The impact of trade on local green and blue water availability

Anne Biewald[*], Hermann Lotze-Campen,
Susanne Rolinski, Holger Hoff

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[*]The author works at the Potsdam Institute for Climate Impact Research (mail: biewald@pik-potsdam.de)

Abstract

International trade of agricultural goods exported from water abundant to water scarce regions can, in theory, alleviate water scarcity problems, which is a widely and controversely discussed issue in the virtual water literature. But how much can trade really help to solve water scarcity problems? And more importantly does trade of virtual water save the valuable blue water which can be rededicated to other purposes than agriculture or does it rather let green water go unused for which an application to other usages is often difficult?

To address these questions we use two models: First, MAgPIE_trade (Model of Agricultural Production and and its Impact on the Environment), to give us explicit trade and production patterns for food crops. And second, LPJmL a dynamic, spatially explicit, global vegetation and agricultural model with closed water and carbon budgets, which simulates the blue and green virtual water content of the produced food crops.

To assess the effect of trade on agricultural production and water availability, we compare two scenarios for the year 2005: one in which trade is completely disabled and one with a business as usual scenario. The difference between the two scenarios tells us how production patterns change when no trade is possible. Coming from there and using the explicit virtual water contents of LPJmL, we can calculate how much virtual water is saved by allowing trade. We can also determine how much blue water has been saved on the regional and the global level by this trade. MAgPIE_trade gives us additionally spatially explicit patterns of agricultural production.

Using the difference in the production of the two scenarios, we can now determine how production patterns change when no trade is possible. LPJml provides than consumptive green and blue water use for each of the produced crops. Combining the outputs of both models, we can now determine where and how much of green and blue water use increased or decreased when trade is eliminated. This information is already interesting but does not tell us if the important blue water has been saved in water abundant or in water scarce regions. Using the MAgPIE_trade output of cell-based water shadow prices (which is a measure of water scarcity), we develop an indicator of the significance of water saving. This significance indicator can answer the question if and where blue water is saved.

Keywords: virtual water trade, blue and green water

1 Introduction

Any trade of agricultural commodities causes flows of virtual water. Virtual water is the amount of water used when producing agricultural commodities, primarily evapotranspiration during crop growth. Resulting virtual water contents vary strongly depending on climate and production conditions. Roughly speaking, one kg of cereals requires about 1000 l of water while one kg of meat contains about 10000 liters of virtual water. Most of the water consumed in agriculture is green water, i.e. soil moisture directly from rainfall. Only about 10% of agricultural water consumption is blue water from irrigation ([14]). International flows of virtual water are likely to increase further with globalization and trade liberalization ([18]). We analyze here the relationship between trade, virtual water flows and local water scarcity.
An importing country saves the amount of water that would have been required locally to produce the imported food. With that, trade can mitigate water scarcity in the importing country ([1]). Note however, that green water is not actually saved by import substitution, but still evaporates back to the atmosphere, even when not producing crops locally. In that case, green water flows are taking place from other types of ecosystems instead of agro-ecosystems.
An exporting country is loosing the amount of water that is required to produce the exported amount of food. This water can no longer be used for other purposes locally. With that, trade can aggravate water scarcity in the exporting country. Note however, that green water flows (evaporation) from cropland which is used for export products are not necessarily larger than green water flows from other land uses which it replaces.
A countrys water scarcity can be defined as the amount of green plus blue water available per capita ([9]). If the focus is on food production, only the green water available from cropland is taken into account ([19],[10]). Virtual water which enters a country with imports can be added to the locally available real water resources, in order to assess the effective water scarcity. In exporting countries accordingly, water used for producing export commodities (i.e. evaporated in the process of growing biomass) may be subtracted from the locally available water resources.
It has generally been accepted, that some countries, in particular Middle East Asia, mitigate increasing water scarcity through the virtual water associated with food imports ([1]). A strong correlation between water availability and net virtual water imports has been shown ([25]). We extend previous analy-

ses, by mapping the main agricultural areas in each of the Middle East Asia countries, which would have to produce more food if their was no trade, and the additional amounts of water that would be required locally to bridge the resulting food gap.

Little attention has been paid so far to the effects on local water resources of agricultural exports from water scarce regions. That is largely due to the lack of analytical tools which can identify at sub-national level the main regions that produce export crops. At national level, none of the major net exporters of virtual water with agricultural commodities (e.g. USA, Canada, Australia, Argentina) is water scarce. We show for the first time at sub-national level that some exporting regions (pixels) are actually water scarce, by comparing the current trade situation with a hypothetical no-trade situation and calculating for the export pixels shadow prices for water.

