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Freshwater savings from marine protein consumption

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Abstract

Marine fisheries provide an essential source of protein for many people around the world. Unlike alternative terrestrial sources of protein, marine fish production requires little to no freshwater inputs. Consuming marine fish protein instead of terrestrial protein therefore represents freshwater savings (equivalent to an avoided water cost) and contributes to a low water footprint diet. These water savings are realized by the producers of alternative protein sources, rather than the consumers of marine protein. This study quantifies freshwater savings from marine fish consumption around the world by estimating the water footprint of replacing marine fish with terrestrial protein based on current consumption patterns. An estimated 7 600 km^3 yr^{-1} of water is used for human food production. Replacing marine protein with terrestrial protein would require an additional 350 km^3 yr^{-1} of water, meaning that marine protein provides current water savings of 4.6%. The importance of these freshwater savings is highly uneven around the globe, with savings ranging from as little as 0 to as much as 50%. The largest savings as a per cent of current water footprints occur in Asia, Oceania, and several coastal African nations. The greatest national water savings from marine fish protein occur in Southeast Asia and the United States. As the human population increases, future water savings from marine fish consumption will be increasingly important to food and water security and depend on sustainable harvest of capture fisheries and low water footprint growth of marine aquaculture.

Keywords: water footprint, fish, freshwater, food security, water security, virtual water

1. Introduction

With a current human population greater than 7 billion and growing toward 9–10 billion by 2050, many resource analysts have become concerned about meeting basic human needs, including access to freshwater (UNEP 2012). Over the last century, water use has grown at more than twice the rate of population increase, raising the possibility of insufficient water supply, especially in areas already experiencing water shortages (WWAP 2012). Over 80% of the water currently used by humans is allocated to food production (Carr *et al* 2012). Marine fisheries however require little to no freshwater inputs, and therefore provide one of the most water-efficient ways of supporting the human diet.

The amount of water required to produce a unit of a good is the water footprint (Hoekstra and Chapagain 2007). The calculation of water footprints includes surface and groundwater (blue water) use, soil water (green water) use, and water required to dilute freshwater pollution to meet water quality standards (grey water) (Hoekstra *et al* 2011). Water footprints are large for many terrestrial protein sources such as: chicken (4325 l kg^{-1}), mutton/goat meat (8763 l kg^{-1}), nuts (9063 l kg^{-1}), and bovine meat (15 415 l kg^{-1}) (Mekonnen and Hoekstra 2010).

Marine capture fisheries and aquaculture however generally do not require freshwater inputs; so despite living in water, marine fish have little to no consumptive water requirements (Hoekstra 2003). Consequently, marine protein has approximately no water footprint ($\sim 0\,\mathrm{l\,kg^{-1}}$). As a result, replacing marine protein with terrestrial protein would result in increases in individual and national water footprints. The water cost of replacing marine protein with terrestrial protein can alternatively be viewed as a current water savings. These water savings are realized by the producers of alternative terrestrial protein sources rather than the consumers of marine protein. A country's water savings can therefore either be realized within the country itself (a lower internal water footprint) or through a lower water footprint of imported food (a lower external water footprint). In this second case, the physical water savings are realized in the producing country (Hoekstra *et al* 2011). While only the internal water footprint is relevant to a country's domestic water resources, increasing reliance on other countries' water resources through trade may be politically undesirable or economically unfeasible Fader *et al* (2013), Seekell *et al* (2011) and is therefore relevant to a country's food security.

The low water footprint of marine fisheries and aquaculture makes marine protein a fundamental source of protein for a low water footprint diet, which is especially important for water stressed regions (Duarte *et al* 2009). In addition to providing water savings, fish are essential to the nutrition and food security of many impoverished countries (Kent 2003). For example, fish provide the highest per cent of animal calories and protein intake in Africa relative to other regions of the world (Tacon and Metian 2009). Apart from African nations, many island nations and countries in Asia and Oceania also rely on fish for much of their protein (FAO 2013). Since many of these same regions are water stressed (WWAP 2012), water savings from marine fish consumption may be important to both domestic food and water supplies.

Continuing current water savings from marine fish consumption depends on future human food preferences, human population growth, the future state of global fisheries, and the development of sustainable aquaculture. Since food is inextricably linked to the water required to produce it, it is important to understand the tradeoffs between water resources and different food sources. Here, we translate marine protein consumption into a current 'water savings' by computing the water costs of replacing marine protein with terrestrial protein using a water footprint framework.

