We are thankful to have the opportunity to resubmit our revised paper. The reviewer comments were very helpful to clarify and improve the original manuscript. All comments by the reviewers have been addressed, and corresponding changes have been made in the manuscript where necessary. Below, a detailed point-wise response to the reviewer's remarks and marked-up manuscript version.

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

General comments:

Response to comments from reviewer RC1

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. We took a number of actions in order to soften most of the study limitations (by limiting areal crops expansion to a maximum factor-alpha for instance). 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 and 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. This discussion was underemphasized in the original manuscript but is now explicitly addressed in the paper. 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 (FAO, 2018).

We added the following:

In the introduction part: "The spatial resolution of the country level reflects the coarse resolution at which FAO monitors and reports water stress in the SDG framework (FAO, 2018); subnational heterogeneity in water scarcity, that is significant in countries like USA or China, is not covered at this resolution". **(Line 120-122)**

In the discussion part: "We minimize average water scarcity in countries; within countries scarcity differences will still appear, both in the reference situation and in the case of the optimized cropping patterns. Still, water scarcity indicators at national levels provide insight; within the framework of the Sustainable Development Goals, indicator 6.4.2 (Level of water stress), is used to monitor Goal 6 (Ensure availability and sustainable management of water and sanitation for all); it is defined similar to water scarcity in our study, 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. Relieving water scarcity in specific hotspots within countries by changing cropping patterns could be studied using the current approach but is beyond the scope of this paper. The sensitivity analysis did show 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; therefore water scarcity reduction in countries with highest scarcity at national level in the current study does not rely on worsening water scarcity in countries with heterogeneous conditions". **(Line 412-424)**

Next, we added 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 as shown in the sensitivity analysis added to the paper results. 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 agree that the term 'hotspot', meant to indicate the world's most water-scarce countries, can easily be misinterpreted. Therefore, we removed the term from the title, and only use the term in the body of the text in discussing limitations to interpretability the results at national scale due to heterogeneity. 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.

The optimization has been updated. While the objective function and most constraints remain the same, we now disallow increases in blue water use in each country. All results have been updated accordingly. Moreover, in order to identify the impact of restricting expansion to rainfed areas only, a sensitivity analysis has been conducted showing the share of effects of shifts in rainfed areas only in the total effects when allowing both rainfed and irrigated areas to increase by the factor α. The sensitivity results show the dominance of only shifting crops within the rainfed area in the contribution of reducing maximum blue water scarcity.

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.

A number of relevant citations, including the ones suggested by the reviewer, has been added to the paper's introduction.

Specific comments

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

This citation and another relevant one has been added to highlight the effect of food loss reduction on water use.

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). **(Line 78-80)**

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 are only changing cropping patterns while maintaining the same global production per crop whereas Davis et al. (2017a) aim for a higher caloric and protein production while reducing water use; that also results in a different global consumption pattern, which hampers the identification of potential water saving effects of just production shifts amongst countries. Second, we consider a larger number of crops (125 crops including vegetables, fruits and pulses which were not considered in Davis et.al., (2017a) study).” **(Line 109-114)**

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.” **(Line 440-443)**

“Changing cropping patterns could reduce global blue water footprint by 21% and global irrigated area by 10%. These findings prove that current high scarcity levels in a serious number of countries is shown to be caused by the current crop allocation pattern, rather than by an inevitability of those scarcities to occur; that suggests that water endowment is insufficiently driving crop allocation to avoid water scarcity. This in consistent with Zhao et al., (2019) who find in their study for China that comparative advantages with respect to labour and water were not reflected in the regional distribution of agricultural production. However, not all countries would benefit similarly in the optimized set, India and China, main crop producers in the reference situation, will only start to have a decrease in their blue water scarcity when the allowed expansion rate is larger than 20%. 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).” **(Line 453-463)**

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: “(With cropping pattern we mean the allocation of crops to rainfed and irrigated land in all countries in the world, where both rainfed and irrigated area of each crop in each country is allowed to expand up to a modest maximum rate (factor α), while respecting the bounds of current total rainfed and total irrigated area per country as well as the global production per crop.)”. **(Line 122-125)**

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”. **(Line 147-149)**

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

We added the following: “Blue water footprint (BWF) refers to the volume of consumptive freshwater use for irrigation that comes from surface and groundwater”. **(Line 160-161)**

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

We minimize average water scarcity in countries; within countries scarcity differences will still appear, both in the reference situation and in the case of the optimized cropping patterns. Still, water scarcity indicators at national levels provide insight; within the framework of the Sustainable Development Goals, indicator 6.4.2 (Level of water stress), is used to monitor Goal 6 (Ensure availability and sustainable management of water and sanitation for all); it is defined similar to water scarcity in our study, 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. Relieving water scarcity in specific hotspots within countries by changing cropping patterns could be studied using the current approach but is beyond the scope of this paper. This has been added to the paper’s discussion. **(Line 412-421)**

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 has been shortened and the results section has been reshaped.

L367ff Also discuss the real-life meaning and consequences of optimized global cropping pattern, 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."

The paper has been improved textually.

Response to comments from reviewer RC2

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

The study on "Changing global cropping patterns to minimize blue water scarcity in the world's hotspots" provides a new view of possibility to reduce crop-related blue water footprint and diminish the severe blue water scarcity worldwide. Plenty work has been done in this study; however, I feel that some parts in the text require careful revisions and improvements before it can be further considered for publication in HESS.

We appreciate the positive appraisal of the commentator and the useful comments that will be addressed in the following response.

1. *Line 31, you mentioned in the abstract 'changing spatial cropping patterns and international crop trade...", but just showing the 'spatial cropping patterns' changes. It could be much better to look at further on hotspot countries in terms of the responses in trade patterns (just changes in crop trade balances).*

We did consider but decided not to discuss trade balance changes in the paper, to keep the central messages of the paper clear; we agree that the abstract should not suggest otherwise. Discussing changes in international trade patterns will go along with discussing which changes in the cropping pattern would rather increase current trade flows, and which would dampen or reverse current trade flows. The basic underlying message would not be different than in the current manuscript, but the comparison to the reference situation is more complicated than for the cropping pattern.

2. *Line 111, in the introduction of study content, information on how many types of crops considered is lacking.*

The following has been added: "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". **(Line 147-149)**

3. *Line 112-113, the first and second constrains seems conflict each other.*

The way how constrains are written now may cause a bit of confusion. A clearer description reads:

"First, **total** rainfed and irrigated harvested areas in each country should not grow beyond their extent in the reference period 1996-2005. Second, the harvested area per country per crop can only expand by a limited rate (which will be varied), both for the rainfed and irrigated area." **(Line 126-129)**

We thank the reviewer for spotting that and we added the word "total" in the two lines he referred to clearly make the difference between total harvested areas that should not grow beyond the total available harvested areas in the reference period and per crop per country harvested area that could be extended which may result in shifts in cropping patterns.

4. How do you define the 'cropping pattern'.

The following explanation has been added to the paper's introduction: With cropping pattern we mean the allocation of crops to rainfed and irrigated land in all countries in the world, where both rainfed and irrigated area of each crop in each country is allowed to expand up to a modest maximum rate (factor α), while respecting the bounds of current total rainfed and total irrigated area per country as well as the global production per crop. **(Line 122-125)**

5. In the analysis, how the green water limits were considered? I am wondering if there are some places with increasing green WFs but have insufficient green water availability?

This is a relevant question from a sharp observation. Green water limitation is considered implicitly in the study through consideration of rainfed harvested area and irrigated harvested area separately and by considering rainfed land productivity. Furthermore, the alpha factor is separately applied to the rainfed and irrigated land. Increasing rainfed production could also be the result of shifting crops to more productive crops (higher rainfed land productivity). This can implicitly increase green water consumption, even when that increase is limited by the alpha factor and the differences in green water consumption by crops. The relevance of the effect is estimated in the sensitivity analysis added to the updated version of the paper.

6. Line 213, for China you show an 4% increase in BWC. It looks tiny for the whole country, but could matter when such increases in BWC happend in a very severe blue water scarce places within the country. At least some discussion regarding this should be in somewhere of the text. In addition, I am also worry about the assumptions of increasing harvested area per crop so that it could resulted in increases in harvested area in each country, or I could be wrong in understanding the first assumption. Given that for example in China, the national policy is controlling not reducing the total crop harvested area to a level with no possibility to increase anymore... The issue is also important for developing countries facing rapid urbanization in land. Maybe better to discuss this in some points.

We thank the reviewer for his suggestion. The optimization algorithm has been updated in a way that an increase in blue water use is no longer allowed. The optimization will try to reduce the water scarcity of all countries starting by the most water-scarce countries when the allowed expansion is low.

About the reviewer's second concern in this comment, the harvested area per country is a constraint in our model. The harvested area for a specific crop could extend by 10% but the total harvested area will remain the same, unless the optimization indicates global production is achieved with less area. Countries will increase the harvested area of the crops in which they have a comparative advantage in terms of blue water and land use and decrease the harvested area of the crops in which they have a comparative disadvantage, this should keep total harvested area per country less or equal to the reference period.

The paper does not consider potential crop land expansions (rainfed or irrigated) to produce additional food to fulfil growing demands, neither does it study effects of improved agricultural practices that may relieve pressure on land and water resources. We agree that the discussion issue raised by the author is relevant in general, but want to restrict specific discussion issues to the scope of the paper.

7. I get confusions when reading the Discussion. It looks too much limitations to get published, too 'optimized' beyond the real. It may be nice to look into the mass of results and pick some countries with results that really meaningful for local national water management. Please carefully consider about how to interprate in the discussion part. Another limitation should be in caution is the issue related to green water availability, scarcity and limits.

The description of the results has been shortened and most important changes has been highlighted and discussed in the discussion

minor comments:

1. *Line 61, better to give the full name of WEF, either in the reference list.*

WEF refers to the World Economic Forum. The full name is specified in the reference list.

2. *Table 1, the initial sources of harvested areas or productions should be listed as well.*

The initial source of the harvested areas and productions is FAOSTAT (FAO, 2015). This is now added in Table 1.

Response to comments from reviewer RC3

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

General comments:

The research on "Changing global cropping patterns to minimize blue water scarcity in the world's hotspots" used a linear optimization algorithm to assess how to change global cropping patterns to reduce blue water-scarce hotspots, with the constraints of global production per crop and current cropland areas. Below are my comments and suggestions:

We thank the reviewer for his critical comments and suggestions.

1. The linear optimization algorithm is set for an optimal reduction of blue water scarcity by changing global spatial cropping patterns. The algorithm set an upper limit of the expansion in cropland by a certain maximum rate for each crop per country (the factor ð˙IZij), and also limit total cropland to the reference extent. However, there is no lower limit of decrease in cropland area, which means cropland area (or crop production) for some crop types would decrease a lot or even disappear (as shown in results part).

Why you set an upper limit, but without a lower limit? If you also set both upper and lower limits of changes in cropland for each crop, do the results change?

The upper limit is set in order to prevent countries to unrestrictedly expand their cropland in crops where they have comparative advantage. The modest allowed changes in cropping areas of individual crops are aimed to avoid implausible expansions of crop production into cropland areas with significantly different rainfed and irrigated land productivity than where the specific crop is produced currently, due to the heterogeneity within a country (e.g. covering different agroecological zones). However, we do allow countries to decrease their cropland freely without setting a lower limit because here the plausible physical validity of the production characteristics is not compromised. In fact, moving from irrigated production to rainfed production as much as possible is directly related to maximizing the reduction of blue water use and thus blue water scarcity which links to the research objective of this paper.

Explicitly setting a lower limit to the allowed change in cropland for each crop will obviously have a significant change in the results. The changes will be more apparent for the most water-scarce countries. If for example we enforce countries to reduce production per crop and production system by at most 50%, the water scarcity will remain at least 50% of the actual one. We added a discussion about the trade-off between the global objective of countries jointly reducing the global blue water scarcity and about the effect of that on each individual country, for example the increase of food import dependency for some countries. we decided not to add alternative formal optimizations to further substantiate this discussion point as results are very predictable and does not significantly contribute to the current paper's objective.

2. Blue water scarcity (BWS): BWS is defined as the total blue water footprint divided by the blue water availability in the country. Here blue water footprint only includes agriculture sector, without water footprint for domestic and industrial. Blue water availability is the natural runoff, which follows Hoekstra et al. (2012), right?

We acknowledge the validity of the point highlighted by the reviewer. Indeed, blue water has other uses than the agricultural sector (e.g. domestic and industrial). However, the share of agriculture consumptive water use is by far the largest, accounting for 92% of water consumption globally (Hoekstra and Mekonnen, 2012) (mentioned in the submitted version of the paper Line 69-70).

We also thank the reviewer for his suggestion to clarify the definitions of the terms used. We, therefore, added the following:

"Blue water scarcity (BWS) is defined per country i as the total blue water footprint divided by the blue water availability in the country (Hoekstra et al., 2012). The blue water footprint (BWF) refers to the volume of consumptive freshwater use for irrigation that comes from surface and groundwater. Blue water availability is taken from FAO (2015) and refers to the total renewable (internal and external resources) which is the long-term average annual flow of rivers (surface water) and sustainably available groundwater (FAO, 2003)". **(Line 159-163)**

3. L145: "A country is considered to be under low, moderate, significant or severe water scarcity when BWS is lower than 20%, in the range 20-30%, in the range 30-40% and larger than 40%, respectively (Hoekstra et al., 2012)". Hoekstra et al (2012) analysed the BWS at basin level and monthly time scale. But this study assesses water scarcity at country level and annual time scale, I think more discussion is needed to illuminate whether the index used here is suitable.

We fully agree that considering BWS at national and annual resolution may (and will) hide scarcity localised in time and space. This does limit the interpretability of results at the coarse resolution, and we acknowledge that the discussion on the suitability could be more explicit. We also note that FAO has selected the very similar indicator 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 added 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. The sensitivity analysis showed that the shifts in rainfed areas only had a dominant share in reducing the maximum blue water scarcity for different expansion factors α, as is discussed in the paper.

4. L148: why you choose maximum national blue water scarcity in the world as the indicator for optimization?

We minimize average water scarcity in countries; within countries scarcity differences will still appear, both in the reference situation and in the case of the optimized cropping patterns. Still, water scarcity indicators at national levels provide insight; within the framework of the Sustainable Development Goals, indicator 6.4.2 (Level of water stress), is used to monitor Goal 6 (Ensure availability and sustainable management of water and sanitation for all); it is defined similar to water scarcity in our study, 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. Relieving water scarcity in specific hotspots within countries by changing cropping patterns could be studied using the current approach but is beyond the scope of this paper. This has been added to the paper's discussion. **(Line 412-421)**

5. There are too much results about the changing cropping patterns and comparative advantages. I think the authors could add more explanation on the mechanism behind the changes, especially for some typical countries.

