https://doi.org/10.5194/hess-2019-461
Preprint. Discussion started: 28 October 2019

Hydrology and Earth System Sciences
Discussions

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

Hatem Chouchane[1]*, Maarten S. Krol[1], and Arjen Y. Hoekstra[1,2]

[1] Twente Water Centre, University of Twente, Enschede, The Netherlands

[2] Institute of Water Policy, Lee Kuan Yew School of Public Policy, National University of Singapore, Singapore

* Contact author: hatemchouchane1@gmail.com, Phone: + 31 53 489 4446

**Postal address**

University of Twente
Faculty of Engineering Technology
Civil Engineering
Department of Water Engineering & Management
P.O. Box 217
7500 AE Enschede

## 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 blue water scarcity in the world's hotspots, 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% and a decrease of global total harvested area of 4%.

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

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## 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 how to mitigate problems related to blue water scarcity (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 (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), improved irrigation scheduling (Jones, 2004) and enhancing water productivity (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). Yet another category of studies focusses on spatial cropping patterns (Davis et al. 2017a) 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 known as virtual water trade (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 (Yang et al., 2006;Chapagain et al., 2006), while other studies have concentrated on analysing food trade in relation to water endowments (Yang et al., 2003;Chouchane et al., 2018). In the current study, 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.

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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), 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), 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.

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. 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. For this purpose, we develop and apply a linear programming optimization algorithm considering a number of constraints. First, 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). 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.

## 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 $\alpha$ (whereby we stepwise increase $\alpha$ 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. The algorithm will thus tend to reduce and equalize blue water scarcity in the most water-scarce countries.

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).

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

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:

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

subject to:

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

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

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

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

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

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. Parameter $\alpha$ 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 $\alpha$); 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 $\alpha = 1.1$).

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) |
| Rainfed and irrigated production per crop in the reference situation | Country | Average for 1996-2005 | (Mekonnen and Hoekstra, 2011) |
| 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 reduced by 9%, while the total global harvested area will be reduced by 4%.

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 reduced to 6%, 4% and 2%, respectively. In these scenarios, global blue water consumption gets reduced by 34, 47 and 58%, respectively, while the total global harvested area gets reduced by 6%, 7% and 9%, 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% | 280 | 39% | 41 | 6% | 25 | 4% | 16 | 2% |
| Saudi Arabia | 6200 | 260% | 940 | 39% | 140 | 6% | 86 | 4% | 54 | 2% |
| Kuwait | 48 | 240% | 8 | 39% | 1 | 6% | 1 | 4% | 0 | 2% |
| Yemen | 2100 | 98% | 3 | 0% | 29 | 1% | 75 | 4% | 47 | 2% |
| Qatar | 51 | 88% | 23 | 39% | 3 | 6% | 2 | 4% | 1 | 2% |
| Egypt | 34000 | 57% | 17000 | 30% | 3400 | 6% | 2100 | 4% | 1300 | 2% |
| Israel | 960 | 54% | 54 | 3% | 49 | 3% | 64 | 4% | 40 | 2% |
| Jordan | 410 | 43% | 0 | 0% | 10 | 1% | 34 | 4% | 21 | 2% |
| Syria | 7000 | 42% | 2600 | 15% | 990 | 6% | 600 | 4% | 380 | 2% |
| Oman | 550 | 39% | 520 | 37% | 82 | 6% | 50 | 4% | 31 | 2% |
| Uzbekistan | 15000 | 31% | 13000 | 27% | 2900 | 6% | 1800 | 4% | 1100 | 2% |
| Cyprus | 240 | 31% | 0 | 0% | 2 | 0% | 28 | 4% | 17 | 2% |
| Pakistan | 74000 | 30% | 67000 | 27% | 14000 | 6% | 8900 | 4% | 5500 | 2% |
| Iran | 40000 | 29% | 40000 | 30% | 8000 | 6% | 4900 | 4% | 3100 | 2% |
| Tunisia | 1300 | 29% | 400 | 9% | 270 | 6% | 170 | 4% | 100 | 2% |
| Algeria | 2700 | 23% | 1100 | 10% | 690 | 6% | 420 | 4% | 260 | 2% |
| Turkmenistan | 5300 | 21% | 500 | 2% | 1500 | 6% | 890 | 4% | 550 | 2% |
| Morocco | 5100 | 18% | 1500 | 5% | 1700 | 6% | 1000 | 4% | 650 | 2% |
| Malta | 9 | 17% | 0 | 0% | 0 | 0% | 2 | 4% | 1 | 2% |
| Lebanon | 770 | 17% | 45 | 1% | 54 | 1% | 160 | 4% | 100 | 2% |
| Sudan | 6100 | 16% | 700 | 2% | 2200 | 6% | 1400 | 4% | 850 | 2% |
| **Global** | **820000** | | **750000** | | **540000** | | **440000** | | **350000** | |

Most countries with severe water scarcity (BWS>40%) in the reference situation will have 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%.