2. Methods

Current water savings from marine protein consumption is examined by calculating the water footprint (l/capita) of replacing marine protein with terrestrial protein in each country. The water footprint of marine capture and marine aquaculture fisheries was taken to be zero, as the freshwater inputs to these systems are considered to be negligible (Verdegem *et al* 2006). Freshwater capture and freshwater aquaculture protein consumption was excluded from the analysis because freshwater aquaculture requires freshwater inputs ranging from very low to very high values depending on the species and production system (Boyd *et al* 2007). As a result, there is not a reliable estimate for the water footprint of freshwater protein that could be used in this analysis. Approximately 35% of the aquatic protein comes from freshwater sources (FAO 2012), which means there are many areas where freshwater protein is important and may provide water savings that unfortunately cannot be included in this analysis, notably in the countries bordering the African Rift Valley Lakes and in China.

To calculate the water savings from marine protein, the water footprint of an average gram of terrestrial protein was computed for each country and multiplied by the grams of marine protein consumed in each country. The sources of protein that would be used to replace fish protein depend on economic development, urbanization, regional soil and climate conditions, patterns of global food trade, and cultural norms (York and Gossard 2004). While this makes substitution sources for marine protein difficult to predict, reasonable estimates were derived from current food consumption patterns in each country. A range of estimates was generated by computing the water footprint of an average gram of protein based on all substitute sources and separately using only animal protein sources.

Current consumption rates for marine protein and over 60 potential substitute sources were obtained for the most recent data year (2009) from the Food and Agricultural Organization's (FAO) food balance sheets (FAOSTAT 2013). The substitutes were grouped into the 15 food categories used by Mekonnen and Hoekstra (2010). Sugar, oil, and butter categories were removed due to the small protein contribution of these foods. The consumption rates for the remaining 12 categories (table 1) were used to calculate the proportion of total protein derived from each category. Water footprints per gram of protein for each food category were obtained from Mekonnen and Hoekstra (2010).

The amount of water required to replace a gram of marine protein varies based on the combination of terrestrial protein substitutes (table 1). The water footprint for a gram of terrestrial protein using all food categories is lower than the footprint using only animal product categories for nearly all countries. Water footprints for the two substitute groups in each country were each multiplied by current fish protein consumption rates to give a range of daily per capita increase in water footprints when fish protein is replaced with terrestrial protein. These values were then compared to current water footprints using the WaterStat database (Mekonnen and Hoekstra 2011) to give per cent water footprint increases (table 2).

As an indicator of water availability, the United Nation's water scarcity index was compared to each country's total renewable water resources per capita (AQUASTAT, FAO 2013). Total renewable resources here means total renewable surface water plus the total renewable groundwater, minus the overlap between the surface and groundwater, and this measure corresponds to the annual theoretical maximum amount of water actually available to a country at a given moment (FAO 2013). This measurement of renewable water resources represents available blue water only. According to the UN index, countries with annual water availabilities: less than $1000\,\mathrm{m^3}$/capita are water scarce, less than $1700\,\mathrm{m^3}$/capita are water stressed, less than $2500\,\mathrm{m^3}$/capita are water vulnerable, and greater than $2500\,\mathrm{m^3}$/capita are water sufficient

Table 1. Water footprints per gram of protein and the corresponding current protein consumption levels as a per cent of total protein intake for the 12 food categories for the United States. The water footprint times the proportion of protein consumed yields a water footprint weighted by the consumption level. The sum of weighted water footprints yields the water footprint for 1 g of protein based on that group of substitutes.