While some authors ([24]) argue that local water resources overexploitation and resulting scarcity are only caused by local decisions and (mis-) management, we still would like to point out the important role of exports, which are driven by external demand for food and associated virtual water ([13]).

Given that water productivities or virtual water contents of crops vary strongly between countries and regions (e.g. [21],[15]), international trade also changes the total amounts of water used, compared to a hypothetical situation of local production only. While estimates vary, previous studies generally find that more crops are traded from countries with higher crop water productivity to countries with lower crop water productivity than the opposite way. Overall water savings due to trade range from about 200-500 km3 per year ([8],[5],[6]).

One important factor in overall food water productivity or water use for food production is the conversion of feed into livestock products such as meat, milk and eggs. Given the high amounts of feed required for a kg of livestock product, their virtual water contents are much higher per kg of product and also per kcal ([17]).

2 Methods and data

2.1 Model description MAgPIE

MAgPIE is a global, spacially explicit landuse model which has been developed at the "Potsdam Institute for Climate Impact Reseach" and is extensively described in [16]. The model works in a dynamic, recursive mode and covers on the demand side ten world regions (see Table 1) and on the production side a variable size of up to 2178 grid cells[1]. The core of the model is a cost minimization function, which minimizes the production cost for 25 agricultural goods for each of the regions. The required calories are produced by 15 food crops, 5 livestock products and fiber, additionally there is feed and bioenergy (see Table 2)

Regions	**Description**
AFR	Sub-Saharan Africa
CPA	Centrally planned Asia (including China)
EUR	Europe (including Turkey)
FSU	Former Soviet Union
LAM	Latin America
MEA	Middle East/ North Africa
NAM	North America
PAO	Pacific OECD (Japan, AUS, NZL)
PAS	Pacific Asia
SAS	Southern Asia (incl. India)

Table 1: Description of the different economic regions

food crops	temperate cereals, maiz, tropical cerals, rice, soybean, rapeseed, groundnut, sunflower, pulses, potato, cassava, sugarbeet, sugarcane, other oilcrops, vegetables, fruits, nuts (one category)
fiber	cotton
bioenergy	trees, gras
livestock	ruminant meat, pigs, eggs, milk, chicken
input f. livestock	fodder, pasture

Table 2: Production activities in MAgPIE

[1]These cells cover the terrestrial part of the globe.

3 categories of costs arise for the production: factor requirement costs; yield increasing technical change costs (as described in [7]) and land conversion costs. One special feature of MAgPIE is the fact that it is coupled to the grid-based dynamic vegetation model LPJmL[3], which simulates the potential crop yields on which the production in MAgPIE is based. The model simulates time steps of 10 years and uses in each period the optimal land-use pattern from the previous period as starting point.
In the original MAgPIE version, trade is simulated endogenously by giving each region a minimum self sufficiency ratio and letting the model allocate the rest of the production to other regions according to comparative advantages. This version of MAgPIE implements bilateral trade by including transport costs and trade barriers into the cost minimization function.

2.2 Model description LPJmL

Vegetation growth and crop yields are calculated with the global, dynamic and process-based model LPJmL. Natural vegetation is represented at the biome level by nine plant functional types [22] and growth, phenology and harvest of 12 crop functional types (CFTs) accounts for the agricultural production [4]. The model ensures a global balance of carbon fluxes (gross primary production, auto- and heterotrophic respiration) and pools (in leaves, sapwood, heartwood, storage organs, roots, litter and soil) and water fluxes (interception, evaporation, transpiration, soil moisture, snowmelt, runoff, discharge). Processes of carbon assimilation and water consumption are parametrized on the leaf level and scaled to the ecosystem level. Carbon and water dynamics are closely linked so that the effects of changing temperatures, declining water availibility and rising CO_2 concentrations are accounted for and their net effect can be evaluated [11, 12]. Physiological and structural plant responses determine water requirements and water consumption - and thereby the virtual water content (VWC) of harvested crops. Due to the source of the water used for plant production, the consumption of blue and green water on irrigated and rainfed cropland can be distinguished. All processes are modelled at a daily resolution and on a global 0.5 grid. Simulations were carried out with the option of grwoing each crop in each grid cell so that the current land use pattern is ignored. Hereby, the shift of crop production under changing climatic conditions into previously unsuitable regions can be captured as well as the loss of until now productive areas.

Water availibility by irrigation is unlimited for the simulations so that the potential crop harvest is calculated given that enough water can be allocated. The suitability of the model (and its predecessor LPJ without cropland) for vegetation/crop and water studies has been demonstrated by validating simulated phenology and yields [4], river discharge [11, 2], soil moisture [23], evapotranspiration [22, 11] and irrigation water requirements [20].

