in the fact that they can form a basis for further study into the alterna-

The water footprints of various end products derived from roundwood, based on global averages, are given in Table 4. The values vary depending on the origin of the roundwood, since the

Table 4

The water footprint of various end products derived from roundwood (rw) in m^3 water per unit of end product. Based on global average water footprint of roundwood weighted by production: $390 m^3/m^3$ coniferous rw; $231 m^3/m^3$ non-coniferous rw; $293 m^3/m^3$ rw on average. Conversion factors are derived from UNECE/FAO (2010). Additional data sources required to determine the conversion factors for energy wood products are indicated in the Table notes.

FAOSTAT code	Product name	Wood type	Conversion factor	Water footprint
Sawnwood				
1632	Sawnwood	coniferous	1.86 m ³ rw/m ³ sawnwood	726 m ³ /m ³ sawnwood
1633	Sawnwood	non-coniferous	1.88 m ³ rw/m ³ sawnwood	433 m ³ /m ³ sawnwood
Veneer and plywood				
1634	Veneer sheets	-	2.21 m ³ rw/m ³ sheets	648 m ³ /m ³ sheets
1634	Veneer sheets	coniferous	2.08 m ³ rw/m ³ sheets	812 m ³ /m ³ sheets
1634	Veneer sheets	non-coniferous	2.35 m ³ rw/m ³ sheets	542 m ³ /m ³ sheets
1640	Plywood	-	2.07 m ³ rw/m ³ panels	607 m ³ /m ³ panels
1640	Plywood	coniferous	2.01 m ³ rw/m ³ panels	785 m ³ /m ³ panels
1640	Plywood	non-coniferous	2.13 m ³ rw/m ³ panels	491 m ³ /m ³ panels
Wood panels from wood pa	rticles ^a			
1646	Particle board	-	2.76 m ³ rw/m ³ panels	809 m³/m³ panels
1646	Particle board	coniferous	2.64 m ³ rw/m ³ panels	1031 m ³ /m ³ panels
1646	Particle board	non-coniferous	2.87 m ³ rw/m ³ panels	662 m ³ /m ³ panels
1647	Hardboard	-	3.56 m ³ rw/m ³ panels	1044 m ³ /m ³ panels
1647	Hardboard	coniferous	3.41 m ³ rw/m ³ panels	1331 m ³ /m ³ panels
1647	Hardboard	non-coniferous	3.71 m ³ rw/m ³ panels	855 m ³ /m ³ panels
1648	MDF	-	2.95 m ³ rw/m ³ panels	865 m ³ /m ³ panels
1648	MDF	coniferous	2.82 m ³ rw/m ³ panels	1101 m ³ /m ³ panels
1648	MDF	non-coniferous	3.07 m ³ rw/m ³ panels	708 m ³ /m ³ panels
1650	Insulating board	-	1.46 m ³ rw/m ³ panels	428 m ³ /m ³ panels
1650	Insulating board	coniferous	1.39 m ³ rw/m ³ panels	543 m ³ /m ³ panels
1650	Insulating board	non-coniferous	1.52 m ³ rw/m ³ panels	350 m ³ /m ³ panels
Wood pulp			3	2.
1654	Mechanical wood pulp	-	2.50 m ³ rw/t pulp	733 m ³ /t pulp
1655	Semi-chemical wood pulp	-	$2.67 \text{ m}^3 \text{ rw/t pulp}$	$783 \text{ m}^3/\text{t}$ pulp
1656	Chemical wood pulp	-	$4.49 \text{ m}^3 \text{ rw/t pulp}$	1316 m ³ /t pulp
1660	Unbleached sulphite pulp	-	$4.64 \text{ m}^3 \text{ rw/t pulp}$	$1360 \text{ m}^3/\text{t}$ pulp
1661	Bleached sulphite pulp	-	4.95 m ³ rw/t pulp	1451 m^3/t pulp
1662	Undieached sulphate pulp	-	$4.45 \text{ m}^3 \text{ rw/t pulp}$	$1305 \text{ m}^3/\text{t}$ pulp
1663	Bleached sulphate pulp	-	$4.55 \text{ m}^3 \text{ rw/t pulp}$	$1334 \text{ m}^3/\text{t}$ pulp
1667	Dissolving wood pulp	-	5.65 m [°] rw/t pulp	1656 m ² /t pulp
Paper ana paperboara	Uncosted mechanical		2 22 m ³ mult paper	$072 m^3/t$ paper
1612		-	$3.32 \text{ m}^3 \text{ mw/t paper}$	975 III-/L paper
1617	Coaled papers	-	$3.70 \text{ m}^3 \text{ mw/t paper}$	1065 III ⁻ /L paper
1612	Case Illaterials	-	$2.75 \text{ m}^3 \text{ rw/t paper}$	1000 m ³ /t paper
1621	Wrapping papers	-	$2.82 \text{ m}^3 \text{ rw/t paper}$	$1099 \text{ m}^3/\text{t paper}$
1621	Other papers packaging	-	$2.75 \text{ m}^3 \text{ rw/t paper}$	$1000 \text{ m}^3/\text{t paper}$
1671	Newsprint	_	$2.87 \text{ m}^3 \text{ rw/t paper}$	$8/1 \text{ m}^3/t \text{ paper}$
1674	Printing + writing paper	_	$3.51 \text{ m}^3 \text{ rw/t paper}$	$1029 \text{ m}^3/\text{t}$ namer
1675	Other paper \perp paperboard	_	$3.29 \text{ m}^3 \text{ rw/t paper}$	$965 \text{ m}^3/\text{t}$ paper
1676	Household + sanitary paper	_	$4.35 \text{ m}^3 \text{ rw/t paper}$	$1275 \text{ m}^3/\text{t}$ naper
1681	Wrang + nackg naper + hoard	_	$3.25 \text{ m}^3 \text{ rw/t paper}$	953 m ³ /t naper
1683	Paper \pm paperboard not else specified	_	$3.29 \text{ m}^3 \text{ rw/t paper}$	965 m ³ /t paper
Energy wood products	ruper - puperbourd not else specifica		5.25 m Twit puper	505 m /r puper
-	Firewood	coniferous	0.12 m ³ rw/GI ^b	47 m ³ /GI
_	Firewood	non-coniferous	$0.09 \text{ m}^3 \text{ rw/GI}^{\circ}$	$21 \text{ m}^3/\text{GI}$
_	Pellets	_	0.14 m ³ rw/G	41 m^3/GI
_	Pressed logs and briquettes	-	0.23 m ³ rw/G	$67 \text{ m}^3/\text{GI}$
-	Bark and chipped fuel	-	0.10 m ³ rw/G	29 m ³ /GJ
-	Wood-based ethanol	-	0.33 m ³ rw/GJ ^d	97 m ³ /GJ
-	Wood-based ethanol	-	7.71 m ³ rw/m ³ ethanol	2260 m ³ /m ³ ethanol
1630	Wood charcoal	-	0.20 m ³ rw/GJ ^e	59 m ³ /GJ
			· · ·	