We thank the reviewer for his suggestion. The results section has been reshaped and some main finding of typical countries has been highlighted. We also added some discussion of major crops producers' countries in the paper's discussion part:

"Findings suggest that China, one of the main producers of the major crop in the world, will abandon soybean production and halve wheat irrigation area. This will relieve some of the pressure on the northern part of China where water scarcity is the most severe (Ma et al., 2020). China will increase the harvested area of rice and rapeseed, the crops with the most significant comparative advantage in terms of land and water. Similarly, our results suggest that the US, another major crops producer, would and restrict soybean production to rainfed systems, abandoning irrigation, in the optimized set in the US. The US focuses on producing maize, mainly rainfed, for which the US has a comparative advantage in terms of water and land productivities. This may be a great relief to the US corn belt where most of irrigated soybeans and maize are located (Zhong et al., 2016) and could be a remedy to the projected water shortage of that region resulting from population growth and climate change (Brown et al., 2019). We also find that India, another major producer of crops in the world, will move away from sorghum production and shift a large share of its rice and wheat production to rainfed conditions. Moving to rainfed production in India could mitigate the effect of the intensive use of irrigation from groundwater and surface water which caused groundwater degradation in many districts of Haryana and Punjab, the largest contributing states to rice and wheat production in India (Singh, 2000)". **(Line 464-476)**

6. Discussion part: Previous studies have done a lot of works on the impacts of changing cropping patterns, international food trade and better water productivity on water scarcity (as list in introduction part). I think the discussion part should add more about the similarity and difference between the results in this study and previous studies.

We highlighted our results in the context of previous studies in the discussion part. For instance, we added the following:

"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. Besides reducing water and land use, changing cropping pattern will also have an impact on reducing GHG emission that results from extensive energy activities in irrigation such as groundwater pumping which accounted for around 61% of total irrigation emissions in China (Zou et al., 2015)". **(Line 440-444)**

"Changing cropping patterns could reduce global blue water footprint by 21% and global irrigated area by 10%. These findings prove that current high scarcity levels in a serious number of countries is shown to be caused by the current crop allocation pattern, rather than by an inevitability of those scarcities to occur; that suggests that water endowment is insufficiently driving crop allocation to avoid water scarcity. This in consistent with Zhao et al., (2019) who find in their study for China that comparative advantages with respect to labour and water were not reflected in the regional distribution of agricultural production. However, not all countries would benefit similarly in the optimized set, India and China, main crop producers in the reference situation, will only start to have a decrease in their blue water scarcity when the allowed expansion rate is larger than 20%. 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)". **(Line 453-463)**

7. More discussions should focus on how the results represented in this study could guide global international food trade, as well as cropping patterns to cope with global water scarcity, especially under future climate change and socioeconomic development. For example, blue water scarcity would intensify in the future as reported in previous studies. And following the results in this study, a water-scare country could reduce agriculture water scarcity by reducing cropland area for some crop types, and import crop production from other countries.

We added discussion in the direction suggested by the reviewer. This closely links to comment 5, where we agree that the extensive result reporting took away from highlighting main patterns in findings that can feed into discussions on the role of agricultural trade in water scarcity alleviation policy.

8. When α is equal to 1.3, 1.5 and 2.0, the maximum national blue water scarcity in the world is reduced to 6%, 4% and 2%, respectively. " In my view, a larger α would result in greater global blue water scarcity reduction, but current study shows the opposite result. So, I just wonder the definition of "the maximum national blue water scarcity in the world"?

Indeed, a higher alpha result in a larger water scarcity reduction. The sentence has been rephrased to better emphasize that a WS reduction to a maximum water scarcity of 2% (for alpha = 2) is a further-reaching reduction than a reduction to 6% for alpha =1.3, thus avoiding that *reduced to* is interpreted as *reduced by*.

9. Figure 4. This figure is not clear. Please give the unit and meaning of this figure.

We thank the reviewer for his suggestion. We edited the title of Figure 4 to include more information about the Figure and make it easy to understand. The title of the Figure is now the following:

"Absolute change in production for cereals, fruits, oil crops, sugar crops and vegetables per country (in 10^6 t/yr) (maps on the left hand) and relative production (ratio of production in optimized and reference situation) for the same crops groups for the case of an optimized cropping pattern with α=1.5 (maps on the right hand), all compared to the reference cropping period (1996-2005): relative production = 1: no change, relative production < 1: countries production is reduced and relative production > 1: countries production is expanded".

10. Figure 5. There are only tiny differences between figures in the left and right. It's better to show the differences or relative changes.

We agree to the comment and we changed both Figures 4 and 5. The new figures show both absolute and relative changes in production for all considered crop groups.

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Changing global cropping patterns to minimize national blue water scarcity ~~in the world's hotspots~~

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Abstract

Feeding a growing population with global natural resource constraints becomes an increasingly challenging task. Changing spatial cropping patterns and international crop trade could contribute to sustain crop production and mitigate water scarcity. Previous studies on water saving through international food trade focussed either on comparing water productivities among food-trading countries or on analysing food trade in relation to national water endowments. Here, we consider, for the first time, how both differences in water productivities and water endowments can be considered to analyse comparative advantages of countries for different types of crop production. A linear optimization algorithm is used to find modifications in global cropping patterns that reduce national blue water scarcity in the world's ~~hotspots~~most severely water-scarce countries, under the constraint of current global production per crop and current cropland areas. The optimization considers national water and land endowments as well as water and land productivity per country per crop. The results are used to assess national comparative advantages and disadvantages for different crops. When allowing a maximum expansion of harvested area per crop per country of 10%, the blue water scarcity in the world's most water-scarce countries can be greatly reduced. In this case, we could achieve a reduction of the current blue water footprint of crop production in the world of ~~9~~21% and a decrease of the total global ~~total~~ harvested ~~area~~and irrigated areas of ~~4%.~~2% and 10% respectively.

Keywords: global food supply; spatial crop distribution; water scarcity; comparative advantage; ~~international trade~~optimization

Introduction

Water scarcity poses a major societal and economic risk (WEF, 2019) and threat to biodiversity and environmental sustainability (Vörösmarty et al., 2010). Population growth and climate change are expected to worsen the situation and impose more pressure on freshwater resources everywhere (Vörösmarty et al., 2000; Parry et al., 2004). Since water consumption already exceeds the maximum sustainable level in many parts of the world (Hoekstra et al., 2012) and population growth in water-scarce countries alone could enforce global international trade in staple crops to increase by a factor of 1.4 to18 towards 2050 (Chouchane et al., 2018) solutions are urgently needed for a more sustainable allocation of the world's limited freshwater resources (Hoekstra, 2014; Konar et al., 2016).

Considerable debate has arisen over the last few decades on the pathways to overcome the problem of water scarcity and its implications (Gleick, 2003), especially for agriculture, the largest consumer of freshwater, accounting for 92% of water consumption globally (Hoekstra and Mekonnen, 2012). A growing number of studies addresses the question of how to mitigate problems related to blue water scarcity (Wada et al., 2014; Kummu et al., 2016~~; Wada et al., 2014~~). Some proposed solutions focus on better water management in agriculture (Evans and Sadler, 2008), for instance improving irrigation efficiency and precision irrigation (Sadler et al., 2005; Greenwood et al., 2010~~; Sadler et al., 2005~~), better agricultural practices like mulching and drip irrigation (~~Nouri et al., 2019;~~ Mukherjee et al., 2010; Chukalla et al., 2015; Nouri et al., 2019), improved irrigation scheduling (Jones, 2004) and enhancing water productivity (Bouman, 2007; Molden et al., 2010; Pereira et al., 2012~~;Bouman, 2007~~). Other suggested solutions focus on changing diets ~~to reduce water consumption~~ (Vanham et al., 2013; Jalava et al., 2014; Gephart et al., 2016)~~. Yet another category of studies focusses on spatial cropping patterns (Davis et al. 2017a~~ and reducing food losses (Munesue et al., 2015; Jalava et al., 2016) to diminish water consumption. Yet another category of studies focusses on spatial cropping patterns (Davis et al., 2017a; Davis et al., 2017b) and the role of international trade in saving water and in bridging the gap between national water demand and supply in water-short countries (Chapagain et al., 2006; Hoekstra and Hung, 2005). The trade in 'embedded water' ~~through food trade is~~ (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). According to international trade theory, countries can profit from trade by focussing on the production and export of goods for which they have a comparative advantage. What precisely constitutes comparative advantage is still subject to debate. Whereas Ricardo's theory of comparative advantage says that a country can best focus on producing goods for which they have relatively high productivity, the Heckscher-Ohlin theory states that a country can best specialize in producing and exporting products that use production factors that are comparatively most abundant. When focussing on the role of water in trade, the first theory would consider relative water productivity (crop per drop), while the second theory would look at relative water abundance (Hoekstra, 2013). Part of the literature on water saving through international food trade has focussed on comparing water productivities among food-trading countries (Chapagain et al., 2006; Yang et al., 2006;~~Chapagain~~ Oki et al., ~~2006~~2017), while other studies have concentrated on analysing food trade in relation to water endowments (Yang et al., 2003; Oki and Kanae, 2004;

Chouchane et al., 2018). In a study for China, Zhao et al., (2019), evaluated spatio-temporal differences in regional water, land and labour productivity of agricultural and non-agricultural sectors across Chinese provinces, and defined comparative advantage on that basis. These comparative advantages were used to track the driving force of virtual water regional trade. Their findings suggest that differences in land productivity were the main forces shaping the pattern of virtual water flows across Chinese regions while neither labour nor water productivity had significant influence.

In the current study, we consider, for the first time, how both differences in water productivitiesproductivity and water endowmentsendowment can be considered to analyse comparative advantages of countries for different types of crop production. While doing so, we also consider differences between countries in land productivities (crop yields) and land endowments (available cropland areas).

Studies on spatial allocation of crop production, given differences in land and water productivity and endowments, are sparse, particularly large-scale studies. In local or regional studies that study best crop choices given land and water constraints, the focus is generally to maximize food production or agricultural value, without the requirement of fulfilling overall crop demand. (Osama et al., (2017), for example, employ a linear optimization model for some regions in Egypt to maximize the net annual return by changing the cropping pattern, given water and land constraints, and conclude that some crops are to be expanded while others are to be reduced. Another example of a regional study is (Ye et al., 2018)Ye et al. (2018), who used a multi-objective optimization model, considering the trade-offs between economic benefits and environmental impact of water use when changing the cropping pattern in a case study for Beijing.

In a study for the US, Davis et al. (2017b) investigated an alternative crop distribution that saves water and improves productivity while maintaining crop diversity, protein production and income. The only global study on changing cropping patterns in order to reduce water use, to our knowledge, is (Davis et al., 2017a)Davis et al., (2017a), who combine data on water use and productivity for 14 major crops and show that changing the distribution of these crops across the currently cultivated lands in the world could decrease blue water use by 12% and feed an additional 825 million people. However, the current study has a number of differences with Davis et al., (20017a). First, we are only changing cropping patterns while maintaining the same global production per crop whereas Davis et al. (2017a) aim for a higher caloric and protein production while reducing water use; that also results in a different global consumption pattern, which hampers the identification of potential water saving effects of just production shifts amongst countries. Second, we consider a larger number of crops (125 crops including vegetables, fruits and pulses which were not considered in Davis et.al., (2017a) study).

Although it has been widely acknowledged that the spatial water scarcity pattern in the world can be explained by where crops are grown and how much they are irrigated (Wada et al., 2011; Mekonnen and Hoekstra, 2016), it has not yet been studied how differences between countries in water and land productivities and endowments can be used to derive comparative advantages of countries for specific crops, and how a change in the global cropping pattern can reduce water scarcity in the

~~places that are~~ most water-scarce places. Here, we explore how we can stepwise minimize the highest national water scarcity in the world by changing cropping patterns and ~~blue water allocation to crops.~~the related blue water allocation to crops. The spatial resolution of the country level reflects the coarse resolution at which FAO monitors and reports water stress in the SDG framework (FAO, 2018); subnational heterogeneity in water scarcity, that is significant in countries like USA or China, is not covered at this resolution. With cropping pattern we mean the allocation of crops to rainfed and irrigated land in all countries in the world, where both rainfed and irrigated area of each crop in each country is allowed to expand up to a modest maximum rate (factor α), while respecting the bounds of current total rainfed and total irrigated area per country as well as the global production per crop. For this purpose, we develop and apply a linear programming optimization algorithm considering a number of constraints. First, total rainfed and irrigated harvested areas in each country should not grow beyond their extent in the reference period 1996-2005. Second, the harvested area per country per crop can only expand by a limited rate (which will be varied~~).~~), both for the rainfed and irrigated area. Third, global production of each crop must remain the same as in the reference period. The optimization takes into account both factor endowments (blue water availability, rainfed land availability and irrigated land availability) in each country and factor productivities (blue water productivity in irrigation, and land productivities in rainfed and irrigated lands) for each crop in each country. In order to focus on aspects of natural resource endowment and productivity in relation to water scarcity, other important aspect such as socio-economic or national food self-sufficiency goals were left out of consideration.

Methods and data

We developed a linear optimization algorithm in MATLAB. In the optimization we allow the global cropping pattern to change, that is to grow crops in different countries than in the reference situation. In the optimization, the cropping areas by crop, country and production system are the independent variables, and the following constraints are considered. First, both total rainfed and total irrigated harvested area per country are not allowed to expand. Second, both crop-specific rainfed and irrigated harvested area per country are allowed to expand, but not beyond a factor α (whereby we stepwise increase α from 1.1 to 2.0 in a number of subsequent experiments). Third, global production of each crop should remain equal to the global production of the crop in the reference situation. For any cropping pattern, the water scarcity in each country is computed, and the country with the highest water scarcity identified. The objective of the optimization is to minimize this highest water scarcity. The algorithm ~~allows blue water scarcity in water-abundant countries to increase, but~~ continuously tries to reduce the blue water scarcity in the countries with the highest blue water scarcity~~.~~ while disallowing blue water scarcity in any country to increase. The algorithm will thus tend to reduce and equalize blue water scarcity in the most water-scarce countries.

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.

Given the cropping pattern, production is computed per country and crop, both for rainfed and irrigated lands based on the harvested area and crop yields:

$$\forall i,j: P_{rf}(i,j) = A_{rf}(i,j) \times Y_{rf}(i,j)$$

$$\forall i,j: P_{ir}(i,j) = A_{ir}(i,j) \times Y_{ir}(i,j)$$

$$\forall i,j: P(i,j) = P_{rf}(i,j) + P_{ir}(i,j)$$

whereby $P_{rf}(i,j)$, $P_{ir}(i,j)$ and $P(i,j)$ are the rainfed, irrigated and total production in country *i* of crop j; $A_{rf}(i,j)$ and $A_{ir}(i,j)$ the rainfed and irrigated harvested area in country i for crop j; and $Y_{rf}(i,j)$ and $Y_{ir}(i,j)$ the rainfed and irrigated crop yield in country *i* for crop *j*.

Blue water scarcity (BWS) is defined per country *i* as the total blue water footprint divided by the blue water availability in the country (Hoekstra et al., 2012). The blue water footprint (BWF) refers to the volume of consumptive freshwater use for irrigation that comes from surface and groundwater. Blue water availability is taken from FAO (2015) and refers to the total renewable (internal and external resources) which is the long-term average annual flow of rivers (surface water) and sustainably available groundwater (FAO, 2003).

$$BWS(i) = \frac{\sum_j P_{ir}(i,j) \times BWF(i,j)}{BWA(i)}$$

where $P_{ir}(i,j)$ is the irrigated production in country *i* of crop *j*, $BWF(i,j)$ the blue water footprint per unit of crop *j* in country *i*, and $BWA(i)$ the blue water availability in country *i*. A country is considered to be under low, moderate, significant or severe water scarcity when BWS (expressed as a percentage) is lower than 20%, in the range 20-30%, in the range 30-40% and larger than 40%, respectively (Hoekstra et al., 2012).