2.3 Model application

In the following we will describe our methodology to derive an index of significance of water saving, telling us not only where blue water is scarce but also where virtual blue water is imported in response to this scarcity or where it is exported despite the fact that water is scarce. In order to this we combine production patterns derived from MAgPIE_trade and virtual water content simulated in LPJmL.

2.3.1 Self sufficiency and export pixel

Using MAgPIE_trade we simulate landuse patterns for 2005 for food crops (see Table 2) on a grid of 0.5 degree cells (approximately 50x50km) for two different scenarios. In the first scenario bilateral trade is enabled, constrained only through transport costs and trade barriers, in the second scenario trade is completely blocked and every region has to sustain itself. Subtracting now in every of the cell the production of food crops in the no trade scenario from the production in the trade scenario, we can interpret the result as follows: if the the difference in this pixel is positive, more has been produced in the trade scenario than in the no trade scenario and therfore the difference between the scenarios is produced for the export and we call the resulting pixel, export pixel. If the difference between the trade and no trade scenario is negative, less has been produced in the case of trade than in the case of no trade, this pixel has been forced to produce food crops because of the elimination of trade and in order to assure self sufficiency of the region, we call these pixels self-sufficiency pixels. In Figure 1 we show the difference between these two scenarios for each pixel.
In both scenarios the demand for agricultural goods (including food crops, fiber, livestock and input for livestock) is the same, but the production of the food crops does not have to be equal, since the livestock is fed with parts of the food crops and livestock efficieny is different in the different regions.

The self-sufficiency pixels are therefore of two kinds, first there are cells which produce more in the no trade scenario because they have to compensate for lack of imports, and second they have to produce more food crop in order to feed the livestock, which they have now to produce themselves. The livestock effect is amplified trough the different livestock efficiencies in the different regions. These two effects can of course be mixed in each cell and can not be seperated on the cell level.
Since we are especially interested in the usage of blue water and therefore in the production of food crops on irrigated areas, we show in Figure 5 the difference of production between the two scenarios for irrigated areas.

2.3.2 Changes in agricultural water consumption induced by trade

In order to develop an index of significance of water saving trough trade, we need not only to know how trade influences production patterns, but also how the altered production patterns can be translated into blue and green agricultural water consumption. LPJmL gives us for every cell and every single crop a virtual water content[2] for blue and for green water, that means it tells us how much water is used to produce a ton of dry matter of the according crop. Multiplying now the blue virtual water content of each crop with the export and self sufficiency pixels of each crop produced on irrigated areas and the green virtual water content for each crop with the pixels of each crop produced on rainfed areas, we obtain the information of how much and where water is saved by trade in each cell (self sufficiency pixels) and how much and where water is used for the export of food crops (export pixels) (See Figure 6).
Since, again we are especially interested in how the consumption of blue water alters through trade, we multiply the virtual water content of blue water with the export and self sufficiency pixels of the irrigated areas and obtain figure 7.

2.3.3 Water scarcity

To obtain the indicator of significance of water saving through trade, we need not only to look at how water consumption changes through trade but where water is scarce. The water shadow price derived from MAgPIE_trade indicates how much the optimizer would value one more unit of water and

[2]The virtual water content is provided in m^3 water per ton dry matter

therefore how scarce water is in the corresponding cell. In figure) the water shadow price is shown for the trade case.

2.3.4 Index

The last exercise combines the water scarcity index (water shadow prices) with the changes in water consumption from the no trade to the trade scenario. With this index we want to track two things, first the cells where blue water is scarce (and which therefore have a water shadow price) and agricultural blue water consumption is reduced through trade and second, where water scarce and water blue consumption is higher in the case of trade than in the case of no trade (export pixel). In other words, we are looking first for cells where the scarce resource blue water really is the determing factor for not producing and second for the cells, where other factors are more decisive than water scarcity and agricultural goods are produced for the export. We construct the index by multiplying the changes in water consumption with the water shadow prices. Negative numbers mean, water is scarce and pixels are self-sufficiency pixels and produce more in the no trade case than in the trade case. Positive numbers mean, water is also scarce, but there is nevertheless production for the export. Pixels where there is no irrigated production or where the water shadow price is zero and therefore not scarce show not up in the index (See Figure 9).

3 Results

in this chapter we introduce the model results and combine them in order to obtain the index explained before.

