Interactive Discussion response to B. Fekete (Referee)

Fader et al. presented a rather complicated accounting of water resources manifested in traded agricultural products, The authors follow the logic of distinguishing green and blue water resources and tabulating the rainfed (green) vs. irrigated (blue) water contents in various traded crops. While, I think the proposed accounting is rather cumbersome, I am open to entertain the conclusion that it is my own fault not seeing the value of the presented work.

Thank you for your honesty. We think that the value of the paper is explained in various parts of the text, especially in the last paragraph of the introduction and in section 5.1. In short, this study was the first in analyzing the land use component in virtual flows and virtual savings globally and also in having based the water footprints in high-resolution calculations of virtual water contents for more than one crop, which is especially important for large countries. We will highlight the novelties of the paper even more in the revised version.

The fundamental goal of the paper, which is to demonstrate how trade actually lowers human footprints both in terms of water and land use is rather important. I recommend the publication of the paper in its present form in a hope that the scientific community either will be able to make more out of it than I do or help to polish the presented concepts further.

Thank you for your recommendation to publish the paper in its present form. While polishing parts of the paper we are optimistic that the scientific community will be convinced by our approach and results.

Green and blue and virtual waters are interesting concepts at first glance that could guide better water resource management, but after closer look one looses confidence that these distinctions are indeed that useful. First of all, the distinction of green and blue water seems to be somewhat arbitrary. For instance, this paper appears to consider rice as primarily an irrigated crop. While this is the common perception in the western world, I had a colleague from Nepal many years ago, who convincingly argued that rice is not an irrigated crop beside the initial inundation (which is often satisfied from local water resources). In Nepal and I suppose in many part of China, Korea or Japan the rice paddies are actually dominantly rain fed. It is also unclear, where rain harvesting fits into the green/blue water distinction.

Rain harvesting is indeed a case where the distinction between green and blue water is difficult. We assume that where our land use dataset has irrigated rice areas, the fields are irrigated whenever they need water. And irrigation water is always blue water. The precipitation on these fields is however also accounted for: if it rains, the fields will need less irrigation water. This seems to be an acceptable assumption, since it is very difficult to get data about the detailed agricultural practices in each country. However, we would like to note that this paper does not consider rice *primarily* as an irrigated crop. For all crops there are irrigated and rainfed areas that are based mainly in the work of other scientific groups (see section 2.1). For example in Nepal this dataset has more than 600,000 ha for rainfed rice (the harvested area can be much higher through multiple cropping) and only ~270,000 ha for irrigated rice. Nevertheless, we will add a sentence on how we dealt with paddy rice.

The incompleteness of the virtual water concept also was raised at a recent Global Water Systems Project meeting in Bonn, where the second author presented some aspects of this work. Apparently, virtual water and virtual land alone cannot explain some of the agricultural trades. Perhaps, one should introduce yellow/red and virtual radiation analogous to the green/blue and virtual waters, where yellow radiation represents solar radiations allowing crops to grow without greenhouse, while red radiation is the artificial heat or radiation needed to grow certain crops in less favorable climate. The yellow/red radiation complementing green/blue water can explain countries like Israel, which imports cereals, while exports high value irrigated crops (fruits and vegetables, etc.) to water rich countries (like Canada, which obviously cannot grow plants like olive trees).

This is a very interesting idea, it would however go beyond the scope of this work. Furthermore, adding these concepts would still not explain trade patterns, since they will always depend, at least partially, on socio-economic factors. Nevertheless, we are willing to add a sentence in the discussion mentioning the role of radiation.

Ultimately, green/blue water seem to miss the value of water. Focusing strictly on water efficiency is misleading since countries with abundant water resources are probably rightfully ignorant about the virtual water content of their agricultural products.
To some degree, green-water is a confusing concept. For instance, the water demand to grow wheat in Canada is a fraction of growing the same crop in Egypt, Libya or Alger, therefore the virtual water value of the Canadian wheat in those countries is much higher. I suppose, one could calculate the water requirement to produce particular crop in importing countries and account virtual water trading accordingly. Even, if the water requirements are the same in the exporting and importing countries the availability of the water and the impact of allocating the demanded water to crop production could be drastically different. Virtual green-water uptake in a region could be similar to the water uptake by the natural ecosystems and as a consequence irrelevant from water resources perspective. The deviation from the water requirement of the natural ecosystem vs. the cultivated land might be a better metric. Land area appropriated for agricultural production is more likely to matter in terms of human footprint.