^a For wood panels from wood particles, we assume that particles are produced from green/rough sawnwood without losses and that 1 m³ of green sawnwood has a solid wood equivalent of 1 m³) (UNECE/FAO, 2010).

^b Higher heating value of softwood = 20.9 GJ/t softwood (Speight, 2010); wood basic density of coniferous fuelwood logs = $0.42 \text{ dry t/green m}^3$ (UNECE/FAO, 2010).

^c Higher heating value of hardwood = 20.0 GJ/t hardwood (Speight, 2010); wood basic density of non-coniferous fuelwood logs = 0.54 dry t/green m³ (UNECE/FAO, 2010).

^d Higher heating value of ethanol = 29.7 GJ/t ethanol (Speight, 2010); ethanol density = 0.789 t/m^3 .

^e Higher heating value of charcoal = 29.6 GJ/t charcoal (Speight, 2010).

water footprint per cubic metre of roundwood produced varies around the globe (Fig. 4). The global average water footprint of one A4 sheet 80 g printing and writing paper is 5.1 l and ranges from 1.0 l/sheet in the subtropics with summer rainfall to 12.9 l/sheet in the temperate zone.

4. Discussion

4.1. Comparison with previous estimates

A rough comparison can be made between our estimates of the water footprint of roundwood and those by Van Oel and Hoekstra (2012) for the main pulp producing countries. Our estimates

of actual evaporation rates are about 30% higher, while our wood yields are about 45% lower. We specifically estimate the evaporation of forests, while Van Oel and Hoekstra (2012) used a general actual evaporation map (which probably underestimates forest evaporation). Where Van Oel and Hoekstra (2012) use rough wood yield estimates per country/region, wood yields in our study are derived from national production and area statistics that were downscaled to the grid level. Moreover, we use different underlying maps of which grid cells are used for roundwood production, which contributes to different spatial average estimates of evaporation rates and water footprints. Without application of the value fraction of roundwood production, our water footprint of roundwood estimates for the main pulp producing countries are significantly higher than those by Van Oel and Hoekstra (2012). After applying the value fractions ($f_{\text{value,rw}}$), our estimates are roughly 20% and 140% of those by Van Oel and Hoekstra (2012) for tropical and temperate/boreal zones, respectively. We used the same wood to paper conversion factor as Van Oel and Hoekstra (2012), so differences in the water footprint of paper (assuming a recovery rate of zero) are also explained by the above.