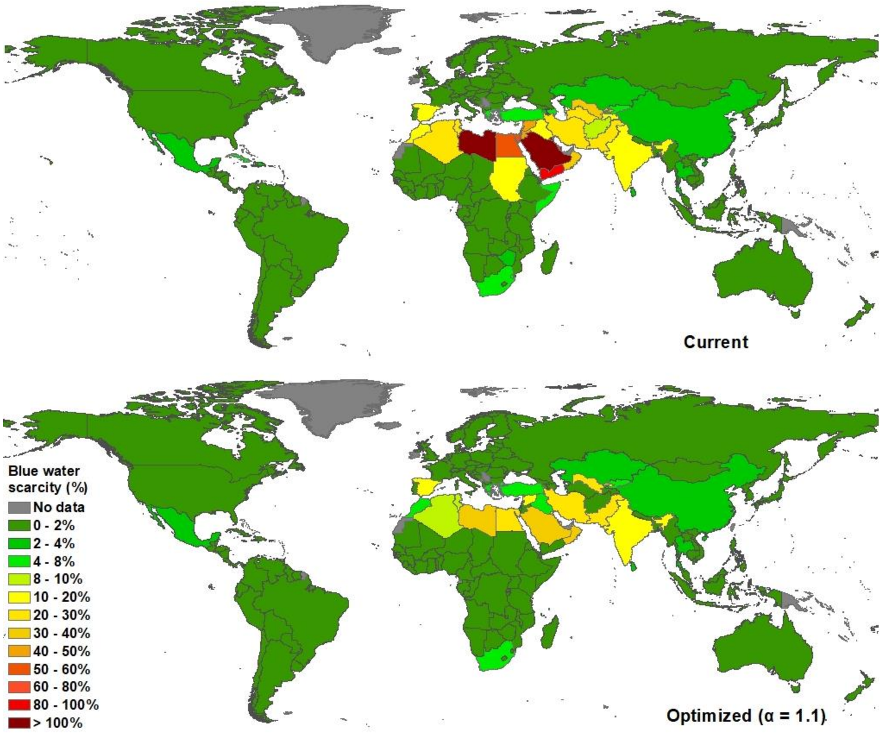


**Figure 1.** Current and optimized (α = 1.1) blue water scarcity.

In the case of α = 1.1, Egypt will have the largest reduction in its blue water consumption in absolute terms, viz. 17,000 $m^3$/yr, which represents 50% of its current BWC and 24% of the global blue water saving. Other countries that have a significant reduction in their BWC in absolute terms include Pakistan, Sudan, Saudi Arabia, Afghanistan, 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 countries that will have an increase in their BWC (e.g. Australia, Austria, Bangladesh, Congo, the Democratic Republic of the Congo, Greece, Japan, Malaysia, Norway, Turkey, Uruguay, and Sierra Leona) have a relatively low initial BWC.

https://doi.org/10.5194/hess-2019-461
Preprint. Discussion started: 28 October 2019

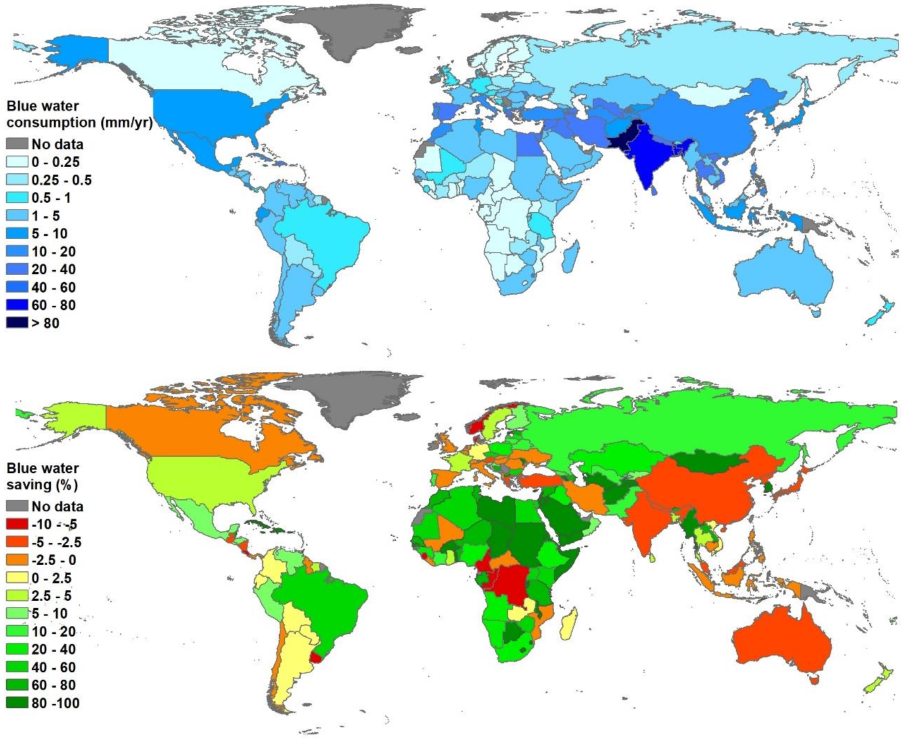


**Figure 2.** Current blue water consumption (BWC) in mm/yr and blue water saving as a percentage of current BWC in the case of an optimized cropping pattern (α = 1.1).

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

The reduction of global blue water consumption is achieved by reallocating crops from countries that initially have a high BWS to countries that have a lower BWS and higher productivity in terms of land and water. Cereal production will be reduced most significantly in Africa and the Americas and expanded in Europe and Asia (Table 3). Irrigated cereal production will be reduced in all world regions whereas global rainfed production increases. In Africa, Egypt will have the biggest percentage of total cereal production decrease. The harvested area of cereals in Africa will be reduced by 8 million hectares in total (Supplemental Table 1), which represents 9% of the current harvested area of cereals in Africa. The irrigated area of cereals in Africa will be reduced by 50% compared to the reference situation and the rainfed area by 5%. North America will have the largest 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 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 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% 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%.

