

Response to Interactive comment on “The green, blue and grey water footprint of crops and derived crop products”

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Response to anonymous referee #1:

We would like to thank the reviewer for his elaborate comments.

#1. The water footprint is an indicator of human appropriation of freshwater resources. It measures both the direct and indirect ‘water use’ of consumers and producers. The term ‘water use’ represent both the consumptive water footprint (green and blue water footprint) and the water required to assimilate the pollution (grey water footprint). As stressed in the 2006-UN Human Development report, water quantity is not the only measure of water scarcity, but quality also plays an important role in the availability of water for human use (UNDP, 2006). Pollution of freshwater resources not only poses a threat to environmental sustainability and public health but also increases the competition for freshwater (Pimentel et al., 1997; Pimentel et al., 2004; UNDP, 2006; UNEP GEMS/Water Programme, 2008). Vörösmarty et al. (2010) have shown that water pollution together with other factors pose a threat to global water security and river biodiversity. Given these facts, taking the grey water footprint alongside the green and blue water footprint is very much justified. The grey component of water use, expressed as a dilution water requirement, has been recognised earlier by for example Postel et al. (1996) and Chapagain et al. (2006).

We agree with the reviewer that the applied model is static and does not simulate physical processes like denitrification and dilution and leaves out local factors which can influence the leaching process. We have acknowledged this limitation of the model in the conclusion part of our paper. However, measuring a pollution level at a point of pollution has more meaning as an indicator of the pollution level than measuring it along a river after it got diluted. We will improve the text in the revised paper to better explain the grey water footprint and why it should be part of the paper.

#2. We have applied the term ‘water footprint’ as defined in the new water footprint assessment manual of the Water Footprint Network (Hoekstra et al., 2011). According to this definition, the water footprint of one single ‘process step’ is the basic building block of all water footprint accounts (Figure 1). The water footprint of a product (alternatively known as ‘virtual water content’) expressed in water volume per unit of product (usually m³/ton) is the sum of the water footprints of the process steps taken to produce the product. The water footprint of an individual or community is the sum of the water footprints of the various products consumed by the individual or community. The water footprint of a producer or a business is equal to the sum of the water footprints of the products that the producer or business delivers. The water footprint within a geographically delineated area (e.g. a province, nation, catchment area or river basin) is equal to the sum of the water footprints of all processes taking place in that area.

The definition of the water footprint is analogous to the definitions of the carbon and ecological footprints. All footprints show consumption of natural resources or pressure on the natural system. A footprint is always an

indicator of the ‘pressure’ on the environment. In order to know the impact of the footprint, one needs to understand footprints in their local and global context indeed, as suggested by the reviewer.

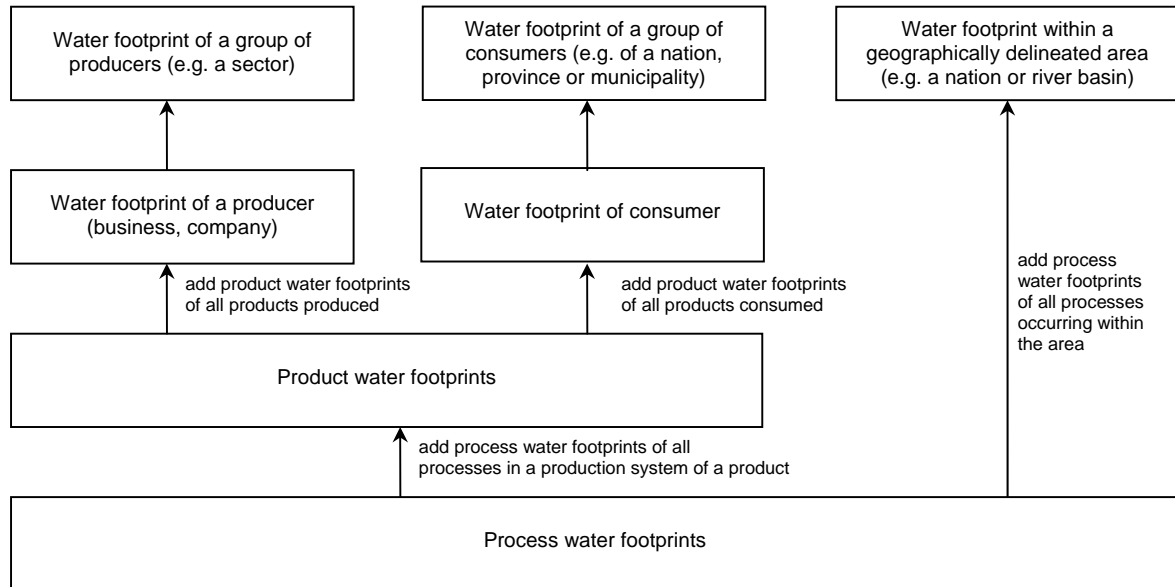


Figure 1. Process water footprints as the basic building block for all other water footprints (Source: Hoekstra et al., 2011).

