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# Inequality or injustice in water use for food?

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## Abstract

The global distributions of water availability and population density are uneven and therefore inequality exists in human access to freshwater resources. Is this inequality unjust or only regrettable? To examine this question we formulated and evaluated elementary principles of water ethics relative to human rights for water, and the need for global trade to improve societal access to water by transferring 'virtual water' embedded in plant and animal commodities. We defined human welfare benchmarks and evaluated patterns of water use with and without trade over a 25-year period to identify the influence of trade and inequality on equitability of water use. We found that trade improves mean water use and wellbeing, relative to human welfare benchmarks, suggesting that inequality is regrettable but not necessarily unjust. However, trade has not significantly contributed to redressing inequality. Hence, directed trade decisions can improve future conditions of water and food scarcity through reduced inequality.

## Introduction

The number of humans subject to water scarcity is increasing, with greater proportions of water-scarce populations being subject to more severe shortages (Rockström *et al* 2009, Kummu *et al* 2010). The geographic distributions of water and population density create natural inequalities in water availability (Seekell *et al* 2011). Most (70–92%) of human water use is dedicated to agricultural production, making food security inextricably linked to water resources (Yang *et al* 2003, Carr *et al* 2012a, Hoekstra and Mekonnen 2012a). Water-scarce countries can balance their water needs by importing 'virtual water' in the form of agricultural plant and animal commodities from other countries, effectively allowing countries access to the water resources of their trade partners (Allan 1998, Carr *et al* 2012b, Hoekstra and Mekonnen 2012a). However, differences in wealth create unequal access to the global trade network (Yang *et al* 2003, Falkenmark *et al* 2009, Seekell *et al* 2011, Carr *et al* 2012a). Hence patterns of inequality in water use may be the result of both natural and trade-induced conditions.

If resources are abundant, large inequalities can exist without precluding populations from meeting their basic needs. However, if resources are scarce, inequality may need to be reduced in order that the basic needs of all are met (Hoekstra 2011, Seekell *et al* 2011, Suweis *et al* 2013). In this regard, nothing is inherently unjust about inequality, yet inequality can contribute to injustices. Considering water availability for food production, inequalities change over time in response to interactions between growing populations, diet, changing trade networks, and the finite supply of freshwater resources (Yang *et al* 2003, Carr *et al* 2012b, 2013). How do we determine if these inequalities are unjust? What is the role of trade in increasing or decreasing water-use inequality? These questions are important for understanding issues of fairness in resource use at the global scale; but they are difficult questions in part because the answers are context dependent (Hoekstra 2011, Hoekstra and Mekonnen 2012b, Ridout and Huang 2012, O'Bannon *et al* 2014). To date, a framework for evaluating whether inequality in human access to freshwater resources is unjust, or simply a regrettable consequence of natural resource distributions, is still

missing. Here, we argue that this depends on how inequality comes about, specifically whether or not inequality is trade-induced and whether or not human rights are met. We address these questions by formulating elementary principles of water ethics relative to human rights for water and defining quantitative benchmarks for human welfare. We then track changes in water availability in the form of combined blue and green virtual water consumption and trade over a quarter century. Finally, we evaluate patterns of water use with and without trade over a 25-year period to identify the influence of trade and inequality on equability of water use.

## Methods

### Ethical basis for human right to water

Access to water for crop production and domestic use is recognized as a human right by the United Nations through Article 11, General Comment 12, and General Comment 15 of the International Covenant on Economic, Social and Cultural Rights (see also Gleick (1998) and Langford (2005)). Declarations of human rights are ethical statements articulated through legislation (Sen 2004). The ethical basis for a right to water derives clearly from the biological need for food and water for life. Deprivation of food and water past a threshold leads to death and hence a deprivation of the right to life (Article 3 of the universal Declaration of Human Rights). The fact that the human right for food and water is ratified by the United Nations, suggests agreement on the moral implications of water accessibility across cultures, development statuses, geographies, and histories. As a consequence, all people are entitled to some minimal allotment of water. This is typically given as at least 800–1000 m$^3$ water per person per year (Allan 1998, Gleick 1998, Falkenmark and Rockström 2004, Islam *et al* 2007). Below this minimal allotment of water, populations are considered to be under high or extreme water stress and malnourishment adversely affects human livelihood (Gleick 1995, Gleick 1998, Islam *et al* 2007).

Regardless of the origin of water scarcity (natural or trade-induced), when inequality in the access to water resources leaves some populations in conditions of extreme water stress (i.e., below the minimal allotment of water), the human rights to water, food, and life are violated and we argue that such an inequality is unjust. We notice that trade-induced inequality may be unjust even without causing extreme water stress if virtual water 'flow' associated with trade occurs towards countries that have high per capita water consumption at the expenses of countries that, as an effect of trade, are unable to meet the dietary requirements of a balanced diet. Prior studies indicate that the global reference level for a balanced diet ranges from 1075 to 1300 m$^3$ water per person per year (Falkenmark and Rockström 2004, Gerten *et al* 2011). We consider the reference level for a balanced diet to also represent a reference level for human wellbeing. This wellbeing threshold is country specific, based on water resources, production, and dietary choices of the population (Gerten *et al* 2011).