Fruit production will be reduced most significantly in Africa and Europe and expanded in the Americas (Table 3). Major fruit production reductions include the decrease of grape production in South Africa, banana production in Tanzania, orange production in Spain and apple production in the Russian Federation. 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 fruit production reduction in Africa, Asia and Europe is mainly irrigated, the irrigated production of fruits will increase in the Americas and Oceania. Half of the 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 by 5%. The irrigated area will be reduced by 12% and the rainfed area by 2%.

**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 | 0.25 | 0.76 | 0.09 | -8.41 | 0.29 | 2.74 | -0.18 | 0.31 | 0.82 | -1.23 |
| | Irrigated | -14.68 | -0.26 | -7.14 | -0.05 | -0.98 | -0.16 | -2.43 | -0.07 | -0.06 | -33.94 | -2.82 |
| | **Total** | **-14.17** | **-0.02** | **-6.38** | **0.05** | **-9.40** | **0.12** | **0.31** | **-0.25** | **0.25** | **-33.12** | **-4.05** |
| Asia | Rainfed | 15.84 | -1.30 | 8.68 | 0.06 | 1.68 | 0.11 | 4.23 | 0.27 | -0.14 | 11.62 | 27.46 |
| | Irrigated | -3.51 | -0.36 | -7.17 | 0.00 | -4.35 | -0.84 | -15.32 | -0.03 | 0.05 | -4.12 | -14.29 |
| | **Total** | **12.32** | **-1.66** | **1.51** | **0.06** | **-2.67** | **-0.73** | **-11.09** | **0.25** | **-0.09** | **7.50** | **13.16** |
| Europe | Rainfed | 17.54 | -0.03 | -2.90 | -0.13 | -1.68 | -0.03 | 8.92 | -0.02 | 0.00 | -9.53 | -9.74 |
| | Irrigated | -1.07 | 0.16 | -2.86 | 0.00 | 0.05 | -0.38 | -1.03 | 0.00 | 0.00 | 2.71 | 1.47 |
| | **Total** | **16.47** | **0.13** | **-5.76** | **-0.13** | **-1.63** | **-0.41** | **7.90** | **-0.02** | **0.00** | **-6.82** | **-8.27** |
| North America | Rainfed | 2.20 | 0.56 | 1.13 | -0.01 | 8.53 | 0.58 | -0.75 | 0.01 | -0.05 | 5.44 | -0.92 |
| | Irrigated | -8.86 | 0.51 | 4.00 | 0.12 | 0.73 | 0.09 | 1.54 | 0.01 | 0.00 | -13.46 | 0.95 |
| | **Total** | **-6.67** | **1.07** | **5.13** | **0.11** | **9.26** | **0.67** | **0.79** | **0.02** | **-0.05** | **-8.02** | **0.03** |
| Oceania | Rainfed | 1.30 | 0.00 | 0.05 | 0.00 | -0.27 | 0.02 | -0.06 | 0.00 | 0.00 | -7.47 | -0.11 |
| | Irrigated | -0.42 | 0.15 | 0.17 | 0.00 | 0.00 | 0.00 | 0.12 | 0.00 | 0.00 | 2.89 | 0.11 |
| | **Total** | **0.88** | **0.15** | **0.23** | **0.00** | **-0.27** | **0.02** | **0.06** | **0.00** | **0.00** | **-4.57** | **0.00** |
| South America | Rainfed | -5.36 | 0.31 | 4.86 | -0.10 | 5.09 | 0.30 | 1.66 | 0.00 | 0.01 | 35.44 | -1.17 |
| | Irrigated | -3.47 | 0.02 | 0.41 | 0.01 | -0.39 | 0.03 | 0.38 | 0.01 | -0.12 | 9.61 | 0.30 |
| | **Total** | **-8.84** | **0.33** | **5.27** | **-0.09** | **4.70** | **0.33** | **2.04** | **0.01** | **-0.11** | **45.04** | **-0.87** |

The production of oil crops will be reduced most significantly in Africa (e.g. oil palm in Nigeria) and expanded in North America (e.g. soybeans in the US). The harvested area will shrink globally by 5% in total. Irrigated areas will be reduced by 17% and rainfed with 3%. Africa and Asia will have the most significant shrinkage in harvested areas of oil crops.

Roots production will partly move from Asia to Europe. The most significant reduction will be due to the decrease of potato production in India and cassava production in Thailand. The largest expansions are potato production in the Russian Federation, Poland, Ukraine and Germany. Globally, the harvested area of roots will be reduced by 5% (25% for irrigated and 3% for rainfed croplands).

