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Towards improvement of grey water footprint assessment: With an illustration for global maize cultivation

Wenfeng Liu [a], Marta Antonelli [a], Xingcai Liu [c], Hong Yang [a, b, *]

[a] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Ueberlandstrasse 133, CH-8600, Duebendorf, Switzerland
[b] Department of Environmental Sciences, University of Basel, Petersplatz 1, CH-4003, Basel, Switzerland
[c] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China

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A B S T R A C T

The grey water footprint refers to the volume of water that is required to assimilate polluted water. It reflects the intensity of water pollution caused by water use for human activities. This study aims to address some major shortcomings associated with grey water footprint accounting in the literature and discuss several ways towards its improvement. Global maize production is used for illustration. The study specifically tackles three issues: the appropriate water quality standards for grey water footprint assessment; grey water footprint for multiple pollutants; and the influence of spatial resolution of the assessment on the level of grey water stress. A biophysical crop model is applied to quantify nitrogen and phosphorus losses to water in maize production on a global scale with a 0.5-degree spatial resolution. The study shows that the grey water footprint calculation is highly sensitive to the water standards applied. The results also suggest that the grey water footprint relating to nitrogen and phosphorus pollution caused by maize production alone has already exceeded their local water availability in many parts of the world. Grey water stress shows a more critical situation at the grid level than at the watershed level for maize cultivation because the former represents the local concentration whereas the latter gives the average situation of the whole watershed. This study highlights the need for standardizing the setting of water quality standards for a consistent grey water footprint assessment taking into consideration the diverse aquatic ecosystems and ambient water quality requirements across regions, as well as the presence of multiple pollutants in water bodies.

1. Introduction

Nitrogen (N) and phosphorus (P) are key elements to life and are essential for crop and livestock production. During the period 1960–2010, the application of N and P fertilizers in agriculture for food production increased nine-fold and three-fold, respectively (Sutton et al., 2013). The use of fertilizers has, on the one hand, improved agricultural productivity, enabling the feeding of a growing world population while coping with the dietary shift towards an increased consumption of meat and dairy products. On the other hand, the use of fertilizers has dramatically increased the amount of N and P entering the terrestrial biosphere (Bennett et al., 2001; Vitousek et al., 2009). Nutrient losses from croplands into water bodies have caused major environmental problems, such as water quality degradation, groundwater contamination, biodiversity loss, fish deaths, and eutrophication (Galloway and Cowling, 2002; Obersteiner et al., 2013; Vitousek et al., 1997).

The need to account for the impacts of agricultural production in terms of water quantity and quality led to the development of water footprint indicators in the early 2000s (Hoekstra, 2003). The water footprint (WF) is a multidimensional indicator of consumptive water use, which accounts for green (rain) water, blue (surface and underground) water resources, and grey (polluted) water. The grey water footprint (GWF) was introduced by Hoekstra and Chapagain (2008) as a measure of the intensity of water pollution caused by water use for human activities. It is defined as the volume of water that is required to assimilate a load of pollutants to a freshwater body, based on natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011). The idea of

* Corresponding author. Eawag, Swiss Federal Institute of Aquatic Science and Technology, Ueberlandstrasse 133, CH-8600, Duebendorf, Switzerland.
E-mail address: hong.yang@eawag.ch (H. Yang).

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measuring water pollution in terms of the amount of water needed to dilute pollutants can be traced back to Falkenmark and Lindh (1974), who pointed out that the amount of water required to dilute pollutants to acceptable levels is about 10–50 times the wastewater flow. The GWF indicator assumes that the gap between a water quality standard and the natural background concentration in a given water body can be used to dilute the pollution loads to meet the water quality standard. It expresses water pollution in terms of a water volume needed to dilute contaminated water to a given quality standard, so that it can be compared with water consumption.

A growing number of studies have provided GWF assessments at various geographical levels. Global GWF assessments have mainly been provided by the Water Footprint Network, e.g., Chapagain et al. (2006), Hoekstra and Mekonnen (2012), and Liu et al. (2012) (Table 1). Other GWF studies have been conducted at the national and regional levels (e.g., Cazcarro et al., 2016; Mekonnen et al., 2016); the river basin level (e.g., Miguel Ayala et al., 2016; Vanham and Bidoglio, 2014; Zhi et al., 2015); the city level (e.g., Manzardo et al., 2016a; Wang et al., 2013); and with a focus on specific products or crops (e.g., Ene et al., 2013; Lamastra et al., 2014; Suttayakul et al., 2016). GWF assessments have overwhelmingly been focused on N-related loads to freshwater. Only a few considered multiple pollutants, such as N, P, COD (chemical oxygen demand), and NH_4 (ammonium) (Dabrowski et al., 2009; Lu et al., 2016; Pellicer-Martinez and Martinez-Paz, 2016). Most GWF assessments used the drinking water standards (e.g., Bulsink et al., 2010; Chapagain et al., 2006; Mekonnen and Hoekstra, 2011, 2010), with a few exceptions that have used ambient water quality standards (e.g., Pellegrini et al., 2016; Pellicer-Martinez and Martinez-Paz, 2016; Zhuo et al., 2016) (Table 1).