When we compare the water footprint of seven wood products in China, we find that our estimates are 5–29% of those by Tian and Ke (2012). We used different methods and data, but the largest difference is probably explained by the fact that we apply a value fraction.

For the southeastern United States, Chiu and Wu (2013) found that the green water footprint of ethanol from forest wood residue is about 400–443 l/l and that the blue water footprint in the forestry stage is minimal. Our estimated water footprint per unit of roundwood in this region is about 70 l/l (Fig. 4). With a roundwood to bio-ethanol conversion factor of 6.8 for the United States (UNECE/FAO, 2010), this translates into a quite similar water footprint of 476 l/l. Where we applied a value fraction to attribute forest evaporation to roundwood production followed by a roundwood to bio-ethanol conversion factor, Chiu and Wu (2013) allocated forest evaporation to bio-ethanol production based on an estimated weight fraction of harvested wood residue for bio-ethanol in the total above-ground wood mass, which also greatly reduces the amount of evaporation attributed to the bio-ethanol.

4.2. Uncertainties regarding method and data

4.2.1. Moisture recycling

Precipitation over land relies on terrestrial evaporation (moisture recycling) to a varying extent around the globe (Van der Ent et al., 2010) and forests play an important role in this (Ellison et al., 2012). When attributing forest evaporation to forestry products, one could argue to reduce total forest evaporation by the portion of evaporation that returns as precipitation (in the same area), based on the idea that this returning water can be used again and therefore is not really consumed (Launiainen et al., 2014). However, green forest evaporation stems from the precipitation amount that already includes the recycled moisture. Reducing the attributed evaporation by the recycled part would wrongly suggest that the recycled water is left for use for other purposes. It is not additional water that can be additionally allocated. As mentioned in the introduction, we are interested in this question of water allocation: which part of the available flow is being appropriated for roundwood production? Therefore, we deliberately attribute the total forest evaporation (that is reduced based on a value fraction) to roundwood production, whatever rate of moisture recycling.

4.2.2. Uncertainties regarding data

The estimates of the water footprint of roundwood production provided in this study are subject to a number of uncertainties. Since the fraction of water in the harvested wood turned out to be negligible (Section 3.1), the main variables governing the end result are the forest evaporation (E_{act}), the area used for roundwood production (A_{rw}), the volume of roundwood produced (P_{act}) and the value fraction of roundwood production ($f_{value,rw}$).

Out of these, we expect the least uncertainty in E_{act} and P_{act} . The estimate of E_{act} is relatively straightforward and bound by annual precipitation and potential evaporation. Pact is based on downscaled national statistics covering the entire study period, although the downscaling to the grid level involved coarse data on long-term maximum sustainable wood yields. The current data limitations regarding A_{rw} (Kuemmerle et al., 2013) makes our estimate of A_{rw} rather uncertain, since it is based on a modeled wood harvest pattern that was scaled to an estimated area used for roundwood production based on national statistics available from 1990 onwards. The estimated relative value of ecosystem services from which we derived $f_{value,rw}$ is associated with some limitations as elaborately described by Costanza et al. (1997) and Costanza et al. (2014). The estimates are based on a limited number of valuation studies that reflect the state at a certain point in time (Costanza et al., 2014). Besides, uncertainties are associated with willingness-to-pay estimates and aggregation of values at specific locations to larger spatial and temporal scales (Costanza et al., 2014). Furthermore, we needed to make a number of assumptions for disaggregating the value of ecosystem services in time and space as outlined in the SI.

4.3. Sustainability of the water footprint

This study has provided spatially-explicit estimates of the water footprint of roundwood production and various forest products. One should be cautious in evaluating differences in the water footprints of a similar product from two different regions in terms of better or worse. The relevance of the data presented rather lies in the fact that they can form a basis for further study into the alternative uses of the same water to produce more or different goods and services.

To judge the sustainability of the water footprint of roundwood production (volume/time), one would need to place the green and blue water components in the context of maximum sustainable levels of green and blue water consumption and consider the competition for the limited green and blue water resources between different demands. This assessment was out of the scope of this study, since maximum sustainable levels are currently not known for green water (Schyns et al., 2015; Hoekstra and Wiedmann, 2014), the major component of the water footprint of roundwood production. Besides, for understanding competing demands for water and the potential conflict between (green) water use for other purposes like crops for food, feed or bioenergy, a broader study would be required. Nevertheless, we can roughly contextualize the water footprint of roundwood production based on previous work.