The optimization can be presented as follows:

~~$\min_{A_{rf},A_{irr}} \left(\max_{i}(\mathrm{BWS}(i))\right)$~~ $\min_{A_{rf},A_{irr}} \left(\max_{i}(\mathrm{BWS}(i))\right)$

subject to:

$$\forall i: \sum_j A_{rf}(i,j) \leq \sum_j A_{rf,ref}(i,j)$$

$$\forall i: \sum_j A_{ir}(i,j) \leq \sum_j A_{ir,ref}(i,j)$$

$$\forall i,j: A_{rf}(i,j) \leq \alpha \times A_{rf,ref}(i,j)$$

$$\forall i,j: A_{ir}(i,j) \leq \alpha \times A_{ir,ref}(i,j)$$

$$\forall j: \sum_i P(i,j) = \sum_i P_{ref}(i,j)$$

$$\forall i: BWS(i) \leq BWS_{ref}(i)$$

where $A_{rf}(i,j)$ and $A_{ir}(i,j)$ are the rainfed and irrigated harvested areas in country *i* of crop *j* in the cropping pattern that is varied in order to minimize the highest national blue water scarcity, $A_{rf,ref}(i,j)$ and $A_{ir,ref}(i,j)$ are the rainfed and irrigated harvested areas in the reference situation~~),~~, $P(i,j)$ is the total (rainfed plus irrigated) production in country *i* of crop *j* in the new cropping pattern, and $P_{ref}(i,j)$ is the total (rainfed plus irrigated) production in country *i* of crop *j* in the reference situation~~.~~, and $BWS_{ref}(i)$ is the blue water scarcity in country *i* in the reference situation. Parameter α is the factor of maximally allowed expansion of the harvested area per crop and country and production system (rainfed or irrigated), which is varied in the optimization experiments between 1.1 and 2. Note that total national croplands (both rainfed and irrigated) are not allowed to expand, but that reductions in land use are always allowed.

A country is considered to have a comparative advantage for producing a certain crop or crop group when the following criteria are met: (1) the relative change (production in the optimized cropping pattern divided by the production in the reference situation) of that crop or crop group continues to increase in that country when we gradually increase the maximum allowed expansion of harvested area per crop per country (the factor α); and (2) the share of the country in the global production of the crop or crop group exceeds 5% (in the optimized cropping pattern at $\alpha = 1.1$).

In order to test the sensitivity of the optimization results to the allowed changes in irrigation, we run the optimization without allowing any expansion of irrigated area. In this case, the factor α will be only applied to the rainfed area while the irrigated area per country per crop will be below or equal to the irrigated area of the same crop in the same country in the reference situation. The optimization objective and constraints remain the same except that the following constraint was added:

$$\forall i,j: A_{ir}(i,j) \leq A_{ir,ref}(i,j)$$

The sources of the data used to perform the optimization are summarized in Table 1.

Table 1. Overview of data used.

Variable	Spatial resolution	Temporal resolution	Source
Blue water availability	Country (internal + external renewable water resources)	Average for 1961-1990	(FAO, 2015)
Harvested irrigated and rainfed land per crop in the reference situation	Country	Average for 1996-2005	(Mekonnen and Hoekstra, 2011), (FAO, 2015)
Rainfed and irrigated production per crop in the reference situation	Country	Average for 1996-2005	(Mekonnen and Hoekstra, 2011), (FAO, 2015)
Blue WF per unit of crop in irrigated production per crop	Country	Average for 1996-2005	(Mekonnen and Hoekstra, 2011)
Yield in rainfed and irrigated production per crop	Country	Average for 1996-2005	(Mekonnen and Hoekstra, 2011)

Results

Changes in blue water scarcity and blue water consumption

When α is 1.1, that means when we allow a maximum of 10% expansion of the reference harvested areas for each individual crop, in every country, both for rainfed and irrigated production, blue water scarcity in the world's seven most water-scarce countries, Libya, Saudi Arabia, Kuwait, Yemen, Qatar, Egypt, and Israel (with current scarcities ranging from 54% to 270%) is reduced to a scarcity of 39% or less (Table 2). In this scenario, the aggregated blue water footprint of crop production in the world ~~will get~~is reduced by ~~9~~21%, while the total global harvested ~~area will be~~and irrigated areas got reduced by ~~4%.~~ 2% and 10% respectively.

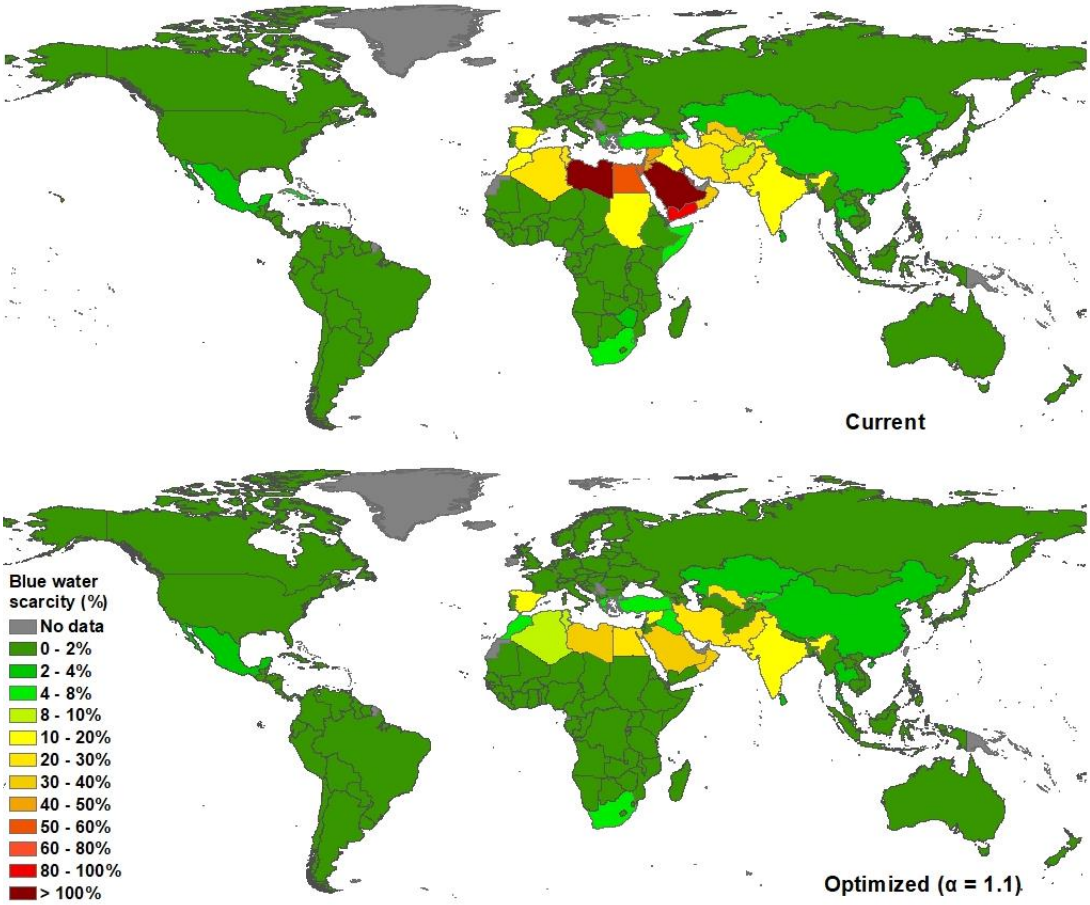
When α is equal to 1.3, 1.5 and 2.0 (i.e., when the maximally allowed expansion of harvested area per crop per country is equal to 30%, 50% and 100%), the maximum national blue water scarcity in the world is further reduced to 6%, 4% and 2%, respectively. In these scenarios, global blue water consumption gets reduced by ~~34, 47~~38%, 48% and ~~58~~60%, respectively, ~~while~~ the total global harvested area gets reduced by 6%, 7% and 9%, respectively and the total global irrigated area gets reduced by 23%, 27% and 37% respectively.

Table 2. Current versus optimized blue water consumption (BWC) and blue water scarcity (BWS) for countries currently having a water scarcity higher than 15%.

Countries	Current		Optimized ($\alpha = 1.1$)		Optimized ($\alpha = 1.3$)		Optimized ($\alpha = 1.5$)		Optimized ($\alpha = 2.0$)	
	BWC (10^6 m^3/yr)	BWS (%)	BWC (10^6 m^3/yr)	BWS (%)	BWC (10^6 m^3/yr)	BWS (%)	BWC (10^6 m^3/yr)	BWS (%)	BWC (10^6 m^3/yr)	BWS (%)
Libya	1900	270%	280210	3930%	41	6%	25	4%	16	2%
Saudi Arabia	6200	260%	940	39%	140	6%	8687	4%	54	2%
Kuwait	48	240%	8	39%	1	6%	1	4%	0	2%
Yemen	2100	98%	32.8	0%	293	10%	7576	4%	4748	2%
Qatar	51	88%	23	39%	3	6%	2	4%	1	2%
Egypt	34000	57%	170003800	307%	3400	6%	2100	4%	1300	2%
Israel	960	54%	54340	319%	49100	36%	6465	4%	40	2%
Jordan	410	43%	070	08%	1055	16%	34	4%	21	2%
Syria	7000	42%	2600690	154%	990	6%	600610	4%	380	2%
Oman	550	39%	520550	3739%	82	6%	5051	4%	3132	2%
Uzbekistan	15000	31%	13000	2726%	2900890	62%	1800	4%	1100	2%
Cyprus	240	31%	059	08%	246	06%	28	4%	1718	2%
Pakistan	74000	30%	6700015000	276%	14000	6%	89009000	4%	55005600	2%
Iran	40000	29%	400008400	306%	8000	6%	49005000	4%	3100	2%
Tunisia	1300	29%	400530	911%	270	6%	170	4%	100	2%
Algeria	2700	23%	19001100	1016%	690	6%	420430	4%	260	2%
Turkmenistan	5300	21%	500520	2%	1500620	63%	890900	4%	550560	2%
Morocco	5100	18%	15003100	511%	1700	6%	11001000	4%	650660	2%
Malta	9	17%	08	015%	03	06%	2	4%	1	2%
Lebanon	770	17%	45730	116%	54260	16%	160	4%	100	2%
Sudan	6100	16%	7002100	26%	2200	6%	1400	4%	850860	2%
Global	**820000**		**750000650000**		**540000510000**		**440000430000**		**350000330000**	

Most countries with severe water scarcity (BWS>40%) in the reference situation will haveshow a moderate (BWS in the range 20-30%) to low water scarcity (BWS<20%) in the optimized situation with α = 1.1 (Figure 1). The blue water scarcity reduction in most countries comes at the price of a slight increase in BWS of some countries. In India, BWS increases from

~~12.1 % to 12.7%, in Iran from 29.1 % to 29.6 % and in Turkey 7.2% to 7.4%.~~However, not all countries would benefit similarly in the optimized situation. China and India, major crops producers in the reference situation, only start to have a decrease in their BWS when α ≥ 1.3.



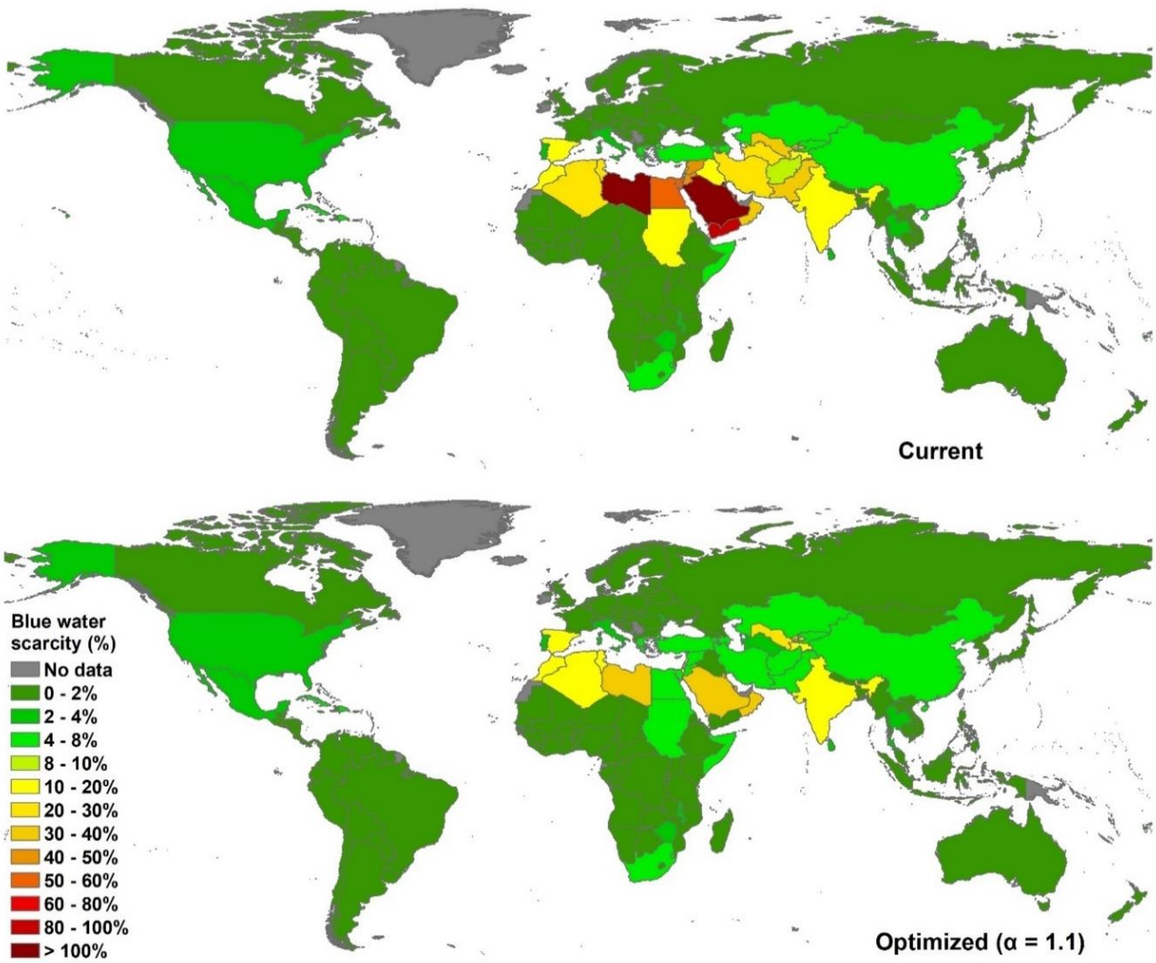
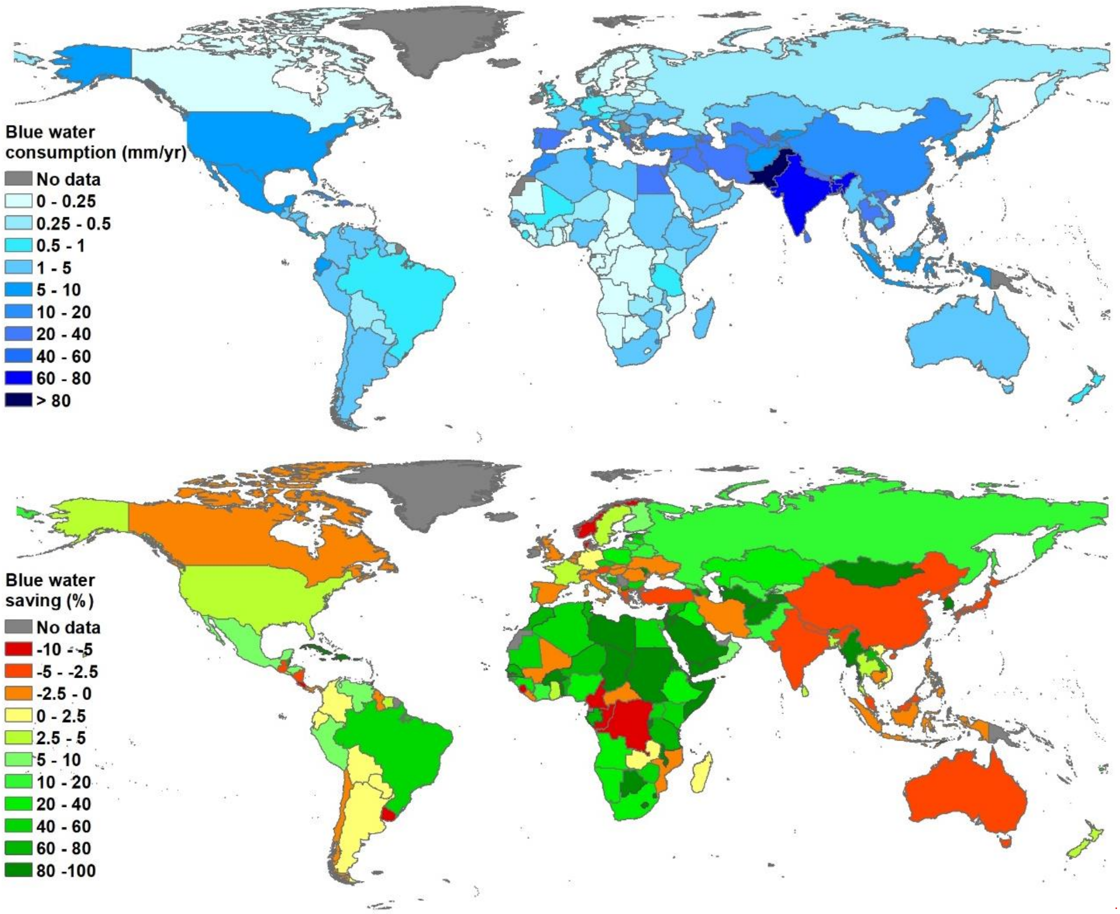