Regardless of the magnitude of individual countries specific thresholds, we argue that no moral obligation exists towards countries whose per capita water availability is above the extreme water stress and below the wellbeing levels (i.e., the human right to life is not violated and inequality is simply a regrettable consequence of the uneven global distribution of natural resources and people). However, we also argue that trade-induced inequality that pushes per capita water availability below the wellbeing level in countries that would otherwise have a higher natural water endowment should be seen as unjust.

### Water use for food production

We calculated the total country-specific values of water use (blue + green water) for food production and resultant food calorie production, and reconstructed detailed global virtual water and calorie trade networks for the period 1986–2010 based on United Nations Food and Agricultural Organization food balance sheets (FAO 2014), international trade data and country/commodity specific blue and green water footprints (Hoekstra and Mekonnen 2012a), and commodity specific caloric content using previously described methods (Carr *et al* 2012b, 2013).

In total, our database included 266 primary and secondary plant and animal commodities (supplemental information table 1, available at stacks.iop.org/erl/10/024013/mmedia). There is, however, a problem of double accounting in the evaluation of the water consumption for food production if we consider both secondary products (e.g., bread) and primary crops (e.g., wheat) because the water used in the production of primary products is already accounted for in the water footprint of the secondary products. In order to remove double accounting, only 145 primary commodities were used for production values with trade allowed amongst all 266 primary and secondary commodities. Meat, fish and other animal based products were treated as primary commodities because the fraction of crops used as feed was removed from this analysis of virtual water trade (to remove double accounting). Similarly seed and crops for other (i.e., non-food) uses were also removed to examine only food available for human consumption. Other animal products derived from meat, milk, and eggs were treated as secondary products and the virtual water content of fish products was assumed to be zero. Our database included 160 countries (supplemental information table 2) representing around 99% of the total global population, depending on the year (supplemental information table 3).

Political boundaries changed over the period of record but were rectified using the approach described by Carr *et al* (2013). Countries with populations less than 1 million were not included in the analysis.

**Identifying ethical thresholds**

Estimation of country-specific wellbeing, $T_{wb}$, and malnourishment thresholds, $T_{mn}$, were first calculated based only on production data, and then corrected to account for the effect of trade. For each country $c$, and year $y$, the production values of each primary crop ($P$) were converted to calorie (kcal), and water equivalents (m$^3$) using calorie estimates per ton, $k_p$, (FAO 2014) and virtual water content per ton, $w_{c,p}$ (Hoekstra and Mekonnen 2012a). It is important to note that the virtual water content of a product depends on country of origin, while the caloric content for each commodity were assumed to remain constant spatially and temporally. We assume that all exports from country $i$ originate from country $i$. In some cases countries re-export commodities that they have imported, but this assumption is necessary because FAO records do not allow us to determine the percentage of exports that is domestic production versus re-export (Konar *et al* 2012). This is a limitation of all trade analyses based on this data (Konar *et al* 2012). Production was split into vegetable, $p_v$, and animal products, $p_a$, and the calorie production per unit volume of water consumption was estimated for plant and animal products for each country as:

$$K_{c,v,y} = \frac{\sum_{P_v} k_{P_v} P_{c,P_v,y}}{\sum_{P_v} w_{c,P_v} P_{c,P_v,y}}$$

$$K_{c,a,y} = \frac{\sum_{P_a} k_{P_a} P_{c,P_a,y}}{\sum_{P_a} w_{c,P_a} P_{c,P_a,y}} \tag{1}$$

where $P_{c,\,p,\,y}$ denotes the production of product $p$, on year $y$, in country, $c$. Given the total per capita calories, $d$, for a reference diet, the fraction of the diet comprised of vegetable and animal products, $f_v$ and $f_a$ respectively (with $f_v + f_a = 1$), then the total volume of water consumed for food production, $T$ for that diet can be calculated as

$$T_{c,y} = \frac{f_v d}{K_{c,v,y}} + \frac{f_a d}{K_{c,a,y}} \tag{2}$$

As noted, we consider two reference diets, $d$. The wellbeing diet ($d_{wb}$) was based on an average daily energy requirement of 2400 kcal. This value was then increased by 25% to $d = 3000$ kcal to account for food waste (e.g., Kummu *et al* 2010, Porkka *et al* 2013, Kummu *et al* 2014) and was considered to be comprised of 80% vegetable and 20% animal products (Gerten *et al* 2011). The malnourishment threshold was based on the minimum daily energy requirement of 1850 kcal increased similarly to $d_{mn} = 2300$ kcal

assuming 20% food waste in the form of calories (Kummu *et al* 2014). Calories from animal products were assumed to comprise only a third of that of the wellbeing diet.

Trade complicates the averaging scheme used above because trade (1) includes secondary products (2) removes calories via exports ($E$), (3) adds calories and virtual water content from commodities imported ($I$). Trade modified estimates of calorie content per unit volume of water consumption for plant and animal products for each country can be expressed as:

$$K_{c,v,y} = \frac{\sum_{P_v} k_{P_v} \left( P_{c,P_v,y} - E_{c,P_v,y} + I_{c,P_v,y} \right)}{\sum_{P_v,c_i} w_{c,P_v} \left( P_{c,P_v,y} - E_{c,P_v,y} \right) + w_{c_i,P_v} I_{c_i,P_v,y}}$$

$$K_{c,a,y} = \frac{\sum_{P_a} k_{P_a} \left( P_{c,P_a,y} - E_{c,P_a,y} + I_{c,P_a,y} \right)}{\sum_{P_a,c_i} w_{c,P_a} \left( P_{c,P_a,y} - E_{c,P_a,y} \right) + w_{c_i,P_a} I_{c_i,P_a,y}}, \tag{3}$$

where the subscript $c_i$ refers to the countries $i$ from which country $c$ imports a given product $p$.