It has been shown that agriculture, mainly cereal production, accounts for 75% of the global GWF related to anthropogenic N loads, with the highest contribution from Asia (Mekonnen and

Table 1
Literature review of standards used for grey water footprint assessment.

Num.	Study area	Nitrogen		Phosphorus		References
		C_{max} (mg N L^{-1})	C_{nat} (mg N L^{-1})	C_{max} (mg P L^{-1})	C_{nat} (mg P L^{-1})	
1	Argentina[R]	10 (USA)*	–	–	–	(Rodriguez et al., 2015)
2	Brazil[G+W]	–	–	0.1 (Brazil)	0	(Miguel Ayala et al., 2016)
3	Brazil[R]	10 (Brazil)*	0.8	–	–	(Scarpare et al., 2016)
4	China[R]	12 (China)*	–	–	–	(Duan et al., 2016)
5	China[W]	1 (China)#	0			(Liu et al., 2016a)
6	China[R]	10 (USA)*	–	–	–	(Huang et al., 2012)
7	China[R]	10 (China)*	0	–	–	(Lu et al., 2016)
8	China[R]	1 (China)#	–	0.2 (China)	–	(Wang et al., 2013)
9	China[R]	1 (China)#	0	0.2 (China)	0	(Wu et al., 2016)
10	China[R]	10 (USA)*	–	–	–	(Xu et al., 2015)
11	China[W]	10 (China)*	0	–	–	(Zeng et al., 2013)
12	China[G+R]	1 (China)#	0.2	0.2 (China)	0.02	(Zhuo et al., 2016)
13	England[R]	12.86 (England and Wales)#	6.38	0.25 (England and Wales)	0.01	(Zhang et al., 2014)
14	Europe[G+R]	3.1 (Liu et al., 2012)	1.5	0.95 (Liu et al., 2012)	0.52	(Mekonnen et al., 2016)
15	Europe[R]	10 (USA)*	–	–	–	(Thaler et al., 2012)
16	Europe[W]	10 (USA)*	0	–	–	(Vanham and Bidoglio, 2014)
17	France[G+R]	10 (USA)*	–	–	–	(Ercin et al., 2013)
18	Global[R]	10 (USA)*	0	–	–	(Chapagain et al., 2006)
19	Global[R]	11.3 (EU)*	–	–	–	(Chapagain and Hoekstra, 2011)
20	Global[G+R]	10 (USA)*	0	–	–	(Hoekstra and Mekonnen, 2012)
21	Global[W]	3.1 (Estimated)	1.5	0.95 (Estimated)	0.52	(Liu et al., 2012)
22	Global[G+W]	2.9 (Canada)#	0.4	–	–	(Mekonnen and Hoekstra, 2015)
23	Global[G+R]	10 (USA)*	0	–	–	(Mekonnen and Hoekstra, 2010)
24	Global[G+R]	10 (USA)*	0	–	–	(Mekonnen and Hoekstra, 2011)
25	Global[G+R]	10 (USA)*	0	–	–	(Mekonnen and Hoekstra, 2014)
26	Indonesia[R]	10 (USA)*	–	–	–	(Bulsink et al., 2010)
27	Italy[G+R]	10 (USA)*	0	–	–	(Aldaya and Hoekstra, 2010)
28	Italy[R]	15 (Italy)#	0	–	–	(Pellegrini et al., 2016)
29	Kenya[G+W]	10 (USA)*	0			(Mekonnen et al., 2012)
30	Latin America and the Caribbean[G+R]	10 (USA)*	–	–	–	(Mekonnen et al., 2015)
31	New Zealand[R]	11.3 (New Zealand)*	0–1.3			(Deurer et al., 2011)
32	New Zealand[R]	11.3 (New Zealand)*	0	–	–	(Herath et al., 2013)
33	Morocco[R]	10 (USA)*	–	–	–	(Schyns and Hoekstra, 2014)
34	Romania[R]	10 (USA)*	–	–	–	(Ene et al., 2013)
35	South Africa[R]	4 (South Africa)#	0.62	0.13 (South Africa)	0.06	(Dabrowski et al., 2009)
36	South Korea[R]	40 (South Korea)#	–	4 (South Korea)	–	(Yoo et al., 2014)
37	Spain[R]	11.3 (EU)*	–	–	–	Cazcarro et al., 2016
38	Spain[R]	11.3 (EU)*	–	–	–	(Chapagain and Orr, 2009)
39	Spain[W]	11.3 (EU)*	–	–	–	(Chico et al., 2013)
40	Spain[R]	5.6 (Spain)#	–	0.13 (Spain)	–	(Pellicer-Martinez and Martinez-Paz, 2016)
41	Taiwan, China[R]	10 (Taiwan)*	0	–	–	(Su et al., 2015)
42	Tunisia[R]	10 (USA)*	0	–	–	(Chouchane et al., 2015)
43	USA[R]	10 (USA)*	0	–	–	(Manzardo et al., 2016b)

R: Regional level; W: Watershed level; G + R: Grid and regional levels; G + W: Grid and watershed levels; *: Nitrogen standard for drinking water; #: Nitrogen standard for surface water; –: no information.