Response to comments from reviewer RC1

Note that reviewer's comments are in italic black, and responses in plain blue font.

General comments:

The authors determine for a large number of crops how crop production could be shifted among the countries of the world to produce the same amount of each crop globally while minimizing the highest value of a country-scale indicator of blue water scarcity, without any extension of the total national cropland but a with a certain maximum allowed extension of cropping area in the countries, both for rainfed and irrigated production. Mainly for reasons described as limitations of the study by the authors themselves (lines 368-378 but also 379-383) I think that the results of the study are not informative and even misleading. This is due to the scale of the study which inclusively considers countries as homogeneous units of analysis, regarding land and water productivities as well as blue water availability.

We thank the reviewer for his critical comments. As the reviewer already noted, most limitations observed in the comments are acknowledged and described in the paper's discussion. The main issue here thus is the extent to which the usage of country-average data and the interpretation of results is appropriate. Firstly, one relevant methodological aspect appears misinterpreted: the allowed land-use changes at country level (limited by factor-alpha) is not an allowable expansion in rainfed / irrigated crop area per country limited by national agricultural area, but rather is an allowable shift in the cropping pattern within the bounds of current rainfed <u>and</u> irrigated area per country. So current production characteristics on currently irrigated lands are not assumed to be valid elsewhere. The modest allowed changes in cropping areas of individual crops prevent significant shifts in crop allocation within a country (e.g. to other agro-ecological zones), avoiding implausible results due to the heterogeneity in rainfed and irrigated land productivity. The impact of the observed heterogeneity in blue water availability can be more influential. Water availability is a complex variable because the same volume of water at a specific location and time can be considered available for use at any downstream location and (if storages are present) at any moment in the year; countries base their water management on these properties and implement policies of water allocation within a river basin, reservoir construction and management and large scale inter-basin water transfers. The extent of such policies to justify only considering total national freshwater availability in assessing water scarcity is limited, however, calling for care in interpreting national-scale water scarcity as an indicator and in performing scenario exercises as in the present manuscript. We agree that this discussion is underemphasized in the paper and will better address it. This discussion closely links to considerations on the choice of *Water stress* (freshwater withdrawal as a proportion of available freshwater resources) at country and region level as indicator 6.4.2 in the SDG framework (UN-Water, 2018). Next, we will add a variation of the current optimization exercise, contributing to assessing the sensitivity of results to the assumed availability of total renewable freshwater at irrigation areas (see response to the next comment).

It should be noted here, that by far the largest impact on water scarcity relief emerges from shifts in cropping patterns of rainfed crops, not depending on the heterogeneity of blue water availability. The dominance of this aspect of the changed global cropping pattern is illustrated using an additional optimization exercise to separate out this effect (see response to the next comment).

Where the scale of analysis chosen in the paper calls for careful introduction of the definition of the exercise and its interpretation, to our knowledge it considers, for the first time, both differences in water productivities and in water endowments to analyse comparative advantages of countries for different types of crop production.

The novelty claimed in the manuscript is consideration of blue water scarcity. Unfortunately, blue water scarcity is only considered as one value per country, computed as the ratio of total blue water use in the the country and blue water availability in the country. This is problematic as their are important crop-producing large countries like India, China and the US (but also Australia) with humid and semi-arid climate zone, where irrigated crop production and thus blue water use is concentrated in the semi-arid/arid regions of the country while blue water availability is high the humid parts of the country. This is why these countries, in which large regions suffer from irrigation-induced water stress and even groundwater depletion, do not appear among the 21 countries with the highest water scarcity (Table 2) for which the authors show to what extent blue water consumption and thus blues water scarcity could be reduced by shifting crop production to other countries (with lower blue water scarcity). One result is that in the optimized distribution of crop production among countries, both China, India and Australia increase their blue water consumption (Fig. 2 bottom). I do not find it plausible that the thus optimized distribution of crop production among countries "minimizes blue water scarcity in the worlds's hotspots"(as is formulated in the title).

I think it is a prerequisite for publication of the study that the authors show the results of a sensitivity analysis regarding the spatial analysis units. Blue water availability values as well as irrigated areas are available at a spatial resolution of 0.5◦ by 0.5◦ , and this information could be used to see how the optimization results change if the blue water availability in the irrigated areas/cropping areas are taken into account instead of average country values. You could have a look at Yano et al. 2015 (Yano S, Hanasaki N, Itsubo N and Oki T 2015 Water scarcity footprints by considering the differences in water sources Sustainability 7 9753–72) where water scarcity at the country and for irrigated areas are computed separately and compared. Blue water availability from various global hydrological model available at www.isimip.com could be used.

The above comment closely connects to the first one. We fully agree that the term world's hotspots of water scarcity is formulated too loosely, and will improve on that. We also agree that modest to low water scarcity indicators at national level may hide hotspots within a country; we do note however that still water stress or water scarcity are widely used as indicators for the human pressure on water resources as national scale, e.g. SDG 6.4.2 Water Stress in FAO's Aquastat, intended for country comparisons in global studies.

Results on insight-raising variations to the optimization exercise will be added as sensitivity study; this concern:

- an exercise to identify the impact of shifts in the rainfed cropping pattern only, only allowing irrigated production areas to decrease for each country and crop;
- an exercise to separate out the impact of allowed water scarcity increases in countries with low scarcity, by disallowing increases in blue water use in each country (contrary to the optimization in the current manuscript).

In addition, it is necessary to broaden the literature review. For example, the work of Taikan Oki and his group have not been considered. Please review Oki et al. 2017, Environ. Res. Lett. 12 044002 and some of the references therein. Oki and Kanae 2004 already showed global water savings by global trade.