With trade modified thresholds calculated using equations (2) and (3), we estimated temporally varying country specific thresholds impacted both by local production and trade. Population weighted global average thresholds for each year demonstrate steady increase over the 25-year period due to changes in the relative importance of crops produced and population. Population weighting across years allows for calculation of both country and global averages (supplemental information table 4). For the 25-year period without trade, the global average threshold was 1208 m$^3$ capita$^{-1}$ year$^{-1}$, above the 1075 m$^3$ yr$^{-1}$ per capita calculated by Gerten *et al* (2011) and below the 1300 m$^3$ yr$^{-1}$ per capita from Falkenmark and Rockström (2004) with country specific thresholds similar to those calculated by Gerten *et al* (2011). When trade is included, the global temporal average is 1160 m$^3$ yr$^{-1}$ per capita. Malnutrition thresholds were 707 and 673 m$^3$ yr$^{-1}$ per capita, without trade and with trade respectively (supplemental information table 4). The fact that trade reduces both the wellbeing and malnourishment thresholds is consistent with the notion of trade-induced water savings (Chapagain and Hoekstra 2008) and it is important to note that trade acts in two ways; first, to modify country specific thresholds for wellbeing and malnourishment, and second to redistribute water resources.

In order to cross compare countries with discrepant thresholds, country specific 'relative water use' for country $c$, year $y$, was calculated with respect to the wellbeing conditions as

$$R_{wu,c,y} = \frac{W_{c,y}}{T_{c,y}} \tag{4}$$

and is expressed as a % (or '% of wellbeing'), with the water use per capita $W$, of country $c$, year $y$, calculated as

$$W_{c,y} = \left( \sum_{p_a, p_v, c_i} w_{c,p_v,p_a} \left( P_{c,p_v,p_a,y} - E_{c,p_v,p_a,y} \right) \right.$$

$$\left. + w_{c_i,p_v,p_a} I_{c_i,p_v,p_a,y} \right) / \text{population}_{c,y}. \qquad (5)$$

In this manner increasing total water use, and/or decreasing the local wellbeing threshold (e.g., by reducing dietary water demands, or importing food from water use efficient countries) both are methods that increase the relative water use, $R_{wu,c,y}$, and consequently improve the wellbeing for a given country.

**Changing influence of trade on inequality**

To evaluate whether water needs for human rights are met globally, we use the population weighted average relative water use, $\overline{R_{wu,c,y}}$ (hereafter called 'average relative water use') as a lumped indicator of global access to water for food and assess whether it meets two benchmarks ($S$) for standard of living. These two benchmarks for mean relative water use ($\mu$) are determined based on a widely used generalized formula for standard of living that relates the mean relative water use and the inequality ($G$) in resource distribution (Yitzhaki 1979, Kakwani 1985, Bishop *et al* 1991)

