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Possible pathways and tensions in the food and water nexus

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Key Points:

- Crop-hydrological models identify global food or water deficits by 2050
- Global plateau in crop production-water extractions from irrigation
- Multiple pathways required to respond to tensions in global food–water nexus

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Abstract "Bottom-up" field-based, crop-hydrological models are used to estimate food production and irrigation water extractions under multiple scenarios of water and nitrogen use and crop yield increases from 2010 to 2050 for 19 countries. The results show: (1) a food deficit before 2050 under a worst case climate change scenario in terms of annual crop yield improvement; (2) substantial water deficits, as a result of irrigation, for major food-producing countries that will prevent these nations from meeting their domestic food requirements in the absence of investments in water infrastructure or food imports; and (3) a plateau in terms of crop food production associated with increased water extractions given no further increase in the current area of irrigated agriculture. Possible pathways to respond to the tensions in the food–water nexus are evaluated and include: (1) higher water productivity; (2) food trade; (3) improvements in both crop yield and "sustainable" total factor productivity; (4) greater investment in water infrastructure; and (5) integrative policies and decision processes. Without a combination of some, or all, of these possible pathways, appropriately adapted to bio-physical and socio-economic circumstances, the world faces grave risks in food and water security out to 2050.

1. Introduction

A generation ago Gleick and his colleagues [*Gleick*, 1993] highlighted an approaching global fresh water crisis that has since become even more pressing. Here, and in contrast with much of the literature that uses "top-down" models, we use "bottom-up" and field-based, crop-hydrological models to highlight the tensions and possible pathways to respond to the global need to increase food production from rain-fed and irrigated agriculture, but within existing water availability. Our work is important because, using field-based models, we calculate a plateau in terms of global crop production and water extracted for irrigated agriculture, highlight either food or water deficits by 2050 for key food-producing countries, and present possible pathways to respond to challenges in the food–water nexus.

The tension between the absolute necessity for food production and the fresh water required to grow this food is increasing because of rising food demand and rising water scarcity in key food-producing countries. This is most acute in irrigated agriculture because, globally, it accounts for 70% of the total water extracted,[1] or some 2,700 km^3 [*Comprehensive Assessment of Water Management in Agriculture*, 2007]. Of the global food supply, irrigated agriculture contributes around 40% of this production from approximately 20% of the arable cropland, which is irrigated for at least part of the year. Thus, given its importance in both food supply and water extractions, effectively managing how surface and groundwater are used in irrigation is of critical importance [*Wichelns and Oster*, 2006] for both global food security and water security.

Overlaying the food–water challenge is the effect of climate change. Notwithstanding the benefits of carbon fertilization, the negative effects of climate change are likely to be nonlinear with yields increasing up to a temperature threshold and then declining sharply beyond this limit [*Schlenker and Roberts*, 2009]. *Lobell and Gourdji* [2012] estimate the net effect of climate change on crop yields out to 2050 could be a negative −3% per decade or a positive +2% per decade. *Nelson et al.* [2014] find that, in the absence of incremental

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[1] In defining water use, we separate water withdrawals, also known as extractions, from water consumption, or consumptive water use. In agriculture, so-called "blue" water extractions refer to physical withdrawals of water from rivers, streams, human-made water storages, and groundwater over a period of time while water consumption refers to the volume of water extracted less than the amount of water returned to water sources. Of total global water extractions, domestic use accounts for about 10% of the total, and industrial use account for about 20%.

yield increases from carbon fertilization, average yields for coarse grains, oil seeds, wheat, and rice in 13 regions of the world would fall, on average, by 17% by 2050 relative to a *no* climate change scenario. Importantly, *Lesk et al.* [2016] show, using global extreme weather data from 1964 to 2007, that during a drought national cereal production reduced by 10.1% on average (9.9–10.2%, 95% confidence interval) and extreme heat led to a production deficit of 9.1% (8.4–9.5%, 95% confidence interval).

Here, we examine the possible gaps between global food supply and food requirements, discuss the implications for water extractions and consumption in agriculture, and then, highlight the possible pathways to promote global food and water security. Our approach, described in Section 2, calculates food production out to 2050 for different scenarios for 19 major cereal producing and consuming countries using the Global Food and Water Systems (GFWS) Platform [*Grafton et al.*, 2015] designed to explore the nexus between food supply and water demand.[2] Using this platform, in Section 3, we evaluate possible food and water deficits using a crop yield increase (CYI) of 0.5% per annum that is represented as a worst case climate change scenario (namely a 20% reduction in CYI to 2050) compared to 17% indicated by *Nelson et al.* [2014], and a CYI of 1% per annum (namely a 40% increase by 2050), which is similar to the current global yield growth [*Fischer et al.*, 2014]. In Section 4, we discuss the implications of the results and the possible pathways to promote global food and water security. We offer our conclusions in Section 5.

2. Model of Global Food and Water Security

The GFWS Platform has an online implementation at http://gfws.fe2wnetwork.org/ and was first described in *Grafton et al.* [2015]. Since its first development, evaluation and testing has been undertaken, but the underlying principles and approach of using APSIM crop models to generate food production and crop water demand remain. The value add of the GFWS Platform is that it provides a means to readily assess the interplay between water and food supply and demand. The platform is based on process crop models that work from the bottom-up in that the modeling results are based on detailed crop physiology, soil water and nutrient mechanisms and, importantly, incorporate crop management interventions.