We will clarify the definition of water footprint in the introduction section.

#3. We accept the suggestion and will refer to the work of Fader et al. (2011).

#4. The difference in the available water use efficiency between rain-fed and irrigated crops is accounted for by taking different rooting depth for the two crop types. The rooting depth of most irrigated crops is half and can be as low as one third of rain-fed crops (Allen et al., 1998). This smaller rooting depth implies that irrigated crops have lower efficiency in using the rain-water compared to rain-fed crops, therefore, lower green water footprint under insufficient rain. We did not change the K_c values but we have changed the K_s value indirectly. Since K_s is a function of crops rooting depth, changing the rooting depth will have an effect on the available soil moisture which will affect the K_s value.

We agree with the reviewer that there could be overestimate of green water footprint by not taking the physiology of plants in to account. But as shown in the discussion part of the manuscript, our results compare well with other similar earlier studies indicating that the possible overestimation of green water footprint is within acceptable range. For example, Liu and Yang (2010) and Fader et al. (2011) have used a plant growth model which takes into account the physiology of plants and come up with a global green water footprint of 4987 Gm³/yr and 6000 Gm³/yr respectively. On the other hand, our estimate based on the simplified approach is 5771 Gm³/yr, which is 16% larger than the estimate by Liu and Yang (2010) and 4% lower than the estimate by Fader et al. (2011). There could be

differences for specific crop and grid level but, in such a global study, we believe these differences are within acceptable range.

#5. The model is not a crop growth model rather soil water balance model. Therefore, effects of factors such as nutrients and pests and diseases on crop growth are not modelled. What the model does is, estimate the soil water balance on a daily basis and calculate the actual yield and evapotranspiration depending on the available soil balance.

The actual yield is estimated using a simplified linear function which accounts for the effect of water stress:

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y \left(1 - \frac{\sum ET_a[t]}{\sum CWR[t]}\right)$$

When there is enough moisture in the soil either through irrigation or enough precipitation, the actual crop evapotranspiration (ET_a) will be equal to the crop water requirement (CWR). Under such condition, the actual yield (Y_a) will be equal to the attainable maximum yield (Y_m). On the other hand, under water stress condition ET_a will be always less than CWR leading to an actual yield below the attainable maximum yield. For irrigated crops we have assumed the applied water is enough to meet the irrigation water requirement of the crop implying ET_a will always be equal to CWR. Therefore, irrigated yield always equals the maximum yield and under water stress actual yield will always be below the maximum yield. The model ensures that, at the grid level, irrigated crop yields are always larger or equal to the yield of the related rain-fed crop.

According to Doorenbos and Kassam (1979) the maximum yield is defined as the harvested yield of a high producing variety, well-adopted to the given growing environment, including the time available to reach maturity, under conditions where water, nutrients and pests and diseases are not limiting factors.

#6. Hoekstra et al., (2009) presents a detailed water footprint accounting scheme. We feel presenting the whole methodology in the current paper will be a repetition as there exist already a number of published works. The study by Gerbens-Leenes et al. (2009) can be considered as sub-set of Hoekstra et al., (2009). The Gerbens-Leenes et al. (2009) methodology states that the water footprint of bio-energy (in m^3/GJ) is calculated as the water used to produce the biomass divided by the amount of energy produced from the biomass in form of ethanol, biodiesel, heat or electricity.

#7. We haven't determined the areas covered by bio-fuel crops currently. The water footprint for bio-energy is estimated by selecting the crops which are appropriate for producing ethanol and biodiesel among the normal crops, i.e. crops which are grown for food.