Figure 1. Current and optimized ($\alpha = 1.1$) blue water scarcity.

In the case of α = 1.1, ~~Egypt will have~~Pakistan, the 3rd largest consumer of blue water in the reference situation, has the largest reduction in its blue water consumption in absolute terms, viz. ~~17~~60,000 m^3/yr, which represents ~~50~~80% of its current BWC and ~~24~~35% of the global blue water saving. Other countries that have a significant reduction in their BWC in absolute terms include ~~Pakistan, Sudan~~Iran, Egypt, Iraq, Syria, Saudi Arabia, ~~Afghanistan,~~Sudan and Turkmenistan~~, Iraq and Syria. Although the largest consumer of blue water in the reference situation, Pakistan, will get its current BWC reduced by 10%, the other two larger consumers, India and China, will have slight increases in their BWC (5% and 4% respectively)~~ (Figure 2). ~~Other~~However, not all countries ~~that will have an increase in their BWC (e.g. Australia, Austria, Bangladesh, Congo,~~ would benefit similarly in the optimized set, India and China, the ~~Democratic Republic~~first and second largest consumer of blue water in the ~~Congo, Greece, Japan, Malaysia, Norway, Turkey, Uruguay, and Sierra Leona)~~reference situation, will only start to have a ~~relatively low initial BWC.~~ decrease in their blue water scarcity when the allowed expansion rate α is larger than 1.2; this is due to the optimization of water scarcity at the level of countries, where India and China have modest national water scarcity.


Blue water
consumption (mm/yr)
No data
0 - 0.25
0.25 - 0.5
0.5 - 1
1 - 5
5 - 10
10 - 20
20 - 40
40 - 60
60 - 80
> 80
Blue water
saving (%)
No data
-10 - -5
-5 - -2.5
-2.5 - 0
0 - 2.5
2.5 - 5
5 - 10
10 - 20
20 - 40
40 - 60
60 - 80
80 -100

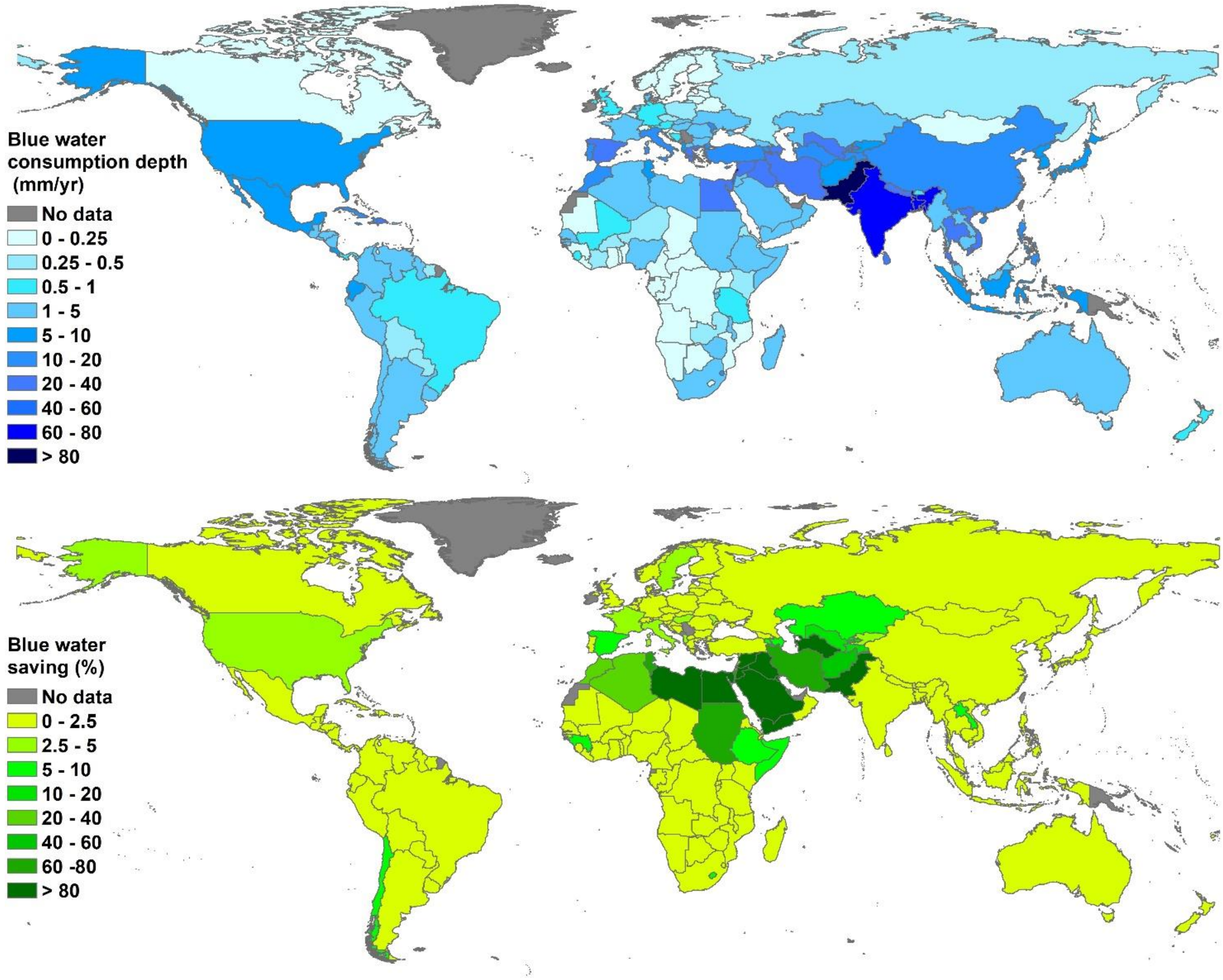


Figure 2. Current blue water consumption ~~(BWC)~~depth in mm/yr and blue water saving as a percentage of current BWC in the case of an optimized cropping pattern (α = 1.1).

The changing global cropping pattern for the case of α = 1.1

The reduction of global blue water consumption is achieved by reallocating the most resource-intensive crops from countries that ~~initially have a high BWS to countries that have a~~ have lower ~~BWS and higher~~ productivity in terms of land and water~~. Cereal~~ to countries with significantly higher productivities, both for rainfed and irrigated production~~ will be~~, and thus reducing irrigation in countries that initially have a high BWS. In the optimised cropping pattern, cereal production is reduced most significantly in Africa~~ and the Americas~~, relative to the reference situation, and South America and expanded in North America and Europe ~~and Asia~~ (Table 3). Irrigated cereal production ~~will be~~is reduced in ~~all~~most world regions (except for a small expansion in Europe and South America) whereas global rainfed production increases. ~~In Africa,~~ For individual countries, Pakistan and Egypt ~~will have~~is the ~~biggest percentage of~~largest decrease in total cereal production~~ decrease. The~~ . The most significant expansions in cereal production are found in the US and China for Maize, in China, India, the Russian Federation and France for wheat production and in India, Indonesia and Vietnam for rice production. In terms of harvested area

~~of~~, the largest areal decrease in cereals ~~in Africa will be reduced by~~is found in Asia with a reduction of 8 million hectares in total (Supplemental Table 1), which ~~represents 9~~represent 3% of the current harvested area of cereals in ~~Africa~~Asia. The irrigated area of cereals in ~~Africa will be~~Asia is reduced by ~~50~~6% compared to the reference situation ~~and~~while the rainfed area ~~by 5%. North America will have the largest~~ has an increase ~~in maize production, although the US will have the largest net reduction in overall cereal production due to a reduction in wheat and rice production. The irrigated and rainfed harvested areas of cereals in North America will be reduced by 21% and 7%, respectively. For South America, the most significant reductions in cereal production are related to rice production in Argentina and Brazil and wheat production in Brazil. The harvested area~~of 1%. Africa has the second-largest decrease of ~~cereals will be reduced by 14% in South America (the~~ irrigated area ~~will shrink by 29% and the rainfed area by 12%). The most significant expansions in cereal production are in France, Germany~~of cereals with 3 million hectares and ~~China for wheat production and in India and China for rice production. Europe has~~ the largest increase ~~in rainfed cereal production. The harvested area will be expanded in total by 2% in Europe (-11%~~ of rainfed area of cereals with 2.6 million hectares. Changes in the global pattern of cereal production for the case of α = 1.1 contribute 50% to the total global reduction in the blue water footprint and 46% to the total global reduction in irrigated ~~and +3% rainfed) and reduced by 1% in Asia (-2% irrigated and +1% rainfed). The global harvested area of cereals will be reduced by 3% in total compared to the reference situation. The irrigated area will be reduced by 6% and the rainfed area by 2%.~~area.

Fruit production ~~will be~~is reduced most significantly in Asia and Africa ~~and Europe~~ and expanded in the Americas (Table 3). Major fruit production reductions include the decrease of apple production in Iran, banana production in Thailand, orange production in Egypt, Iran and Pakistan and grape production in ~~South Africa, banana production in Tanzania, orange production in Spain and apple production in the Russian Federation~~France. In North America, the most significant expansion in fruit production is the increase in orange, grape and apple production in the US; in South America, the largest fruit production increases are oranges in Brazil and bananas in Ecuador. Although the reduction in fruit production ~~reduction~~ in ~~Africa,~~ Asia and ~~Europe is~~Africa mainly ~~irrigated~~concerns irrigation, the irrigated production of fruits ~~will increase in the Americas and Oceania. Half of~~increases in the North America and Europe. The largest share of increase in irrigated production in North America comes from the increase in irrigated production of oranges, apples and grapes in the US. The world's harvested area of fruits ~~will be reduced~~reduces by ~~5~~2%. The irrigated area ~~will be reduced~~reduces by ~~12% and~~19% while the rainfed area ~~by 2%.~~increases by 4%. Changes in fruit production contributed 12% to global blue water savings and 9% to total global reductions in irrigated area.

Table 3. Change in production per product group per continent in absolute terms (10^6 t/yr) when shifting from the cropping pattern in the reference period (1996-2005) to the optimized cropping pattern (with $\alpha = 1.1$)

-	-	Cereal	Fibres	Fruits	Nuts	Oil crops	Pulses	Roots	Spices	Stimulants	Sugar crops	Vegetables
Africa	Rainfed	~~0.50~~3.2	0.~~25~~3	~~0.76~~3.5	0.~~09~~1	-8.~~41~~9	0.~~29~~4	~~2.74~~7.0	~~-~~0.~~18~~0	0.~~31~~4	~~0.82~~3.2	~~-1.23~~0.7

	Irrigated	-14.6817.2	-0.267	-7.1455.8	-0.050	-0.981.3	-0.163	-2.434.0	-0.071	-0.060	-33.9421.8	-2.829.5
	Total	**-14.170**	**-0.023**	**-6.382.3**	**0.051**	**-9.4010.2**	**0.121**	**0.312.9**	**-0.251**	**0.254**	**-33.1218.6**	**-4.058.9**
Asia	Rainfed	15.8416.1	-1.303	8.6811.0	0.061	1.684.6	-0.112	4.236.9	0.273	-0.140	11.6210.6	27.4634.0
	Irrigated	-3.5114.5	-0.362.6	-7.1719.2	-0.002	-4.358.3	-0.842	-15.324.9	-0.032	-0.052	-61.4.12	-14.2913.8
	Total	**12.321.6**	**-1.663**	**1.51-8.2**	**-0.061**	**-2.673.7**	**-0.734**	**-11.091.9**	**0.251**	**-0.092**	**7.-50.8**	**13.1620.1**
Europe	Rainfed	17.546.4	-0.030	-2.900.1	-0.130	-1.680.7	-0.031	8.92-0.6	-0.020	0.000	-9.530.1	-9.747.0
	Irrigated	-1.070.8	0.162	-2.861.3	0.000	0.055	-0.381	-1.038	0.000	0.000	2.713.1	1.47-2.4
	Total	**16.477.2**	**0.131**	**-5.761.2**	**-0.130**	**-1.632**	**-0.411**	**7.901.3**	**-0.020**	**0.000**	**-6.823.3**	**-8.279.5**
North America	Rainfed	2.2011.6	0.566	1.132	-0.010	8.535.1	0.585	-0.759	0.010	-0.052	5.448.9	-1.0.92
	Irrigated	-8.860.7	0.515	4.003.5	0.121	0.734	0.091	1.547	0.010	0.000	-13.468.2	-0.957
	Total	**-6.6710.9**	**1.071**	**5.134.7**	**0.111**	**9.265.5**	**0.676**	**0.799**	**0.020**	**-0.052**	**-8.0217.1**	**0.03-1.7**
Oceania	Rainfed	1.300.4	0.000	0.051	0.000	-0.271	-0.023	-0.061	0.000	0.000	-7.471.1	-0.111
	Irrigated	-0.423	0.151	-0.171	0.000	0.000	0.000	0.121	0.000	0.000	2.899	0.111
	Total	**0.881**	**0.151**	**-0.231**	**0.000**	**-0.271**	**-0.023**	**0.061**	**0.000**	**0.000**	**-4.570**	**0.000**
South America	Rainfed	-5.366.3	0.313	4.861	-0.100	5.096.9	0.300	1.66-7.2	0.000	0.010	35.444	-1.170.3
	Irrigated	-3.470.6	0.020	0.416	0.010	-0.391	0.030	0.382	0.010	-0.120	9.616	0.303

Total	-8.845.7	0.3333	5.274.7	-0.091	4.707.0	0.3331	2.04-7.0	0.010	-0.110	45.040	-0.870

The production of oil crops will beis reduced most significantly in Africa (e.g. oil palm in Nigeria) and expanded in North Americathe Americas (e.g. soybeans in the US)., Brazil and Argentina). The harvested area will shrinkshrinks globally by 53% in total. Irrigated areas will be reducedreduce by 17% and 30% although global rainfed with 3%. area remain the same as the reference situation. Asia and Africa and Asia will have the most significant shrinkage in harvested areas of oil crops. Reallocating oil crops contributed 7% to global reductions in blue water footprint and 19% to total global reductions in irrigated area.