$$\mu = \frac{S}{(1 - \theta G)} \qquad (6)$$

Here, $S$ is the global standard of living, set here as a relative water use of 100%. The benchmark, $\mu$ becomes the value of global average relative water use that is necessary to produce that standard of living given $G$, the inequality in the distribution of resources. Here $G$ is expressed as the Gini coefficient of water resource distribution (e.g., Seekell *et al* 2011) which ranges from zero (perfect equality, e.g., all people have access to the same volume of water) to one (perfect inequality, only e.g., one person has access to water and all others have no access). Lastly, $\theta$ is a parameter ranging from 0 to 1 that determines the extent of inequality penalization (Yitzhaki 1979, Kakwani 1985, Bishop *et al* 1991).
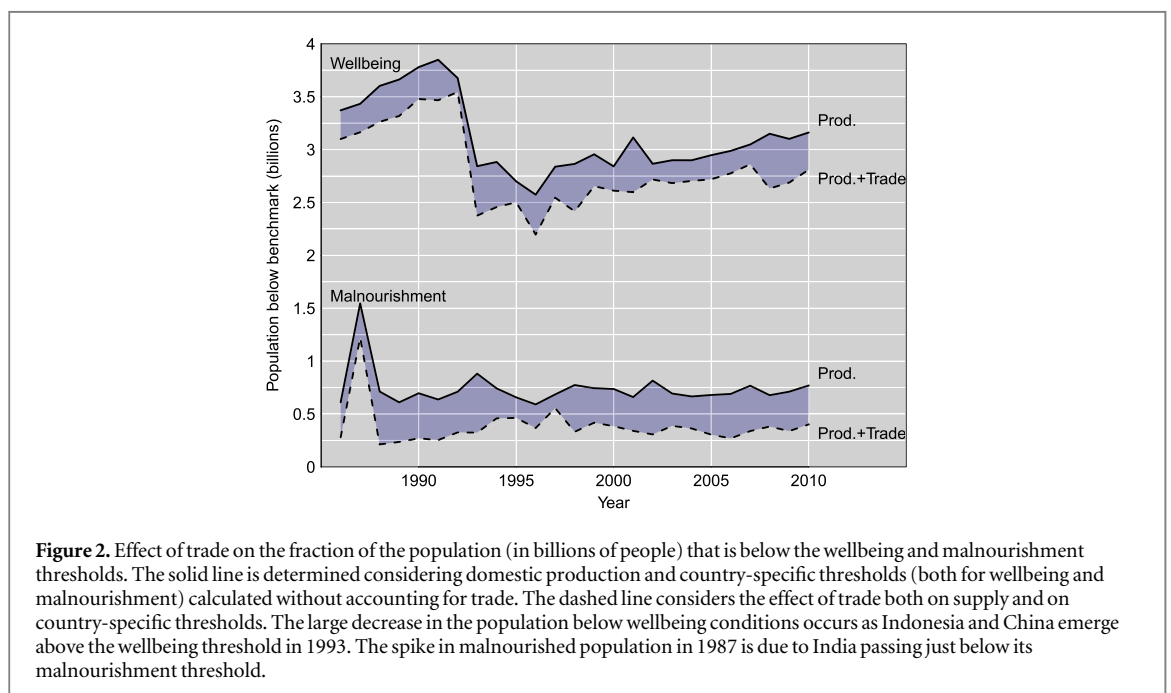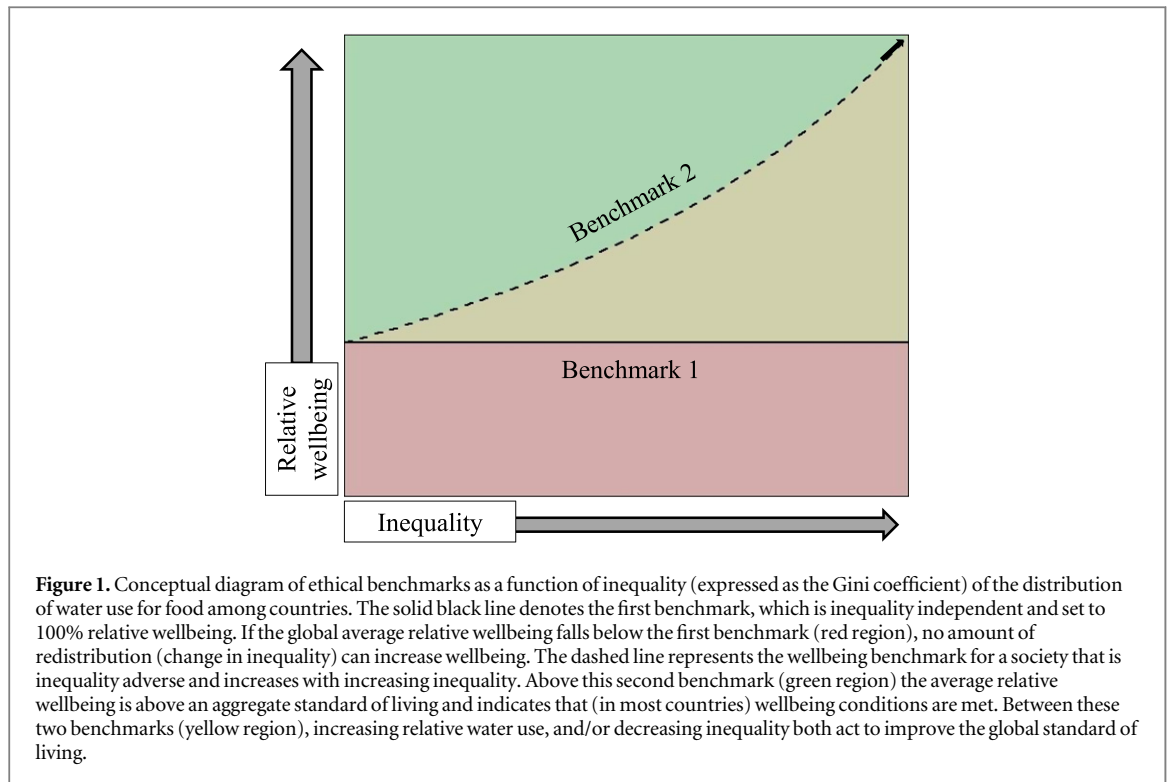
The first benchmark we define is independent of inequality and is equivalent to setting $\theta = 0$. This represents a society with no aversion to inequality (Kakwani 1985) and as such, the global average relative water use benchmark reduces to $\mu = 100\%$ of the wellbeing threshold. We also define a second benchmark that depends on the distribution of relative water use by incorporating a strong penalization for inequality, with $\theta = 1$, and represents a society extremely averse to inequality (Kakwani 1985). This is because inequality in water use among countries may prevent wellbeing conditions to be met despite the fact that the global average relative wellbeing is greater than one. As defined, the second benchmark has no penalty when there is no inequality (e.g. $G = 0$) but, as inequality in