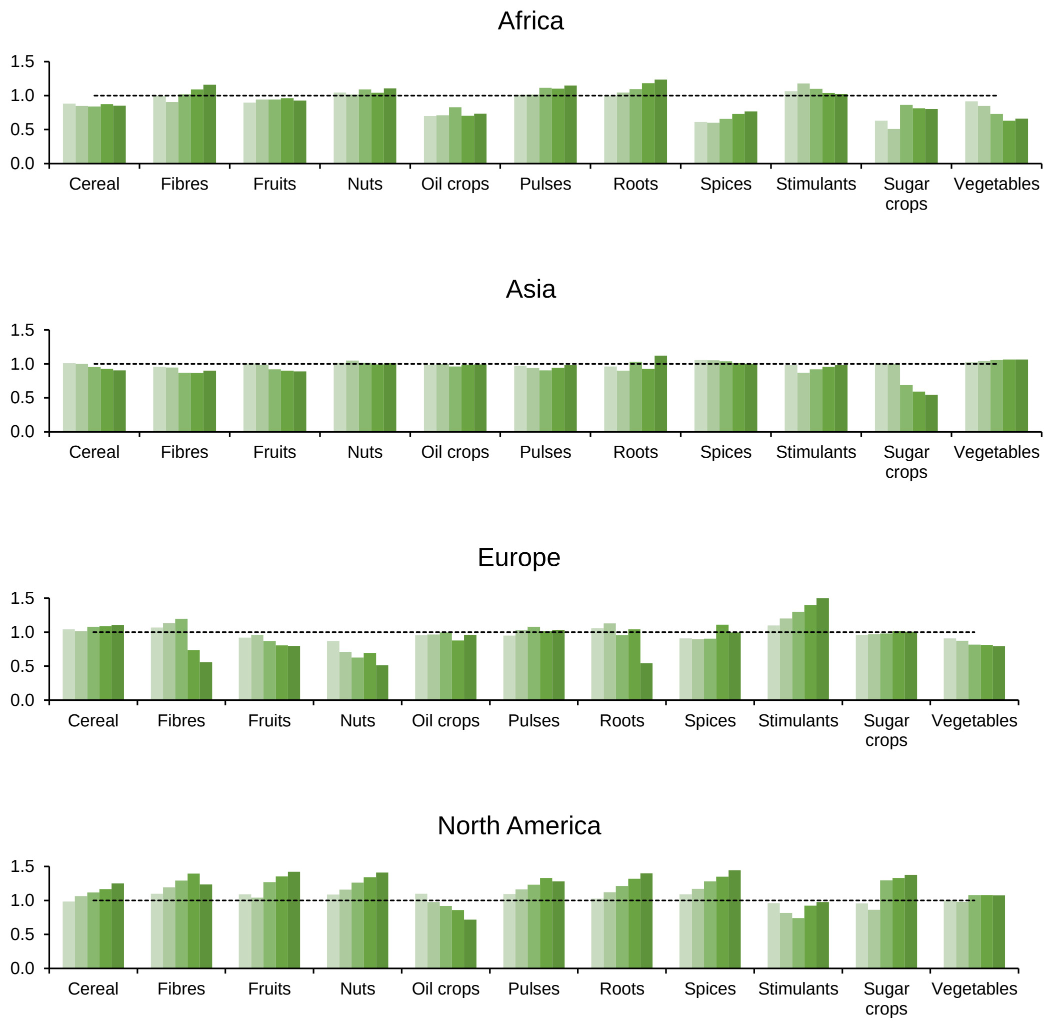
Sugar crop production will be reduced most significantly in Africa and expanded in South America. Sugar cane production will be mainly reduced in Egypt and Sudan and expanded in Brazil. The global harvested area of sugar crops will be reduced in total by 3%.

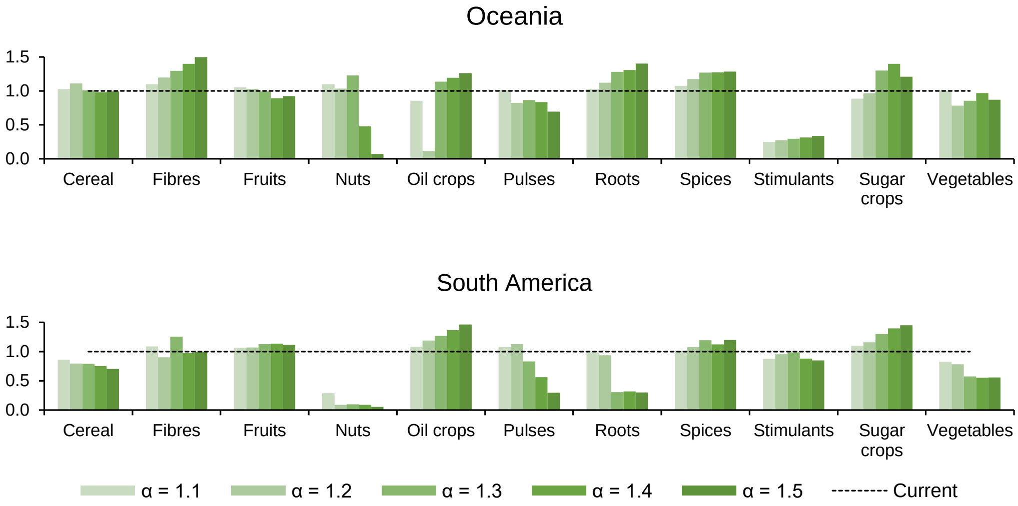
Vegetable production will be reduced most significantly in Europe and expanded in Asia. Major reductions in vegetable production are for cabbages and tomatoes in the Ukraine. The most significant expansions are the increases in tomato and watermelon production in China. The global harvested area of vegetables will be reduced by 7%, with a reduction of 14% for irrigated and 5% for rainfed croplands.