This paragraph contains more than one interesting point, thank you for that. First, even if a country has enough water, it is useful to know how much it is using and virtually exporting and importing, especially in the context of climate change where water richness and scarcity could be temporal concepts. Second, what you propose (calculating the water requirements in the importing country) is exactly what we called water savings and is thus considered and analyzed in the paper – we will point this out more clearly in the revised version. Third, it would be very interesting to analyze the water scarcity/abundance in the exporting countries and the trade-offs in its use. This is however neither trivial in terms of the methods nor short in its analysis and interpretation, and is thus planned for a future study. Nevertheless we will add some sentences relating qualitatively water and land scarcity/abundance to flows. Forth, even if the water requirement of the natural ecosystem could be equal or higher than the requirements of cultivated land, the agricultural green water consumption is *not* an irrelevant concept, since it is not the same – ecologically, economically and socially – to produce ecosystem services than agricultural commodities. We will add this remark to section 5.3 in order to clarify this point. Fifth, land area appropriated for agricultural production is the focus of the ecological footprint community. Nevertheless, we also considered this aspect important and included thus the land savings as a complement of the water savings (not as replacement).

I tried to build a glossary of terms and acronyms introduced in this paper (see below) and I have to say it is mind boggling. I wonder, if it is the best way to communicate the ultimate goal for sustainability, which is to satisfy human consumptions while minimizing the disruption of natural ecosystems.

Thank you for the glossary, we will compile a similar one for the revised version of the paper. If you would not repeat the same concept in blue, green and total (e.g. BVWE, GVWE, VWE, etc), the list becomes much shorter and in our opinion absolutely manageable in terms of length and complexity for the reader. Furthermore, we think that it is necessary to be precise about the exact definitions, to avoid confusion as of the use of terms like “green”, “blue”, “footprint”, “saving” etc.

Interactive Discussion response to S. Siebert (Referee)

The paper describes the calculation of green and blue water footprints of nations and land and water savings through trade of crop products. The manuscript is well written, interesting and certainly of interest for a large community. The study is comprehensive, innovative and helps a lot to better understand the relation between global trade and natural resources use. Interesting also the comparisons to results of many other related studies making this article to a good overview on the state of the art in this field of research. The content of the paper fits very well to the scope of the journal. I would therefore highly recommend to consider it for publication in HESS.

Thank you very much for this appreciation.

1) The authors use a modified version of the dynamic global vegetation and water balance model LPJmL to compute crop production, crop water use and related virtual water and virtual land contents of crop products. I understand that the development of such a model is always work in progress and that the recent model version is built "on top" of previously existing versions. However, I feel it difficult to really understand which methods, data and assumptions were implemented in the model version used in this study explicitly. It seems that it is required to read several publications just to understand how the green and blue virtual water content of crops was computed (see section 3.1) and that only parts of the developments described in previous publications are still used in the most recent version of the model. I would like to encourage the developer team therefore to find alternative ways for a more transparent model version documentation and description. Please provide such a more complete documentation for future articles (e.g. as electronic supplement).

We found it difficult to include all the equations that would be needed to understand each detail of the model and the work conducted here. Thus, we had to focus on a suite of equations as a compromise, especially since the paper also describes various new indicators. In general, we think that the equations included in the paper and the overview given by Fader et al. (2010), which is quoted there, are enough to understand how e.g. virtual water content is calculated. We think also that repeating the equations included in Fader et al. (2010) – even if easily done – would unnecessarily extend the paper (which already includes many equations and abbreviations).

2) When assuming a constant level of production, land and water savings are achieved by increasing global average crop yields and global average water productivity. This can happen in-situ by agricultural intensification (e.g. fertilizer application, plant protection, breeding) or ex-situ by replacing national crop products grown in regions of low crop yields and low water productivity by imports from regions with higher crop yields and higher water productivity. It would be very interesting to see how much global average crop yields and global average water productivity were increased as result of the trade between nations.

This is an interesting point, we will calculate this figure and briefly discuss this issue.

3) The concept used in this study to compute land and water savings by trade is assuming that a country "saves" the water and land that it would have needed to produce the related crop products (section 3.4). It is however difficult to compute these "savings" because assumptions on potential crop yields and potential water productivity *in case of required domestic production are necessary. It is assumed here that crop yields and water productivity for this extra production would be similar to those computed for the actual production. I would like to see some discussion on this assumption because it is known that a higher domestic demand can result in an intensification of production and therefore less land and water requirements. On the other hand it also maybe required to increase production in marginal areas resulting in lower yields and lower water productivity.*

Yes, we also think it is a good idea to discuss this assumption and will do it in the revised paper.