We will broaden the literature review and consider for example the work of Taikan Oki and his group.

Specific comments

L76: Jalava et al. 2016 also studied the effect of food loss reduction (https://doi.org/10.1002/2015EF000327)

Results will be discussed in the context of this reference; a citation will be added.

L79: Explain more clearly to a broader audience what the definition of virtual water is (also: does not only relate to food).

The definition of virtual water has been changed into the following: The trade in 'embedded water' (also known as virtual water trade) is the hidden flow of water if food or other commodities are traded from one place to another (Allan, 1998).

L102ff. Explain more clearly the study of Davis et al. 2017a, and compare their methods and results to your study (e.g. in the discussion section).

We add the following:

In the introduction: "However, the current study has a number of differences with Davis et al. (20017a). First, we consider a larger number of crops (125 crops including vegetables, fruits and pulses which were not considered in Davis et.al., (2017a) study). Second, we are changing cropping patterns while maintaining same global production per crop while Davis et al. (2017b) aim for higher calories and protein production while reducing water use which could result in producing different crops in the optimized set than in the current set."

In the discussion we add:

"The current study supports the findings of Davis et al (2017a) on the benefits of crop redistribution on water saving which could be a potential strategy for sustainable crop production and an alternative to the large investments that are usually needed to close up the technological and yield gaps in developing nations."

"Changing cropping patterns could reduce global blue water footprint by 9%. However, not all countries would benefit similarly in the optimized set, India and China, for example, would have a slight increase in their blue water consumption by 5% and 4% respectively. This is in line with the findings of Davis et al. (2017a) who find in their simulations that water scarcity persists in many important agricultural areas (the US Midwest, northern India, Australia's Murray-Darling Basin, for example), indicating that extensive crop production in these places prohibits water sustainability, regardless of crop choice (Davis et al.2017a)."

L111: Define clearly here that "cropping patterns "mean the distribution of production of a certain crop among the nations/countries but not within.

We add the following explanation: "(By changing cropping patterns, we mean that the allocation of crops to rainfed and irrigated land within a country changes, where both rainfed and irrigated area of a certain crop can be expanded up to a modest maximum rate, while respecting the bounds of current total rainfed and total irrigated area per country)".

L118: Expand methods section with respect to considered crops/crop groups, algorithm for optimization, e.g. how was ensemble of potential cropping patterns produced?

We add: "We considered 125 crops of the main crops groups (cereals, fibres, fruits, nuts, oil crops, pulses, roots, spices, stimulants, sugar crops and vegetables) (for an extensive list of crops used see (Chouchane et al., 2019)); optimization was performed using the linear optimization routine from the Optimization Toolbox of MATLAB".

L139: BWS only takes into account irrigation water use but not the other use sectors. Define blue water footpring.

We added the following: "Blue water footprint (BWF) refers to the volume of consumptive freshwater use for irrigation that comes from surface and groundwater".

L159: Explain why you chose to minimize (only) the highest national blue water scarcity.

Within the framework of the Sustainable Development Goals, SDG 6.4.2 (*Level of water stress*), is used as an indicator for *Goal 6. Ensure availability and sustainable management of water and sanitation for all*; it is defined similar to water scarcity here, also at the resolution of countries, but based on water extractions rather than consumptive water use. Where lowering the water stress level is a goal for each country, from a global equity perspective lowering stress in countries with highest water scarcity is prioritised. This is operationalised by choosing the maximum national water scarcity as an objective function in the optimization.

L220-364. Please shorten the lengthy description of the changing cropping patterns and comparative advantages shown in figures and tables but try to explain the results.

This will be shortened in the revised version.

L367ff Also discuss the real-life meaning and consequences of optimized global cropping patteren, in particular reduced blue water consumption in the countries listed in Table 2. E.g. if BWC is reduced from 1900 to 280 million m3/yr in Libya, crop production (Fig. 4) and income would be strongly reduced, too. Could the production/income loss be somehow related to GDP to understand the problems that would result from the analyzed global-scale optimization?

Consequences of the changes in the global cropping pattern on agricultural economy, farm economy and food self-sufficiency are outside of the scope of this paper. Changes towards the optimized cropping patterns identified here would require agroeconomic policies, e.g. on commodity prices, price- and farm income subsidies or trade regulations to reflect implicit resource use.

We already mentioned some impacts related to reduced production in real life. We mentioned the countries with the largest decrease in their blue water footprint of crop production (last paragraph in the discussion) and the impact that could result from that. However, this doesn't mean directly that the total production is reduced. Since for some countries, when possible, they will switch to rainfed production. So, income reduction is not necessarily proportional to the reduction in blue water consumption. To be able to assess the impact of the reduction in BWC on the country GDP we should be able to trace back the consumption per crop per country and initial import and export. By calculating the changes in consumption, import and export we could assess the changes in the GDP. This is out of the paper scope for now.

L408 ff. I would not use the grammatic form of "will", e.g. in "Cereal production will get reduced in Africa". Maybe better: "If blue water scarcity was globally optimized, cereal production would be reduced in Africa according to our analysis."

We will improve the grammatic form through the paper.

References

Chouchane, H., Krol, M. S., and Hoekstra, A. Y.: Dataset for Changing global cropping patterns to minimize blue water scarcity in the world's hotspots, TU.Centre for Research Data, Dataset, https://doi.org/10.1016/j.wroa.2018.09.001, 2019.

UN-Water: Progress on Level of Water Stress – Global baseline for SDG indicator 6.4.2. UN-Water, Geneva, Switzerland, 2018.