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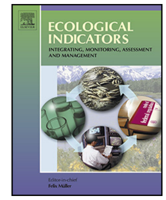

Original articles

Water footprint benchmarks for crop production: A first global assessment

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ABSTRACT

In the coming few decades, global freshwater demand will increase to meet the growing demand for food, fibre and biofuel crops. Raising water productivity in agriculture, that is reducing the water footprint (WF) per unit of production, will contribute to reducing the pressure on the limited global freshwater resources. This study establishes a set of global WF benchmark values for a large number of crops grown in the world. The study distinguishes between benchmarks for the green–blue WF (the sum of rain- and irrigation water consumption) and the grey WF (volume of polluted water). The reference period is 1996–2005. We analysed the spatial distribution of the green–blue and grey WFs of different crops as calculated at a spatial resolution of 5 by 5′ with a dynamic water balance and crop yield model. Per crop, we ranked the WF values for all relevant grid cells from smallest to largest and plotted these values against the cumulative percentage of the corresponding production. The study shows that if we would reduce the green–blue WF of crop production everywhere in the world to the level of the best 25th percentile of current global production, global water saving in crop production would be 39% compared to the reference water consumption. With a reduction to the WF levels of the best 10th percentile of current global production, the water saving would be 52%. In the case that nitrogen-related grey WFs in crop production are reduced, worldwide, to the level of the best 25th percentile of current global production, water pollution is reduced by 54%. If grey WFs per ton of crop are further reduced to the level of the best 10th percentile of current production, water pollution is reduced by 79%. The benchmark values provide valuable information for formulating WF reduction targets in crop production. Further studies will be required to test the sensitivity of the benchmark values to the underlying model assumptions, to see whether regionalization of benchmarks is necessary and how certain WF benchmark levels relate to specific technology and agricultural practices.

1. Introduction

Agriculture is the largest freshwater user, accounting for 99% of the global consumptive (green plus blue) water footprint (Hoekstra and Mekonnen, 2012). Growing populations, coupled with changing preferences in diets and rising demand for biofuels, will put increasing pressure on the globe's freshwater resources (Falkenmark et al., 2009; Gleick, 2003; Rosegrant et al., 2009). The consumptive water use (from both precipitation and irrigation) for producing food and fodder crops is expected to increase at 0.7% per year from its estimated level of 6400 billion m^3/year in 2000 to 9060 billion m^3/year in order to adequately feed the global population of 9.2 billion by 2050 (Rosegrant et al., 2009). The growing freshwater scarcity is already evident in many parts of the world (Gleick, 1993; Hoekstra et al., 2012; Oki and Kanae, 2006; Postel, 2000; Vörösmarty et al., 2010; Wada et al., 2011).

Raising water productivity in agriculture ("more crop per drop") can contribute to reducing the pressure on the global freshwater resources (Passioura, 2006; Rockström, 2003). The water footprint (WF) offers a quantifiable indicator to measure the volume of water consumption per unit of crop, as well as the volume of water pollution (Hoekstra and Chapagain, 2008; Hoekstra et al., 2011). The green WF measures the volume of rainwater consumed during the growing period of the crop; the blue WF measures the volume of surface and groundwater consumed. The grey WF measures the volume of freshwater that is required to assimilate the nutrients and pesticides leaching and running off from crop fields and reaching groundwater or surface water, based on natural

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background concentrations and existing ambient water quality standards (Hoekstra et al., 2011).

WF benchmarks for crop production can be an instrument to compare actual WFs in certain regions or even at field level to certain reference levels and can form a basis to formulate WF reduction targets, aimed to decrease water consumption and pollution per unit of crop (Hoekstra, 2013a,b). WFs of crops vary enormously across regions and within regions (Brauman et al., 2013; Fader et al., 2011; Finger, 2013; Hoekstra and Chapagain, 2007; Mekonnen and Hoekstra, 2011; Siebert and Döll, 2010). There are no previous studies that aimed to develop benchmarks for the WF of crops, but a number of studies exist on benchmarking water productivities. The water productivity (ton/m^3) in crop production is in fact the inverse of the green–blue WF (m^3/ton) of crop production. Water productivity studies can be grouped into four classes: field studies, modelling studies, studies based on remote sensing, and studies employing a combination of field measurement and modelling or satellite data. In field studies, the relationship between seasonal water use and crop yield is determined from field measurements (Oweis et al., 2000; Rahman et al., 1995; Sadras et al., 2007; Sharma et al., 1990, 2001; Zhang et al., 1999, 1998). Water productivity studies based on field measurements are bound to experiments on a relatively small number of fields, so that results are always limited to local conditions such as climate, soil characteristics and water management practices and cannot easily be scaled up for larger areas. In modelling studies, soil water balance and crop growth models are used to estimate the components of the seasonal crop water balance (Amir and Sinclair, 1991; Asseng et al., 1998, 2001). The limitation of model studies is that they generally do not account for all constraining factors and may exclude important factors such as pests, diseases and weeds and their use is limited by data availability and quality (Grassini et al., 2009). Remote sensing studies use satellite data to estimate the spatial variation of water productivity (Biradar et al., 2008; Cai et al., 2009; Zwart and Bastiaanssen, 2007; Zwart et al., 2010a,b). The use of remote sensing allows estimating the water productivity over large areas. A number of studies combined measured data with simulation models (Grassini et al., 2009; Robertson and Kirkegaard, 2005; Sadras et al., 2003) and others combined measured data with remote sensing data (Cai and Sharma, 2010). While crop water productivity is receiving an increasing amount of attention, minimizing water pollution (the grey WF) per unit of crop production receives much less attention. It is clear, though, that the grey WF per unit of crop varies greatly from place to place depending on agricultural practices (Chapagain et al., 2006; Mekonnen and Hoekstra, 2010, 2011).