The Agricultural Production Systems sIMulator (APSIM) crop production models [*McCown et al.*, 1996; *Keating et al.*, 2003] are based on actual crop response functions responding to the climate, soils, nitrogen fertilization, and crop water applications. This allows the nexus between both blue and green water consumption and food production to be explored and considered against plant genetics, water, fertilizer, and management options. While such an approach is valuable, its principal limitation is its spatial extrapolation from specific sites. By comparison, many existing global food–water models are top-down, do not have actual crop responses [*Gerten et al.*, 2011; *Wada et al.*, 2016] based on crop physiology or incorporate soil water–nutrient dynamics. Top-down models have the advantage that they are well suited to broad scale and for global studies [*Bondeau et al.*, 2007; *Gerten et al.*, 2011]. For example, the model LPJmL [e.g., *Bondeau et al.*, 2007] simulates plant functional types by representing natural vegetation, grazing land, and 12 crop functional types based on the world's major food crops. The crop functional types in this approach are generalized and climatically adapted plant prototypes designed to capture the most widespread types of agricultural plant traits. While the LPJmL type model can be used to test the impact of different management or land use scenarios on the biogeochemical cycles, as related to food production, it is not a crop physiologically based model derived from actual crop responses. In our view, both bottom-up and top-down approaches are valuable, but each has its own strengths and weaknesses.

The GFWS Platform is able to estimate the gap between food supply and food requirements, and also the gap between water extracted for irrigation and the current fresh water supply. This is accomplished on a scenario basis by specifying alternative annual CYIs, crop water consumption, nitrogen fertilizer application, and the cropped area of rain-fed (green water) and irrigated (green plus blue water) agriculture out to 2050 from a base period of 2007–2010.

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[2] A web-based version of this platform is available at http://gfws.fe2wnetwork.org/. Unlike many other global food and water models, such as the International Institute for Applied Systems Analysis World Food System Model or the International Water Management Institute's WATERSIM model, the GFWS platform is freely accessible for anyone to use to generate their own scenarios and results.

2.1. Food Requirements

The exogenous drivers of the platform are per capita food consumption values (kcal/person/day) and human population projections that determine minimum human food requirements. The population growth specification is adopted from the projections made available by the World Bank obtained from http://data.worldbank.org/data-catalog/population-projection-tables. The population data comes from the World Bank population growth projections and other demographic data from 2010 to 2050, at 5-year intervals. Food requirement is expressed as kcal per capita per day and the default used by the GFWS Platform is the Food and Agriculture Organization of the United Nations (FAO) per capita food requirement projection obtained from www.fao.org/docrep/009/a0607e/a0607e00.htm.

2.2. Food Supply

Scenarios of food supply are calculated by multiplying crop yield per hectare (determined by fertilizer and water use) by land area per crop adjusted by CYIs. Agricultural water use is determined by land use, crops, and area under irrigation as defined by FAO statistics noting that land under informal irrigation, especially in Africa, would increase the estimated global irrigated land area.

In the current version of the GFWS platform, 19 countries are included. These countries and the APSIM sites used for modeling crop responses are: Argentina (Rosaria); Australia (Wagga Wagga); Bangladesh (Dhaka); Brazil (Maringa); Canada (Edmonton); China (Zhegzhou and Chansha); Egypt (Cairo); France (Toulouse); India (Lucknow); Indonesia (Jakarta); Mexico (Mexico City); Pakistan (Lahore); Poland (Warsaw); Russia (Volgograd); Thailand (Bangkok); Turkey (Ankara); U.S.A. (Kansas City); Ukraine (Kiev); and Vietnam (Hanoi). The major crops we model include: wheat, rice, maize, sorghum, barley, oats, and soybean and were selected based on their relative importance to the global calorie supply. In terms of annual tonnage, based on production figures from FAOSTAT Agriculture databases for 2002, the principal crops globally are: wheat (568 Mt), rice (579 Mt), maize (602 Mt), soybean (180 Mt), barley (132 Mt), and sorghum (55 Mt). Oats is of second order importance and contributes globally some 28 Mt, but it is still larger in production than both millet (26 Mt) and rye (21 Mt).

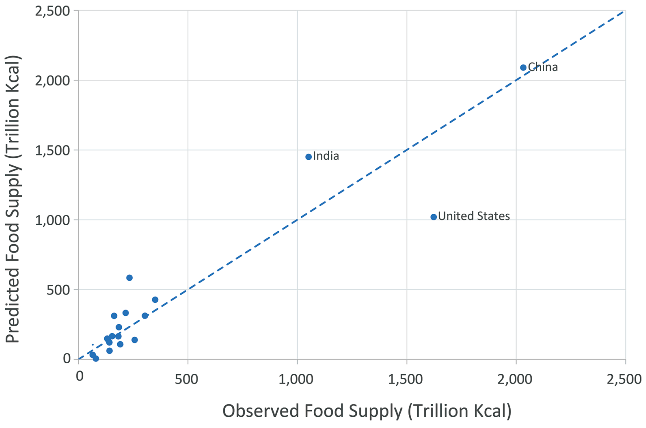

Figure 1. Predicted food supply for the 19 countries in the Global Food and Water Systems platform and observed food supply of the 19 countries based on FAO data for 2010.