Although rainfed harvested areas will be reduced in Africa and North America for example (Supplemental Table 1), rainfed cereal production in these two continents will increase by 0.5 and 2.2 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 by considering which crops in a country are expanding when we gradually move from $\alpha = 1.1$ to $\alpha = 1.5$. As a summary, Figure 3 shows at the level of continents and crop groups, the ratio of change in total production when we move from the reference cropping pattern (period 1996-2005) to the optimized cropping pattern, considering a stepwise increase in the maximally allowed expansion rate in harvested area per crop per country (from $\alpha = 1.1$ to $\alpha = 1.5$). Most of the changes in production under an allowed 10% areal expansion (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 for the case of $\alpha = 1.1,\ 1.2\ and\ 1.3$ in Europe but will be reduced for higher expansion rates. This can be explained by the fact that other suitable regions, namely Oceania, North America and to a lesser extent Africa, will continue expanding fibres production, allowing Europe to rather focus on cereals, sugar crops and stimulants production (Figure 3). North America reduces cereal production when $\alpha = 1.1$ (Table 3) but increases cereal production when $\alpha = 1.2$ and will have the largest expansion in cereal production for $\alpha = 1.5$ (Supplemental Table 1). This can have two reasons. The first reason is that for the smallest expansion rate, North America 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. 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 4 shows the 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.





291 **Figure 3.** Ratio of total production in the optimized cropping pattern to total production in the reference cropping pattern

292 (period 1996-2005), per crop group and per continent, for α = 1.1 to α = 1.5.

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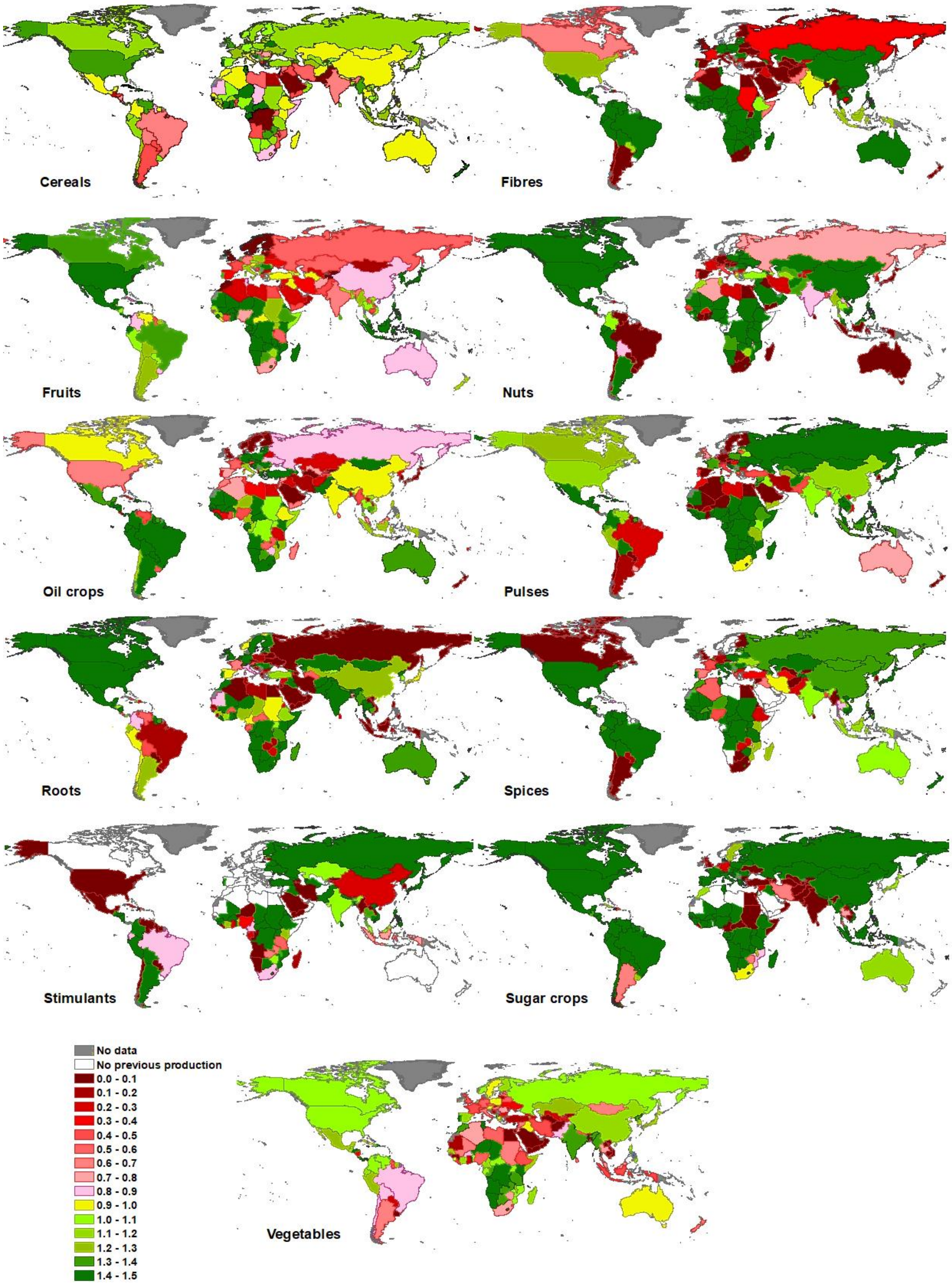

**Figure 4.** Relative change in production per country and per crop group for the case of an optimized cropping pattern with $\alpha = 1.5$.

https://doi.org/10.5194/hess-2019-461
Preprint. Discussion started: 28 October 2019