To our knowledge, there has been no previous study providing global benchmark values for green–blue and grey WFs of crops. The studies cited above are limited to either a few crops or specific locations. The objective of the current study has been to develop global WF benchmark values for 124 crops based on the spatial variability of crop WFs as found in our earlier global WF assessment of crop production (Mekonnen and Hoekstra, 2011).

2. Method and data

The study distinguishes between benchmarks for the green–blue WF and the grey WF of crops. The approach has been to analyse the spatial distribution of the green–blue and grey WFs of different crops as calculated at a spatial resolution of 5 by 5′ with a dynamic water balance and crop yield model. Details on the model used have been reported in Mekonnen and Hoekstra (2010, 2011). Basically, the model computes a daily soil water balance and calculates crop water requirements, actual crop water use (both green and blue) and actual yields. Green–blue WFs are calculated by dividing the evapotranspiration of green and blue water over the growing period by the crop yield. Grey WFs are calculated based on nitrogen application rates, leaching-runoff fractions and water quality standards for nitrate. We did not consider the grey WF from other nutrients (like phosphorous) or pesticides. The model was applied at a global scale for the period 1996–005. In total, 124 crops were studied.

We first analysed the WF of wheat in terms of m^3/ton at three different spatial resolution levels – country, provincial and grid level – in order to identify the proper spatial resolution for developing WF benchmarks for crop production. After choosing the grid level as the best option for further analysis, the variability in WFs of crops over all crop growing grid cells in the world was used for developing the benchmarks. Per crop, we ranked the WF values for all relevant grid cells from smallest to largest and plotted these values against the cumulative percentage of the corresponding production. From the graph, we could thus read the WF values at different production percentiles.

For an analysis of differences in WFs between developing versus industrialised countries, we used the country classification based on income from the World Bank (2012); in which countries are divided according to the 2007 per capita gross national income. The groups are: low income (≤USD 935), lower middle income (USD 936–3705), upper middle income (USD 3706–11455) and high income (≥USD 11,456).

In order to analyse differences in WFs between different climatic regions, we used the Köppen–Geiger climate classification (Kottek et al., 2006) to group the world into four major climate classes: tropics (arid and equatorial), temperate, boreal (snow) and tundra (polar). Since little or no crop cultivation exists in the boreal and tundra regions of the world, we have focused on the tropics and temperate regions.

3. Results

3.1. The distribution of the green–blue water footprint of wheat at three spatial resolutions.

The distribution of the green–blue water footprint (WF) of wheat was analysed at three different spatial scales by considering the average green–blue WF in m^3/ton and production data in ton/year at country, provincial and grid level. Figs. 1–3 have been obtained by plotting the green–blue WF, sorted from smallest to largest, against the cumulative percentage of production. Although the figures for the three spatial scales of analysis show similar patterns, the points in the country-scale analysis (Fig. 1) do not form a smooth curve like the points in the provincial-scale (Fig. 2) and grid-scale analysis (Fig. 3), caused by the limited number of points in the country-scale analysis. The green–blue WF values at the respective production percentiles decrease when moving from the country to the grid level. In addition, we see that the WF at the 50th percentile of production is not necessarily equal to the global average WF, which is a characteristic of any skewed distribution. As we can see from the grid-based analysis, the variability of the WF of the best half of the global wheat production is smaller than the variability of the WF of the worst half, so that the global average WF (1620 m^3/ton) turns out to be larger than the WF at the 50th percentile of production (1391 m^3/ton). The latter value means that 50% of global wheat production occurs at a green–blue WF of 1391 m^3/ton or less.

There are two reasons that favour the grid over the provincial or country level analysis. First, particularly the country level analysis is weak as it provides a very dispersed curve and the analysis will get even weaker for crops which are grown in only a few countries. Second, there can be significant WF differences within provinces and countries, which are hidden in the analysis at those levels. The