Model results can be compared to current levels of crop production and, overall, provide similar production levels to those reported in FAO statistics. Figure 1 provides a mapping of the observed food supply to calculate food supply for the 19 countries included in the GFWS Platform for 2010. The mapping assumes 150 kg/ha N is applied on irrigated and non-irrigated land and 150 mm of water sourced from rivers, groundwater, and aquifers is beneficially consumed on irrigated land. Such levels of fertilizer and water applications are similar to the overall average applications in the 19 countries, but we note there are very large differences in their rates of use across countries. The overall relationship between the predicted to observed food supply has an adjusted R^2 of 0.857 with an intercept of zero and an estimated slope of 0.959 (std. error 0.07), which indicates only a moderate bias in the model's overall predictions for 2010.

The GFWS platform interface provides a suite of set-up scenario designs built on national agricultural databases, drawn from tens of thousands of crop yield simulations that we calculated in APSIM under different combinations of water and nitrogen fertilizer applications. The APSIM crop simulation [*McCown et al.*, 1996; *Keating et al.*, 2003] is fully documented, well supported and has been widely used for more than two decades (see www.apsim.info/Products/Publications.aspx). The weather data used to drive the APSIM models are drawn from the SWAT current climate database at http://globalweather.tamu.edu/ while the planting and harvesting calendar for irrigated crops is obtained from *Food and Agriculture Organization of the United Nations* [2011] information and database at www.fao.org/nr/water/aquastat/main/index.stm.

2.3. Crop Yield Increases

While the GFWS platform allows for a range of different annual CYIs as a percentage of the base year yield, we assume only two alternative constant CYI to 2050 with a low of 0.5% per annum intended to represent a worst case climate change scenario and a high of a 1.0% per annum. This is a simplification of what will likely happen to CYIs to 2050 which will vary by country and over time, but provides a boundary of possible outcomes. A CYI of 1.0% per annum is justified on the basis that the annual proportional CYI has declined globally over the last 40 years and is currently about 1.0% per annum for both rice and wheat [*Food and Agriculture Organization of the United Nations*, 2016]. A CYI of 0.5% per annum represents a plausible decline in CYI associated with climate change.

2.4. Water and Fertilizer Application Rates

The GFWS platform allows for the water consumed on farmers' fields to be adjusted from 0 to 500 mm using surface, sprinkler, and drip application methods for irrigated crops. For both rain-fed and irrigated crops, elemental nitrogen fertilizer (F) rates can be varied, at 50 kg/ha increments, over the range from 0 to 250 kg/ha.

In the GFWS platform, fresh water is applied on farmer fields to supply the beneficial water consumption required for each crop. The water applied is based on APSIM estimates for the irrigated crop areas for each country adjusted for the on-farm efficiency of the method of irrigation. Three different proportions of water transpired by the crops are provided in the platform relative to the total water delivered to a farmer's field, but results are only reported for surface irrigation with an assumed rate of water transpiration from crops of 60%. Thus, if the beneficial water consumption were 1,000 L in a farmer's field for a given crop, the water delivered to the field would be 1,667 L. The difference is either evaporated from the soil or returned to the hydrological systems of the landscape, catchment, and basin through deep drainage and/or surface run-off.

2.5. Land Available for Both Rain-Fed and Irrigated Cropping

The land available in the GFWS platform is scaled relative to land use of 2007–2010 and comes from the World Bank database at http://search.worldbank.org/quickview?name=%3Cem%3EArable%3C%2Fem%3E+%3Cem%3Eland%3C%2Fem%3E+%28hectares%29&id=AG.LND.ARBL.HA&type=Indicators&cube_no=2&qterm=Arable+land.

2.6. Water Resource and Area of Irrigated Crops

The estimated water resource and total irrigated crop area for each country comes from the FAO AQUASTAT main database.

3. Scenarios of the Food and Water Nexus

In this section, we examine: first, the possible gaps between global food requirements for cereals, including soybeans, and food cereal supply and, second, possible water deficits between water extractions for irrigation and current total water supply. The levels of water extraction are based on the assumed level of water transpiration by crops (60%) and fertilizer applied in each of the scenarios. All water and fertilizer applications are relative to a zero base, rather than current levels of fertilizer use and water extractions. The food supply results represent estimates for only the 19 major cereal-producing countries and then summed for all these 19 countries.

3.1. Food Surpluses/Deficits to 2050

In 2010, the actual food supply of the 19 countries was 7,501 trillion kcals, while we calculate a supply of 7,863 trillion kcals. Figure 2 presents from 2010 to 2050 the difference between the food surplus from the 19 countries included in the GFWS platform and the global food requirements for all countries in the world as a percentage of the world's food requirements. Results are provided for two scenarios of per capita kilocalories intake over time: first, a scenario from the *Food and Agriculture Organization of the United Nations* [2006] and, second, a higher rate of growth in per capita kilocalorie intake that is a 62% increase above the FAO