the distribution increases, more than 100% of the wellbeing diet per person per year on average is necessary to achieve an 'equality minded' aggregate standard of living. Unlike the first benchmark, the second benchmark can be crossed both by changing relative local water, $R_{wu,c,y}$, use via production and trade and/or by changing the distribution of water use among countries (i.e., changing inequality). For each year we calculate the inequality ($G$) in water use for food production and, for each country, the relative water use (per capita water use divided by their country specific wellbeing threshold, equation (5)). We then take the population weighted average to determine the global average relative water use; the result is a point in the phase space of inequality ($G$) and relative water use (%) (figure 1) and can be referenced to the above benchmarks. To evaluate the effect of trade on access to water for food, both $G$ and the average relative water use, $\overline{R_{wu,c,y}}$, are calculated considering both the case with and without trade. In other words, for each country we consider both the water use for domestic food production, and the water use associated with the net food availability (domestic production + trade).

The two benchmarks are used as references for interpreting relative water-use records in the context of value-based questions. If the global average relative water use lies in the region above the second benchmark (figure 1, green region), the aggregate standard of living indicates that (in most countries) wellbeing conditions are met. In this situation, inequality may just be regrettable because it is not expected to contribute to loss of wellbeing. By definition, if the global average relative water use falls below the first benchmark (figure 1, red region), even a distribution with pure equality is unable to meet wellbeing requirements. In this scenario, wellbeing can be met only by increasing relative water use. However, if the global average relative wellbeing falls in the region between these two benchmarks (figure 1, yellow region) both relative water use and inequality play important roles in determining the standard of living. Addressing inequality or relative water use provides mechanisms by which to improve a global standard of living and meet wellbeing conditions. Hence the context dependent nature of inequality is reflected in these benchmarks in that inequality influences standard of living between the two benchmarks, but not above the upper or below the lower benchmark.

## Results

Overall, trade reduces the fraction of the global population below the undernourishment and wellbeing levels (figure 2). To understand how changes in mean relative water use and inequality interact to achieve this, we calculated the trajectories of mean global relative water-use during the period 1986–2010 through the phase space of relative wellbeing and

**Figure 1.** Conceptual diagram of ethical benchmarks as a function of inequality (expressed as the Gini coefficient) of the distribution of water use for food among countries. The solid black line denotes the first benchmark, which is inequality independent and set to 100% relative wellbeing. If the global average relative wellbeing falls below the first benchmark (red region), no amount of redistribution (change in inequality) can increase wellbeing. The dashed line represents the wellbeing benchmark for a society that is inequality adverse and increases with increasing inequality. Above this second benchmark (green region) the average relative wellbeing is above an aggregate standard of living and indicates that (in most countries) wellbeing conditions are met. Between these two benchmarks (yellow region), increasing relative water use, and/or decreasing inequality both act to improve the global standard of living.



**Figure 2.** Effect of trade on the fraction of the population (in billions of people) that is below the wellbeing and malnourishment thresholds. The solid line is determined considering domestic production and country-specific thresholds (both for wellbeing and malnourishment) calculated without accounting for trade. The dashed line considers the effect of trade both on supply and on country-specific thresholds. The large decrease in the population below wellbeing conditions occurs as Indonesia and China emerge above the wellbeing threshold in 1993. The spike in malnourished population in 1987 is due to India passing just below its malnourishment threshold.