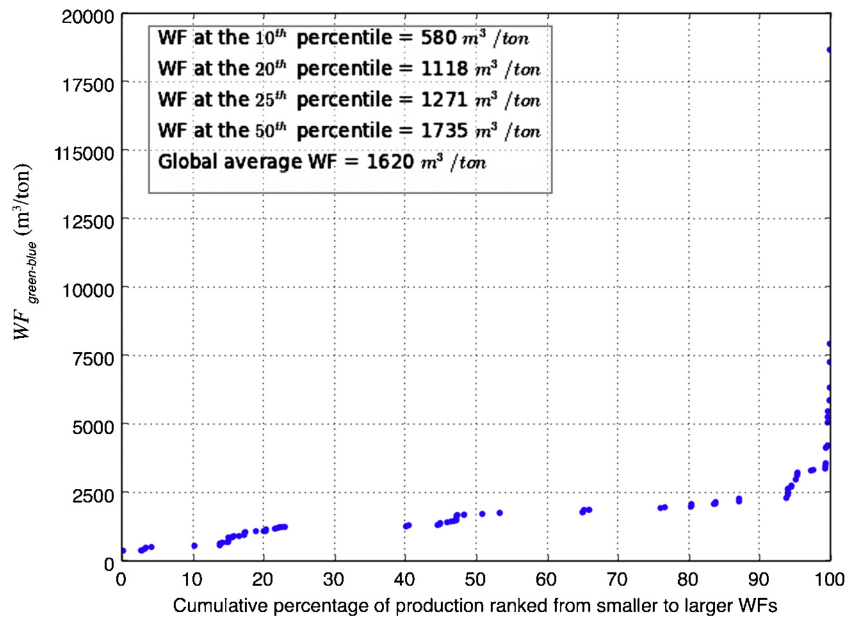

Fig. 1. Green–blue WF of wheat (in m^3/ton) for all wheat-producing countries in the world, plotted from smallest to largest WF.

averages at provincial and even more so at country level are generally biased towards the worse footprints (because of the skewed distributions), so that the WFs at the various production percentiles found with the grid-based analysis are closer to reality than in case of the analyses at the lower resolution levels. Therefore, for the remainder of this study, we analyse the distribution of crop WFs at the grid level.

3.2. The green–blue water footprint of different crops at different production percentiles

The distribution of the green–blue WF for ten selected crops at different production percentiles is shown in Table 1. The values were derived by plotting the green–blue WF of the respective crops from smallest to largest WF against the cumulative percentage of crop production. The curves are relatively flat in the first (best) half of the global production. The second (worst) half of the global production shows a steeper curve, with very large WF values for the last 10–20% of production. As a result, the WF at the 50th percentile of production is generally smaller than the global average WF, as was already explained in the previous section for the case of wheat. Supplementary Material – Appendix A provides the green–blue WF at different production percentiles for all 124 crops studied.

The maps in Fig. 4 show the spatial variability of the green–blue WF of the ten selected crops across the world. The ranges are chosen such that one can easily see in which parts of the world, production occurs at WFs in the range of the best 10% of global production, etc. One can immediately see that relatively small WFs are not inherent to high-income countries or humid regions and

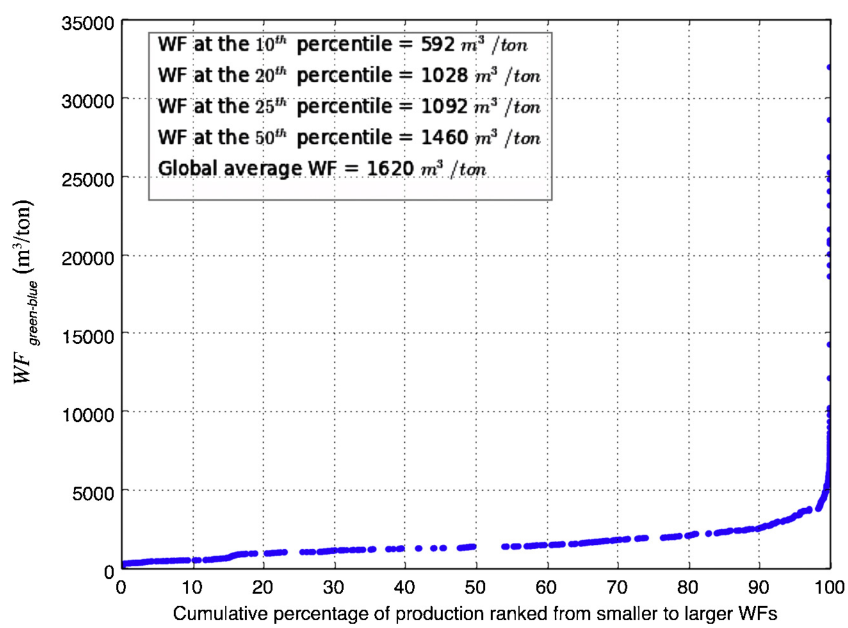

Fig. 2. Green–blue WF of wheat (in m^3/ton) for all wheat-producing provinces in the world, plotted from smallest to largest WF.