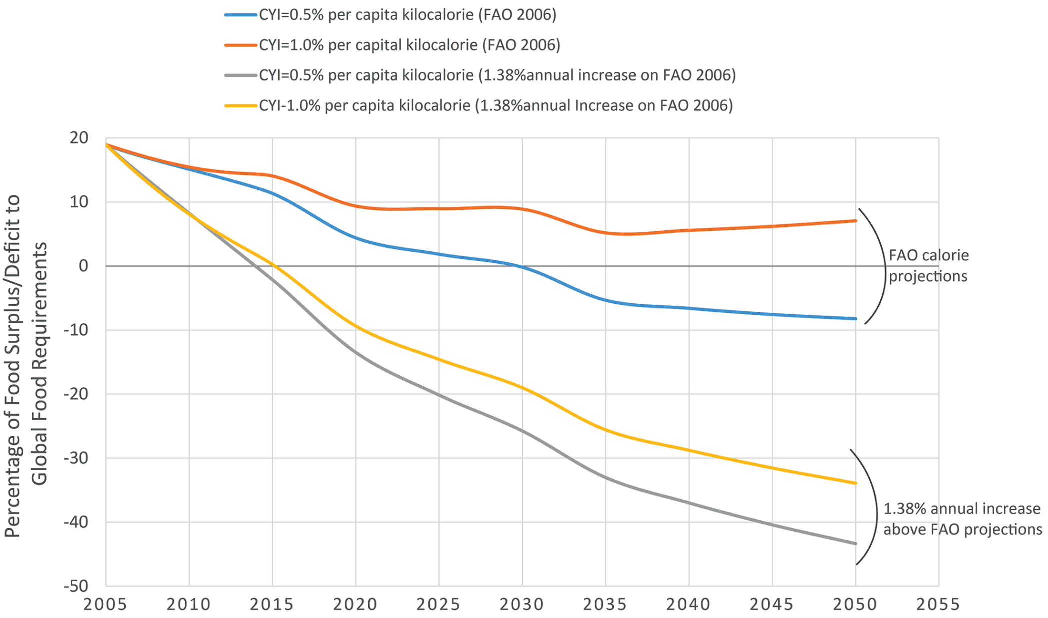

Figure 2. Ratio (as a %) of the difference in the food supply from the 19 countries in the Global Food and Water Systems platform and global food requirements over global food requirements 2010–2050 assuming $F = 200$ kg N/ha and irrigated agricultural water consumption of 200 mm. The scenarios differ in terms of the assumed annual crop yield improvements from 2010 to 2050 (0.5 and 1.0%) and the projected rate of increase in per capita kilocalorie consumption [*FAO*, 2006] and projection for a linear 1.38% per annum increase on *FAO* [2006] projections.

projection by 2050 that is consistent with data (low-income countries group E in Figure 2b) from *Tilman et al.* [2011]. When applied to UN median population projections, these two food demand scenarios generate a 51 and 128% increase, respectively, in global demand for crop calories by 2050, which are levels consistent with those presented in Table 1 of *Keating et al.* [2014].

For each global food requirement, we provide food supply under two annual CYIs: first, a CYI of 1.0% per annum which is our "base case" and, second, a lower CYI of 0.5% per annum that represents our worst case effect of climate change even accounting for carbon fertilization. In all cases, we assume water consumption on irrigated land of 200 mm, which requires water application of 334 mm, and a nitrogen fertilizer application rate of 200 kg/ha N. All scenario calculations begin at the same base food requirement and food supply in 2005.

At the specified levels of irrigation and fertilization ($I = 200$ mm and $F = 200$ kg/ha N) and the FAO per calorie projections, we observe there is an *insufficient* food surplus from the world's 19 largest food-producing nations alone to meet the global food requirements of all countries by 2030 (CYI = 0.5%). In the case of higher per capita calorie consumption, representing a 1.38% linear annual increase on *FAO* [2006] projections, there is an almost immediate food deficit (CYI = 0.5% and CYI = 1.0%) if the only food available is produced by the 19 countries in the GFWS platform. Only in the case of the FAO-projected food requirements and an annual CYI of 1.0% is there a small food surplus of about 8% of global food requirements, or about half of its current level by 2050.

The key insights from the scenarios in Figure 2 are: first, the gap between food surplus in the 19 largest food-producing nations and global food requirements from all countries is increasing to 2050. This implies that future food production in countries, other than the 19 nations modeled and especially in nations with current food deficits and rapidly growing populations, needs to increase at a *faster* rate than those we calculate in 19 major food-producing countries to avoid a decrease (increase) in the global food surplus (deficit) in coming decades. Second, an average CYI of *less* than 1% per year, and that might arise with the negative effects of climate change, may result in large global food deficits. Third, the need for food exports from the world's 19 largest food-producing nations to other countries in the world to help ensure there is sufficient food available globally. Fourth, dietary trends as a result rising per capita incomes that lead to much greater per capita calorie requirements will make global food deficits much worse.[3]

3.2. Food Surpluses/Deficits and Water Applications

To put current global water extractions for irrigation into context, only about 12,500 km^3 is geographically and temporally accessible as renewable groundwater or base river flow [*Postel et al.*, 1996]. While this volume is several times larger than what is extracted for irrigation, the volume of water in rivers and river channels is, on average, at any point in time only about 2,120 km^3 [*Korzun*, 1974], which is *less* than the global annual water extracted for irrigation. Notwithstanding the importance of annual run-off as a measure of water availability, inter-annual variability and unpredictable timing of extreme events (floods and droughts) also pose important risks to water scarcity in some parts of the world [*Hall et al.*, 2014].