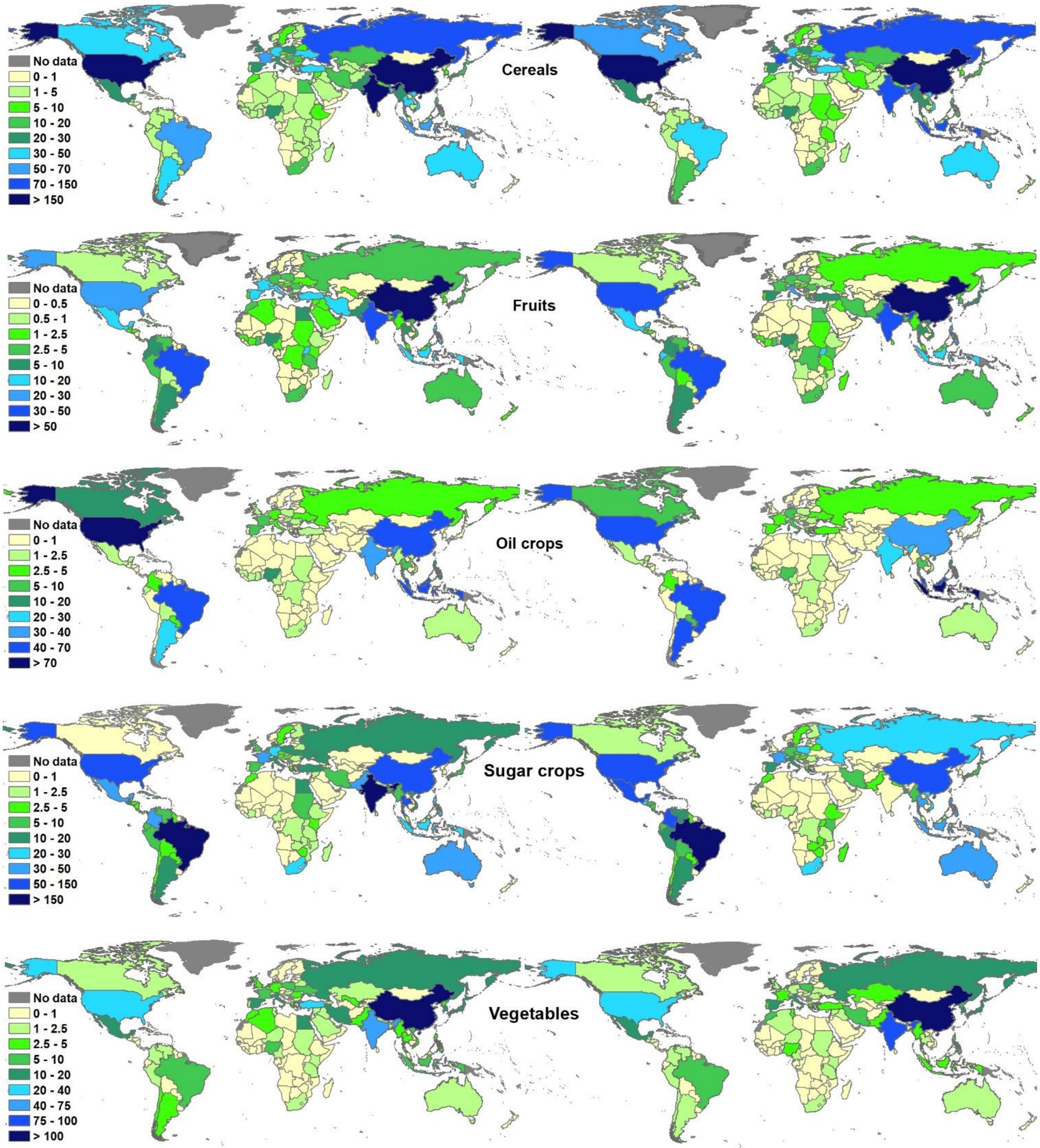

**Figure 5.** Production per crop group per country (in $10^6$ t/yr) in the reference situation (maps on the left hand) and in the case of an optimized cropping pattern with $\alpha = 1.5$ (maps on the right hand).

*Cereal production*. France and the US have both a large relative change (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 $\alpha = 1.5$, cereal production of France and the US will increase by 23 and 30%, 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% for China and 27% 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% and 84% 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% and 9% 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% 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% 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 will decrease by 16% in the optimized cropping patterns (when $\alpha = 1.5$). For bananas, Ecuador, Indonesia 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 have a comparative advantage, with shares in global grape production rising from 7%, 15% and 9% (reference) to 10%, 22% and 13% ($\alpha = 1.5$). 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 Spain and Iran have a comparative disadvantage (Supplemental Figure 2).

*Oil crops.* For oil crops, we find Argentina and Brazil to have a comparative advantage. Their shares in global oil crops production will raise from 6% and 9% respectively (reference) to 9% and 13% ($\alpha = 1.5$). China, Malaysia and the US, contributing 9%, 12% and 17% respectively to global oil crops production in the reference situation, have a comparative disadvantage and will reduce their oil crops production by 10%, 21% and 33% 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%, 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%, 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% 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% 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 entirely in the optimized situation.

## Discussion

One of the limitations of this study lies in the spatial resolution used in the analysis. Limited by data and our optimization model capability, 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 achieved, due to spatial differences in crop suitability. This could mislead the optimization to 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 limit the expansion in cropland by a certain maximum rate for each crop per country (the factor $\alpha$) and limit total cropland to the reference extent. The analysis at country level also has implications for measuring water scarcity. Assessing water scarcity at country level hides the water scarcity that manifests itself in particular places within countries (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.

Another limitation of this study is the focus on water and land endowments and productivities, 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 play a role in determining comparative advantages as well. Other factors could be included in a future study by refining the optimization model. 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 land and water perspective 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 will affect the future ability of countries to produce crops.