		All substitutes		Animal substitutes	
Food Category	WF (l/g)	Per cent of protein (%)	Weighted WF (l/g protein)	Per cent of protein (%)	Weighted WF (l/g protein)
Vegetables	26	2.3	0.60	—	—
Starchy roots	31	2.2	0.68	—	—
Fruits	180	2.1	3.78	—	—
Cereals	21	21.6	4.54	—	—
Pulses	19	2.5	0.48	—	—
Nuts	139	2.1	2.92	—	—
Milk	31	28.4	8.80	42.2	13.08
Eggs	29	3.7	1.07	5.4	1.57
Chicken	34	15.7	5.34	23.4	7.96
Pig	57	7.2	4.10	10.8	6.16
Sheep and goat	63	0.2	0.13	0.3	0.19
Bovine	112	12.0	13.44	17.9	20.05
Substitute WF (l/g protein)	—	—	45.88	—	49.00

Table 2. Current fish consumption levels multiplied by the calculated water footprints for the two groups of substitutes in five countries gives the daily per capita water savings. Five countries are presented as examples. Comparing these values to current water footprints gives the per cent increase. All subs means that all food sources were weighted to calculate the average water footprint for a gram of protein, while animal subs means that only animal food sources were used.

Country	Fish Consumption (g protein/cap/day)	Substitute WF (l/g protein)	WF Increase (l/cap/day)	Current WF (l/cap/day)	Per cent increase
Solomon Islands	11.0			1978.7	
All subs		39.6	435.6		22.0
Animal subs		70.0	770.0		38.9
Gambia	7.6			2428.1	
All subs		32.3	245.5		10.1
Animal subs		47.6	361.8		14.9
Denmark	7.7			4475.2	
All subs		41.6	320.3		7.2
Animal subs		45.7	351.9		7.9
United States	5.5			7782.2	
All subs		45.9	252.5		3.2
Animal subs		49.0	269.5		3.5
Lesotho	0.2			4488.8	
All subs		26.0	5.2		0.1
Animal subs		61.7	12.3		0.3

(WWAP 2012). This metric is used at the country level to correspond with the FAO food consumption data, and it therefore does not account for water scarce regions within countries. Additionally, the water availability index does not account for the seasonality of rain in some countries, where water scarcity may occur during part of the year even if annual precipitation is sufficient.

Data on each country's agricultural land was obtained from FAOSTAT as an indicator for land availability and access to green water. FAOSTAT defines agricultural land as the sum of land under temporary agricultural crops, temporary meadows for mowing or pasture, land under market and kitchen gardens, land temporarily fallow, land under permanent cultivation, and permanent meadows and pastures. A land scarcity was considered where there was less than 0.1 ha/capita based on the results of Cassidy *et al* (2013). While water scarcity can be better evaluated by including measurements of both blue and green water availability (Rockstromp *et al* 2009), data on green water availability was not available for this study. So although agricultural land does not provide a direct measurement of green water availability, which requires an assessment of factors including precipitation and soil type, it does indicate a country's ability to access green water through agricultural lands. In some countries, additional green water can be accessed by converting natural ecosystems into agricultural land (Ridoutt and Pfister 2010), but this land was not included in this analysis. Data on renewable water resources and agricultural land together indicates which countries would likely be able to replace marine protein with terrestrial protein domestically. Since it cannot be predicted

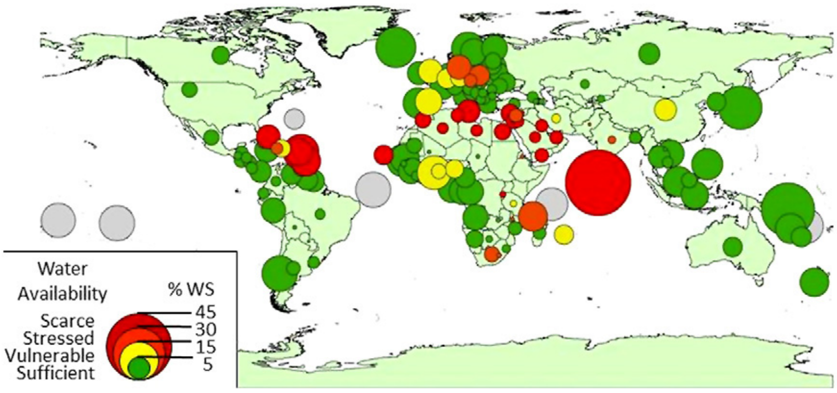

Figure 1. Bubble area is proportional to the per cent water savings from marine fish protein. Bubble color represents current water scarcity status, where red is scarce, orange is stressed, yellow is vulnerable, and green is sufficient, according to United Nations standards (grey indicates lack of data on renewable water resources).

from which countries a given country would import alternative terrestrial protein, this analysis cannot speak to the impacts of replacing fish protein in a given country on the water securities of the countries from which it imports. It should be recognized though that a product with a large water footprint is not necessarily environmentally damaging when it is produced in a region with little water stress (Ridoutt and Pfister 2010). We do note though that increasing reliance on food imports and increasing external water footprints may not be politically or economically feasible for some countries (Fader *et al* 2013, Seekell *et al* 2011). By considering these factors of renewable water resources and agricultural land we assessed where fish protein is most important to national food and water securities.