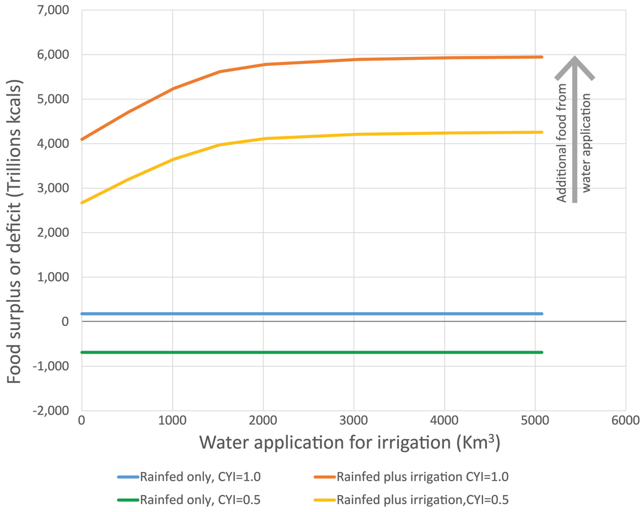

Figure 3. Food deficit or surplus in 2050 in the 19 countries with increasing water application using the current area of irrigated and rain-fed crop land. The scenarios differ in terms of the assumed rate of fertilizer application (200 kg/ha N) and assumed crop yield increases (0.5 and 1.0%/year) and assume the *FAO* [2006] per capita food requirement projection.

Figure 3 provides, for the 19 countries included in the analysis, the relationship between water applications required for irrigation in cubic kilometers and the food surplus/deficit (food supply less food requirement, in trillions of kcal for the 19 countries) for 2050 using the current area of rain-fed and irrigated crop land. The scenarios differ in terms of the assumed annual crop yield increase (CYI) from 2010 to 2050 (0.5 and 1.0%) for a specified fertilizer application of 200 kg/ha N while noting that FAO data for 2005 for the 19 countries averaged 175.5 kg/ha N for rain-fed cropping with a range from 16 kg/ha N in Russia to 548 kg/ha N in China. Collectively, these 19 countries generate from both irrigated and rain-fed cropping a food surplus for themselves. In the absence of water extractions, the yields from irrigated agricultural land are calculated to be the same as rain-fed agriculture.

Figure 3 highlights the importance of irrigation, when combined with adequate fertilizer inputs and crop yield productivity, to achieve a food surplus. For instance, in some scenarios, irrigation increases the food surplus by up to 50%, which is similar to the findings of top-down models [*Siebert and Döll*, 2010].

Figure 3 shows that the food supply from additional water applied for irrigation purposes rises from zero to between 1,500 and 2,000 km^3, depending on the scenario, and then reaches a plateau between 2,000 and 2,500 km^3. In the case of an annual CYI of 1.0%, this results in an additional 2,000 trillion kcal relative to the case with no water extractions for irrigation, or about 35% of the total food requirements of the 19 countries.

The generic food–water response in Figure 3 is well known at the individual plot or field level, e.g., *Payero et al.* [2008] in Figures 6 and 8a, but not at an aggregate level. As far as we are aware, our results are the first to identify a food surplus/deficit-water consumption plateau effect using a bottom-up crop production model for multiple countries. This plateau in food supply from irrigated agriculture arises, in part, because the yield per unit of water declines at high levels of water applications [*Elliott et al.*, 2014] for the level of N fertilization and crop evapotranspiration. The plateau in crop production with increasing water application arises, with a given level of nutrient input, from potential evapotranspiration (ETp) and crop genetics. This is

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[3] We acknowledge that our analysis does not allow for price responsiveness such that both producers and consumers may respond to changes in resource availability, and consequent changes in prices and technology, over time.

because yield is linearly related to crop evapotranspiration (ETc) and once ETc satisfies the ETp requirement any further water applied cannot be not transpired and, therefore, contribute to yield. As a result, increasing irrigation for crop season beyond ETc = ETp does not result in any further increased crop yield, e.g., *Zwart and Bastiaanssen* [2004] and *Payero et al.* [2008].