#8. The interpretation given in the paper is partially valid but we can improve the analysis by including some remark on the fact that for some crops such as rapeseed, the global average rain-fed yield is larger than global average irrigated yield which will result a lower water footprint under rain-fed compared to irrigated crops. The reason for this is that those countries with high yield happen to be countries with large share of rain-fed harvested crop area. For example, high crop yield is observed for rapeseed in most part of Western Europe where it is almost completely rain-fed. On the other hand in countries such as Algeria, Pakistan and India where the share of irrigated crop is high, the irrigated yield is quite low compared the rain-fed yield in Western Europe.

#9. Yes, there is an extra category for domestic and industrial water abstraction in the AQUASTAT. But, according to AQUASTAT definition domestic water withdrawal represents the water withdrawal and supply by public utility. However, in most developing countries, particularly in rural places, public water supply is very low. The majority of rural population get their water supply from streams, groundwater or natural spring waters. Besides, AQUASTAT specifically states, the agricultural water withdrawal includes the water use for animal drinking.

#10. We accept the comment and will rewrite it in the revised version.

#11. We will remove the y from the plots as suggested by the reviewer.

#12. FAO (2005) data represents irrigation water requirement not water withdrawal so we have not used irrigation efficiency. As commented by the Anonymous referee #2, we will revise the accompanying statements.

Related to technical comments:

#13. In this context, the term 'water use' is synonymous to 'water consumption' but we prefer to use the term 'water use' which is well know as 'crop water use' and expressed in m^3/ha or in mm per production period (Allen et al., 1998).

#14. Thank you for the suggestion. We will reformulate the sentence in reference to 'importance of rain'

#15. We accept the other technical comments and will address them in the revised paper.

References:

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M.: Crop evapotranspiration: guidelines for computing crop water requirements, FAO Drainage and Irrigation Paper 56, Food and Agriculture Organization, Rome, 1998.

Chapagain, A.K., Hoekstra, A.Y., Savenije, H.H.G., and Gautam, R.: The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries, *Ecol. Econ.* 60(1), 186–203, 2006.

Doorenbos, J. and Kassam, A.H.: Yield response to water, FAO Drainage and Irrigation Paper 33, FAO, Rome, 1979.

- Fader, M., Gerten, D., Thammer, M., Heinke, J., Lotze-Campen, H., Lucht, W. and Cramer, W. : Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade, *Hydrol. Earth Syst. Sci. Discuss.*, 8, 483-527, doi:10.5194/hessd-8-483-2011, 2011.
- FAO: Review of agricultural water use per country, Food and Agriculture Organization, Rome, “available at: www.fao.org/nr/water/aquastat/water_use/index.stm , 2005”.
- Gerbens-Leenes, W., Hoekstra, A.Y., and Van der Meer, T.H.: The water footprint of bioenergy, *P. Natl. Acad. Sci.* 106 (25), 10219-10223, 2009.
- Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., and Mekonnen, M. M.: Water footprint manual: State of the art 2009, Water Footprint Network, Enschede, the Netherlands, available at: www.waterfootprint.org/downloads/WaterFootprintManual2009.pdf , 2009.
- Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. and Mekonnen, M.M. (2011) The water footprint assessment manual: Setting the global standard, Earthscan, London, UK.
- Liu, J. and Yang H.: Spatially explicit assessment of global consumptive water uses in cropland: green and blue water, *J. Hydrol.* 384, 187-197, 2010.
- Pimentel, D., Houser, J., Preiss, E., White, O. Fang, H., Mesnick, L., Barsky, T., Tariche, S., Schreck, J. and Alpert, S.: Water Resources: Agriculture, the Environment, and Society, *BioScience*, 47(2), 97-106, 1997.
- Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B., Karabinakis, E., Clark, S., Poon, E., Abbett, E. and Nandagopal, S.: Water resources: Agricultural and environmental issues, *BioScience*, 54(10), 909-918, 2004.
- Postel, S.L., Daily, G.C. and Ehrlich, P.R.: Human appropriation of renewable freshwater, *Science*, 271 (5250), 785–788, 1996.
- UNDP: Beyond scarcity: power, poverty and the global water crisis, Human Development Report 2006, United Nation Development Program, 2006.
- UNEP GEMS/Water Programme: Water Quality for Ecosystem and Human Health, 2nd edn, UNEP GEMS/Water Programme, 2008.
- Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R. and Davies, P. M.: Global threats to human water security and river biodiversity, *Nature*, 467(7315), 555-561, 2010.