Roots production will partly movemoves from South America to Africa, Asia toand Europe. The At countries level, the most significant reduction will beis due to the decrease of potato production in IndiaPoland and Iran and cassava production in Thailand.Brazil, China and Vietnam. The largest expansions are sweet potato production in China, potato production in the Russian Federation, Poland, Ukraine and GermanyCassava and Yams in Nigeria. Globally, the harvested area of roots will beis reduced by 5% (254% (11% for irrigated and 3% for rainfed croplands).

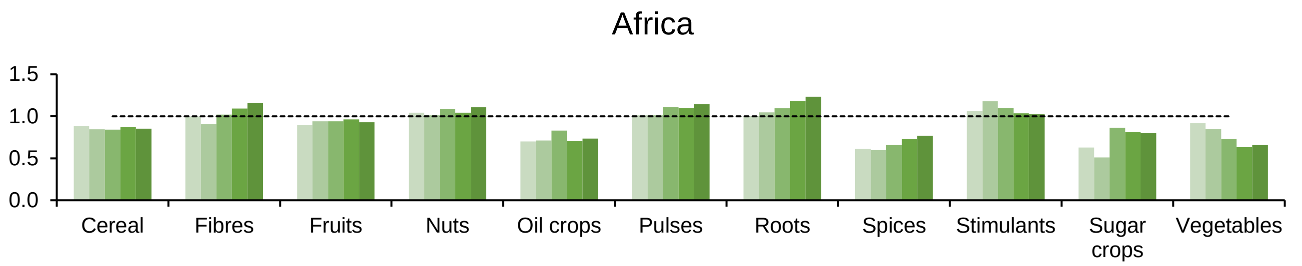
Sugar crop production will beis reduced most significantly in Asia and Africa and expanded in South America.the Americas. Sugar cane production will beis mainly reduced in Pakistan, India and Egypt and Sudan and expanded in Brazil. The global irrigated harvested area of sugar crops will beis reduced in total by 3%.10% while the global rainfed area increases by 8% Changes in sugar crops production contribute 10% to the total blue water savings globally.

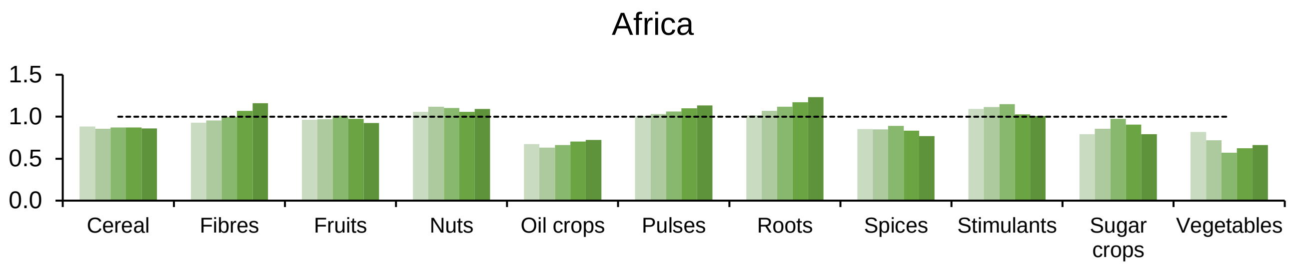
Vegetable production will beis reduced most significantly in Europe and Africa and expanded in Asia. Major reductions in vegetable production are for cabbages and tomatoes in the Ukraineproduction in Iran and Egypt. The most significant expansions are the increases in tomato and watermelon production in China. The global harvested area of vegetables will beis reduced by 74%, with a reduction of 1417% for irrigated and 5% forcroplands while the rainfed croplands. area remains the same as reference situation. Reallocating vegetables contributed 5% to global reductions in blue water footprint and 7% to global reductions in total irrigated harvested area globally.

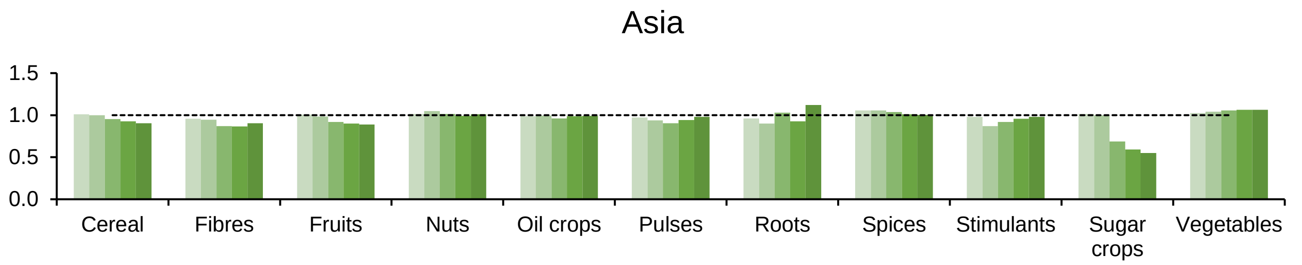
Although cereal rainfed harvested areas will bearea is reduced in Africa and North America when α = 1.1 for example (Supplemental Table 1), rainfed cereal production in these two continents will increase by 0.5 and 2.211.6 million t/y, respectively. This illustrates that by allocating production to more productive countries we can reduce water and land use and increase production at the same time.

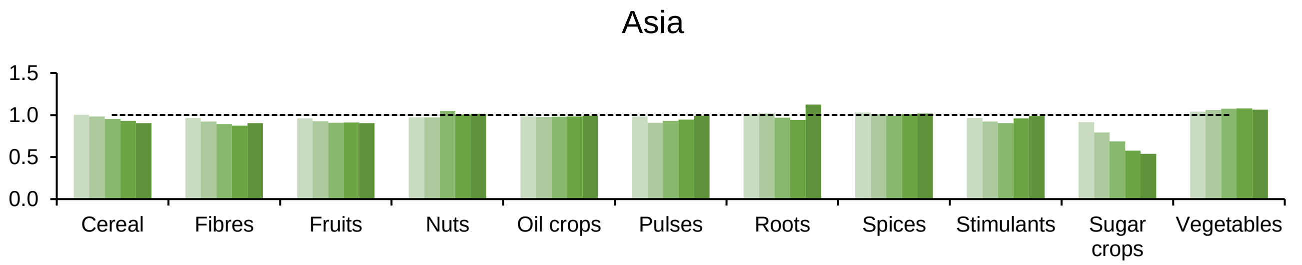
Comparative advantages

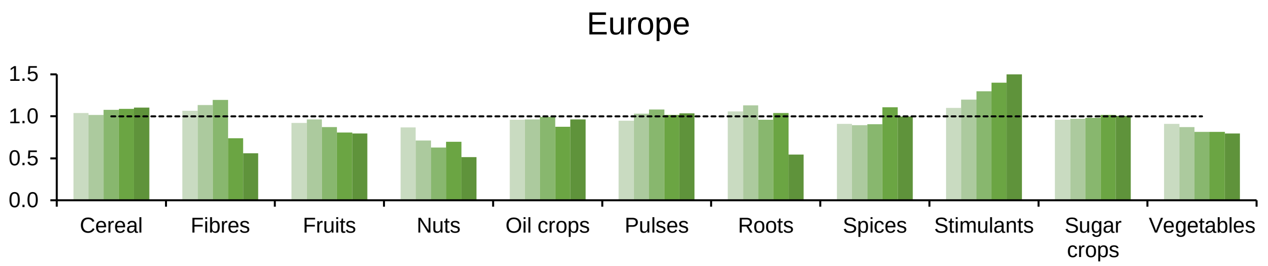
We explore comparative advantages of countries byto contribute to the goal of relieving global water scarcity; in the following, we use the term “comparative advantage” to indicate comparative advantage for this specific goal, as that is where results from the study provide insight in; comparative advantages to e.g. contribute to increasing agroeconomic revenue or to reduce agricultural carbon footprint could result in different conclusions. Our exploration of comparative advantage is considering which crops in a country are expanding when we gradually move from α = 1.1 to α = 1.5. As a summary, Figure 3 shows at the level of continents and crop groups, the ~~ratio of~~relative change in total production when we move from the reference cropping pattern (period 1996-2005) ~~to~~along the optimized cropping pattern, considering a stepwise increase in the maximally allowed expansion rate in harvested area per crop per country ~~(~~from ~~α = 1.1~~$\alpha = 1.1$ to α = 1.5~~)~~. Most of the changes in production ~~under an allowed 10%~~already occur for the modest areal expansion rate per crop of 10% (Table 3) will continue under larger expansion rates, with some exceptions. This is, for example, the case for fibres in Europe and oil crops in North America. Fibres production ~~will expand~~expands for the case of $\alpha = 1.1,\ 1.2\ and\ 1.3$ in Europe but ~~will be reduced~~again reduces for higher expansion rates. This can be explained by the fact that ~~other~~even more suitable regions, namely Oceania, North America and to a lesser extent Africa, ~~will~~ continue expanding fibres production,[5] allowing Europe to rather focus on cereals, sugar crops and stimulants production (Figure 3). North America ~~reduces cereal~~expands oil crops production when $\alpha = 1.1$ (Table 3) but ~~increases cereal~~decreases oil crops production when $\alpha = 1.2$ and ~~will have~~has the largest ~~expansion~~reduction in ~~cereal~~oil crops production for $\alpha = 1.5$ (Supplemental Table 1). ~~This can have two reasons.~~ The ~~first~~ reason behind this is that for the smallest expansion rate, ~~North America~~the US still needs to produce oil crops, and the global production could not be reached without the expansion of oil crops in ~~North America and thus limited harvested area can be allocated to cereals. The second reason is that, as mentioned previously, even at the lowest expansion rate, the US will have the largest increase in maize production. From $\alpha = 1.2$ the expansion of maize in the US will be larger than the reduction of other cereal crops in North America, which results in a positive net expansion of cereals.~~the US which limits the allocation of harvested areas to more suitable crops in the US such as maize and sugar crops. From $\alpha = 1.2$ the US will focus on producing maize in which they have a comparative advantage and give up a part of oil crops production. This example for North America shows that it is hard to have a robust conclusion on comparative advantages by looking at the level of continents. In order to explore comparative advantages, we will need to look at country level. ~~Figure~~Figures 4 ~~shows~~and 5 show the absolute and relative changes in production per crop group per country when we move from the cropping pattern in the reference situation to the optimized cropping pattern with α = 1.5. ~~Figure 5 gives the production per crop group per country in absolute terms for both the reference cropping pattern and the optimized cropping pattern with α = 1.5.~~

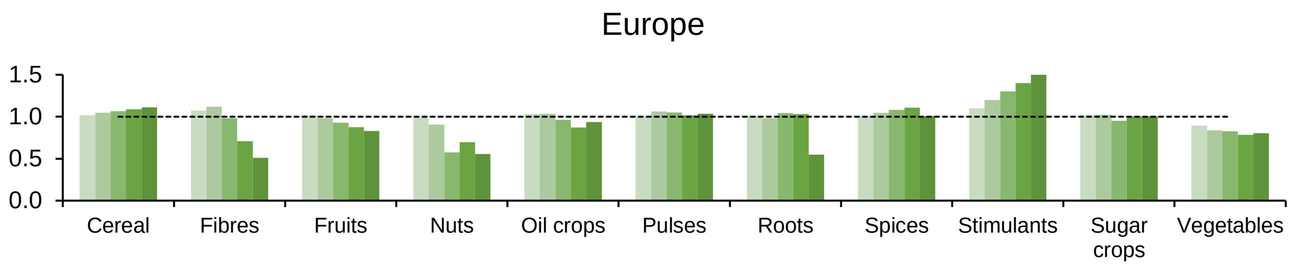

Africa
1.5
1.0
0.5
0.0
Cereal
Fibres
Fruits
Nuts
Oil crops
Pulses
Roots
Spices
Stimulants
Sugar crops
Vegetables

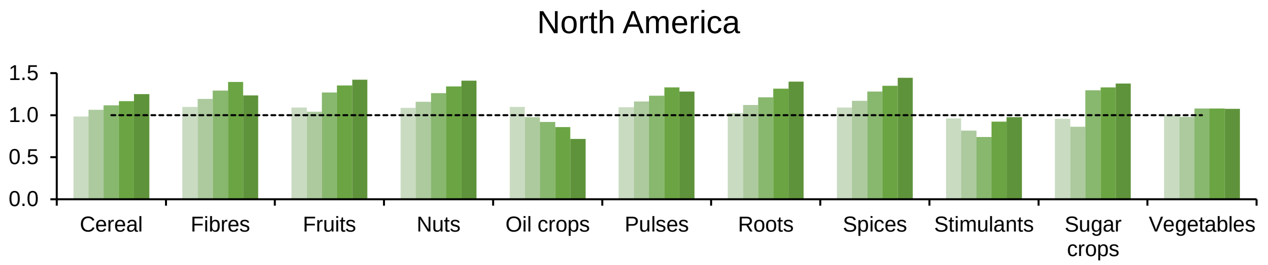

Africa
1.5
1.0
0.5
0.0
Cereal
Fibres
Fruits
Nuts
Oil crops
Pulses
Roots
Spices
Stimulants
Sugar crops
Vegetables

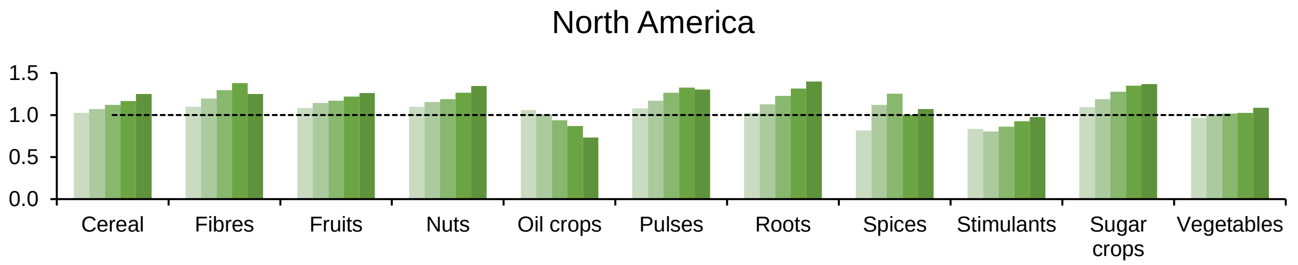

Asia
1.5
1.0
0.5
0.0
Cereal
Fibres
Fruits
Nuts
Oil crops
Pulses
Roots
Spices
Stimulants
Sugar crops
Vegetables