3. Results and discussion

Marine foods provide an essential low water footprint source of protein for much of the world, allowing for water savings of 300–390 $km^3\ yr^{-1}$ (4–5%) globally. While these values are small compared to the current water footprint of human food production (7600 $km^3\ yr^{-1}$), such water savings may become increasingly important globally to feed a growing population. Additionally, water savings from marine protein may already be important to the food and water security of specific countries, particularly economically disadvantaged and water scarce nations.

The contribution of marine protein to water savings is highly uneven around the globe (figure 1). Per cent increases reveal which countries experience the largest current water savings from marine protein consumption relative to current water consumption. National per cent increases range from a minimum of a 0.04–0.06% increase in Mongolia to a maximum of a 42–50% increase in Maldives (figure 1). The importance of water savings from marine protein to food and water security varies greatly due to differences in reliance on marine fish protein, the water footprints of substitute terrestrial protein, population size, and freshwater availability.

Figure 2 presents the relative importance of marine protein to food and water security by comparing each country's agricultural land and renewable freshwater availability, with circle radii proportional to per capita water savings from marine protein consumption. The four quadrants (A–D) of figure 2 are based on agricultural land scarcity (∼0.1 ha/capita) and countries with some degree of water stress (∼2500 m^3/capita/yr).

For any given country, there are essentially three options for replacing marine protein with terrestrial protein: increase land under food cultivation, increase the productivity of land which generally involves irrigation and fertilizer application (Mueller *et al* 2012), or increase importation of terrestrial foods. The first of these options is limited by national green water resources and available agricultural land, the second affects blue and grey water resources, and the third increases reliance on other countries' food and water resources. This last option (importation of food) may be limited by countries' political or economic environments (Fader *et al* 2013, Seekell *et al* 2011).

Countries with sufficient agricultural land, but low renewable water resources (figure 2, quadrant A) are primarily countries in Africa and the Middle East. The countries with the largest per capita water savings and per cent water saving from marine protein in quadrant A are Kiribati (1051 l/capita/day, 12–14%), Samoa (707 l/capita/day, 12–13%), and Ghana (417 l/capita/day, 12–13%). Countries in quadrant A with lower water savings may also find water savings from marine protein important to food and water security since even small increases in blue water demand cannot be met domestically. In some cases countries in quadrant A may be able to replace some or all marine protein domestically by increasing green water use on agricultural lands, but irrigation is limited by low blue water availability.

Countries with both low agricultural lands and low renewable water resources (figure 2, quadrant B) have a limited ability to increase terrestrial production domestically due to restricted land, green water, and blue water resources. Countries in quadrant B with a large water savings from marine protein include Maldives (1719 l/capita/day, 42–50% WS), the Republic of Korea (665 l/capita/day, 12–18% WS), and Barbados (552 l/capita/day, 9–10% WS). These countries receive the greatest water benefit from marine protein (and consequently are most vulnerable to the loss of this protein). Many countries falling in this category are in the Middle East