inequality (figure 3). First we assessed national relative water consumption for food production in the absence of trade (figure 3(A))—the volume of virtual water accessible to a nation without trade. The global mean relative water use began (and remained throughout the study period) above both the malnourishment threshold (which we found to correspond to a relative water use of roughly 58%) and the wellbeing threshold (i.e., relative water use = 100%) and remained almost unchanged for 15 years. As such, this paper focused on the case of the impact of trade and inequality on wellbeing rather than malnourishment. Over this 15-year interval, the inequality in water use based on production data decreased arriving at a minimum Gini of 0.2 in 1999. This reduction in inequality in the first 15 years (figure 3(A)) reversed in the last 10 years of the study period due to large increases in water use for food in some countries (e.g., due to an increase in human appropriation of freshwater resources for food production), which also increased the global average relative water use, raising it nearer to the second benchmark. From this perspective, water rich nations (in terms of water use for food production) are increasing the global average wellbeing by increasing
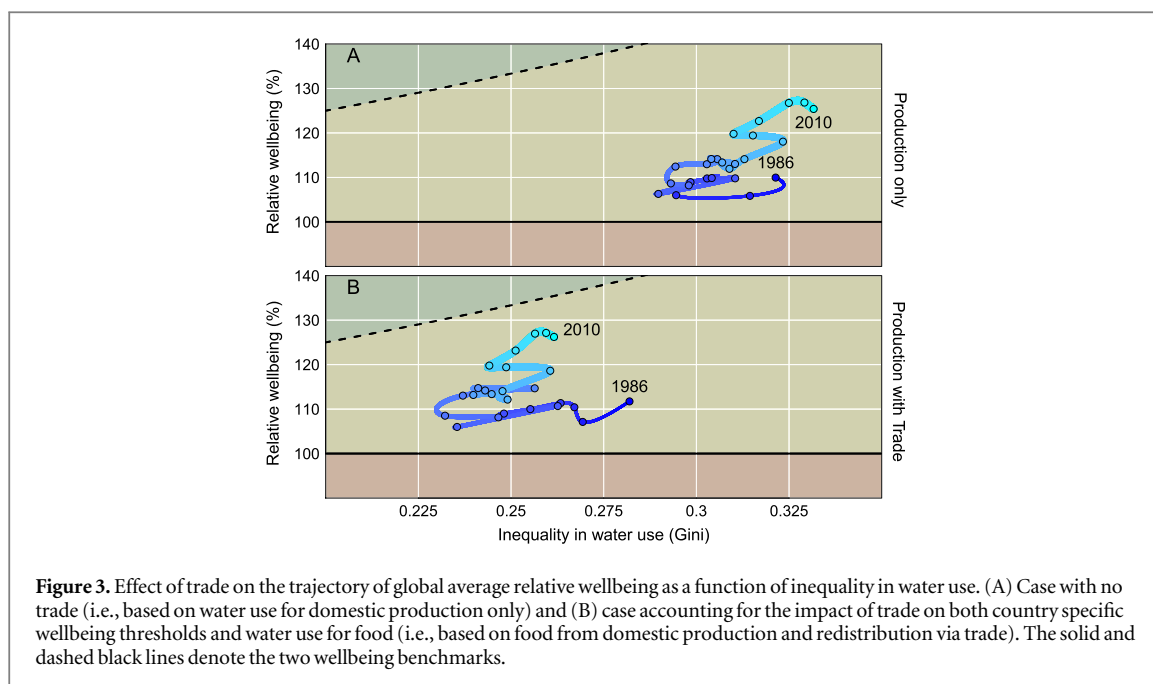
**Figure 3.** Effect of trade on the trajectory of global average relative wellbeing as a function of inequality in water use. (A) Case with no trade (i.e., based on water use for domestic production only) and (B) case accounting for the impact of trade on both country specific wellbeing thresholds and water use for food (i.e., based on food from domestic production and redistribution via trade). The solid and dashed black lines denote the two wellbeing benchmarks.
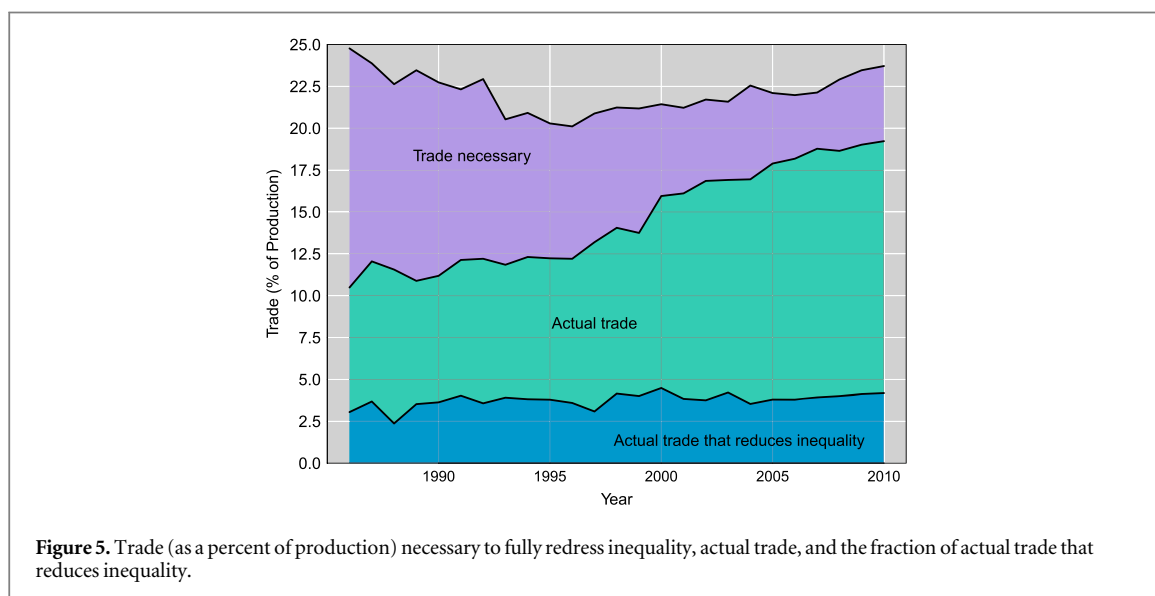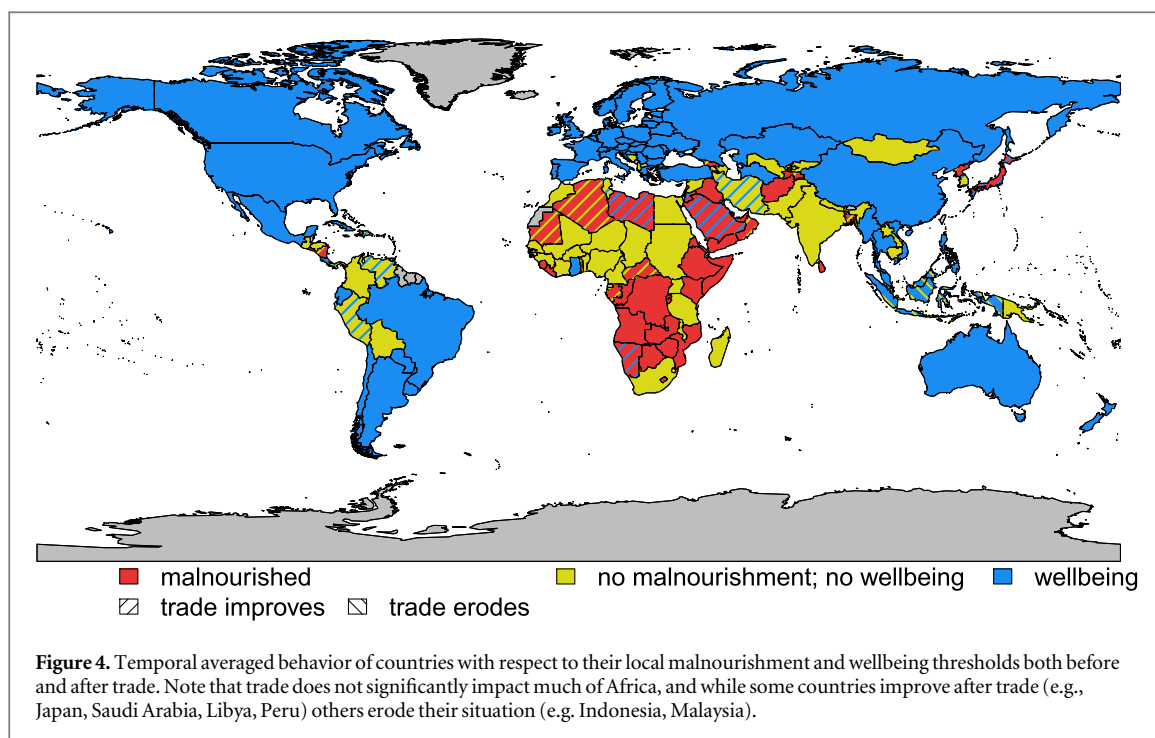
the average relative water use; however, they are also enhancing inequality, thereby maintaining the vertical distance from the upper aggregate standard of living derived benchmark.