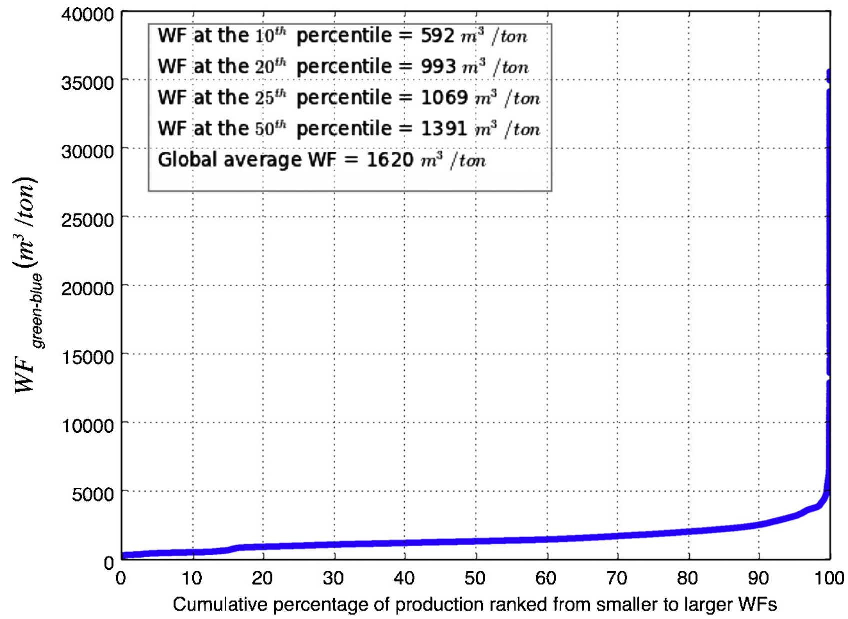

Fig. 3. Green–blue WF of wheat (in m^3/ton) for all wheat-producing grid cells in the world, plotted from smallest to largest WF.

that large WFs are not intrinsically connected to low-income countries or (semi-) arid regions. This is more precisely shown in Table 2. Although low WFs as found in the best 10–20% of global production are mostly found in high income and temperate regions, we can find the different percentiles in all parts of the world, also in low income and tropical regions. High-income countries have a greater capacity to implement best available technology and best practices than less developed countries, but the presence of the best percentiles of production in the less developed and tropical countries indicates that reduction of WFs to the best 10th percentile of current global production is technically feasible everywhere.

In order to compare the results from this study with the literature, we collected data from a number of water productivity studies for different crops and locations. We used four publications (Doorenbos and Kassam, 1979; Hatfield et al., 2001; Sadras et al., 2007; Zwart and Bastiaanssen, 2004) that summarize crop water productivities from various studies. Since the different studies relate to dissimilar climate and soil conditions and water management practices, the water productivity values for a given crop vary over a wide range. Fig. 5 shows the inverse of the water productivity ranges collected from literature together with the green–blue WF at different production percentiles from the current study. In most cases, the ranges found in the literature overlap well with the values found in this study. In some cases, the lowest value found in the literature is substantially smaller than the WF at the best 10th percentile of global production (millet, sorghum, cotton, soybean, chickpea, maize, banana), while other cases show the reverse (barley, green bean, pepper, potato and sugar beet). The values from literature are too random and probably not representative enough to reflect global variability to draw any conclusions here based on the comparison. In general though it can be said that this study is the first in its sort and that it will be useful to study the sensitivity of the benchmark values presented here to the underlying model and data.

3.3. The grey water footprint of different crops at different production percentiles

The nitrogen-related grey WF for ten selected crops at different production percentiles is presented in Table 3. The variability in the grey WF across crops and space is mainly due to differences in nitrogen (N) application (kg/ha) and crop yield (ton/ha). The grey WF at different production percentiles for all crops is provided in Supplementary Material – Appendix B.

Application of N fertilizer influences crop water productivity by affecting the rate of photosynthesis, canopy size and the harvest index (Sadras et al., 2007). N application generally increases grain yield and water productivity significantly (Belder et al., 2005), but

Table 1
Green–blue water footprint for a few selected crops at different production percentiles.

Crop	Green–blue water footprint (m^3/ton) at different production percentiles				Global average
	10th	20th	25th	50th	
Barley	447	516	546	1029	1292
Cotton	1666	1821	1898	2880	3589
Maize	503	542	562	754	1028
Millet	2292	2741	2905	3653	4363
Potatoes	92	137	154	216	224
Rice	599	859	952	1476	1486
Sorghum	1001	1082	1122	1835	2960
Soybean	1553	1605	1620	1931	2107
Sugar cane	112	123	128	175	197
Wheat	592	992	1069	1391	1620