4.3.1. Addition of the forestry sector to the water footprint of humanity

We can place the global water consumption attributed to roundwood production in the context of the global water footprint for the period 1996–2005 as estimated by Hoekstra and Mekonnen (2012), who considered the following five sectors: crop production, pasture, water supply in animal raising, industrial production, and domestic water supply. Addition of the forestry sector raises the global consumptive (green plus blue) water footprint of production for the period 1996–2005 by 12%.

4.3.2. Trade-offs between water for food, feed, energy and wood

The estimated water footprints of roundwood represent the volume of water that is allocated to wood production, albeit implic-

itly through land-use decisions (Rockström and Gordon, 2001). Alternatively, this water could be used for the generation of other terrestrial ecosystem services or crop production (Rockström et al., 1999; Rockström and Gordon, 2001). We made a rough comparison between the value of water for roundwood and three major food/feed crops (Table 5) as well as the water footprint of bio-ethanol per unit of energy from these four sources (Table 6). Both regarding economic water productivity and the water footprint of bio-ethanol, roundwood is comparable with maize, ranking somewhat better compared to wheat and worse compared to sugar beet. It should be noted that the water footprint of secondgeneration bio-ethanol obtained from crop residues is smaller than the water footprint of first-generation bio-ethanol from these crops (Mathioudakis et al., 2017).

Mekonnen et al. (2015) compared the water footprint of heat from various energy sources, including that from firewood based on Van Oel and Hoekstra (2012). Although our estimates of the water footprint of heat from wood (i.e. firewood, pellets, briquettes, bark, chips, charcoal) are different (Section 4.1), they remain orders of magnitude larger than the water footprint from other energy sources such as coal, lignite, oil, gas and nuclear (Mekonnen et al., 2015). From this perspective, burning wood for the generation of heat and electricity still is not recommended (Mekonnen et al., 2015).

4.4. Reduction of the water footprint

4.4.1. Intensification vs. extensification of wood production

Intensification of wood production has two counteracting effects on the water footprint per unit of roundwood produced (WF_{rw} , Eq. 7). Effect A is that the value of wood production increases, partially at the expense of other ecosystem service values ($f_{value,rw}$ increases), such that the water consumption attributed to roundwood production increases. Effect B is that more wood is produced per ha with the same amount of water. Intensification of wood production can only reduce WF_{rw} if the additional wood value per ha (effect B) outweighs the loss of value of other ecosystem services (effect A).

The relationship between $f_{\text{value,rw}}$ and the intensity of forest exploitation (see SI) determines whether effect A is stronger than effect B or vice versa and hence whether WF_{rw} increases (when effect A > effect B) or decreases (when effect A < effect B) with intensified production. This relationship is different in (sub)tropical forests compared to temperate/boreal forests, and furthermore depends on the long-term maximum sustainable yield (Y_{sus}): the higher Y_{sus} the larger the theoretical potential to obtain a high value of wood production from the forest.

For (sub)tropical forests we found that intensification leads to an increase in WF_{rw} for $Y_{sus} < 25 \text{ m}^3/\text{ha}$ (which is always the case in our study; see Table 1). For temperate/boreal forests we found that intensification results in an increase in WF_{rw} for Y_{sus} $<4.5 \text{ m}^3/\text{ha}$, but a decrease in WF_{rw} for higher Y_{sus} . Although we recognize that further research is needed into the value of forests and their maximum sustainable yields - with more spatiotemporal detail than was available for this study - the following general rule seems to apply: in forests with a relatively high Y_{sus}, intensification can be beneficial in terms of water use efficiency, since the positive effect of intensification (effect B) can outweigh the loss of value of other ecosystem services (effect A).

4.4.2. Recycling

The water footprint of roundwood can effectively be reduced through recycling. The use of recycled wood nullifies the attributed evaporation to roundwood production, since no new wood is produced. In this study, recovery rates were not considered. Hence, water footprint estimates refer to newly produced products.

conomic water pro verage WF of crops	ductivity (EWP obtained from) of roundwood (rw) compared (Mekonnen and Hoekstra (2011))	to three major food/feed crops. and ranges from Mekonnen an	. EWP is calculated as the price d Hoekstra (2014).	divided by the gree	n plus blue water fo	otprint (WF). Global
Alternative uses	Price ^a	WF _{min} ^b (m ³ /unit of product)	WF _{avg} (m ³ /unit of product)	WF_{max}^{c} (m ³ /unit of product)	<i>EWP</i> _{max} US\$/m ³)	EWP _{avg} (US\$/m ³)	EWP _{min} (US\$/m ³)
Roundwood	94 \$/m ³ rw	68 m ³ /m ³ rw	293 m ³ /m ³ rw	584 m ³ /m ³ rw	1.4	0.3	0.2
Wheat	289 \$/t	992 m ³ /t	1620 m ³ /t	2091 m ³ /t	0.3	0.2	0.1
Maize	349 \$ /t	542 m ³ /t	1028 m ³ /t	1385 m ³ /t	0.6	0.3	0.3
Sugar beet	81 \$/t	58 m ³ /t	108 m ³ /t	151 m ³ /t	1.4	0.8	0.5