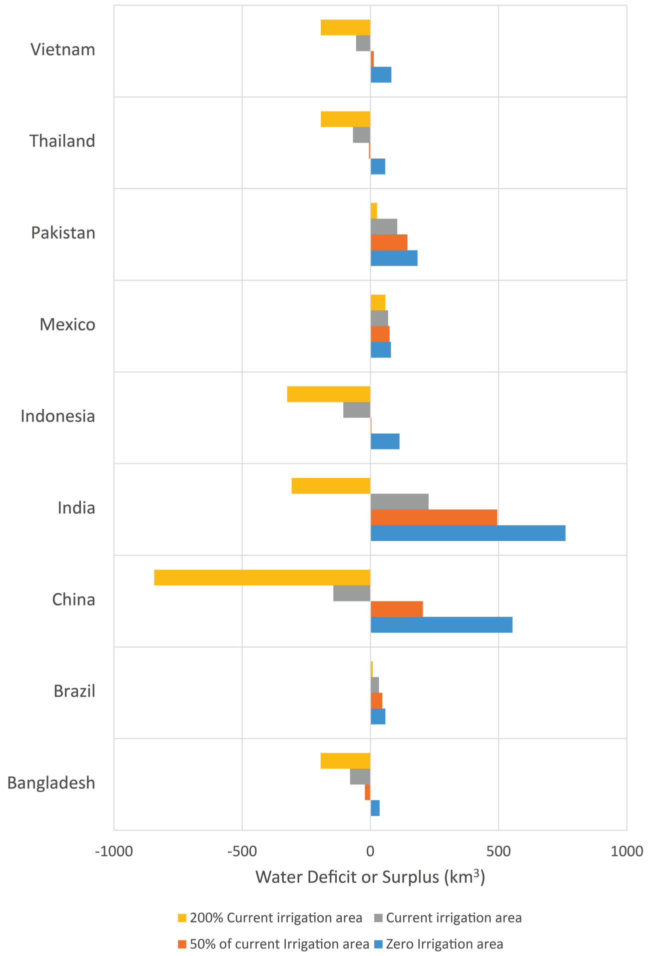

Figure 4. Water deficit or surplus for a selection of key cereal-producing countries in 2050 when the area of irrigation is given as zero, 50% of current area, current area, and twice current area of irrigation while applying 200 mm and 200 kg/ha N and a crop yield improvement of 0.5% per annum.

The plateaus in Figure 3 highlight the beneficial effects of water on food supply up to the plateau, but the diminishing returns of water applied beyond 2,000 km^3 unless the area of irrigation land is increased. Importantly, the water volume where the plateau occurs is comparable to the current global estimates of water applied for irrigation. In other words, for a given crop yield increase and fertilizer application, applying additional water to the world's *current* irrigated cropland would appear to deliver little in extra food supply. Thus, *if* more water were to be used in irrigated agriculture, our results suggest that this would only increase food supply if the total area of irrigated cropland were also to rise in a manner consistent with projections of *Jägermeyr et al.* [2016]. Further, unless annual crop yield increases were to rise from their current rate of 1% for wheat, rice and soybeans (1.5% for maize), as reported by *Fischer et al.* [2014], or N fertilizer were to be applied at a higher rate, then reductions in *current* water extractions would *lower* food production, especially for the scenarios where there is a high food surplus.

An indication of climate change impacts on the food surplus/deficit can be seen in Figure 3 by comparing the surplus for rain-fed plus irrigation cropping at 200 kg/ha N at a rate of CYI of 1.0% per annum to a CYI of 0.5% per annum. The reduction in food surplus attributable to a worst case climate change scenario (0.5% per annum CYI) for the 19 countries examined is of the order of 1,800 trillion kcal, or equivalent by 2050 to about 30% of the food requirements in these 19 countries.

3.3. Cross-Country Water Surpluses/Deficits

Figure 4 highlights the water surplus/deficit for key cereal-producing countries where the fresh water supply represents the annual volume of water that can be currently extracted from lakes, rivers, storages, and aquifers to meet the annual water demand from the existing water infrastructure. For all 19 countries, the fresh water supply is less than the annual renewable fresh water resource which is the total natural renewable surface and groundwater that is available over 1 year. For instance, China's water supply is some 550 km^3, but its total annual renewable water resource is about 2,800 km^3. China is also an example of a country with highly variable spatial water availability, which has reduced the potential of irrigation for food

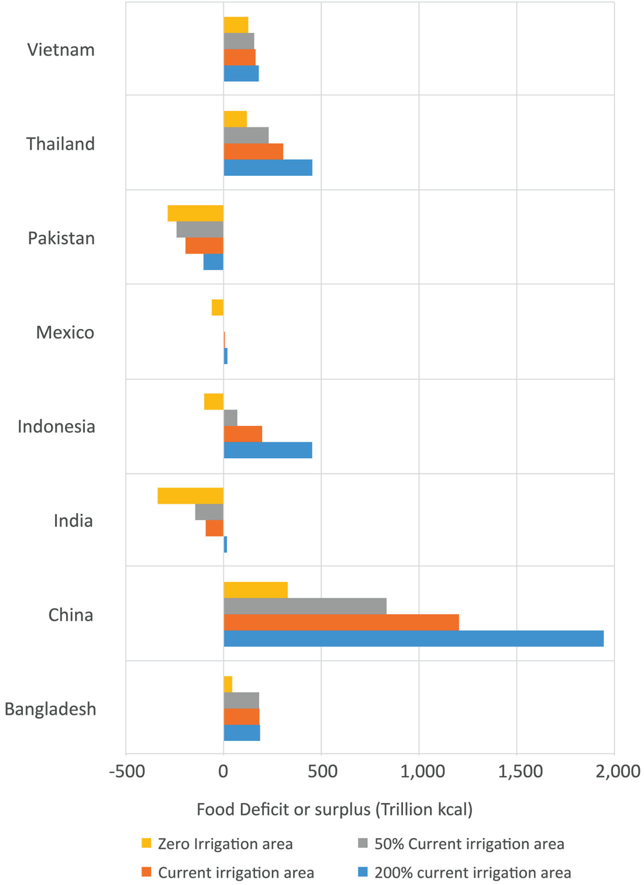

Figure 5. Food deficit or surplus for a selection of key cereal-producing countries in 2050 when the area of irrigation is given as zero, 50% of current area, current area, and twice current area of irrigation while applying 200 mm of irrigation and 200 kg/ha N, and a crop yield improvement of 0.5% per annum while assuming the *FAO* [2006] per capita food requirement projection.

production in the north and led to the south–north water project that transfers water from the Yangtze River in southern China to the northern part of China [*Pohlner*, 2016].