Asia
1.5
1.0
0.5
0.0
Cereal
Fibres
Fruits
Nuts
Oil crops
Pulses
Roots
Spices
Stimulants
Sugar crops
Vegetables


Europe
1.5
1.0
0.5
0.0
Cereal
Fibres
Fruits
Nuts
Oil crops
Pulses
Roots
Spices
Stimulants
Sugar crops
Vegetables


Europe
1.5
1.0
0.5
0.0
Cereal
Fibres
Fruits
Nuts
Oil crops
Pulses
Roots
Spices
Stimulants
Sugar crops
Vegetables


North America
1.5
1.0
0.5
0.0
Cereal
Fibres
Fruits
Nuts
Oil crops
Pulses
Roots
Spices
Stimulants
Sugar crops
Vegetables


North America
1.5
1.0
0.5
0.0
Cereal
Fibres
Fruits
Nuts
Oil crops
Pulses
Roots
Spices
Stimulants
Sugar crops
Vegetables

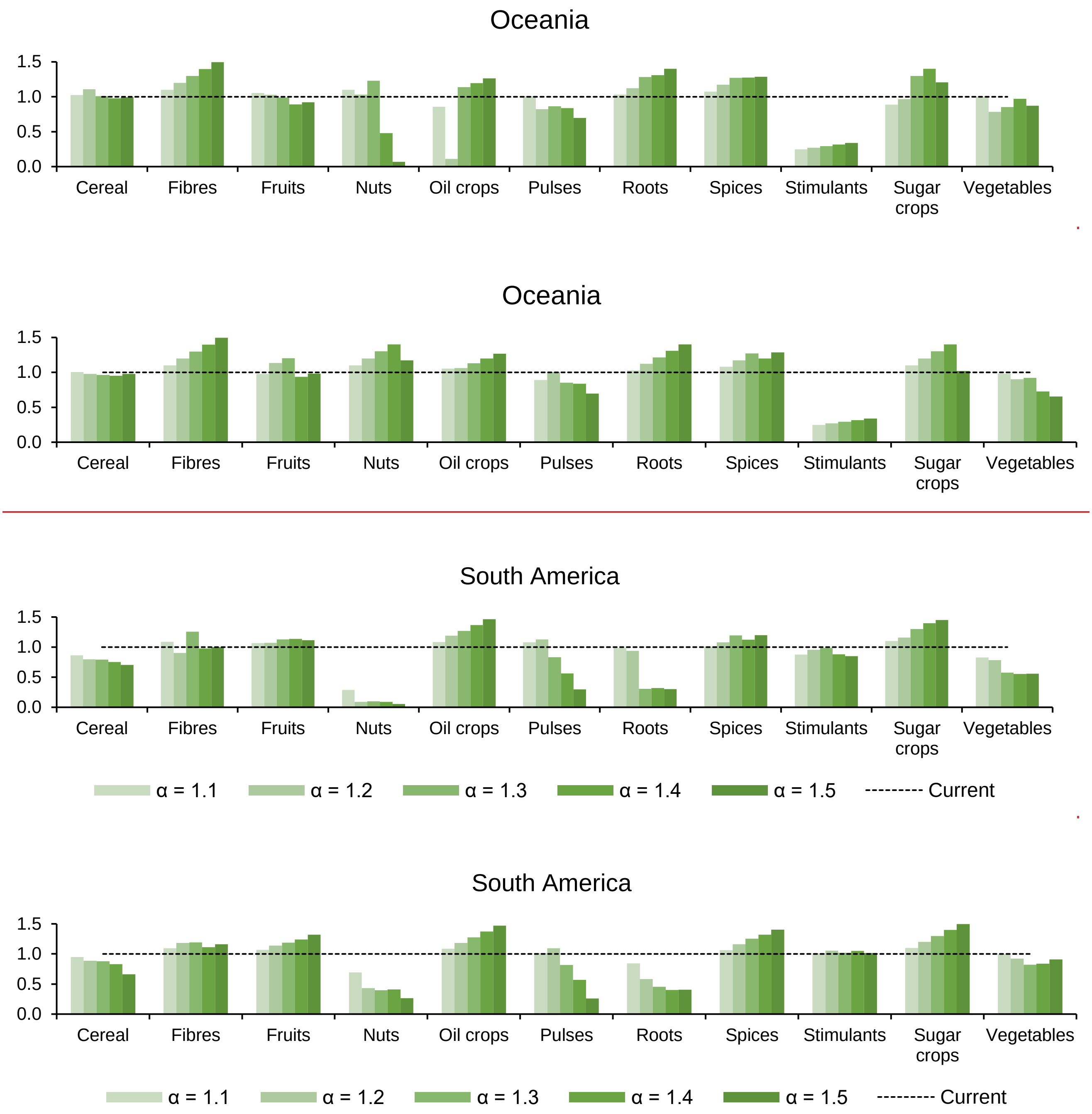
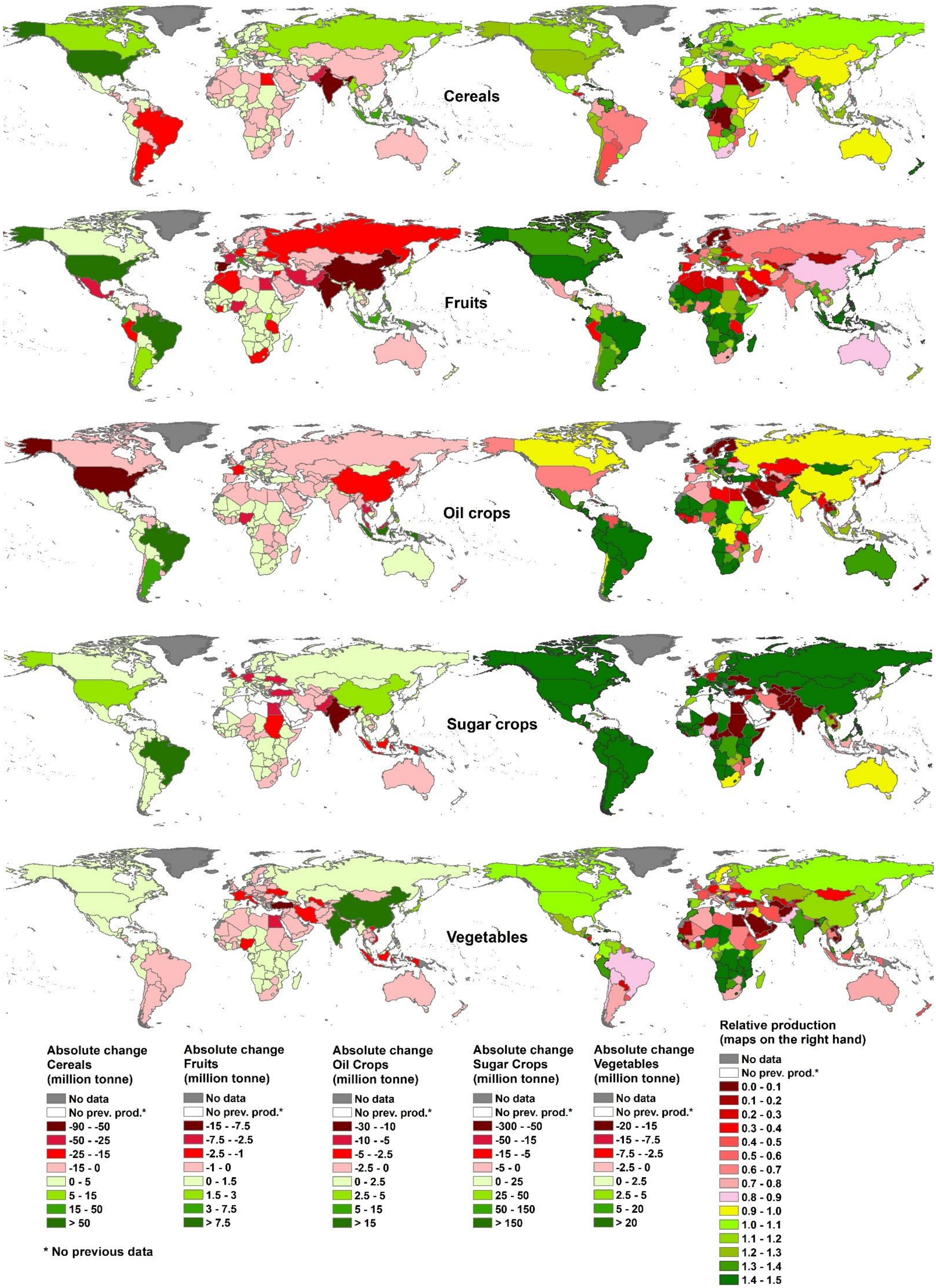


Figure 3. Ratio of total production in the optimized cropping pattern to total production in the reference cropping pattern (period 1996-2005), per crop group and per continent, for α = 1.1 to α = 1.5.


Cereals
Fruits
Oil crops
Sugar crops
Vegetables
Absolute change Cereals (million tonne)
No data
No prev. prod.*
-90 - -50
-50 - -25
-25 - -15
-15 - 0
0 - 5
5 - 15
15 - 50
> 50
Absolute change Fruits (million tonne)
No data
No prev. prod.*
-15 - -7.5
-7.5 - -2.5
-2.5 - -1
-1 - 0
0 - 1.5
1.5 - 3
3 - 7.5
> 7.5
Absolute change Oil Crops (million tonne)
No data
No prev. prod.*
-30 - -10
-10 - -5
-5 - -2.5
-2.5 - 0
0 - 2.5
2.5 - 5
5 - 15
> 15
Absolute change Sugar Crops (million tonne)
No data
No prev. prod.*
-300 - -50
-50 - -15
-15 - -5
-5 - 0
0 - 25
25 - 50
50 - 150
> 150
Absolute change Vegetables (million tonne)
No data
No prev. prod.*
-20 - -15
-15 - -7.5
-7.5 - -2.5
-2.5 - 0
0 - 2.5
2.5 - 5
5 - 20
> 20
Relative production (maps on the right hand)
No data
No prev. prod.*
0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
1.0 - 1.1
1.1 - 1.2
1.2 - 1.3
1.3 - 1.4
1.4 - 1.5
* No previous data

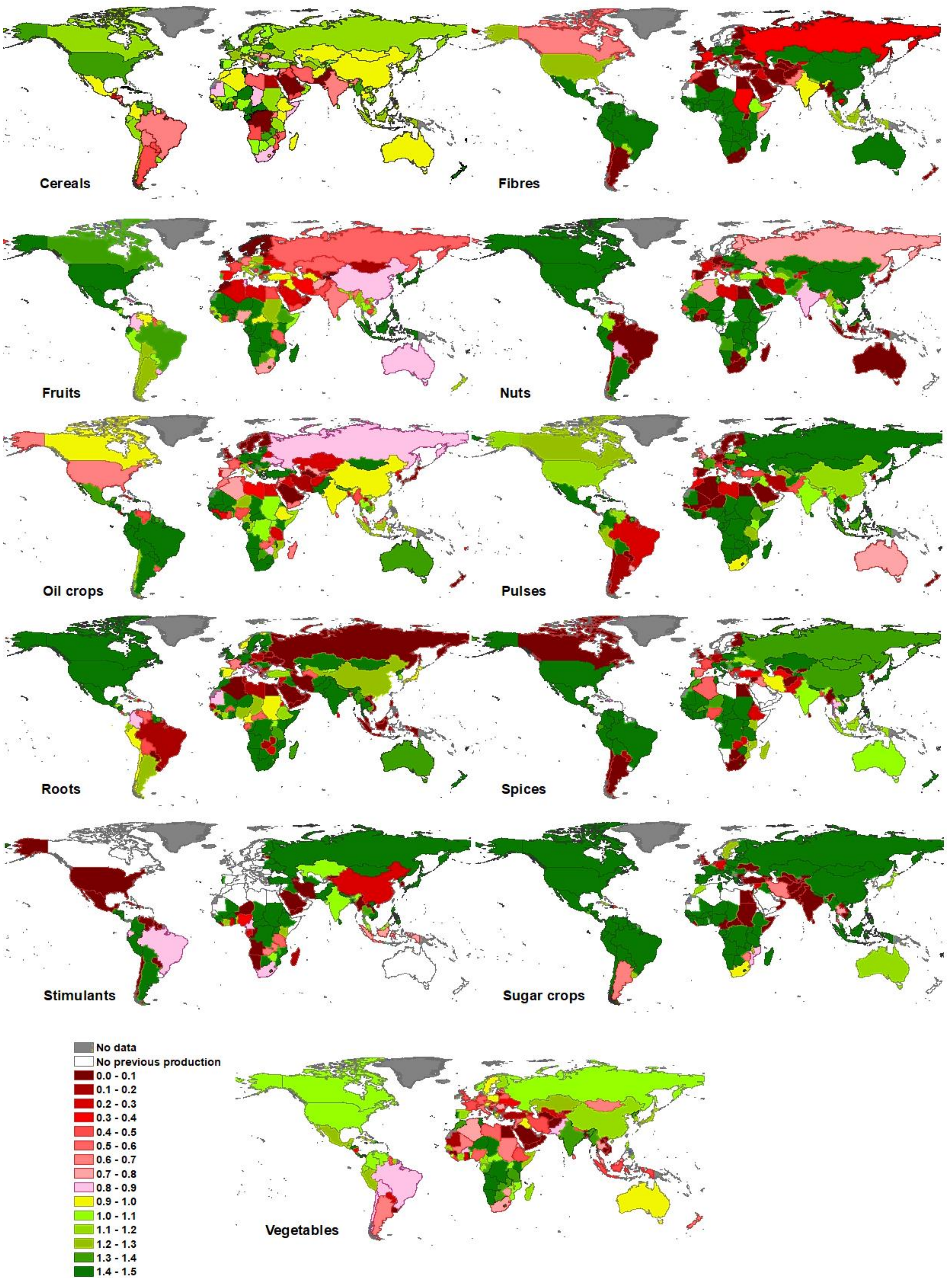
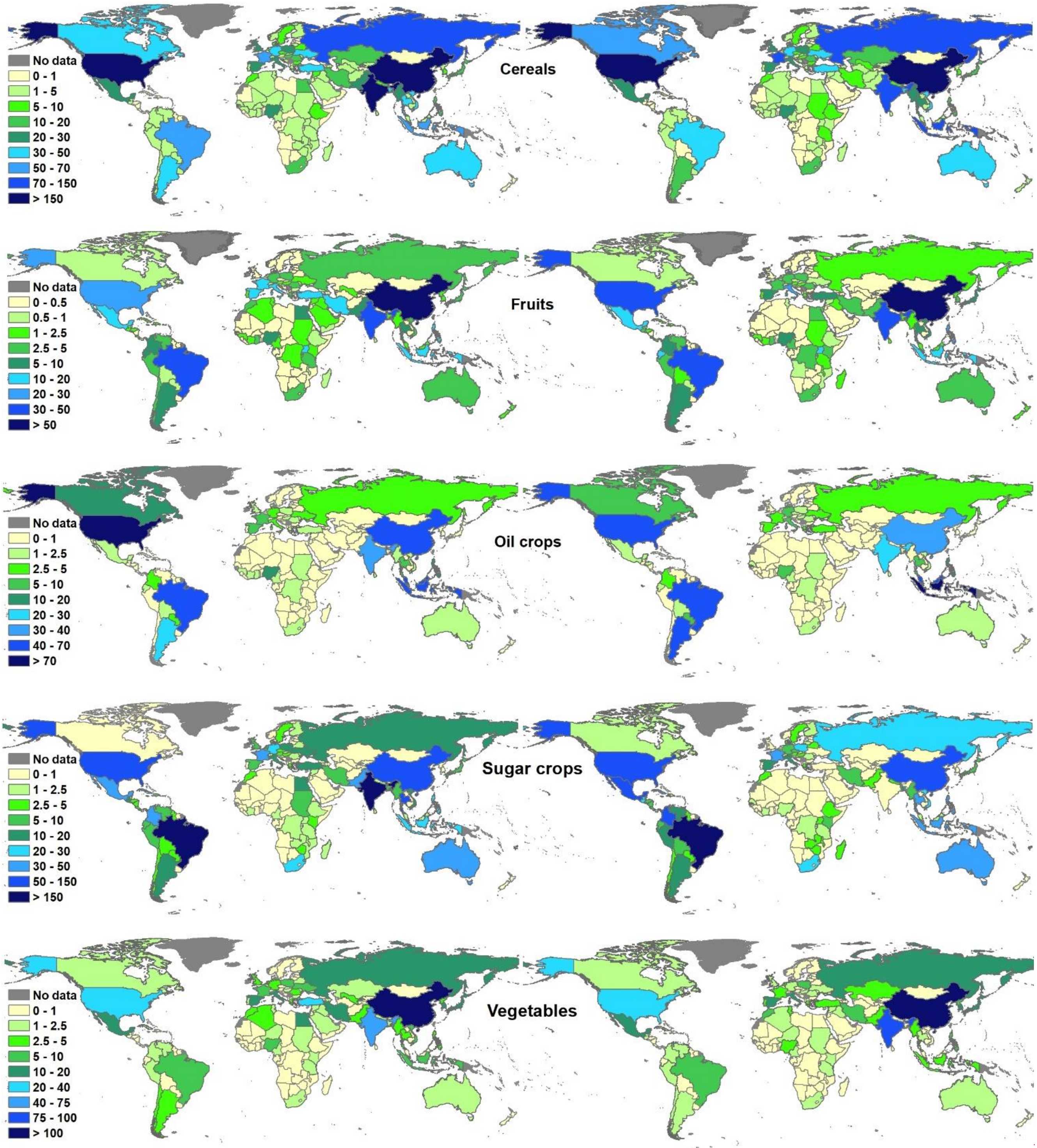