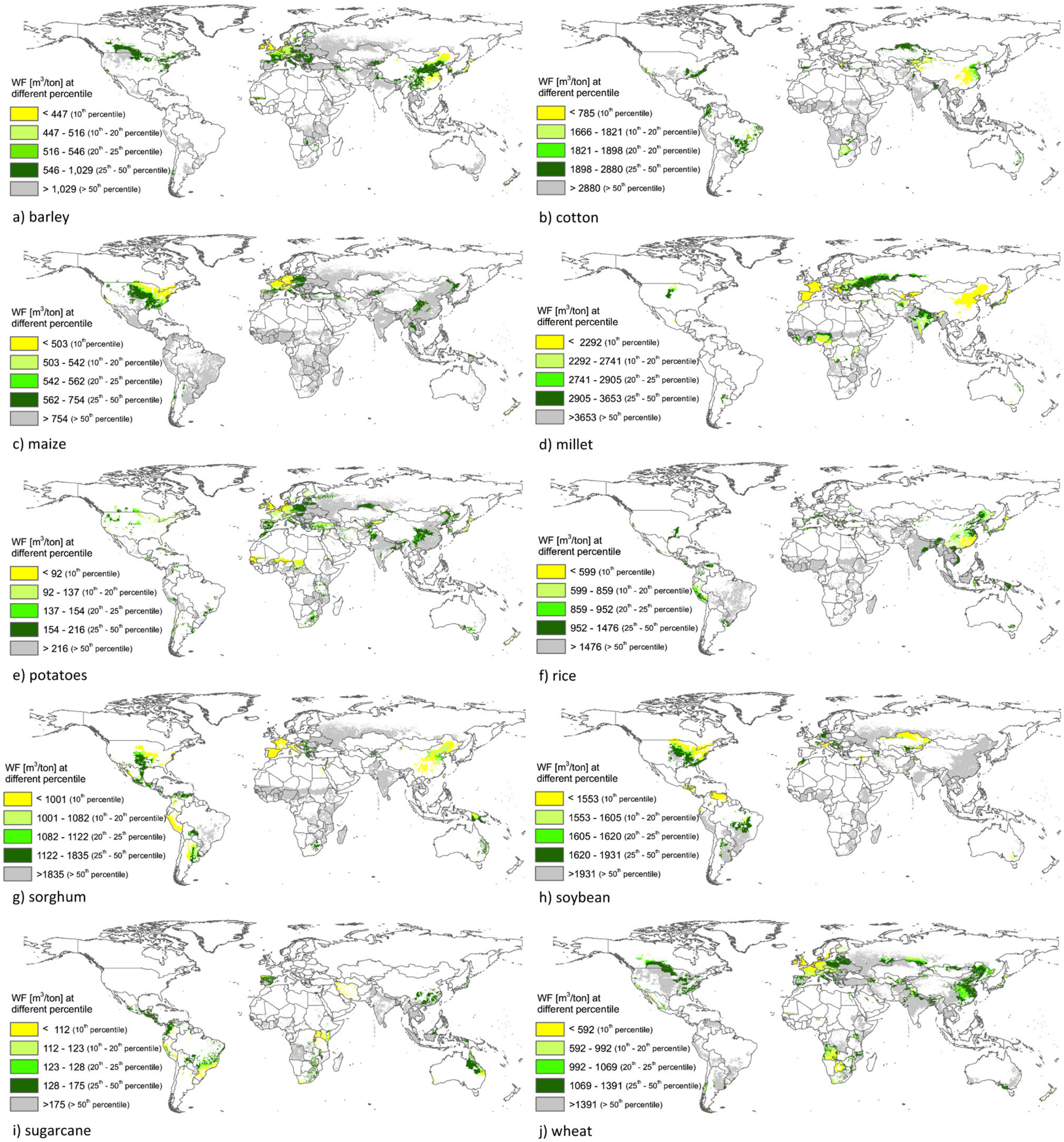

Fig. 4. Spatial distribution of the green–blue water footprint of selected crops (in m^3/ton), classified based on the WFs at the different production percentiles.

the increase in crop yield and water productivity is achieved only up to a certain level of fertilization (Sandhu et al., 2012). Ensuring adequate N supply is critical for good water productivity, but only a fraction of the applied N fertilizer is recovered by plants (Addiscott, 1996; King et al., 2001; Ma et al., 2008; Noulas et al., 2004) and on average about 16% of the applied N is presumed to be lost either by denitrification or leaching (Addiscott, 1996). Therefore, there is a trade-off between higher crop water productivity and increasing water pollution resulting from the loss of N to the freshwater system. This trade-off needs to be considered carefully because maximizing water productivity may result in deteriorating water quality through nutrient pollution.

3.4. Water saving and reduced water pollution when reducing water footprints down to benchmark values

Table 4 presents the global green–blue water saving that could be achieved when, worldwide, the WF in crop production would be brought down to certain benchmark values. As benchmark values, we have used the WFs associated with the best 10th, 20th, 25th and 50th percentile of current production. The global water saving related to improved water productivity in crop production increases when the WF benchmark values get smaller (from the 50th to the 10th percentile). If the gap between current WF levels and the global benchmark values at the 25th percentile of current

Table 2
Percentage of grid cells in different income and climate regions in which crops have a WF below the WF at the 10th, 20th, 25th, or 50th percentile of global production.