4) The reported total land and water savings by trade between nations are impressive but I would highly appreciate a better distinction of flows from countries rich in land and water resources to countries with scarcity of resources and vice versa. This could help to better understand whether such virtual water and virtual land flows are intended or just a by-product of other needs. The research question behind this is non-trivial. According to the agricultural intensification theory growing population and growing demand for crop products result in shortage of agricultural land, therefore in agricultural intensification and finally in higher crop production per unit land and lower per cap cropland use. To save land by virtual land flows it is however required that flows are directed from regions with high yields to regions with low yields. Consequently, when thinking the agricultural intensification theory reversely this would mean that flows are required from regions short in agricultural land to regions without such shortages : : : .
Any thoughts related to this problem?

We agree that it is a good idea to provide some examples in the text about the direction of the virtual land and water flows, qualitatively related to scarcity, and will do that in the revised paper.

5) Because of time constraints I could not manage to check all equations in this manuscript in detail. Please have another careful look on that, in particular that all variables are explained, that all units of the variables are reported and that the conversion between units is correct.

Thank you, we will do that and also provide a glossary as proposed by another referee.

Minor comments:
Page 488, lines 15-17: representing the soil in five layers in contrast to two layers before and implementation of root distributions is for sure a serious modification of the model since this will have implications for runoff generation, plant drought stress, crop yields and therefore virtual water contents as well. Did you check the consequences of this modification and can you explain a bit better how the model was improved thereby?

Yes, we did check the consequences. Since virtual water content – the basis for all other water calculations – is a ratio between water consumption and yield and since yields are calculated with a calibrated management, VWC did not change much from one version to the other. We will mention this in the revised version. The improved soil hydrology will be documented soon by other authors.
We will also consider all other minor comments that you have made.

Interactive Discussion response to A. Y. Hoekstra

The paper adds to the growing body of literature in this field. The innovation in this paper particularly lies in the inclusion of both water and land (although the paper doesn't yet take full advantage of this in terms of drawing conclusions about possible tradeoffs to be made between land and water footprints when making decisions that affect both).

We absolutely agree that it would be very interesting to look at the trade-offs between land and water, but rather in a separate work than in this paper.

The paper is rather comprehensive: it uses a model with high resolution, includes all major crop categories and makes a distinction between green and blue water consumption and looks at the virtual water content per crop category and country. It quantifies international virtual water and land flows as well as at the savings related to these virtual water and land flows. Finally the paper quantifies water footprints of countries related to crop consumption per country.
The paper is a bit unbalanced by focusing more on water than land, not only in terms of analysis but also in terms of embedding in the literature. I have a water background myself, so I cannot add very much regarding the land component of the paper, but it is clear to me that much more relevant previous work has been done in the field of land use studies, particularly in the ecological footprint literature. The authors would improve the paper by reviewing the literature on EF and referring how this work relates to that.

We made some remarks on this in section 5.3. and will extend it in the revised version.

Apart from this general remark and a number of specific comments (see below) that will strengthen the paper, it is clear that this paper needs to be published. It enriches the existing literature in the field.

Thank you for this appreciation.

Specific comments
In abstract, introduction and 4.3 it is said that the water footprints of nations are calculated; better formulate more precise: the water footprint of nations insofar related to the consumption of crops. [I admit that later on I read the disclaimer in section 5.2, but that's a bit late, also when presenting the results better not write 'the water footprint of countries' when only the wf related to the consumption of crops is meant].

We see your point and will reformulate this part.

Intro: When the authors write that "The grid-based study of Mekonnen and Hoekstra (2010) is restricted to wheat and does not consider plant physiologic water stress under irrigated conditions" I am not sure what they mean. That study does account for the effects of water stress on yield under non-optimal irrigation.

We understood that Mekonnen and Hoekstra (2010) account for stress in case there is not enough soil water, as you said, if irrigation is non-optimal. But plants can be water-stressed also with saturated soils, because of an even higher atmospheric moisture demand (higher than the plant can physiologically supply, as simulated by our model). This is what we called physiologic stress and we thought Mekonnen and Hoekstra

(2010) did not account for that, but please correct me if I am wrong. In any case, we will reformulate this sentence.