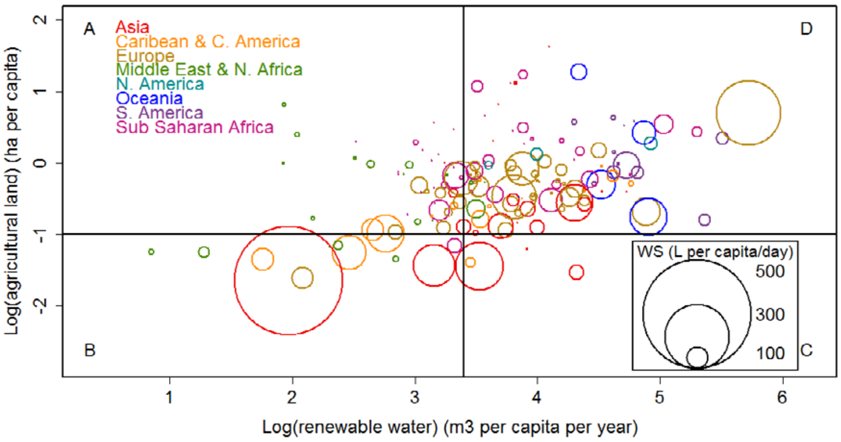

Figure 2. The logarithm of annual renewable water resources was plotted against the logarithm of the total agricultural land for each country. The vertical line at log(2500) distinguishes water sufficient from water scarce, while the horizontal line at log(0.1) distinguishes sufficient agricultural land from insufficient agricultural land based on the estimated minimum agricultural land requirement estimated by (Cassidy *et al* 2013). The radius of each circle is proportional to the per capita water savings from marine protein consumption in each country. Each country's geographic region is indicated by the circle color.

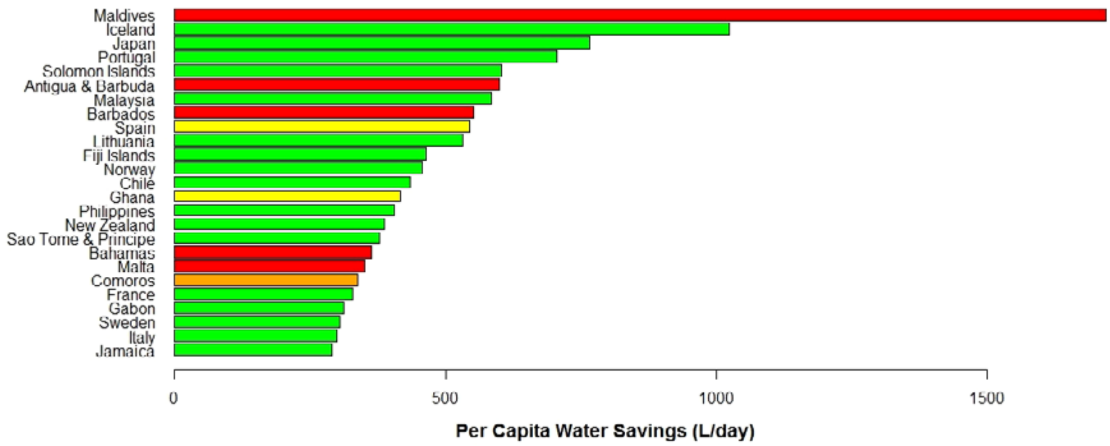

Figure 3. Per capita water savings from marine fish consumption (l/day) for the top 25 countries. The color of the bar represents the current water scarcity status of each country, where red is scarce, orange is stressed, yellow is vulnerable, and green is sufficient, according to United Nations standards.

and Northern Africa, and have low water savings from marine protein. These countries may still find water savings from marine protein as important since land and renewable water are limited.

Only four countries are classified as having sufficient renewable water resources but insufficient land (figure 2, quadrant C): Japan (767 l/capita/day, 18–23%), Brunei Darussalam (236 l/capita/day, 2–3%), Trinidad and Tobago (171 l/capita/day, 3–4%), and Bangladesh (36 l/capita/day, 1–2%). These countries may be able to increase terrestrial food production if yield can be increased on available agricultural land, but may be more likely to increase their external water footprint instead by importing terrestrial protein.

The majority of countries currently have both sufficient agricultural land and sufficient renewable water resources (figure 2, quadrant D). For these countries, the water savings from marine protein consumption are typically less important for food and water security. There are however cases where the climate is unfavorable for terrestrial food production (e.g. Iceland), or technological and infrastructure limitations may prevent increased terrestrial food production. These countries may also increase their external footprint through trade if they were to replace marine protein with terrestrial protein.

Of the 25 countries with the largest per capita water savings from marine fish, seventeen are water sufficient, while five are already water scarce, one is stressed, and two are vulnerable (figure 3). While island, Asian, and coastal African countries experience the largest per capita water savings and per cent water savings relative to current water footprint, the countries with the largest total volumetric water savings from marine protein consumption are those with large populations and high terrestrial protein substitute water footprints. Multiplying the per capita increase by population reveals that the largest total water savings (in terms of water volume) occur in the China, Japan, Indonesia, and the United States (figure 4).