Crop	Percentage of grid cells with WF below the 10th percentile					Percentage of grid cells with WF below the 20th percentile					Percentage of grid cells with WF below the 25th percentile					Percentage of grid cells with WF below the 50th percentile				
	Income class			Climate class		Income class			Climate class		Income class			Climate class		Income class			Climate class	
	Low income	Middle income	High income	Temperate	Tropics	Low income	Middle income	High income	Temperate	Tropics	Low income	Middle income	High income	Temperate	Tropics	Low income	Middle income	High income	Temperate	Tropics
Barley	1	4	9	9	1	1	6	17	15	2	1	7	22	18	3	10	26	63	47	11
Cotton	1	9	3	12	2	2	18	7	21	5	2	22	8	25	6	7	48	52	56	18
Maize	0	0	27	8	0	0	0	38	12	0	0	0	44	14	0	2	8	75	29	3
Millet	8	34	69	40	9	18	43	78	50	18	22	49	84	54	22	37	79	100	73	34
Potatoes	8	0	17	6	8	14	3	59	18	13	15	5	71	23	16	26	28	95	47	30
Rice	0	5	5	7	0	0	13	29	19	2	0	18	41	26	3	8	35	86	50	13
Sorghum	1	16	49	32	4	2	24	57	40	8	2	26	62	45	9	5	39	96	66	22
Soybean	0	10	26	12	9	0	11	36	15	10	0	11	39	16	10	1	20	73	27	21
Sugar cane	8	10	10	15	6	10	14	18	20	9	11	17	22	22	12	20	48	77	55	37
Wheat	0	2	11	5	3	5	8	23	13	9	7	14	25	17	11	20	33	46	40	22

production is eliminated, the global water saving would be 39%. In absolute terms, the largest WF reduction is observed for cereal crops: wheat (375 billion m^3/year), rice (350 billion m^3/year), maize (296 billion m^3/year), sorghum (111 billion m^3/year) and barley (110 billion m^3/year). In the case of further reduction to the levels of the best 10th percentiles of current global production, the global water saving would be 52% compared to today. The potential reduction of the green–blue WF related to crop production for all crops is presented in Supplementary Material – Appendix C.

The possible reductions in water pollution are even greater than the possible reductions in consumptive water use (Table 5). In the case that grey WFs in crop production are reduced, worldwide, to the level of the best 25th percentile of current global production, water pollution is reduced by 54%. If grey WFs per ton of crop are further reduced to the level of the best 10th percentile of current production, water pollution is reduced by 79% compared to today's pollution level. The potential reduction of the water pollution related to crop production for all crops is presented in Supplementary Material – Appendix D.

4. Discussion

We developed WF benchmark values for crop production based on the spatial variability in WFs of crops worldwide, using the global assessment published earlier (Mekonnen and Hoekstra, 2011). The current study is the first proposing global WF benchmarks for crops based on such spatial variability analysis. It will be useful to carry out similar analyses with other models than the one used in Mekonnen and Hoekstra (2011) to test the sensitivity of the outcomes to the model used. In addition, as proposed by (Hoekstra, 2013a,b), it would be useful to develop WF benchmarks from insights on what can be reached based on best available technology and practice. The current study shows the spatial distribution of WFs in terms of m^3/ton based on regional differences in evapotranspiration and yields, but it provides no insight in why WFs are relatively small or large in specific regions and how WFs can actually be lowered in those regions where they are large.

We have established global WF benchmark values instead of specific benchmarks for different agro-climatic or economic regions. One may argue that climatic or soil conditions can be a limiting factor for reducing the WF and different regional benchmark values should be established depending on growing conditions per region. However, although climatic and soil factors are important in determining evapotranspiration from crop fields and yields, the green–blue WF of crops in m^3/ton is largely determined by agricultural management rather than by the environment in which the crop is grown (Rockström et al., 2007; Mekonnen and Hoekstra, 2011). The higher evaporative demand in tropical climates compared to temperate regions is largely compensated for by more efficient photosynthetic pathways, which results in higher crop growth per unit of transpiration flow, so that the total crop water requirements are on average similar between hydro-climatic zones (Rockström, 2003). A large increase in crop yields, without an increase or even with a decrease in field evapotranspiration, is achievable for most crops across the different climate regions of the world through proper nutrient, water and soil management (Mueller et al., 2012). Therefore, water productivities as shown in the best 10th percentile of global crop production can be achieved irrespective of climate, which is also shown in our comparison of WFs of crops across different climate regions. We acknowledge, though, that further study may refine our global benchmarks into climate–soil-specific benchmarks. Another discussion refers to setting benchmarks for low versus high-income countries. One may propose another (less strict) WF benchmark for low-income countries, with