Figure 4. ~~Relative~~Absolute change in production ~~per country~~for cereals, fruits, oil crops, sugar crops and ~~per crop group~~vegetables per country (in 10^6 t/yr) (maps on the left hand) and relative production (ratio of production in optimized and

reference situation) for the same crops groups for the case of an optimized cropping pattern with ~~$\alpha = 1.5$~~$\alpha = 1.5$ (maps on the right hand), all compared to the reference cropping period (1996-2005): relative production = 1: no change, relative production < 1: countries production is reduced and relative production > 1: countries production is expanded.


Cereals
No data
0 - 1
1 - 5
5 - 10
10 - 20
20 - 30
30 - 50
50 - 70
70 - 150
> 150
Fruits
No data
0 - 0.5
0.5 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 20
20 - 30
30 - 50
> 50
Oil crops
No data
0 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 20
20 - 30
30 - 40
40 - 70
> 70
Sugar crops
No data
0 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 20
20 - 30
30 - 50
50 - 150
> 150
Vegetables
No data
0 - 1
1 - 2.5
2.5 - 5
5 - 10
10 - 20
20 - 40
40 - 75
75 - 100
> 100

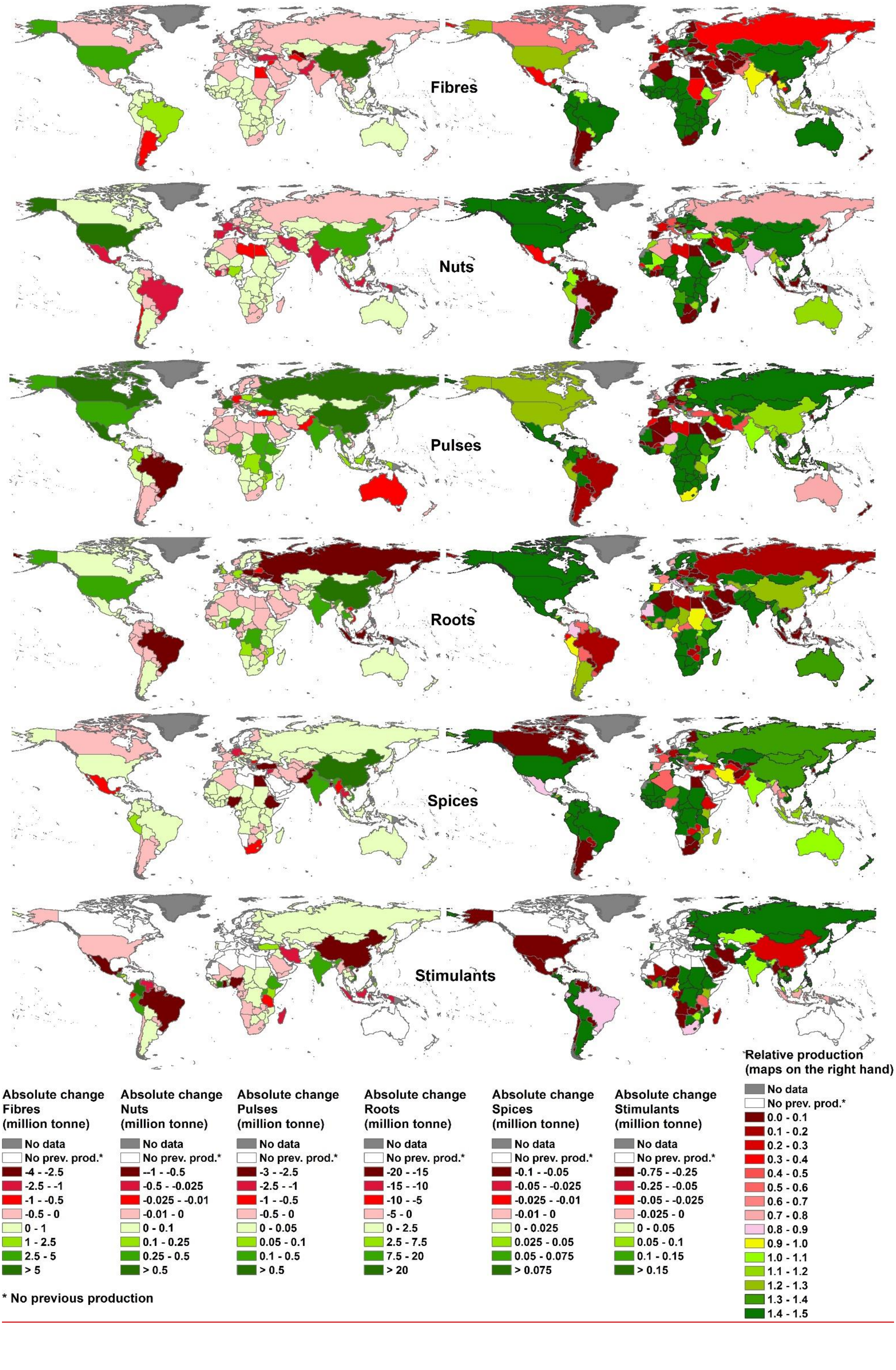

Fibres
Nuts
Pulses
Roots
Spices
Stimulants
Absolute change Fibres (million tonne)
No data
No prev. prod.*
-4 - -2.5
-2.5 - -1
-1 - -0.5
-0.5 - 0
0 - 1
1 - 2.5
2.5 - 5
> 5
Absolute change Nuts (million tonne)
No data
No prev. prod.*
--1 - -0.5
-0.5 - -0.025
-0.025 - -0.01
-0.01 - 0
0 - 0.1
0.1 - 0.25
0.25 - 0.5
> 0.5
Absolute change Pulses (million tonne)
No data
No prev. prod.*
-3 - -2.5
-2.5 - -1
-1 - -0.5
-0.5 - 0
0 - 0.05
0.05 - 0.1
0.1 - 0.5
> 0.5
Absolute change Roots (million tonne)
No data
No prev. prod.*
-20 - -15
-15 - -10
-10 - -5
-5 - 0
0 - 2.5
2.5 - 7.5
7.5 - 20
> 20
Absolute change Spices (million tonne)
No data
No prev. prod.*
-0.1 - -0.05
-0.05 - -0.025
-0.025 - -0.01
-0.01 - 0
0 - 0.025
0.025 - 0.05
0.05 - 0.075
> 0.075
Absolute change Stimulants (million tonne)
No data
No prev. prod.*
-0.75 - -0.25
-0.25 - -0.05
-0.05 - -0.025
-0.025 - 0
0 - 0.05
0.05 - 0.1
0.1 - 0.15
> 0.15
Relative production (maps on the right hand)
No data
No prev. prod.*
0.0 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
0.9 - 1.0
1.0 - 1.1
1.1 - 1.2
1.2 - 1.3
1.3 - 1.4
1.4 - 1.5
* No previous production

Figure 5. ~~Production per crop group~~Absolute change in production for fibres, nuts, pulses, roots, spices and stimulants per country (in 10^6 t/yr) ~~in the reference situation~~ (maps on the left hand) and relative production (ratio of production in optimized and reference situation) for the same crops groups for the case of an optimized cropping pattern with ~~α = ~~α=1.5 (maps on the right hand~~).~~), all compared to the reference cropping period (1996-2005): relative production = 1: no change, relative production < 1: countries production is reduced and relative production > 1: countries production is expanded.

Cereal production. The US and to a lesser extent Indonesia and France ~~and the US~~ have ~~both~~ a large absolute and relative ~~change~~changes (Figure 4~~) and absolute change (Figure 5~~) for cereals and thus a comparative advantage (given the combination of their water endowments and water productivities compared to other countries). In the case of α = 1.5, cereal production of the US, Indonesia and France ~~and the US~~ will increase by ~~23~~30, 26 and ~~30~~23%, respectively, compared to the reference situation. India has a comparative disadvantage in cereals and will reduce its production by 40% in the optimized cropping pattern with α = 1.5. Looking at the main cereal crops separately (wheat, barley, maize and rice) and combining information on relative and absolute changes, we find that France and the Russian Federation have a comparative advantage in wheat production, with large absolute increases when we optimize the global cropping pattern (Supplemental Figure 1). India and China, contributing 12% and 17% respectively of global wheat production in the reference period, have a comparative disadvantage and shrink their wheat production by ~~46~~41% for China and ~~27~~26% for India when $\alpha = 1.5$. For barley, we find Canada, France, Spain, and Turkey to have a comparative advantage. Germany and the Russian Federation, contributing 9% and 11% respectively to the global barley production in the reference period, have a comparative disadvantage and will decrease their barley production respectively by ~~40~~28% and ~~84~~88% when $\alpha = 1.5$. For maize, the US is found to have a comparative advantage, while, Brazil, contributing 6% to global maize production in the reference period, has a comparative disadvantage and will reduce its maize production with 64% in the optimized situation ($\alpha = 1.5$). For rice, China, Indonesia and Vietnam have a comparative advantage, with shares in global rice production raising from 32%, 9% and 5% respectively in the reference situation to ~~40%, 11~~22%, 29% and ~~9~~27% in the optimised situation (when $\alpha = 1.5$). India, contributing 22% to global rice production in the reference period, has a comparative disadvantage and will decrease its rice production with 43% when $\alpha = 1.5$ compared to the reference situation.

Fruit production. Comparative advantages for fruit production are found for Brazil and the US, which will increase their respective shares in global fruit production from 7% and 6% in the reference situation to ~~10~~11% and 9% in the optimized cropping pattern (when $\alpha = 1.5$). China and India, contributing 14% and 10% respectively to global fruit production in the reference period, appear to have a comparative disadvantage and will reduce their fruit production by ~~14~~13% and 31% respectively in the optimized situation (when $\alpha = 1.5$). Zooming in to the top-4 produced fruits – apples, bananas, grapes and oranges – we find the following. For apples, the US has a comparative advantage; the country will increase its share in global apple production from 8% (reference) to 12% (when $\alpha = 1.5$). China, contributing 35% to the global apple production in the reference period, has a comparative disadvantage~~. Apple production in China~~ and will decrease its apple production by ~~16~~12%

in the optimized cropping patterns (when $\alpha = 1.5$). For bananas, Ecuador, ~~Indonesia~~Brazil and the Philippines have a comparative advantage. ~~Brazil and~~ India, contributing ~~9% and~~ 22% ~~respectively~~ to global banana production in the reference, have a comparative disadvantage. For grapes, ~~China,~~ Italy ~~and,~~ the US and China have a comparative advantage, with shares in global grape production rising from 15%, 9% and 7~~%, 15% and 9~~% (reference) to ~~10%,~~ 22~~% and~~%, 13% and 10% ($\alpha = 1.5$). France and Spain, contributing 13% and 9% respectively to the global grapes production in the reference situation, have a comparative disadvantage and will entirely abandon grapes production when $\alpha = 1.5$. For oranges, Brazil and the US have a comparative advantage, while Mexico, Spain and Iran have a comparative disadvantage (Supplemental Figure 2).

Oil crops. For oil crops, we find Indonesia, Brazil and Argentina ~~and Brazil~~ to have a comparative advantage. Their shares in global oil crops production will raise from ~~6~~13, 9% and ~~9~~6% respectively (reference) to ~~9~~16, 13% and ~~13~~9% ($\alpha = 1.5$). ~~China,~~The US and Malaysia ~~and the US,~~ contributing ~~9%, 12%~~17%, and ~~17~~12% respectively to global oil crops production in the reference situation, have a comparative disadvantage and will reduce their oil crops production by ~~10%, 21~~32% and ~~33~~14% respectively in the optimized cropping pattern (when $\alpha = 1.5$). Focussing on soybean, which contributes 36% to the global oil crops production, we find the comparative advantage for Argentina and Brazil. The share of Argentina and Brazil in global soybeans production will rise from 14% and 22% respectively (reference) to 21 and 33% ($\alpha = 1.5$). China and the US have a comparative disadvantage in soybeans production. While the US, contributing 43% to the global soybean production in the reference period, will reduce its production by ~~30~~31%, China, contributing 9% in the reference period, will entirely stop its soybean production in the optimized pattern (when $\alpha = 1.5$) (Supplemental Figure 3).