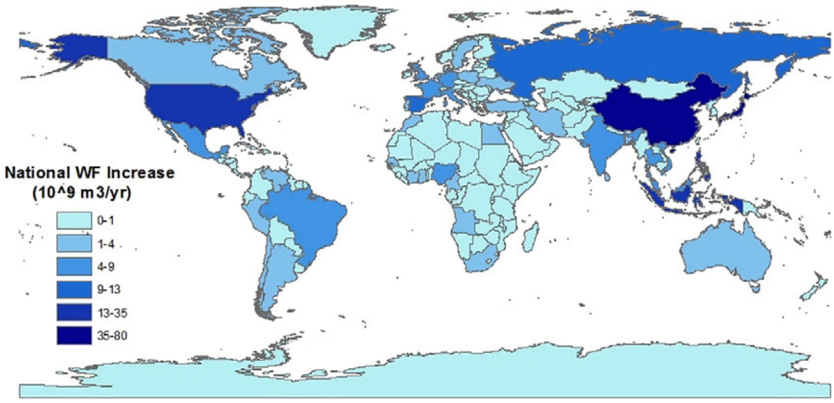

Figure 4. National increases in water footprints in the absence of marine fish protein (10^9 m^3 yr^{-1}).

Continuing or increasing freshwater savings through marine protein consumption depends on future human food preferences, populations growth, the future state of global fisheries, and the development of sustainable aquaculture. As noted, water savings from marine protein consumption is dependent on the water costs of alternate terrestrial protein sources. Meat consumption levels are generally high in developed countries, but are increasing rapidly in developing countries (Delgado 2003, Tilman *et al* 2011). If the current increase in meat consumption continues, replacing marine protein with terrestrial protein will require more water on average. These water costs may however be reduced through technological advances and improved water use efficiency (Hoekstra and Chapagain 2007). Further, future per capita and national savings from marine protein consumption depend on whether marine capture fishery and aquaculture production can keep up with population growth. For example, if marine production remains at current levels until 2050, a calculation with FAO population projections reveals that global per capita marine protein consumption would decline by 0.8 g day^{-1}. National changes in per capita marine protein consumption multiplied by the water footprint of replacing this protein with terrestrial protein yields a global increase of 55–75 km^3 yr^{-1} (0.7–1% increase over current water use).

Maintaining or increasing water savings from marine protein is highly dependent on the future production levels of marine capture and aquaculture fisheries. Marine and freshwater capture fishery production has leveled off in recent years (FAO 2013), and there has been much controversy over the future trajectory of global fisheries (Worm *et al* 2009). Additional changes in fisheries production due to climate change has added to the uncertainty about the future of global fisheries and aquaculture (Cheung *et al* 2013, Merino *et al* 2012). Effective management of capture fisheries however has the potential to not only avoid fishery collapses, but to allow for rebuilding and possibly increased yield (Worm *et al* 2009, Costello 2012). Such efforts can contribute to long-run food and water security, but may have short-term social and economic impacts from fishing restrictions (Worm *et al* 2009). Included in these pressures on fisheries are current trends to establish marine protected areas (MPAs) that limit or ban fishing. These MPAs may benefit specific fisheries but may also have hidden environmental costs as humans switch to other food sources (Hilborn 2013).

While the state of global fisheries is controversial, there are specific fisheries known to be in decline, with small unassessed fisheries in significantly worse condition than large assessed ones (Costello 2012). Since the importance of marine fish protein to domestic food and water security is spatially variable, specific regions are more adversely impacted by fishery declines than others. Consequently, nations which are most vulnerable to fisheries declines should incorporate water security as an additional risk factor in fisheries management as well as in the cost-benefit analysis of entering into international fishing agreements. These agreements are of particular concern for developing nations in West Africa and South East Asia, where foreign nations frequently fish both legally and illegally, but monitoring is limited (Mallory 2013) and fish catches are systematically underreported (Pauly *et al* 2013).