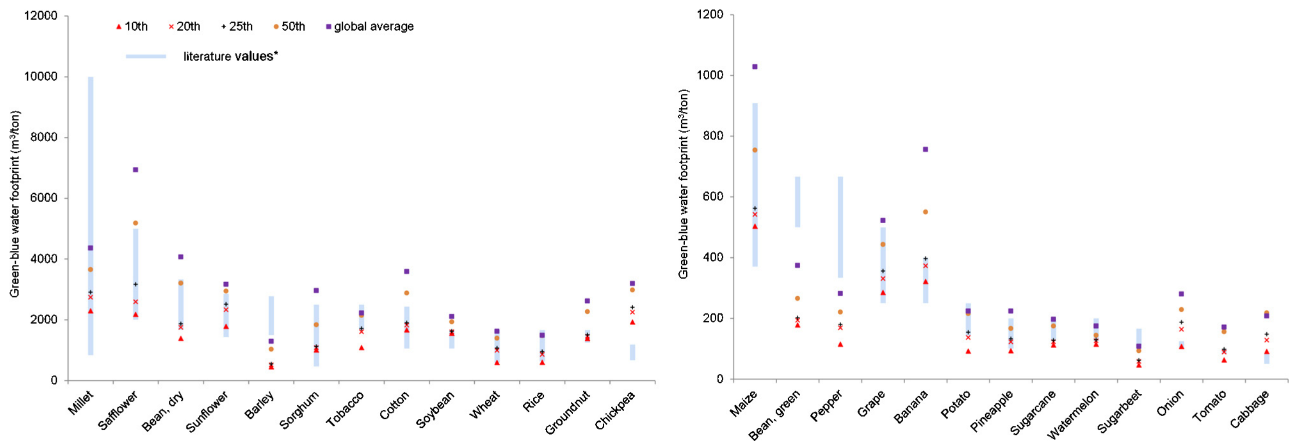

Fig. 5. Comparison of the green–blue WF of selected crops at different production percentiles with values reported in literature.Sources of the literature values: wheat, maize, rice and cotton from Zwart and Bastiaanssen (2004); sorghum, millet, soybean, sunflower from Sadras et al. (2007); barley and chickpea from Hatfield et al. (2001); the rest from Doorenbos and Kassam (1979).

Table 3
Grey water footprint at different production percentiles.

Crop	Grey water footprint (m^3/ton) at different production percentiles				Global average
	10th	20th	25th	50th	
Barley	23	53	64	121	131
Cotton	0	63	175	469	440
Maize	71	128	138	171	194
Millet	0	0	0	63	115
Potatoes	16	22	24	38	63
Rice	71	129	162	215	187
Sorghum	0	0	0	40	87
Soybean	9	9	10	11	37
Sugar cane	3	7	8	11	13
Wheat	27	82	99	144	208

the argument that achieving a certain water productivity in a low-income country is more difficult than in a high-income country, but there are two arguments against that, first, reality shows that for most of the crops studied, the water productivities that can be associated with the best 10th percentile of global crop production can be found in both low and high-income countries (Table 2). Second, there seems little reason to set other environmental standards for developing and industrialised countries, even though it can indeed be a greater challenge in developing countries to achieve certain improvements.

When developing green–blue WF benchmarks we have not distinguished between rain-fed and irrigated agriculture. Intuitively one would assume that water productivities in irrigated agriculture are generally higher, thus WF benchmarks should be lower, but this appears not to be the case. As Mekonnen and Hoekstra (2011) have shown, the global average consumptive (green–blue) WF per ton of crop is lower in irrigated than in rain-fed agriculture for some crops (e.g. maize, rice, coffee, cotton) but higher for other crops (e.g. soybean, sugarcane, rapeseed). The former case can be explained by the fact that irrigated yields are

Table 4
Global green–blue water saving if everywhere the water footprint of crop production is reduced to the level of the best 10th, 20th, 25th or 50th percentile of current production.

Crop	Global total green–blue water footprint (billion m^3/year)	Green–blue water saving (%) in the case of worldwide WF reduction to the level of the best *x*th percentile of current production			
		10th	20th	25th	50th
Barley	184	66	61	60	36
Cotton	207	54	50	49	30
Maize	648	51	48	46	35
Millet	126	49	39	36	25
Potatoes	70	59	42	36	17
Rice	881	60	44	40	18
Sorghum	177	67	64	63	50
Soybean	363	26	24	23	15
Sugar cane	254	43	38	35	21
Wheat	964	64	43	39	25
Others	2750	47	40	37	23
Total	6625	52	42	39	25

Table 5
Reduced water pollution if everywhere in the world the grey water footprint of crop production is reduced to the level of the best 10th, 20th, 25th or 50th percentile of current production.

Crop	Global total grey water footprint (billion m^3/year)	Reduced water pollution (%) in the case of worldwide grey WF reduction to the level of the best *x*th percentile of current production			
		10th	20th	25th	50th
Barley	19	83	63	57	27
Cotton	25	100	88	68	31
Maize	122	65	40	36	23
Millet	3	100	100	100	70
Potatoes	20	76	67	64	50
Rice	111	64	38	24	4
Sorghum	5	100	100	100	70
Soybean	6	76	76	74	73
Sugar cane	17	78	52	46	30
Wheat	123	88	65	58	43
Others	280	85	73	68	42
Total	732	79	61	54	33

generally larger than rain-fed yields, not just because of the additional water, but also because other differences (e.g. crop varieties grown, nutrient supply). The reverse case can be explained by the fact that marginal water productivity decreases with increasing water supply, so that beyond a certain point more irrigation may still increase land productivity (ton/ha), but not water productivity (ton/m^3). In general, the higher water productivities that can be observed in some of the rain-fed agriculture are not specific to rain-fed agriculture; they can also be achieved in irrigated agriculture (by applying smart irrigation technology and practice). Reversely, the higher water productivities found in some of the irrigated agriculture are not specific to irrigated agriculture; provided that green water resources are sufficient, they could also be achieved in rain-fed agriculture (by better soil and nutrient management).