Sugar crops. Brazil and China have a comparative advantage in sugar crops production, with shares in global sugar crops production rising from 23% and 6% respectively (reference) to 35% and 9% (optimized cropping pattern with $\alpha = 1.5$). India, currently contributing 18% to the global sugar crops production, has a comparative disadvantage and will quit sugar crops production almost entirely. Considering sugar beet and sugar cane separately, we find that France, Poland, the Russian Federation and the US have a comparative advantage in sugar beet production. Germany, Turkey and ~~the~~ Ukraine, contributing 11%, 7% and 6% to the global sugar beet production (reference), have a comparative disadvantage and will decrease their sugar beet production by ~~77~~72%, 100% and 94% respectively (when $\alpha = 1.5$). For sugar cane, Brazil and China have a comparative advantage; their shares in global sugar cane production will increase from 28% and 6% respectively (reference) to 42% and 10% (optimized cropping pattern with $\alpha = 1.5$). India, contributing 22% to global sugar cane production in the reference period, has a comparative disadvantage and will decrease its sugar cane production by almost 100% (Supplemental Figure 3).

Vegetables. China and India have a comparative advantage in vegetable production. Their shares in global vegetable production will rise from 45% and 9% respectively (reference) to 52 and 12% respectively (optimized cropping pattern with $\alpha = 1.5$). Turkey, contributing 4% to global vegetable production in the reference, has a comparative disadvantage and will reduce its vegetable production by ~~88~~83% in the optimized pattern (when $\alpha = 1.5$) compared to the reference situation. Looking at the most produced vegetable crop, tomato, which contributes 15% to global vegetable production, we find that China and the US have a comparative advantage (Supplemental Figure 3). The share of China and the US in the global production of tomatoes will increase from 21% and 11% respectively (reference) to ~~32~~30% and 16% respectively (when $\alpha = 1.5$). Egypt and Turkey, contributing 6% and 8% to global tomatoes production in the reference, have a comparative disadvantage and will stop their production almost entirely in the optimized situation.

Sensitivity to restricting expansion to rainfed areas

By allowing only rainfed areas per crop to expand up to 10%, and irrigated area per crop only to shrink, global blue water consumption of crop production is reduced by 16%. When α is equal to 1.3, 1.5 and 2.0 (i.e. when harvested area per crop per country can expand by up to 30%, 50% and 100%), global blue water consumption gets reduced by 31%, 41% and 54%, respectively. The maximum blue water scarcity is reduced to a scarcity of 62%, 14%, 5% and 3% when α equal to 1.1, 1.3, 1.5 and 2.0 respectively (Table 4).

Table 4. Current versus optimized maximum BWS when allowing both irrigated and rainfed areas to expand and when allowing only rainfed areas to expand and the share of rainfed areas sifts in reducing maximum BWS for the case when α equal to 1.1, 1.3, 1.5 and 2.0 respectively

Factor α	Maximum BWS: Current*	Maximum BWS: Optimized: Expansion in both irrigated and rainfed areas	Maximum BWS: Optimized: Expansion in only rainfed areas	Reduction in maximum BWS compared to reference situation: Expansion in both irrigated and rainfed areas	Reduction in maximum BWS compared to reference situation: Expansion in only rainfed areas	Share of rainfed shifts in reducing maximum BWS
$\alpha = 1.1$	272%	39%	62%	-86%	-77%	90%
$\alpha = 1.3$	272%	6%	14%	-98%	-95%	97%
$\alpha = 1.5$	272%	4%	5%	-99%	-98%	99%
$\alpha = 2.0$	272%	2%	3%	-99%	-99%	99.6%

* independent of α

The shifts in only the rainfed area give a dominant contribution to the reduction of the maximum BWS in the case when allowing both rainfed and irrigated areas to expand. Contributions from only rainfed shifts amount to 90% of the total reduction when α equal to 1.1 to 97, 99 and 99.6% when α equal to 1.3, 1.5 and 2.0 respectively. The dominance effect of shifts in rainfed areas proves that the optimization results are not very sensitive to modest allowed expansion in irrigated areas per crop.

Discussion

~~One of the~~ Our study has some limitations ~~of this study lies~~that need careful consideration in ~~the spatial resolution used in the analysis.~~interpreting results. Limited by availability of some of the required data and ~~our~~operational computational limitations of optimization ~~model capability~~software, we analyse the global cropping pattern at the country scale rather than at sub-national or grid~~-~~-scale. However, having a high average yield for a specific crop in a certain country doesn't necessarily mean that everywhere in that country the same performance in terms of land and water productivity ~~will be~~is achieved, due to spatial differences in crop suitability. This could ~~mislead the optimization to~~result in reallocating crops to countries that have a very limited suitable production area but are productive in terms of water and land in the reference situation. To constrain this effect, we do not allow total cropland per country to expand, so that areal expansion for one crop replaces the land use of another crops with a shrinking area; also, we limit the expansion in cropland by a certain maximum rate for each crop per country (the factor α~~) and limit total cropland to the reference extent.~~). The analysis at country level also has implications for ~~measuring~~the interpretability of water scarcity indicators. Assessing water scarcity at the level of a country level and an average year hides the water scarcity that manifests itself in particular places within countries or on particular periods (Mekonnen and Hoekstra, 2016). ~~We minimize *average* water scarcity in countries; within countries there will still be differences, not only in the reference but also in case of the optimized cropping patterns~~We minimize *average* water scarcity in countries; within countries scarcity differences will still appear, both in the reference situation and in the case of the optimized cropping patterns. Still, water scarcity indicators at national levels provide insight; within the framework of the Sustainable Development Goals, indicator 6.4.2 (Level of water stress), is used to monitor Goal 6 (Ensure availability and sustainable management of water and sanitation for all); it is defined similar to water scarcity in our study, 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. Relieving water scarcity in specific hotspots within countries by changing cropping patterns could be studied using the current approach but is beyond the scope of this paper. The sensitivity analysis did show 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; therefore water scarcity reduction in countries with highest scarcity at national level in the current study does not rely on worsening water scarcity in countries with heterogeneous conditions.

Another limitation of this study is the focus on water and land endowments and productivities and on global water scarcity reduction as a shared goal, while other production factors such as labour, knowledge, technology and capital can be limiting factors to expand production of certain crops in some countries and certainly agroeconomic aspects may play a role in ~~determining~~considering comparative advantages as well. Other factors could be included in a future study by refining the optimization model~~.~~; other objective functions could emphasize trade-offs between economic and environmental goals. Moreover, agricultural, trade and food security policies could be other factors that drive cropping patterns rather than water and land availability (Davis et al., 2018). Here, we purposely limited our analysis to considering comparative advantages from a perspective of land and water ~~perspective~~resource use to understand the specific role of these two particular factors. By no means we suggest that the 'optimized cropping patterns' found here are 'better' than the reference pattern because what is best depends on a lot more factors than included here, including political preferences. Rather, our results are instrumental in illustrating directions of change if we would put emphasis on the factors land and water endowment and productivity and put particular value to reducing water scarcity in the most water-scarce places.

The scope of the current study is restricted to the exploration of alternative cropping patterns to reduce water scarcity in the reference situation; we therefore use reference resource efficiencies. We do not take into consideration the future increase in food demand due to population growth, nor of ~~climate change or~~ agronomic developments that may increase resource use efficiencies, nor of climate change that will affect the future ability of countries to produce crops. 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. Besides reducing water and land use, changing cropping pattern will also have an impact on reducing GHG emission that results from extensive energy activities in irrigation such as groundwater pumping which accounted for around 61% of total irrigation emissions in China (Zou et al., 2015).

The results suggest that ~~Europe~~Asia, for example, could contribute to global water scarcity mitigation by reducing its production of fruits~~,~~ and sugar crops ~~and vegetables~~ while increasing its cereal and vegetable production. This implies that ~~Europe~~Asia will move to economically less attractive crops~~ such as cereals~~. This illustrates the possible trade-off between the goal of reducing water scarcity in the most water-scarce countries and the goal of economic profit by producing cash crops by individual countries or regions. The optimization results do not pretend that the changes in production patterns are likely to occur, but merely that these changes reduce water scarcity most; national and international policies would be required to promote such water-saving changes to be implemented (Klasen et al., 2016).

~~For some countries, results show that the blue water footprint of crop production will be reduced by almost 100%: Antigua and Barbuda, Armenia, Barbados, Brunei Darussalam, Burkina Faso, Burundi, Cape Verde, Comoros, Cyprus, Djibouti, Dominican Republic, Eritrea, Gambia, Haiti, Jamaica, Jordan, Lesotho, Malawi, Malta, Mauritius, Moldova, Puerto Rico, Somalia, Swaziland, Timor-Leste, Togo and Trinidad and Tobago. This means that these countries will rely almost entirely on rainfed agriculture insofar possible and imports and thus be~~Changing cropping patterns could reduce global blue water footprint by 21% and global irrigated area by 10%. These findings prove that current high scarcity levels in a serious number of countries is shown to be caused by the current crop allocation pattern, rather than by an inevitability of those scarcities to occur; that suggests that water endowment is insufficiently driving crop allocation to avoid water scarcity.. This in consistent with Zhao et al., (2019) who find in their study for China that comparative advantages with respect to labour and water were not reflected in the regional distribution of agricultural production. However, not all countries would benefit similarly in the optimized set, India and China, main crop producers in the reference situation, will only start to have a decrease in their blue water scarcity when the allowed expansion rate is larger than 20%. 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).

Findings suggest that China, one of the main producers of the major crop in the world, will abandon soybean production and halve wheat irrigation area. This will relieve some of the pressure on the northern part of China where water scarcity is the most severe (Ma et al., 2020). China will increase the harvested area of rice and rapeseed, the crops with the most significant comparative advantage in terms of land and water. Similarly, our results suggest that the US, another major crops producer, would and restrict soybean production to rainfed systems, abandoning irrigation, in the optimized set in the US. The US focuses on producing maize, mainly rainfed, for which the US has a comparative advantage in terms of water and land productivities. This may be a great relief to the US corn belt where most of irrigated soybeans and maize are located (Zhong et al., 2016) and could be a remedy to the projected water shortage of that region resulting from population growth and climate change (Brown et al., 2019). We also find that India, another major producer of crops in the world, will move away from sorghum production and shift a large share of its rice and wheat production to rainfed conditions. Moving to rainfed production in India could mitigate the effect of the intensive use of irrigation from groundwater and surface water which caused groundwater degradation in many districts of Haryana and Punjab, the largest contributing states to rice and wheat production in India (Singh, 2000).

For some of the most water-scarce countries, results show that blue water consumption in crop production is reduced by more than 70% compared to the reference situation: Cyprus, Egypt, Iran, Jordan, Kuwait, Libya, Pakistan, Saudi Arabia, Syria, Turkmenistan and Yemen. This means that these countries, with modest rainfed agricultural areas, will rely more heavily on imports and thus become highly dependent on other countries. Most of these countries already have a high dependency on crop ~~import~~imports in the reference situation. This reflects a trade-off between reducing water scarcity and increasing food security~~.~~ on the one hand and shows the important role of food trade in relieving water scarcity in many places in the world on the other.

Conclusion

When allowing a 10% maximum expansion of harvested area per crop and per country, while not allowing an increase in total rainfed or irrigated cropland per country, a global blue water saving in the world of ~~70~~170,000 million m^3/yr is achievable, which is ~~9~~21% of the current global blue water footprint. ~~Hereby,~~Changes in the cropping pattern of rainfed production have a dominant effect, relieving irrigated areas to contribute to production; the total global harvested area would decrease by ~~4%.~~2% while the total global irrigated area would decrease by 10%. The blue water scarcity in the ~~world's~~ seven ~~most~~countries with highest national water-scarce ~~countries~~, Libya, Saudi Arabia, Kuwait, Yemen, Qatar, Egypt, and Israel (with current scarcities ranging from 54% to 270%), can be reduced to a scarcity of 39% or less. Optimizing the global cropping pattern to reduce the highest national water scarcity comes ~~along~~ with trade-offs, ~~whereby~~where severely water-scarce countries ~~will~~ reduce water scarcity at the expense of ~~increased import-dependency~~decreased food self-sufficiency.

When considering how to change the global cropping pattern in order to reduce water scarcity in the world's most severely water-~~scarcity hotspots~~scarce countries, we ~~particularly~~specifically find the following major shifts. Cereal production ~~will get~~is reduced in Africa and ~~the Americas~~South America and increased in North America and Europe ~~and Asia~~. Fruits production ~~will be~~is reduced most significantly in Asia and Africa and ~~Europe and~~ expanded in the Americas. Oil crops production ~~will be reduced most significantly in Africa (e.g. oil palm in Nigeria) and expanded in North America (e.g. soybeans in the US). Sugar crop production will be~~is reduced most significantly in Africa and expanded in ~~South America.~~the Americas. Sugar ~~cane~~crop production ~~will be mainly~~is reduced most significantly in ~~Egypt~~Asia and ~~Sudan~~Africa and expanded in ~~Brazil~~the Americas. Vegetable production ~~will be~~is reduced most significantly in Europe and Africa and expanded in Asia. ~~The most significant expansion in vegetable production will be an increase in tomatoes~~ Reallocating cereal crops is the main contributor to global blue water saving with a contribution of 50% for the case of $\alpha = 1.1$, followed by fruit, sugar crops and ~~watermelons in China.~~fibres with 12%, 10% and 9% respectively.

From ~~an~~a water and land perspective and aiming for global water scarcity reduction, comparative advantages for cereal production are found for ~~France and~~ the US and to a lesser extent Indonesia and France, whereas India has a comparative disadvantage. The comparative advantage of ~~France~~the US refers to ~~wheat and barley,~~maize, for France to Wheat and ~~the comparative advantage of the US to maize~~Barley and for Indonesia to rice. India's comparative disadvantage in cereal production particularly refers to wheat and rice. For fruit production, Brazil and the US are found to have a comparative advantage, whereas China and India have a comparative disadvantage. More in particular, the US has a comparative advantage for apples, grapes and oranges, and Ecuador and Brazil for ~~oranges~~banana, while China has a comparative disadvantage in apples, and India for bananas. For oil crops, Indonesia, Brazil and Argentina ~~and Brazil~~ have a comparative advantage, and ~~China,~~the US and Malaysia ~~and the US~~ a comparative disadvantage. Argentina and Brazil have a comparative advantage for soybean, while the US and China have a comparative disadvantage. For sugar crops production, Brazil and China are found to have a comparative advantage, while India have comparative disadvantage for sugar crops. Brazil and China have a comparative advantage for sugar cane, while India has a comparative disadvantage for sugar cane. For vegetables, we find China and India to have a comparative advantage and Turkey to have a comparative disadvantage. China has a comparative advantage for tomatoes and Turkey a comparative disadvantage.

By considering differences in national water and land endowments, following the Heckscher-Ohlin (H-O) theory of comparative advantage, as well as differences in national water and land productivities, following Ricardo's theory of comparative advantage, we combine two rationales that are both relevant. With the optimization exercises carried out in this study we show that blue water scarcity can be reduced to reasonable levels throughout the world by changing the global cropping pattern, while maintaining current levels of global production and reducing land use.

Data availability

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Author contribution

The three authors designed the research, analysed the data and wrote the paper. H.C carried out the calculations.

Competing interests

The authors declare that they have no conflict of interest.

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