ŝ Table Price for roundwood is the average export unit price in UNECE countries for the period 2005-2014 obtained from (UNECE/FAO, 2015). Prices for crops are average producer prices period 2005–2014 obtained from (FAOSTAT, 2016b)

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WF at 20th percentile of production. *WF* at 80th percentile of production.

nueksua, 2011) allu	Ialiges II UIII (IMEI	VUILLEIL ALLA LIOCKSULA, ZU14). VVAU	בו ומחלחווורא ובובו וח וווב אפובו		stage (LIUP allu WL	Jud grownij.	
Bio-ethanol from	Energy yield ^a	<i>WF</i> _{min} ^b (m ³ /unit of product)	$WF_{\rm avg}~(m^3/{\rm unit}~{\rm of}~{\rm product})$	WF_{max}^{c} (m ³ /unit of product)	<i>WF</i> _{min} (m ³ /GJ)	WF _{avg} (m ³ /GJ)	WF _{max} (m ³ /GJ)
Roundwood	3.0 GJ/m ³ rw	68 m ³ /m ³ rw	293 m ³ /m ³ rw	584 m ³ /m ³ rw	23	98	195
Wheat	10.2 GJ/t	992 m ³ /t	1620 m ³ /t	2091 m ³ /t	98	159	206
Maize	10.0 GJ/t	542 m ³ /t	1028 m ³ /t	1385 m ³ /t	54	103	139
Sugar beet	2.6 GJ/t	58 m ³ /t	108 m ³ /t	151 m ³ /t	22	41	58
a Energy vield of rou	Indwood is the in	verse of the conversion factor for	r wood-based ethanol in Table	4. Energy vield of crops obtaine	d from (Mekonnen	and Hoekstra, 20	11).

at 20th percentile of production. at 80th percentile of production.

^b WF

Water footprint (WF) of bio-ethanol from roundwood (rw) compared to the WF of first-generation bio-ethanol from three crops. Global average WF of crops obtained from (Mekonnen and

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IE	Schung	at	al	Advancas	in	Water	Pacourcos	107	(2017	400 501
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Van Oel and Hoekstra, (2012) already concluded that increasing paper recovery rates is a powerful way to reduce the water footprint of paper. Other wood products can also be recycled in various ways. Wooden pallets or furniture can be reused or be remanufactured from recovered wood, just like particle board (Falk and McKeever, 2004). In construction, wood recovered during demolition is potentially suitable for reuse or remanufacture, particularly into flooring (Falk and McKeever, 2004). Chipped or shredded wood can be used as basis for fuel, landscaping mulch, composting bulk agent, sewage sludge bulking medium, or animal bedding (Falk and McKeever, 2004). Ideally, the cascading use principle is applied, in which wood is used, recycled and reused as long as possible before ultimately being used as an energy source (Dammer et al., 2016). It is obvious that reduced consumption of end products from wood will eventually reduce the total water consumption related to roundwood production.

5. Conclusion

The global water consumption attributed to roundwood production for lumber, pulp, paper, fuel and firewood has risen from 768 \times 10 $^9~m^3/y$ in 1961–1970 to 961 \times 10 $^9~m^3/y$ in 2001–2010. Recycling of wood products could effectively reduce this volume, thereby leaving more water available for the generation of other ecosystem services. Intensification of wood production can only reduce the water footprint per unit of wood if the additional wood value per ha outweighs the loss of value of other ecosystem services, which is often not the case in (sub)tropical forests. Alternatively using the water for crop production is generally not beneficial (even apart from the negative effects of converting forest to cropland), since roundwood is rather comparable with major food, feed and energy crops in terms of economic water productivity and energy yield from bio-ethanol per unit of water. The results of this study contribute to a more complete picture of the human appropriation of water and feed into the debate on water for food, feed, energy and wood.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.advwatres.2017.05.013.

References

Bauhus, J, Puettmann, K, Messier, C, 2009. Silviculture for old-growth attributes. Forest Ecol. Manag. 258, 525–537. http://dx.doi.org/10.1016/j.foreco.2009.01.053.