3.1 Self sufficiency and export pixel

Figure 1 shows the export and self-sufficiency pixels for the production of food crops in 2005 in 10^{15} Joule. Orange pixels depict self-sufficiency pixels (more food crops are produced in the no trade scenario than in the trade scenario) and green shows export pixels, the positive difference in production between the trade and the no-trade scenario will be exported in the trade scenario.
The self-sufficiency pixels outweigh the export pixel, because of the two effects (livestock and export effect) which are responsible for the creation of an self-

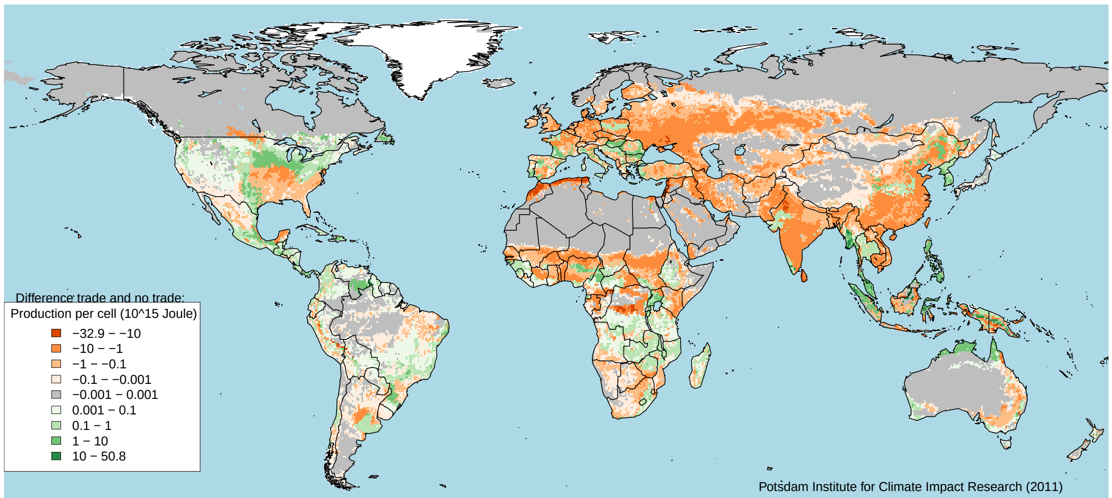

Figure 1: Self-sufficiency and export pixel for rainfed and irrigated areas

sufficiency pixel. The sum of export and self-sufficiency pixels does not add up to zero.

Whereas the reason for the creation of export pixels are unambigious (if a cell produces more in the trade than in the no trade case, the more production in the trade case can only be used for the export), the drivers for the self-sufficiency cells are twofold. As already mentioned, it is not possible to separate the effects on the cell level, but on the regional level we can determine which of the two effects is mostly responsible for self-sufficiency cells in each region.

Figure 2 shows the exports, imports and the self-sufficiency production of each region. For two of the main net exporters of food crops (see Figure 2), North America and Latin America the export effect is stronger than the livestock effect and they produce more in the trade than in the no trade case (see table 4). For Europe, also a main exporter of food crops the livestock effect is stronger than the export effect (the production in the no trade case is higher than in the trade case), since the import of livestock is so high (see table **??**). Import regions such as China and Africa produce more in the no trade than in the trade case, not only due to the lack of imports, but also because they have inefficient livestock systems. The highest negative difference in production between trade and no trade shows the Former Soviet Union which combines very inefficient livestock systems with livestock imports. Pacific Asia which exports food crops and has a relatively high livestock efficiency, is the region with the highest positive difference between not trade and trade.

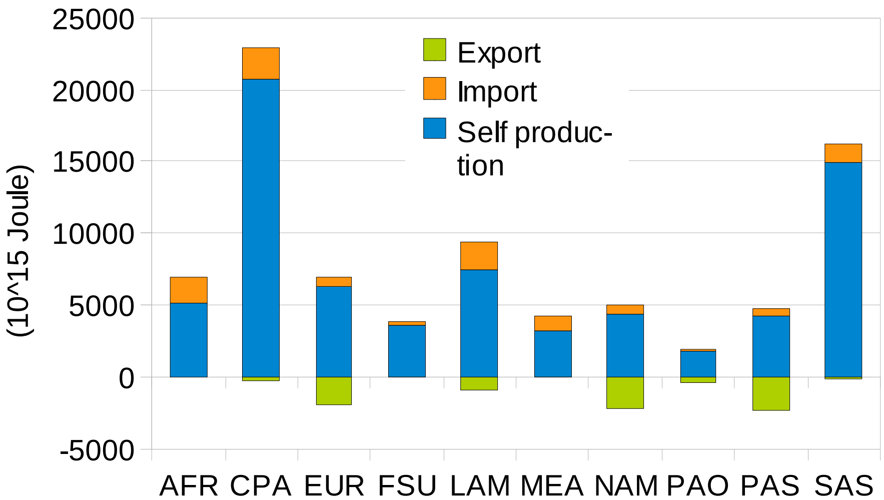

Figure 2: Export, Import and Self-supply for food crops in the trade scenario, 2005