In section 2.2 it says: "Only raw commodity classes were used." That means that not all trade flows of crop products have been included and thus results in a conservative estimate of international virtual water flows and thus a bias in the estimation of water footprints of nations (too high estimate for net exporters of the excluded crop products; too low estimate for net importers of the excluded crop products).

Good idea, we will include this explanation in the text.

Section 3.3 & 4.3: A major omission in the analysis of water footprints of nations is the exclusion of trade in animal products. Virtual water flows related to trade in animal products were included in: Chapagain, A.K. and Hoekstra, A.Y. (2008) The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products, Water International 33(1):19-32 [this publication deserves inclusion in the refs anyway]. Excluding trade in animal products in the estimation of water footprints of national consumption implies that crops that are used as feed for animals that produce meat or other animal products for export will count for the water footprint of national consumption of the country considered, which should not be the case. Reversely, when animal products are imported into a country the water footprint of the importing country is higher than follows from the results of this study. It would be good to add this disclaimer somewhere in the discussion of the results.

You are right; we will include these thoughts in the discussion, as well as the suggested reference.

In 4.4.1 about water savings reference should be made to other earlier studies. Proper ref is made to Oki and Kanae (2004), De Fraiture et al (2004) and Yang et al (2006), but not to: Chapagain, A.K., Hoekstra, A.Y., and Savenije, H.H.G. (2006) Water saving through international trade of agricultural products, Hydrology and Earth System Sciences 10(3): 455-468. The latter seems to be the most comprehensive of the four studies.

We will add this reference.

Section 5.2. It reads: "Moreover, future studies would have to relate the current consumption to the resource base, i.e. assess whether virtual water export aggravates water scarcity in the exporting country". This sort of analysis has been done a number of times already, see for example Van Oel, P.R., Mekonnen M.M. and Hoekstra, A.Y. (2009) The external water footprint of the Netherlands: Geographically-explicit quantification and impact assessment, Ecological Economics 69(1): 82-92.

Thank for this information, we will add the reference, though it is for one country only.

Regarding the worldwide high-resolution estimation of the virtual water content of crops, a very similar study was published end 2010: Mekonnen, M.M. and Hoekstra, A.Y. (2010) The green, blue and grey water footprint of crops and derived crop prod-ucts, Value of Water Research Report Series No.47, UNESCO-IHE, Delft, the Netherlands, http://www.waterfootprint.org/Reports/Report47-WaterFootprintCrops-Vol1.pdf. I guess *that the authors hadn't seen this report when finalizing their manuscript, but since the similarities are so striking it is worth making in section 4.1 some rough comparison and reference.*

We will add a short reference to it, and also to the related paper now online for Open discussion in *HESS*.

Interactive Discussion response to Anonymous Referee #3

Fader and coauthors conducted a hydro-agronomical simulation globally and estimated virtual water contents, internal/external water footprints, and water savings/losses comprehensively. Notably, they mentioned that they first estimated "virtual land flow". They intensively compared their results with earlier studies. Many of the authors' findings can be seen elsewhere, at least qualitatively. For example, quantitative estimation of virtual water contents and water footprints has been reported in dozens of scientific journals. All of them pointed out similar geographical patterns of virtual water exports and imports. Separating virtual water into blue (evapotranspiration originated from irrigation) and green (that from precipitation) is a relatively new research topic, but several papers have been published on it. "Virtual land" seems to be firstly appeared in this paper, but the concept is rather simplistic and I couldn't find clear implications in this manuscript. If the authors do not agree with these points, I strongly suggest the authors emphasize what are newly found in this study.

Thank you for your critical evaluation of the novelty of our paper. Even if we see the point that a lot of work was already done on this field, we think that it was necessary to do it in a comprehensive way, detailing the separation of green and blue and going a step forwards in the inclusion of the land component. We will follow your recommendation and better point out what is new and what our present calculations for the land component mean.

Nonetheless, I believe this paper is considered for publication, because of two reasons. First, the authors used the LPJmL model in this study. LPJmL is one of state-of-the-art global hydrological models, incorporating advanced sub-models of human activities, and it has been intensively tested through a number of applications by active research groups. Therefore, the results of LPJmL will be of interest to the large scale hydrological modeling community. Second, both "virtual water" and "virtual land" is literally virtual (i.e. quite difficult to physically measure if not impossible), and numerical simulation is the only practical way to estimate them. To increase confidence in scientific understanding, we need to increase the number of models and simulations.