We have developed global benchmarks for the combined green–blue WF of crops, no separate green WF and blue WF benchmarks. The reason is that the ratio green to blue will depend on local green water resources availability. Location-specific blue WF benchmarks can be developed as a function of the overall consumptive WF benchmarks and local green water availability. If a certain location receives sufficient rain to achieve a certain global benchmark on consumptive WF, the location-specific blue WF benchmark will be zero. The less rain, below a certain point, the higher the fraction blue will need to be to achieve a certain water productivity or WF benchmark. This exercise has not been carried out as part of the current study.

There are several strategies to increase crop water productivities and reduce the WF of crops (Table 6). It would be highly valuable to develop insight in how various techniques and practices affect green, blue and grey WFs in terms of m^3/ton, and how certain combinations of techniques and practices will be required to reduce WFs to the benchmark values proposed in this study.

The use of fertilizers will often improve water productivity, because yields will increase while water consumption can remain more or less equal. However, above a certain fertilizer application rate, yields may still slightly increase, but the effect of nutrient leaching and runoff to the freshwater system will start to dominate. When applying fertilizers, the trade-off between higher crop water productivity (smaller green–blue WF) and potential pollution of the groundwater and streams through nutrients (grey WF) should be considered carefully. Setting a grey WF benchmark value as done in this report may help to integrate the issue of water pollution into the discussion on water use efficiency in agriculture, a discussion that is usually fully focused on the consumptive side of freshwater appropriation, leaving out the pollution side.

When applying WF benchmark values as target levels, trade-offs may be required when setting specific green, blue and grey WF targets. Particularly, grey WFs can often be easily reduced by reducing the use of fertilizers and pesticides (and applying the amounts still used in the optimal way at the best time so that yields

Table 6
Technology and practices to reduce the water footprint in crop production.
Sources: Hatfield et al. (2001); Kijne et al. (2003); Sadras et al. (2007); Hoekstra et al. (2011).

Strategies	Technology and practices
Increasing yield	• Soil nutrients management (optimizing crop rotation, the use of crop residues, erosion control, appropriate tillage, proper application and timing of manure or artificial fertilizer) • Precision irrigation: synchronizing water application with crop water demand • Weed and pest control (through crop rotation, proper tillage, biological pest control) • Breeding of superior crop varieties with higher yield and better disease resistance
Reducing non-beneficial evapotranspiration	• Crop scheduling to reduce evaporation during fallow period • Plant spacing and row orientation • Affecting canopy development through agronomy and breeding • Minimum tillage to reduce soil water evaporation and conserve soil water during fallow periods • Use of crop residue and mulches to reduce soil water evaporation and improve nutrient recycling • Improved irrigation techniques (drip & subsurface irrigation) • Effective control of weeds to reduce transpiration from weeds
Enhancing effective use of rainfall	• Synchronizing crop scheduling and rainfall • Water harvesting and supplemental irrigation

are not affected), but at some point this may reduce yield and – since the evapotranspiration rate remains equal – thus increase the green–blue WF in terms of m^3/ton. A similar thing can happen when reducing the blue WF by applying less irrigation water, for instance by deficit precision irrigation using drip technology, since at some point further reduction of irrigation may lower the yield so that the blue WF per hectare may still diminish, but the green, blue and grey WF per unit of crop will increase.

5. Conclusion

With increasing water scarcity, there is a growing interest in improving crop water productivity in order to meet the growing global food demand with the limited freshwater resources. The challenge is thus to produce more crops with less water, thus reducing the WF per unit of crop produced. This study has developed WF benchmark values for a large number of crops grown in the world. The study shows that water savings and reduced water pollution can be very substantial – 39% of global water saving and 54% of reduced water pollution – if WFs per unit of crop are reduced to levels similar to the best quarter of global production. Our estimation of the potential reduction in the global WF of crop production is not meant to imply that this reduction is easily attainable. Raising yields in low-income countries will require large investments in capacity building and appropriate technologies.

WF benchmarks for crops as developed in this study can be used to provide an incentive for farmers to reduce the WF of their crops towards reasonable levels and thus use water more efficiently. When granting water consumption permits to farmers and developing regulations on fertiliser use, it makes sense for governments to take into account the relevant WF benchmarks for the specific crops grown. The benchmarks are equally relevant for the food-processing industry, which increasingly focusses on the efficient and sustainable use of water in their supply chain (Sikirica, 2011; TCCC, TNC, 2010; Unilever, 2012). The same holds for the apparel sector, particularly regarding cotton (Franke and Mathews, 2013), for the cosmetics industry, which uses various sorts of agricultural inputs (Francke and Castro, 2013), and the biofuel sector (Gerbens-Leenes et al., 2009). WF benchmarks will enable the actors along supply chains – from farmers through intermediate companies to final consumers – to compare the actual WF of products against certain reference levels (Hoekstra, 2014). The benchmark values can be used to measure performance, to set WF reduction targets and monitor progress in achieving these targets.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.06.013.

Appendix A–D. Supplementary data

The following are Supplementary data to this article:

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