Regions	Energy requirements
AFR	4219
CPA	1854
EUR	746
FSU	1872
LAM	3258
MEA	4658
NAM	836
PAO	920
PAS	1049
SAS	1105

Table 3: Livestock requirements in GJ per ton dry matter

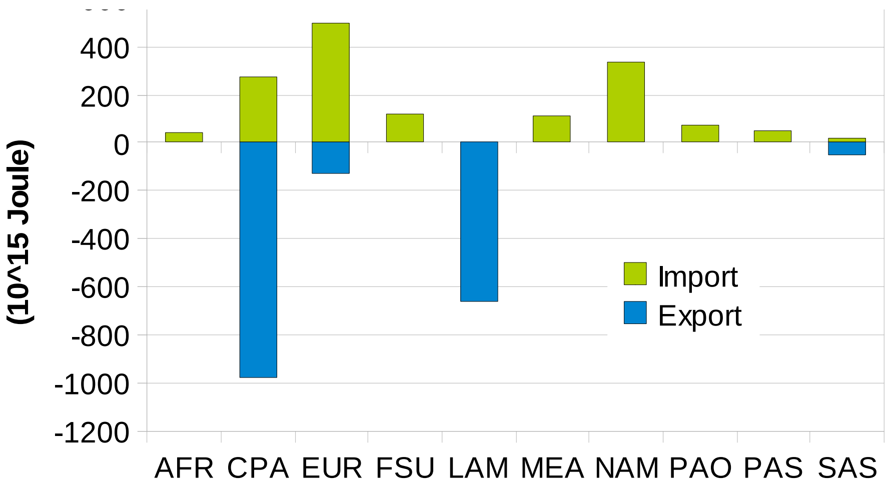

Figure 3: Import and Export of livestock, 2005

Regions	Total calories	Total calories irrigated
AFR	-4358	86
CPA	-3650	-411
EUR	-652	58
FSU	-5596	-74
LAM	61	393
MEA	-3688	110
NAM	528	5
PAO	204	35
PAS	1321	1076
SAS	-3005	20
GLO	-18836	1298

Table 4: Changes in food crop production induced by trade compared to the no trade scenario on the regional and the global level (m^{15} Joule)

Figure 4 shows the more production in case of the no trade scenario compared to the trade scenario and distinguishes the effects in the regional level. For all regions except Latin America (which is a big livestock exporter), the reason for more production of food crops in the no trade case are a mixture of the livestock and the export effect.

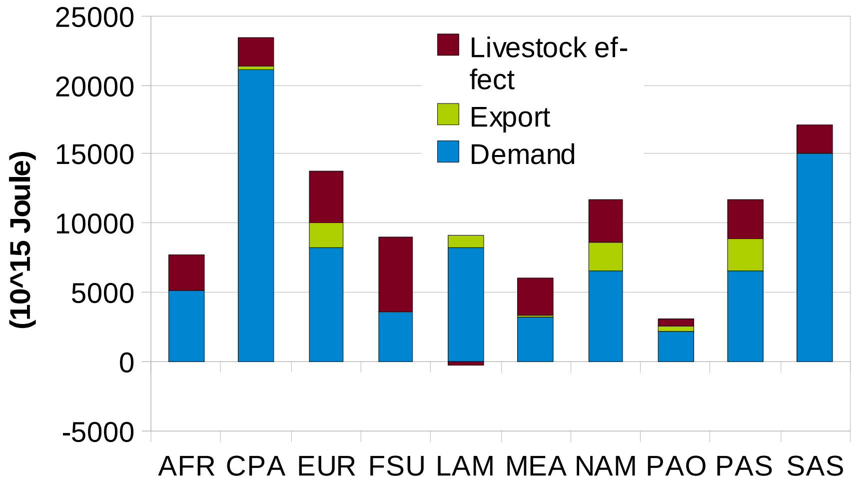

Figure 4: More production in the no trade scenario, divided into the export and the livestock effect

On the irrigated areas, more food crops are produced globally in the trade than in the no trade case (see Table 4). The only regions with a negative trade, no trade difference are the China and the Former Soviet Union. (See figure 5).