A country's fresh water supply can, in principle, be augmented by capital investments in water infrastructure so long as it is sufficiently below the annual renewable fresh water resource. A larger annual renewable water resource than the annual water supply means that, with additional infrastructure investments, the fresh water supply can be increased. However, this can only be accomplished with large capital investments—of at least $200 billion/year on a global basis [*Addams et al.*, 2009]. Such massive investment in water-scarce countries, such as in China, will likely come at the expense of water flows that generate ecosystem services [*Welling*, 2015].

The water surplus/deficit in 2050 is the current fresh water supply less the calculated volume of water applied to irrigation. The water surplus or deficit in Figure 4 depends greatly on the area irrigated with large deficits identified for most countries, should the irrigation area double in size. The water deficit for Bangladesh, China, Indonesia, Thailand, and Vietnam for the *current* area of cropland irrigated exists because current levels of water application in cropland irrigation are *less* than 200 mm. Our results highlight the "knife-edge" nature of the tension faced by such countries in terms of meeting their own food requirements domestically while not compromising their own water security including the healthy ecological function of the rivers, wetlands, lakes, and estuaries. These findings do not suggest that options to overcome water deficits and meet domestic food requirements do not exist, which include reductions in the area irrigated and improved irrigation practices [*Dalin et al.*, 2015; *Jägermeyr et al.*, 2016], but that in the absence of sustainable pathways acute food and water tensions will continue [*Zhuo et al.*, 2016].

3.4. Cross-Country Food Surpluses/Deficits

Figure 5 presents the differences between national food supply and food requirements for the same countries given in Figure 4 assuming the *FAO* [2006] projection on future per capita kilocalories requirements. In this case, increasing the area in irrigated cropland raises food supply and reduces (increases) existing food deficits (surpluses). For both India and Pakistan, under the assumed scenarios, food deficits in 2050 exist for all cases except when India has its irrigation area doubled. In Figure 5, the results show food surpluses for Bangladesh, Thailand, and Vietnam in 2050 when there is zero irrigation. This arises because the crop yield from rain-fed agriculture is assumed for the irrigated land area and because in these countries the yield for rain-fed agriculture is relatively high. The high yield predicted under rain-fed conditions is a factor why these countries avoid a food deficit without irrigation and points to the importance of green water in food production, despite large areas under irrigation.

3.5. Food and Water Nexus

The nexus between food supply and water extractions for irrigation for the selected countries in 2050 is shown in Figure 6 assuming the current national irrigation area using 200 mm, 200 kg/ha N, and with a more optimistic annual CYI of 1.0% than used in Figures 4 and 5. In Figure 6, the *location* of the spheres for each country is jointly determined by a nation's water surplus/deficit, the difference between national fresh water supply and the fresh water extractions from irrigation, and the food surplus/deficit, the difference between a country's domestic food production and its projected domestic food requirements. Thus, in Figure 6, Pakistan has a food deficit, but a water surplus, while China has a water deficit, but a food surplus. It is important to note that with the CYI of 1.0% in Figure 6, instead of the 0.5% in Figure 5, the food deficits in India, Indonesia, and Mexico displayed in Figure 5 do not occur. Again, our results show the critical importance of maintaining CYI of at least 1.0% per annum.

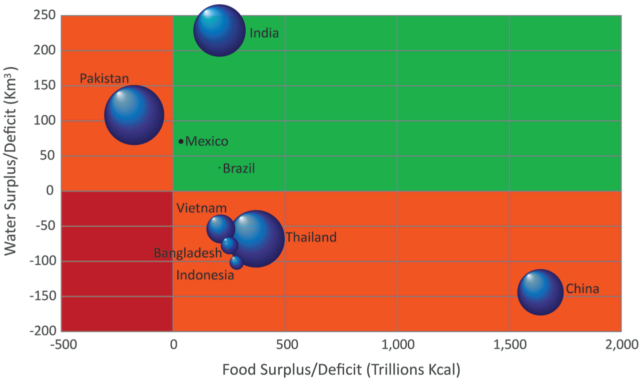

Figure 6. Food and water deficit and surplus in 2050 for a selection of key cereal-producing countries for the current area of irrigation while applying 200 mm of irrigation and 200 kg/ha N using a crop yield improvement of 1.0% per annum and assuming the *FAO* [2006] per capita kilocalories projection of food requirements and the current annual fresh water resource.

The *size* of each sphere for the countries in Figure 6 represents water stress or the ratio of fresh water extractions from irrigation to the annual fresh water resource of the country [*Gleick et al.*, 2009] and is sized relative to Pakistan which has the highest ratio of all countries.[4] The larger is the sphere, all else equal, the less able is a country to increase its water supply to overcome a water deficit or to increase the amount of water extracted for irrigation, or for other purposes. For instance, the relative large-sized spheres for Pakistan and India show that they each have relatively high water stress which, all else equal, limits their options to increase their overall water supply to meet increased water demands.

Figure 6 shows the *apparent* water surplus of about 250 km^3 in India and is a best case scenario. For instance, the 2030 Water Resource Group, under business as usual, projects total water extractions in India to approximately double to about 1,500 km^3, which would be close to India's total renewable fresh water resource. Given that we treat water extractions for non-agricultural uses as fixed, our water surplus/deficit calculations in 2050 for countries, such as India, with rapidly growing economies and populations almost certainly obscures water security issues beyond the irrigation sector.