The addition of trade (figure 3(B)) provides a method for redistribution of water use impacting both thresholds (table S4) and the virtual water supply to each country. Inequality in water use still declines between 1986 and 1999, but due to trade, the impact of increased water use for production is reduced. Examining the average relative water use of the upper and lower quartiles in similar phase (figure S1) space demonstrates that a fraction of the large increase in water use for production in the upper 25% (figure S1A) is being transferred to other countries (figure S1B). This transfer results in a shift in the distribution of water-use that, while not substantially changing the global average relative water use, moves the system nearer to the upper aggregate standard of living threshold, due to the decrease in inequality. Trade also helps raise the wellbeing of the lower quartile (compare figures S1C and S1D). But are these changes in relative wellbeing due to changes in the distribution of water use, or changes in the country specific thresholds? Recalculating the Gini coefficient including the impact of trade on the distribution of water use, but calculating relative water use referenced to domestic production thresholds (instead of the trade modified thresholds) demonstrated that over the 25-year period, the impact of trade on inequality is due to roughly 60% redistribution of virtual water resources, and 40% changes in country specific wellbeing thresholds of water for food.

Is this access to water resources through trade provided not only to high-water-use nations but also to the lower-water-use nations? Is trade truly redressing inequality? A temporally averaged global picture of where countries lay relative to their respective wellbeing and malnourishment thresholds (both before and after trade) shows that while some countries improve their water scarcity situation via trade, in many cases trade does not raise countries above their individual thresholds and some countries trade to their own detriment (figure 4). For instance, throughout the 25-year period, Ethiopia, Malawi, Cote d'Ivoire, Malaysia, Swaziland, Papua New Guinea, Zambia, Zimbabwe and Mauritius were involved in trade that pushed them below or further below their country-specific malnourishment thresholds. However, Indonesia and Malaysia were the only countries, which routinely dropped below their country specific wellbeing thresholds for 13 and 12 years of the 25-year period, respectively. More generally, our analysis indicates trade occurs between relatively water rich nations, with no degradation of wellbeing conditions in other countries.

How much water must be transferred from the water-use rich to the water-use poor countries to meet the human wellbeing requirement? We examined how much of the water used for production needs to be traded to provide pure equality (Seekell *et al* 2011). Over the quarter century, roughly 21% of the water used for production should have been traded to produce an equitable distribution (figure 5). Actual trade has almost doubled over that period from 11 to 20% of production. Interestingly, only a quarter of that trade is directly redressing inequality, implying that three quarters of the trade is among water use rich countries. If redirected, trade could have a much larger impact on enhancing the global standard of living.

**Figure 4.** Temporal averaged behavior of countries with respect to their local malnourishment and wellbeing thresholds both before and after trade. Note that trade does not significantly impact much of Africa, and while some countries improve after trade (e.g., Japan, Saudi Arabia, Libya, Peru) others erode their situation (e.g. Indonesia, Malaysia).



**Figure 5.** Trade (as a percent of production) necessary to fully redress inequality, actual trade, and the fraction of actual trade that reduces inequality.