- Blanchez, J., 1997. Forest resources and roundwood supply in the Asia Pacific countries: situation and outlook to the year 2010. Asia-Pacific Forestry Towards 2010. Asia-Pacific Forestry Sector Outlook Study Working Paper Series (FAO).
- Brown, C., 2000. The Global Outlook for Future Wood Supply From Forest Plantations. FAO, Forestry Policy and Planning Division.
- Canadell, J, Jackson, RB, Ehleringer, JB, Mooney, HA, Sala, OE, Schulze, E-D, 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia 108, 583–595. http://dx.doi.org/10.1007/bf00329030.
- Chave, J, Coomes, D, Jansen, S, Lewis, SL, Swenson, NG, Zanne, AE, 2009. Towards a worldwide wood economics spectrum. Ecol. Lett. 12, 351–366. http://dx.doi.org/ 10.1111/j.1461-0248.2009.01285.x.
- Chini, LP, Hurtt, GC, Frolking, S, 2014. Harmonized Global Land Use for Years 1500 -2100, V1. ORNL Distributed Active Archive Center.
- Chiu, Y-W, Wu, M, 2013. The water footprint of biofuel produced from forest wood residue via a mixed alcohol gasification process. Environ. Res. Lett. 8, 035015.

Costanza, R, d'Arge, R, de Groot, R, Farber, S, Grasso, M, Hannon, B, et al., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.

- Costanza, R, de Groot, R, Sutton, P, van der Ploeg, S, Anderson, SJ, Kubiszewski, I, et al., 2014. Changes in the global value of ecosystem services. Global Environ. Change 26, 152–158. http://dx.doi.org/10.1016/j.gloenvcha.2014.04.002.
- Döll, P. Hoffmann-Dobrev, H. Portmann, FT, Siebert, S, Eicker, A, Rodell, M, et al., 2012. Impact of water withdrawals from groundwater and surface water on continental water storage variations. J. Geodyn. 59–60, 143–156. http://dx.doi.org/ 10.1016/j.jog.2011.05.001.
- Dammer, L, Bowyer, C, Breitmayer, E, Eder, A, Nanni, S, Allen, B, et al., 2016. Mapping Study on Cascading Use of Wood Products. WWF, Gland, Switzerland.
- de Graaf, IEM, van Beek, LPH, Wada, Y, Bierkens, MFP, 2014. Dynamic attribution of global water demand to surface water and groundwater resources: effects of abstractions and return flows on river discharges. Adv. Water Resour. 64, 21–33. http://dx.doi.org/10.1016/j.advwatres.2013.12.002.
- Ellison, D, Futter, MN, Bishop, K, 2012. On the forest cover-water yield debate: from demand- to supply-side thinking. Global Change Biol. 18, 806–820. http://dx.doi. org/10.1111/j.1365-2486.2011.02589.x.
- Falk, RF, McKeever, DB, 2004. Recovering wood for reuse and recycling: a United States perspective. Management of Recovered Wood Recycling, Bioenergy and Other Options. European COST E31 Conference. Thessaloniki.
- Fan, Y, Li, H, Miguez-Macho, G, 2013. Global patterns of groundwater table depth. Science 339, 940–943. http://dx.doi.org/10.1126/science.1229881.
- FAOSTAT, Forestry Production, 2016a, Rome, Italy, http://faostat3.fao.org (accessed 29.07.16).
- FAOSTAT, Producer prices annual 2016b, Rome, Italy, http://faostat3.fao.org/ download/P/PP/E (accessed 11.10.16).
- Hanasaki, N, Inuzuka, T, Kanae, S, Oki, T, 2010. An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model. J. Hydrol. 384, 232–244. http://dx.doi.org/10. 1016/j.jhydrol.2009.09.028.