3.2 Changes in agricultural water consumption induced by trade

Figure 6 depicts the water which is used for agricultural production in the trade scenario compared to the no trade scenario. Here again, green export pixels, which means higher water usage in the no trade than in the trade scenario, outweigh the self-sufficiency pixels because of the implementation of livestock. The only export region which uses more water in the trade than in the no trade case is Pacific Asia. For North America, the livestock effect is concerning water consumption now more important than the export effect.
Since we are interested in the blue water savings trough trade, figure 7 shows the pixel in which water is saved in the trade case compared to the no-trade scenario (orange self-sufficiency pixel) and the green export pixel in which less water is used in the no trade scenario. Regions which are main exporters

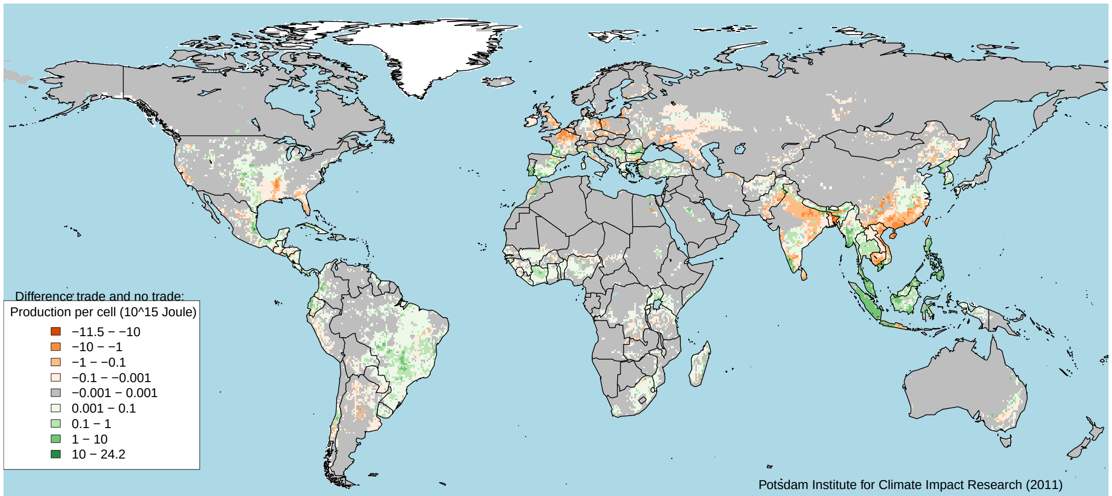

Figure 5: Self-sufficiency and export pixel for irrigated areas

of irrigated production are South Asia, Pacific Asia and Europe and these are also the regions with many green pixels.
In Table 5 the differences in water consumption for the trade and the no trade case are summed up over the regional and the global level. On the global level the difference in the absolute amount of blue and green water is negative, that means more water is used in the no trade than in the trade scenario. This result complies perfectly with the theory of comparative advantage. On the regional level some regions use more in the trade than in the no-trade scenario (Pacific Asia, Pacific OECD and Latin America) and all the other regions use less and save therefore water trough trade. Espeically dry regions such as Africa, Middle East Asia, the Former Soviet Union and South Asia save a lot of water through trade. The highest water savings per capita are in the Former Soviet Union and than in Middle East Asia. The changes in blue water consumption induced by trade are antithetic to the first results. On the global level more blue water is used for agriculture in the trade scenarios than in the no-trade scenario. That means most of the irrigated agricultural production goes into the export, but it also means that regions which have exported irrigated agricultural goods in the trade scenario have to satisfy their demand by growing the same crops on non irrigated areas,