## Discussion

The global network of virtual water transfers reconstructed from agricultural trade records and nation/commodity specific water footprints shows that virtual water transfers doubled over the period 1986–2010 (from about $1 \times 10^{12} \, m^3 \, y^{-1}$ to about $2.8 \times 10^{12} \, m^3 \, y^{-1}$), exceeding the rate of global population growth, but the burden of this growth is increasingly placed on the water resources of just a few countries (Carr *et al* 2012b, Suweis *et al* 2013). Our analysis shows that this trade is mainly among water-rich countries and that reductions in inequality through virtual water transfers from water-rich to water-scarce countries can improve global standards of living. The analysis above also extends the current

understanding of the influence of trade on water security (e.g., Hoekstra and Mekonnen 2012b, Carr *et al* 2013) by quantitatively linking ethical concepts to network analyses in order to understand water resources in terms values and norms. This is a first step in creating a critical, but currently missing, link for understanding human-water interactions at the global scale, which are determined by feedbacks between human values, water availability and virtual water trade, and water scarcity (Sivapalan *et al* 2014). Previous analyses have been limited largely to identifying water scarce regions and quantifying volumes of virtual water trade (e.g., Hoekstra and Hung 2005, Falkenmark *et al* 2009, Rockström *et al* 2009), or calculating summarying statistics describing changes in the structure of virtual water trade networks (Carr

*et al* 2012b, Konar *et al* 2012). The type of framework presented here could be extended further to benefit other types of global-scale network analyses, for instance, advancing understanding of food transfer networks and their impact on access to food (e.g., Porkka *et al* 2013). It is important to note that the framework presented here is calculated at a country level, and within country inequality in access to food is likely to play a significant role in meeting the needs of an individual country's population.

At the country scale, our analysis indicates that trade overall improves equality and justice in the access to water for food production. We do not claim, however, that this fact makes the underlying institutional arrangements necessarily just. Even if those arrangements act to overall improve the fulfillment of human rights with respect to a baseline scenario without such arrangements (i.e., with no trade, in our case). In fact, it has been argued that the comparison with such a baseline scenario could be 'morally irrelevant' (Pogge 2008). What matters is whether an institutional design fails or not to redress an avoidable unfullfillment of human rights (Pogge 2008). These types of broader considerations on institutional justice associated with a global order, however, are beyond the scope of our work.

Previous reports have recognized that political trade decisions are typically not made with explicit considerations of water implications and have called for liberalizing agricultural trade policies to improve water use efficiency of production (Allan 1998, Chapagain and Hoekstra 2008, Wichelns 2010, Hoekstra 2011). From the perspective given here, reduced trade barriers will not necessarily improve standard-of-living because access to virtual water transfers is unequal. Further, in model simulations of fully liberalized economies virtual water transfers are not driven by water scarcity (Ramirez-Vallejo and Rogers 2004). Our analysis suggests that on average, while trade-induced inequality is not necessarily unjust, directed trade decisions can improve conditions of water and food scarcity, and increase relative wellbeing (figure 5). It is apparent that even though trade overall acts to reduces inequality and improve conditions towards those of wellbeing, some countries are largely unaffected by trade and remain below malnourishment thresholds (figure 4). Moreover, current human rights agreements place ethical obligations on the international community and these types of trade decisions need to be considered.

Our focus in the present manuscript is on the relationship between international trade, ethics, and water scarcity. We leverage blue and green water estimates of water use based on food commodity production to generate country level estimates water use for food, rather than water availability (Gerten *et al* 2011) or production potential (Kummu *et al* 2014). This approach inherently incorporates each country's cultural, social, political, economic, agricultural

production and trade decisions, but is limited by by the quality of the production and trade data (FAO 2014), assumptions on food waste (Kummu *et al* 2012), and the constituents of a wellbeing and malnourishment diet (Gerten *et al* 2011). It should be noted that adaptive measures other than directed trade may be possible to contribute to water security. For instance, reduced consumption of animal protein could reduce water use in some regions if replaced with more water use efficient protein sources (Gephart *et al* 2014, Jalava *et al* 2014). Another measure could be to reduce food waste (and hence demand for food production). A third option would be would be to improve the water-use efficiency of agricultural production, potentially allowing more crop production that could be transferred to water scarce countries (Wallace 2000). How would these other measure impact our results here? In each case water scarcity should be reduced and as should the need for directed food transfers. The water status of countries should rise relative to their specific 'wellbeing' and 'malnourishment' thresholds, but predicting exact global outcomes is difficult because all of these approaches require overcoming difficult-to-quantify cultural, political, economic, or technological barriers.

It is important to note that virtual water transfers are associated with complex tradeoffs. While virtual water transfers increase standard of living, improve water-use efficiency (Chapagain and Hoekstra 2008, Dalin *et al* 2012), and enhance access to water and food in water scarce regions (Allan 1998); this increased connectivity may reduce the global resilience (D'Odorico *et al* 2010), externalize pollution with the potential to allow wealthy countries to unfairly distance themselves from environmental degradation (Carr *et al* 2012a, 2013, Hoekstra and Mekonnen 2012a, O'Bannon *et al* 2014), and puts individual countries at risk by artificially increasing their carrying capacity (Seekell 2011, Suweis *et al* 2013). We cannot resolve these types trade-offs here, but the emerging field of socio-hydrology stands to contribute quantitative understanding to these types of important and challenging questions.

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