- Hoekstra, AY, Mekonnen, MM, 2012. The water footprint of humanity. Proc. Natl. Acad. Sci. 109, 3232–3237. http://dx.doi.org/10.1073/pnas.1109936109.
- Hoekstra, AY, Wiedmann, TO, 2014. Humanity's unsustainable environmental footprint. Science 344, 1114–1117. http://dx.doi.org/10.1126/science.1248365.
- Hoekstra, AY, Chapagain, AK, Aldaya, MM, Mekonnen, MM, 2011. The Water Footprint Assessment manual: Setting the Global Standard. Earthscan, London.
- Hoekstra, AY., 2013. The Water Footprint of Modern Consumer Society. Routledge, London, UK.
- Hoekstra, AY., 2017. Water Footprint Assessment: Evolvement of a New Research Field. Water Resour. Manag. http://dx.doi.org/10.1007/s11269-017-1618-5.
- Hurtt, GC, Chini, LP, Frolking, S, Betts, RA, Feddema, J, Fischer, G, et al., 2011. Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Clim. Change 109, 117–161. http://dx.doi.org/10.1007/s10584-011-0153-2.
- IUCN and UNEP-WCMC, 2016. The World Database on Protected Areas (WDPA). UNEP-WCMC, Cambridge, UK. Available at: www.protectedplanet.net (accessed 05.16).
- Jürgensen C, W Kollert, A Lebedys. Assessment of Industrial Roundwood Production from Planted Forests. Planted Forests and Trees Working Paper Series, No. FP/48/E. The Food and Agricultural Organization of the United Nations (FAO). Rome 2014.
- Köhl, M, Lasco, R, Cifuentes, M, Jonsson, Ö, Korhonen, KT, Mundhenk, P, et al., 2015. Changes in forest production, biomass and carbon: Results from the 2015 UN FAO global forest resource assessment. Forest Ecol. Manag. 352, 21–34. http: //dx.doi.org/10.1016/j.foreco.2015.05.036.
- Komatsu, H, Cho, J, Matsumoto, K, Otsuki, K, 2012. Simple modeling of the global variation in annual forest evapotranspiration. J. Hydrol. 420–421, 380–390. http: //dx.doi.org/10.1016/j.jhydrol.2011.12.030.
- Kuemmerle, T, Erb, K, Meyfroidt, P, Müller, D, Verburg, PH, Estel, S, et al., 2013. Challenges and opportunities in mapping land use intensity globally. Curr. Opin. Environ. Sustain. 5, 484–493. http://dx.doi.org/10.1016/j.cosust.2013.06.002.
- Launiainen, S, Futter, MN, Ellison, D, Clarke, N, Finér, L, Högbom, L, et al., 2014. Is the water footprint an appropriate tool for forestry and forest products: the fennoscandian case. Ambio 43, 244–256. http://dx.doi.org/10.1007/ s13280-013-0380-z.
- Liu, J, Yang, H, 2010. Spatially explicit assessment of global consumptive water uses in cropland: green and blue water. J. Hydrol. 384, 187–197. http://dx.doi.org/10. 1016/i.jhydrol.2009.11.024.
- Liu, J, Zehnder, AJB, Yang, H, 2009. Global consumptive water use for crop production: the importance of green water and virtual water. Water Resour. Res. 45, W05428. http://dx.doi.org/10.1029/2007wr006051.
- Loveland, TR, Brown, J, Ohlen, D, Reed, B, Zhu, Z, Yang, L, et al., 2009. ISLSCP II IGBP DISCover and SiB Land Cover, 1992-1993. ORNL Distributed Active Archive Center.
- Lutz, J, 2011. How Trees Grow. Forest Research Notes 8 (2).
- Mathioudakis, V, Gerbens-Leenes, PW, Van der Meer, TH, Hoekstra, AY, 2017. The water footprint of second-generation bioenergy: a comparison of biomass feedstocks and conversion techniques. J. Clean. Prod. 148, 571–582. http://dx.doi.org/ 10.1016/j.jclepro.2017.02.032.