Rising global aquaculture production suggests that this industry may be able to replace some protein currently provided by capture fisheries (Duarte *et al* 2009) and increase the global water savings from marine protein. Future water savings from marine aquaculture, however, is dependent on its sustainable development. First, the use of capture fisheries for the production of fish meal and fish oil for feed can lead to a net loss of fish protein for some aquaculture systems (Naylor *et al* 2000, Tacon and Metian 2009). Some have therefore suggested that aquaculture should incorporate more terrestrially-based feed (Bell and Waagbo 2008), but this change would increase the water footprint of marine aquaculture. This can be observed in analyses which have found that water requirements for feed in some freshwater aquaculture systems are already quite high (Verdegem and Bosma 2009). In order to reduce the costs associated with feeds, sustainable aquaculture could focus on lower trophic level, species and integrated production systems, which can reduce effluents, diversify products and increase productivity (Naylor *et al* 2000). The development of sustainable aquaculture is likely an important component of meeting the increasing protein demands of a growing population without substantially increasing the water footprint of humanity.

It is important to note that when considering the costs of replacing fish protein with terrestrial protein, water resources are not the only constraints or environmental impacts to consider. Changes in food production patterns have important implications for carbon, nitrogen, and phosphorus cycles as well as land use. For example, the increased land required to produce terrestrial protein to replace fish protein has been demonstrated to be substantial (13–63% increase) in a case study of the Mekong River basin (Orr *et al* 2012). Such impacts are also important to consider when evaluating tradeoffs between marine capture and aquaculture fisheries. For example, while aquaculture production can result in high nutrient levels in surrounding waters (Islam 2005), capture fisheries are typically more energy intensive than many aquaculture systems (Costa-Pierce 2010). Additionally, in some cases there may be social, political and economic constraints that would prevent marine protein from being entirely replaced with terrestrial protein. In countries where there are not protein deficiencies, this may not be problematic, but in other countries, a decline in per capita fish protein would mean that more people would not be able to meet their protein needs. This would lead to higher rates of malnutrition, while increasing pressure on water resources, outcomes contrary to the Millennium Development Goals (United Nations 2010).

4. Conclusion

Water and food resources are inextricably linked, and the water resource implications of changes in fisheries practices must therefore be considered. This study demonstrates the large freshwater savings from marine fish consumption, particularly in Asia, Oceania, and several coastal African nations. These substantial water savings should be accounted for in the consideration of fisheries management policies and in the promotion of sustainable aquaculture. Further, the unequal importance of water savings from marine fish should be integrated into future international fishing agreements to protect the joint global food and water security.

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References

Bell J G and Waagbo R 2008 Safe and nutritious aquaculture produce: benefits and risks of alternative sustainable aquafeeds *Aquaculture in the Ecosystem* ed M Holmer, K Black, C M Duarte, N Marba and I Karakassis (Berlin: Springer) pp 185–225

Boyd C E, Tucker C, McNevin A, Bostick K and Clay J 2007 Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture *Rev. Fish. Sci.* **15** 336–60

Carr J A, D'Odorico P, Laio F and Ridolfi L 2012 Recent history and geography of virtual water trade *PLoS-One* **8** e55825

Cassidy E S, West P C, Gerber J S and Foley J A 2013 Redefining agricultural yields: from tonnes to people nourished per hectare *Environ. Res. Lett.* **8** 034015

Cheung W W L, Watson R and Pauly D 2013 Signature of ocean warming in global fisheries catch *Nature* **497** 365–8

Costa-Pierce B A 2010 Sustainable aquaculture systems: the need for a new social contract for aquaculture development *Mar. Technol. Soc. J.* **44** 88–112

Costello C, Ovando D, Hilbon R, Gaines S D, Deschenes O and Lester S E 2012 Status and solutions for the world's unassessed fisheries *Science* **338** 517–20

Delgado C L 2003 Rising consumption of meat and milk in developing countries has created a new food revolution *Am. Soc. Nutr. Sci.* **133** 3907S–10S

Duarte C, Holmer M, Olsen Y, Soto D, Marbà N, Guiu J, Black K and Karakassis I 2009 Will the oceans help feed humanity? *BioScience* **59** 967–76

Fader M, Gerten D, Krause M, Lucht W and Cramer W 2013 Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints *Environ. Res. Lett.* **8** 014046

FAO (Food and Agriculture Organization (FAO)) 2012 *The State of World Fisheries and Aquaculture* (Rome: FAO)

FAO 2013 AQUASTAT database, *Food and Agriculture Organization of the United Nations* (Rome: FAO) accessed (14 January 2013)

FAOSTAT (Food and Agriculture Organization of the United Nations) 2013 *Commodity Balances, Crops, Primary Equivalent (Dataset)* (Rome: FAO) (latest update: 02 May 2012), accessed (2 January 2013) http://ref.data.fao.org/ac2f9731-8464-4589-89fd-7e8242009929