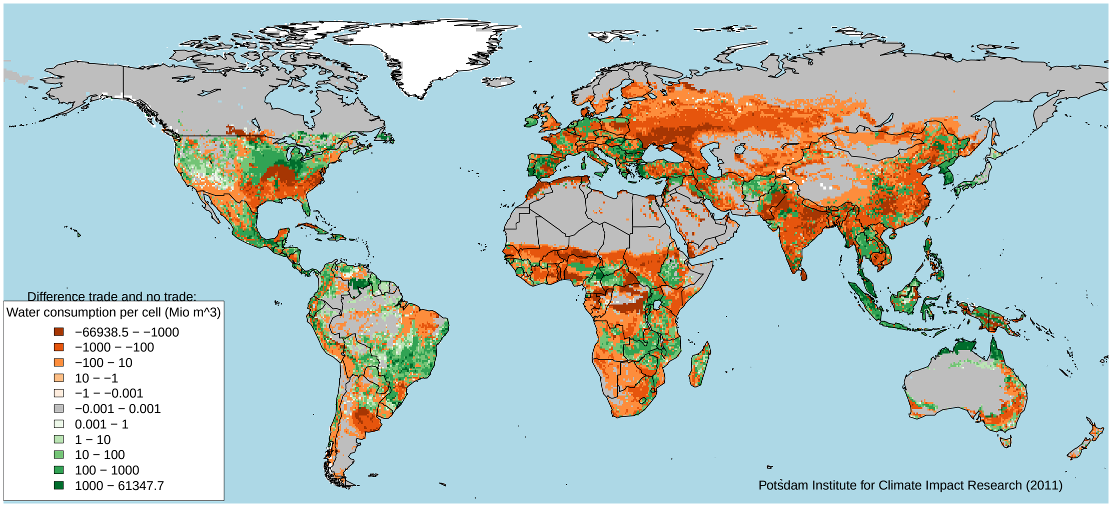

Figure 6: Self-sufficiency and export pixel for blue and green water

which also explains the huge negative water savings in the combined blue and green water. The regions which save blue water trough trade are again water scarce regions such as Middle East Asia, China and the Former Soviet Union. The per capita savings are again highest in the Former Soviet Union, but here followed by China. Regions which export high amounts of virtual water are Europe, South Asia and Pacific Asia, the regions with the highest per capita export of virtual water are Europe and Pacific East Asia.

3.3 Water scarcity

Figure 8 shows the water shadow price for 2005 and the trade scenario. The maximum water shadow price can be found in the Former Soviet Union and in parts of Middle East Asia. This are mainly regions which do not have irrigated areas, but the high water shadow price indicates that water is scarce there and that the possibility to irrigate agricultural production is highly appreciated. Countries which do have irrigation, such as India, Spain, Portugal and Argentinia have very realistic water prices which are around 10-20 cents per m^3.

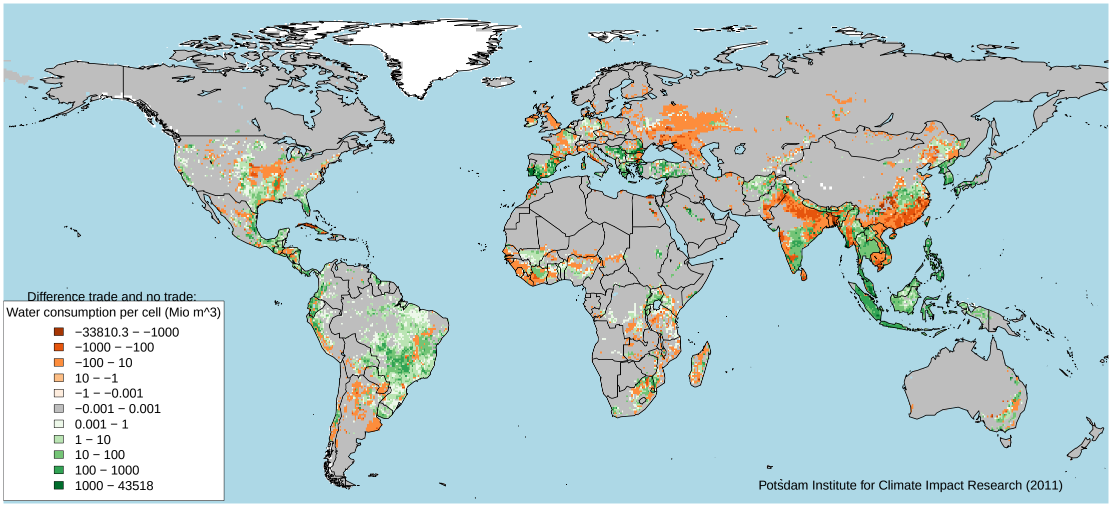

Figure 7: Self-sufficiency and export pixel for blue water

Regions	blue and green water	blue water	blue and green water per capita	blue water per capita
AFR	-1946096	11997	-2619	16
CPA	-793376	-192282	-536	-130
EUR	-168947	181093	-287	307
FSU	-1702735	-57023	-5816	-195
LAM	595527	85807	1082	156
MEA	-1351539	-15595	-3784	-44
NAM	-501791	1165	-1512	3.5
PAO	562557	5377	3860	37
PAS	568653	149801	1230	324
SAS	-1325566	151930	-843	97
GLO	-6063312	322271	-929	49

Table 5: Changes in water consumption induced by trade compared to the no trade scenario on the regional and the global level (m^3), absolut and per capita

3.4 Index

Finally we can use all the previously achieved results to construct our index of the significance of water savings, for this purpose we multiply the water