- Matthews, E. Payne, R. Rohweder, M. Murray, S. 2000. Pilot Analysis of Global Ecosystems: Forest Ecosystems. World Resources Institute.
- Mekonnen, MM, Hoekstra, AY, 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577–1600. http:// dx.doi.org/10.5194/hess-15-1577-2011.
- Mekonnen, MM, Hoekstra, AY, 2014. Water footprint benchmarks for crop production: a first global assessment. Ecol. Indic. 46, 214–223. http://dx.doi.org/10. 1016/j.ecolind.2014.06.013.
- Mekonnen, MM, Gerbens-Leenes, PW, Hoekstra, AY, 2015. The consumptive water footprint of electricity and heat: a global assessment. Environ. Sci.: Water Res. Technol. 1, 285–297. http://dx.doi.org/10.1039/C5EW00026B.
- Miller, GR, Chen, X, Rubin, Y, Ma, S, Baldocchi, DD, 2010. Groundwater uptake by woody vegetation in a semiarid oak savanna. Water Resour. Res. 46, W10503. http://dx.doi.org/10.1029/2009WR008902, n/a-n/a.
- New, M, Lister, D, Hulme, M, Makin, I, 2002. A high-resolution data set of surface climate over global land areas. Clim. Res. 21, 1–25.
- Oki, T, Kanae, S, 2006. Global hydrological cycles and world water resources. Science 313, 1068–1072. http://dx.doi.org/10.1126/science.1128845.
- Postel, SL, Daily, GC, Ehrlich, PR, 1996. Human appropriation of renewable fresh water. Science 271, 785–788. http://dx.doi.org/10.1126/science.271.5250.785.
- Rockström, J, Gordon, L, 2001. Assessment of green water flows to sustain major biomes of the world: implications for future ecohydrological landscape management. Phys. Chem. Earth, Part B: Hydrol., Oceans Atmos. 26, 843–851. http: //dx.doi.org/10.1016/S1464-1909(01)00096-X.
- Rockström, J, Gordon, L, Folke, C, Falkenmark, M, Engwall, M, 1999. Linkages among water vapor flows, food production, and terrestrial ecosystem services. Conserv. Ecol 3, 5.
- Rockstrom, J, Steffen, W, Noone, K, Persson, A, Chapin, FS, Lambin, EF, et al., 2009. A safe operating space for humanity. Nature 461, 472–475.
- Rost, S, Gerten, D, Bondeau, A, Lucht, W, Rohwer, J, Schaphoff, S, 2008. Agricultural green and blue water consumption and its influence on the global water system. Water Resour. Res. 44, W09405. http://dx.doi.org/10.1029/2007wr006331.
- Savenije, HHG., 2004. The importance of interception and why we should delete the term evapotranspiration from our vocabulary. Hydrol. Process. 18, 1507–1511. http://dx.doi.org/10.1002/hyp.5563.
- Schyns, JF, Hoekstra, AY, Booij, MJ, 2015. Review and classification of indicators of green water availability and scarcity. Hydrol. Earth Syst. Sci 19, 4581–4608. http://dx.doi.org/10.5194/hess-19-4581-2015.
- Siebert, S, Döll, P, 2010. Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. J. Hydrol. 384, 198–217. http://dx.doi.org/10.1016/j.jhydro1.2009.07.031.
- Simpson, WT., 1998. Equilibrium Moisture Content of Wood in Outdoor Locations in the United States and Worldwide. US Dept. of Agriculture, Forest Service, Forest Products Laboratory.
- Speight, JG., 2010. The Biofuels Handbook. Royal Society of Chemistry.
- Steffen, W, Richardson, K, Rockström, J, Cornell, SE, Fetzer, I, Bennett, EM, et al., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347.
- Tian, MH, Ke, SF, 2012. Virtual water content and trade analysis of primary woody products in China. Int. Forest. Rev. 14, 380–390. http://dx.doi.org/10. 1505/146554812802646639.
- UNECE/FAO, 2010. Forest Product Conversion Factors for the UNECE Region. Geneva Timber and Forest Discussion Paper 49. UNECE/FAO, Geneva.
- UNECE/FAO, TIMBER database: Export and Import Unit Prices (1964-2014), 2015, http://www.unece.org/fileadmin/DAM/timber/statsdata/unit-price-1964-2014. xlsx (accessed 10.10.16).
- Van der Ent, RJ, Savenije, HHG, Schaefli, B, Steele-Dunne, SC, 2010. Origin and fate of atmospheric moisture over continents. Water Resour. Res. 46, W09525. http:// dx.doi.org/10.1029/2010WR009127, n/a-n/a.
- Van Oel, PR, Hoekstra, AY, 2012. Towards quantification of the water footprint of paper: a first estimate of its consumptive component. Water Resour. Manag. 26, 733–749. http://dx.doi.org/10.1007/s11269-011-9942-7.
- Van Velthuizen, H, Huddleston, B, Fischer, G, Salvatore, M, Ataman, E, Nachtergaele, F, et al., 2007. Mapping biophysical factors that influence agricultural production and rural vulnerability. Environment and natural resources series 11. FAO & IIASA, Rome.
- Vanham, D, 2016. Does the water footprint concept provide relevant information to address the water-food-energy-ecosystem nexus? Ecosyst. Serv. 17, 298–307. http://dx.doi.org/10.1016/j.ecoser.2015.08.003.
- Wada, Y, Wisser, D, Bierkens, MFP, 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dyn. 5, 15–40. http://dx.doi.org/10.5194/esd-5-15-2014.
- Zanne, AE, Lopez-Gonzalez, G, Coomes, DA, Ilic, J, Jansen, S, Lewis, SL, et al., 2009. Data from: towards a worldwide wood economics spectrum. Dryad Data Repos..
- Zhang, L, Dawes, W, Walker, G, 1999. Predicting the effect of vegetation changes on catchment average water balance. Technical Report 99/12. Cooperative Research Centre for Catchment Hydrology, CSIRO Land and Water.
- Zhang, L, Dawes, WR, Walker, GR, 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour. Res. 37, 701–708. http://dx.doi.org/10.1029/2000WR900325.