Hilborn R 2013 Environmental cost of conservation victories *Proc. Natl Acad. Sci.* **110** 9187

Hoekstra A Y 2003 Virtual water: An introduction *Virtual Water Trade: Proceedings of the International Expert Meeting on Virtual Water Trade* (Delft: IHE-Delft)

Hoekstra A Y and Chapagain A K 2007 Water footprints of nations: water use by people as a function of their consumption pattern *Water Resour. Manag.* **21** 35–48

Hoekstra A Y, Chapagain A K, Alday M M and Mekonnen M M 2011 *The Water Footprint Assessment Manual: Setting the Global Standard* (London: Earthscan)

Islam S 2005 Nitrogen and phosphorus budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: review and analysis towards model development *Mar. Pollut. Bull.* **50** 48–61

Kent G 2003 Fish trade, food security and the human right to adequate food *Report of the FAO Expert Consultation on Int. Fish Trade and Food Security (Casablanca, Jan. 2003) FAO Fisheries Report No.* 708 (Rome: FAO) pp 49–70

Mallory T G 2013 China's distant water fishing industry: evolving policies and implications *Mar. Policy* **38** 99–108

Mekonnen M M and Hoekstra A Y 2010 The green, blue and grey water footprint of farm animals and animal products *Value of Water Research Report Series No.* 48 (Delft: UNESCO-IHE)

Mekonnen M M and Hoekstra A Y 2011 National water footprint accounts: the green, blue and grey water footprint of production and consumption *Value of Water Research Report Series No.* 50 (Delft: UNESCO-IHE)

Merino G *et al* 2012 Can marine fisheries and aquaculture meet fish demand from a growing human population and changing climate? *Glob. Environ. Change* **22** 795–806

Mueller N D, Gerber J S, Johnston M, Ray D K, Ramankutty N and Foley J A 2012 Closing yield gaps through nutrient and water management *Nature* **490** 254–7

Naylor R L, Goldburg R J, Primavera J H, Kautsky N, Beveridge M C M, Clay J, Folke C, Lubchenco J, Mooney H and Troell M 2000 Effect of aquaculture on world fish supplies *Nature* **405** 1017–24

Orr S, Pittock J, Chapagain A and Dumaresq D 2012 Dams on the Mekong River: lost fish protein and the implications for land and water resources *Glob. Environ. Change* **22** 925–32

Pauly D *et al* 2013 China's distant-water fisheries in the 21st century *Fish Fish.* doi:10.111/faf.12032

Ridoutt B G and Pfister S 2010 A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity *Glob. Environ. Change* **20** 113–20

Rockstromp J, Falkenmark M, Karlberg L, Hoff H, Rost S and Gerten D 2009 Future water availability for global food production: The potential of green water for increasing resilience to global change *Water Resour. Res.* **45** W00A12

Seekell D A, D'Odorico P and Pace M L 2011 Virtual water transfers unlikely to redress inequality in global water use *Environ. Res. Lett.* **6** 024017

Tacon A and Metian M 2009 Fishing for feed or fishing for food: Increasing global competition for small pelagic forage fish *Ambio* **38** 294–302

Tilman D, Balzer C, Hill J and Befort B L 2011 Global food demand and the sustainable intensification of agriculture *Proc. Natl Acad. Sci. USA* **108** 20260–4

UNEP (United Nations Environment Programme) 2012 21 issues for the 21st century *Results of the UNEP Foresight Process on Emerging Environmental Issues* (Nairobi: UNEP)

United Nations 2010 *The Millennium Development Goals Report* (New York, NY)

Verdegem M C J and Bosma R H 2009 Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use *Water Policy* **11** 52–68

Verdegem M C J, Bosma R H and Verreth J A J 2006 Reducing water use for animal production through aquaculture *Int. J. Water Resour. Dev.* **22**

Worm B *et al* 2009 Rebuilding global fisheries *Science* **325** 578–85

WWAP (World Water Assessment Programme) 2012 *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk* (Paris: UNESCO)

York R and Gossard M H 2004 Cross-national meat and fish consumption: exploring the effects of modernization and ecological context *Ecol. Econom.* **48** 293–302