We agree on these points – and thank you for recommending publication of the paper.

The text is fairly easy to read. However, the current form requires readers' good memory to remember dozens of acronyms, good knowledge of earlier works to understand the meaning of comparison between this study and earlier ones, and good patience to read through long text. Possibly, the authors could improve readability of this paper by:
- adding nomenclature of acronyms

We will definitely do that.

- adding a table which summarizes methodology of earlier studies

We think this would go beyond the scope of this study, since it is not a review paper. But we may point out even better differences to earlier studies when comparing our results with those.

- moving some of the contents to appendices, particularly comparison between this study and earlier ones.

Good idea, we will probably consider this.

Specific comments
Page 484, line 24, "Thus, countries with high levels of per capita water consumption affect mainly the water situation in their own country": I couldn't clearly understand what the authors meant here. What is "the water situation in their own country"?

We will rephrase this sentence to clarify what we meant.

Page 486, line 21, "probably overestimating the production in these regions and thus underestimating VWC": I couldn't understand how the authors concluded this.

We will think about this sentence (not only this part, but the previous concept) and how it can be rephrased, but in principle if there is no physiological water stress and we assume this kind of stress always reduces production, there will be a higher production than if stress was considered. And if VWC relates water consumption and production to each other and we assume that water consumption stays constant, VWC would be lower at higher production.

Page 496, line 25, "Due to the higher spatial resolution of our calculations, we believe our estimates to be more precise": This is not obvious. There is no relationship between spatial resolution itself and the precision of simulation.

You have a point, we will rephrase this sentence.

Page 496, line 27, "The agreement between our results and Hanasaki et al.'s (2010) resuts is mostly very good" : How did the authors judge that the agreement was "very good"? The authors also mentioned that their results showed also "good agreement" with Mekonen and Hoekstra (2010) and Siebert and Döll (2010). Does it mean all of these studies reported very similar virtual water content (VWC) of major crops?

We will try to specify this without unnecessarily extending the paper.

Page 500, line 9, "the blue water consumption (BE) in the LPJmL-based study by Rost et al. (2008) (1258km3), mainly because we considered only part of the cropland and also because that study was based on different land use dataset with some differences in parameterizations" : I couldn't understand why this large discrepancy appeared in global total blue water estimation between this study (449 km3) and Rost et al. (1258 km3). Both studies used LPJmL and calculated similar crops (Chapter 2.1). I would like to suggest the authors add some clear quantitative explanation here.

Indeed, these two numbers are not comparable, and you probably have overlooked our statement in the same paragraph that our total estimate for crops including the category "other crops" is 923 km^3. This is comparable to the 1,258 km^3 found by Rost et al. (2008) but still lower, mainly because the earlier study used a land use dataset that demonstrated a smaller cropland area and differed in terms of the area equipped for irrigation; moreover, there are differences in model parameterizations, crop management is calibrated in the present version, etc. The remaining difference is mainly due to different land use datasets used as input. We will clarify this in the revised section.

Page 505, line 20, "This study is the first to make a process-detailed and spatially explicit differentiation of blue and green water in virtual water contents, virtual water flows and both country internal and external water footprints for the majority (through not all) of the world's crop types": As the authors mentioned in Introduction, Aldaya et al. (2010), Hanasaki et al. (2010), and others have already estimated them, if not all. I would like to suggest the authors write here with care, what is truly shown "first".

We appreciate your suggestion, but as we explain in the introduction, all these previous studies had limitations that ours do not have. This means, if you prefer, that ours is the first study showing together *exporting and importing* flows, differentiating internal/external and green/blue footprint, for the major crops globally and based on high resolution computations. We will take care of this in the revision.

Page 506, line 8, "In general, we think that the LPJmL model used here can better account for effects of climate variability on crop production, yields and virtual water contents than stand-alone hydrological models of models that use prescribed crop calendars": This is true only if all of the parameters of LPJmL are properly given to the entire study domain. If the parameters are wrong, the performance of complex process models can fall below simplistic conceptual models.

This is true but we believe to have taken care of the parameterization (and validation/calibration) as good as it is possible for a global study. Nonetheless, we will slightly modify this statement.

Technical corrections
Page 502, line 11: "WPFs" reads "WFPs". Page 505, line 15: "patters" reads "patterns"
Will be corrected.