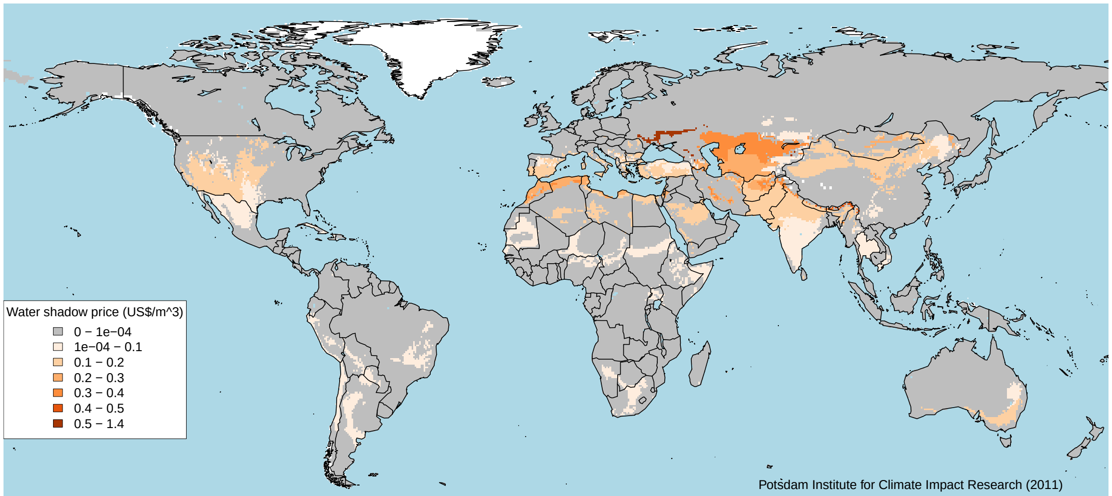

Figure 8: Water scarcity in the trade scenario

shadow price with the negative or positive water savings resulting from the difference between trade and no trade. This multiplication will narrow down the amount of visible pixels, since cells which have no irrigated production or no water shadow price disappear. The highest negative index of significance of water savings (that means virtual water is not exported and production is forced through self-sufficiency) can be found in India, Morroco, Middle Africa, parts of North America and Mexico, these are the countries where water scarcity really is the driving factor for production on irrigated areas. The highest positive values for our index (which means water is scarce and despite this fact there are exports of virtual water) can be found in Portugal, Spain, Turkey, Afghanistan and parts of China.

4 Discussion

This article used export and self-sufficiency pixels (derived as the difference between trade and no trade) and virtual water contents in order to develop an indicator for the significance of blue water scarcity. The index shows that there are indeed many countries where little or no virtual water is imported because of the water scarcity of the region (e.g. Morroco). Other countries,

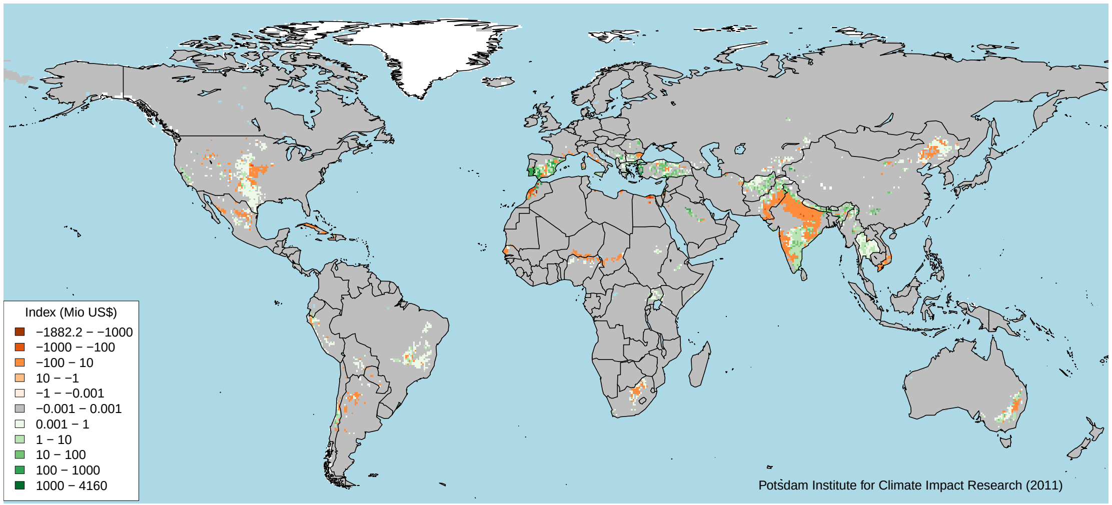

Figure 9: Indicator of significance of water saving: Difference in water consumption (trade and no trade) (m^3) * Water shadow price ($Mio\ US\$/m^3$)

such as Portugal, Spain or Afghanistan export virtual water although their blue water is scarce.

Our experiments with the trade and no trade scenarios have also shown that in the case where every region has to sustain itself much more green water is used and less blue water. This results indicate that it might be possible to shift production from irrigated to rainfed production and still be able to feed the global population.

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