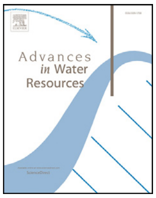
Advances in Water Resources 000 (2017) 1–12

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres



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

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ARTICLE INFO

Article history:
Received 10 January 2017
Revised 15 May 2017
Accepted 16 May 2017
Available online xxx

Keywords:
Water consumption
Evapotranspiration
Forestry
Timber
Bioenergy
Ecosystem services

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 m^3/y (96% green; 4% blue) in 2001–2010. The water footprint per m^3 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 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. 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.

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). 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 biofuel.

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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http://dx.doi.org/10.1016/j.advwatres.2017.05.013
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Please cite this article as: J.F. Schyns et al., The water footprint of wood for lumber, pulp, paper, fuel and firewood, Advances in Water Resources (2017), http://dx.doi.org/10.1016/j.advwatres.2017.05.013

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 × 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 × 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:

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

in which E_{act} is the actual forest evaporation (m/y), A_{rw} the area used for roundwood production (m^2), P_{act} the actual roundwood harvested (m^3/y), f_{water} the volumetric moisture content of freshly harvested wood (m^3 water/m^3 wood), and $f_{\mathrm{value,rw}}$ 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):

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

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 ^{0}C) 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:

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

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}):

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

$$WU_{\mathrm{blue}}[x,t] = WU[x,t] \times f_{\mathrm{blue}}[x,t] \quad (5)$$

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

- Capillary rise is at its maximum in a very dry year ($E_{\mathrm{act}}/Pr = 1$) and moves linearly to zero in an extremely wet year ($E_{\mathrm{act}}/Pr = 0$). 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 ($d_{\mathrm{cap,max}}$, in m) depends on the soil type. When d_{cap} is non-limiting (≤ 0), the roots take up a share $d_{\mathrm{cap,max}}$ of z_{r} through capillary rise under very dry conditions. This share decreases linearly to zero when d_{cap} approaches $d_{\mathrm{cap,max}}$ (beyond, there is no capillary uptake at all).

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

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

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 m^3 water/m^3 roundwood) for the period of m years is defined as:

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

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 ($f_{\mathrm{conversion}}$, in m^3 roundwood/unit of end product):

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

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