The results suggest that Europe, for example, could contribute to global water scarcity mitigation by reducing its production of fruits, sugar crops and vegetables while increasing its cereal production. This implies that Europe 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 highly dependent on other countries. Most of these countries already have a high dependency on crop import in the reference situation. This reflects a trade-off between reducing water scarcity and increasing food security.

## Conclusion

When allowing a 10% maximum expansion of harvested area per crop and per country, while not allowing an increase in total cropland per country, a global blue water saving in the world of 70,000 million $m^3$/yr is achievable, which is 9% of the current global blue water footprint. Hereby, the total global harvested area would decrease by 4%. The 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%), 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 severely water-scarce countries will reduce water scarcity at the expense of increased import-dependency.

When considering how to change the global cropping pattern in order to reduce water scarcity in the world's water-scarcity hotspots, we particularly find the following major shifts. Cereal production will get reduced in Africa and the Americas and increased in Europe and Asia. Fruits production will be reduced most significantly in 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 reduced most significantly in Africa and expanded in South America. Sugar cane production will be mainly reduced in Egypt and Sudan and expanded in Brazil. Vegetable production will be reduced most significantly in Europe and expanded in Asia. The most significant expansion in vegetable production will be an increase in tomatoes and watermelons in China.

From and water and land perspective, comparative advantages for cereal production are found for France and the US, whereas India has a comparative disadvantage. The comparative advantage of France refers to wheat and barley, and the comparative advantage of the US to maize. 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 Brazil for oranges, while China has a comparative disadvantage in apples, and India for bananas. For oil crops, Argentina and Brazil have a comparative advantage, and China, Malaysia and the US a comparative disadvantage. 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.

## Acknowledgements

The work by M.S.K. and A.Y.H was partially funded by the European Commission Project "Moving Towards Adaptive Governance in Complexity: Informing Nexus Security" (MAGIC), EU-H2020 Grant Proposal No. 689669. The datasets generated during and/or analysed during the current study are available in the supplementary information file and the 4TU.ResearchData repository (CC-BY-NC-ND), https://doi.org/10.4121/uuid:f2f5cba2-655d-473a-b547-fde94a386dfc.

## References

Allan, J. A.: Virtual Water: A strategic resource global solutions to regional deficits, Ground Water, 36, 545-546, https://doi.org/10.1111/j.1745-6584.1998.tb02825.x, 1998.

Bouman, B. A. M.: A conceptual framework for the improvement of crop water productivity at different spatial scales, Agricultural Systems, 93, 43-60, https://doi.org/10.1016/j.agsy.2006.04.004, 2007.

Chapagain, A. K., Hoekstra, A. Y., and Savenije, H. H. G.: Water saving through international trade of agricultural products, Hydrol. Earth Syst. Sci., 10, 455-468, https://doi.org/10.5194/hess-10-455-2006, 2006.

Chouchane, H., Krol, M. S., and Hoekstra, A. Y.: Expected increase in staple crop imports in water-scarce countries in 2050, Water Research X, 1, 100001, https://doi.org/10.1016/j.wroa.2018.09.001, 2018.

Chukalla, A. D., Krol, M. S., and Hoekstra, A. Y.: Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching, Hydrol. Earth Syst. Sci., 19, 4877-4891, https://doi.org/10.5194/hess-19-4877-2015, 2015.

Davis, K. F., Rulli, M. C., Seveso, A., and D'Odorico, P.: Increased food production and reduced water use through optimized crop distribution, Nature Geoscience, 10, 919-924, 10.1038/s41561-017-0004-5, 2017a.

Davis, K. F., Seveso, A., Rulli, M. C., and D'Odorico, P.: Water savings of crop redistribution in the united states, Water, 9, 83, https://doi.org/10.3390/w9020083, 2017b.

Davis, K. F., Chiarelli, D. D., Rulli, M. C., Chhatre, A., Richter, B., Singh, D., and DeFries, R.: Alternative cereals can improve water use and nutrient supply in India, Science Advances, 4, eaao1108, 10.1126/sciadv.aao1108, 2018.

Evans, R. G., and Sadler, E. J.: Methods and technologies to improve efficiency of water use, Water Resources Research, 44, 10.1029/2007WR006200, 2008.

FAO: FAOSTAT Online Database, Statistics Division, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy., 2015.

Gleick, P. H.: Global Freshwater Resources: Soft-Path Solutions for the 21st Century, Science, 302, 1524-1528, 10.1126/science.1089967, 2003.

Greenwood, D. J., Zhang, K., Hilton, H. W., and Thompson, A. J.: Opportunities for improving irrigation efficiency with quantitative models, soil water sensors and wireless technology, Journal of Agricultural Science, 148, 1-16, 10.1017/S0021859609990487, 2010.

Hoekstra, A. Y., and Hung, P. Q.: Globalisation of water resources: international virtual water flows in relation to crop trade, Global Environmental Change, 15, 45-56, 10.1016/j.gloenvcha.2004.06.004, 2005.

Hoekstra, A. Y., and Mekonnen, M. M.: The water footprint of humanity, Proceedings of the National Academy of Sciences of the United States of America, 109, 3232-3237, 10.1073/pnas.1109936109, 2012.

Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., and Richter, B. D.: Global monthly water scarcity: Blue water footprints versus blue water availability, PloS one, 7, e32688, 10.1371/journal.pone.0032688, 2012.

Hoekstra, A. Y.: The water footprint of modern consumer society, Earthscan, from Routledge, London; New York, xvi, 204 pages pp., 2013.

Hoekstra, A. Y.: Sustainable, efficient, and equitable water use: the three pillars under wise freshwater allocation, Wiley Interdisciplinary Reviews: Water, 1, 31-40, doi:10.1002/wat2.1000, 2014.

Jalava, M., Kummu, M., Porkka, M., Siebert, S., and Varis, O.: Diet change—a solution to reduce water use?, Environmental Research Letters, 9, 074016, 10.1088/1748-9326/9/7/074016, 2014.

Jones, H. G.: Irrigation scheduling: advantages and pitfalls of plant-based methods, Journal of Experimental Botany, 55, 2427-2436, 10.1093/jxb/erh213, 2004.

Klasen, S., Meyer, K. M., Dislich, C., Euler, M., Faust, H., Gatto, M., Hettig, E., Melati, D. N., Jaya, I. N. S., Otten, F., Pérez-Cruzado, C., Steinebach, S., Tarigan, S., and Wiegand, K.: Economic and ecological trade-offs of agricultural specialization at different spatial scales, Ecological Economics, 122, 111-120, https://doi.org/10.1016/j.ecolecon.2016.01.001, 2016.

Konar, M., Evans, T. P., Levy, M., Scott, C. A., Troy, T. J., Vörösmarty, C. J., and Sivapalan, M.: Water resources sustainability in a globalizing world: who uses the water?, Hydrological Processes, 30, 3330-3336, 10.1002/hyp.10843, 2016.

Kummu, M., Guillaume, J. H. A., de Moel, H., Eisner, S., Flörke, M., Porkka, M., Siebert, S., Veldkamp, T. I. E., and Ward,

P. J.: The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability, Scientific reports, 6, 38495-38495, 10.1038/srep38495, 2016.

Mekonnen, M. M., and Hoekstra, A. Y.: The green, blue and grey water footprint of crops and derived crop products, Hydrol. Earth Syst. Sci., 15, 1577-1600, 10.5194/hess-15-1577-2011, 2011.

Mekonnen, M. M., and Hoekstra, A. Y.: Four billion people facing severe water scarcity, Sci Adv, 2, e1500323, 10.1126/sciadv.1500323, 2016.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., and Kijne, J.: Improving agricultural water productivity: Between optimism and caution, Agricultural Water Management, 97, 528-535, https://doi.org/10.1016/j.agwat.2009.03.023, 2010.

Mukherjee, A., Kundu, M., and Sarkar, S.: Role of irrigation and mulch on yield, evapotranspiration rate and water use pattern of tomato (Lycopersicon esculentum L.), Agricultural Water Management, 98, 182-189, https://doi.org/10.1016/j.agwat.2010.08.018, 2010.

Nouri, H., Stokvis, B., Galindo, A., Blatchford, M., and Hoekstra, A. Y.: Water scarcity alleviation through water footprint reduction in agriculture: The effect of soil mulching and drip irrigation, Science of The Total Environment, 653, 241-252, https://doi.org/10.1016/j.scitotenv.2018.10.311, 2019.

Osama, S., Elkholy, M., and Kansoh, R. M.: Optimization of the cropping pattern in Egypt, Alexandria Engineering Journal, 56, 557-566, https://doi.org/10.1016/j.aej.2017.04.015, 2017.

Parry, M. L., Rosenzweig, C., Iglesias, A., Livermore, M., and Fischer, G.: Effects of climate change on global food production under SRES emissions and socio-economic scenarios, Global Environmental Change, 14, 53-67, 2004.

Pereira, L. S., Cordery, I., and Iacovides, I.: Improved indicators of water use performance and productivity for sustainable water conservation and saving, Agricultural Water Management, 108, 39-51, https://doi.org/10.1016/j.agwat.2011.08.022, 2012.

Sadler, E. J., Evans, R. G., Stone, K. C., and Camp, C. R.: Opportunities for conservation with precision irrigation, Journal of Soil and Water Conservation, 60, 371-378, 2005.

Vanham, D., Hoekstra, A. Y., and Bidoglio, G.: Potential water saving through changes in European diets, Environment international, 61, 45-56, 10.1016/j.envint.2013.09.011, 2013.

Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B.: Global water resources: vulnerability from climate change and population growth, Science, 289, 284, 2000.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., and Davies, P. M.: Global threats to human water security and river biodiversity, Nature, 467, 555, 10.1038/nature09440, 2010.

Wada, Y., van Beek, L. P. H., Viviroli, D., Dürr, H. H., Weingartner, R., and Bierkens, M. F. P.: Global monthly water stress:

2. Water demand and severity of water stress, Water Resources Research, 47, 10.1029/2010WR009792, 2011.

Wada, Y., Gleeson, T., and Esnault, L.: Wedge approach to water stress, Nature Geoscience, 7, 615, 10.1038/ngeo2241, 2014.

WEF: The Global Risks Report 2019, 2019.

Yang, H., Reichert, P., Abbaspour, K. C., and Zehnder, A. J.: A water resources threshold and its implications for food security, Environmental science & technology, 37, 3048-3054, 2003.

Yang, H., Wang, L., Abbaspour, K. C., and Zehnder, A. J. B.: Virtual water trade: an assessment of water use efficiency in the international food trade, Hydrol. Earth Syst. Sci., 10, 443-454, 10.5194/hess-10-443-2006, 2006.

Ye, Q., Li, Y., Zhuo, L., Zhang, W., Xiong, W., Wang, C., and Wang, P.: Optimal allocation of physical water resources integrated with virtual water trade in water scarce regions: A case study for Beijing, China, Water research, 129, 264-276, https://doi.org/10.1016/j.watres.2017.11.036, 2018.