Additional water risks may also arise for the countries in Figure 6 if the area irrigated were to increase or the amount of water consumed per hectare were to rise. For instance, if India's irrigation area were to double by 2050, under existing crop yield output per volume of water consumed, India would have an annual water deficit of some 300 km^3.

By contrast to India, China in 2050 is calculated to have a food surplus, but a water deficit of some 140 km^3. This discrepancy for China and other countries where there is a food surplus, but with a water extraction deficit, can only be reconciled by increased food imports and/or additional investments to increase the sustainable fresh water supply. This may also be true for countries where we have calculated a water surplus should there be a substantial increase in water extractions, other than for irrigation.

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[4] The fresh water supply represents the annual volume of water that can be currently extracted from lakes, rivers, storages, and aquifers to meet the annual water demand from the existing water infrastructure. The annual renewable fresh water resource represents the total natural renewable surface and groundwater that is available over 1 year. The annual renewable fresh water resource represents a fixed natural limit of total fresh water, but the fresh water supply can, in principle, be augmented by capital investments in water infrastructure so long as it is sufficiently below the annual renewable fresh water resource.

Our results highlight, from a bottom-up crop-hydrological model platform, the importance of how water is extracted and consumed in irrigated agriculture to meet food requirements. Our scenarios show, first and foremost, that increasing water extractions on current irrigated crop areas, but without a concomitant increase in nitrogen, will do little to increase food supply. Thus, effectively managing how water and fertilizer are used to increase yields, along with better farm practices that do not degrade soils or water quality that lower crop yields, is critical to reconciling food and water gaps out to 2050 [*Wichelns and Oster*, 2006; *Tilman et al.*, 2011; *Pingali*, 2012; *Carberry et al.*, 2013; *Keating et al.*, 2014; *Zhuo et al.*, 2016]. Importantly, we highlight the critical importance of irrigated agriculture in supplying global food requirements, and also a global plateau effect for food surplus/deficit above 2,000 km^3 of water extractions beyond which additional water use will do little to increase food supplies unless there is an increase in the irrigated land area.

4. Discussion: Possible Pathways to Tensions in the Food and Water Nexus

Our results highlight, using a bottom-up crop-hydrological model platform, the tension at the food and water nexus to meet future food requirements within the constraint of current fresh water supplies. The dilemma of physical limits in terms of water extractions, coupled with the need to increase food production, is already sufficiently pronounced at a global level that "business as usual," at least in terms of water applications for agriculture, appears unsustainable. For instance, under reasonable assumptions in terms of CYI (1.0%/year), fertilizer application (200 kg/ha N) and water consumption on irrigated land (200 mm), there is a substantial reduction in food surplus from the world's largest 19 food-producing countries by 2035. Given a lower CYI (0.5%/year), there could be a global food deficit by 2030.

In this section, we highlight five possible food supply pathways to respond to this global challenge.[5]

4.1. Water Productivity

The GFWS platform considers the on-farm irrigation efficiency for three methods of irrigation, namely, surface, sprinkler, and drip where 60, 75, and 90% of water applied is consumed in transpiration by the crop. Thus, depending on the method of irrigation, some 40, 25, or 10% of water applied on-farm is evaporated by the soil or drains to surface water and or groundwater systems in the landscape. By contrast, expected improvements in water productivity, the ratio of crop produced to water consumed in crop transpiration would be modest—about 10% [*Perry et al.*, 2009].

Reduced water extractions from both off-farm irrigation system and on-farm irrigation efficiency can help to reconcile food and water trade-offs [*Wada et al.*, 2014], but neither resolve the overuse of water in the context of ecosystem losses, nor is it necessarily associated with maximum farmer net revenue or crop yields [*Wichelns*, 2015]. Notably, an increase in beneficial water consumption, all else equal, may be associated with reductions in water movement to deep drainage, groundwater recharge and also return flows to streams that can negatively affect riverine ecosystems [*Grafton et al.*, 2013]. Thus, while on-farm irrigation efficiency improvements can be important, they must also be considered in terms of impact on river and groundwater ecosystems. This is because more water efficient irrigation technologies may also result in lower return flows at the hydrology of the basin and reduced aquifer recharge unless the water saved through irrigation efficiency translates to a reduction in fresh water extractions. To illustrate, based on modeling on the Lower Rio Grande in New Mexico, the higher the capital subsidies for more water-use efficient irrigation technologies, the lower the downstream flows [*Ward and Pulido-Velazquez*, 2008]. Thus, at best, improvements in water productivity coupled with increases in on-farm and irrigation system efficiencies, are only a partial response to the multiple tensions of the food–water nexus.

4.2. Food Trade

As shown in Figure 2, we find a growing gap between the food supply in the world's largest food-producing countries and the food requirements for the entire world. Much of this gap is explained by a rapidly growing population in Africa over the coming decades. While Africa can do much to feed itself [*World Bank*, 2012],

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[5] There are also pathways to reduce food demand, such as dietary shifts that involve eating less meats [*Tilman and Clark*, 2014] and ways to increase the more effective utilization of the food produced, such as reducing on- and off-farm food losses [*Gustavsson et al.*, 2011], but these fall outside our focus on food supply and resource constraints.

it will need to do much better in terms of increasing its food supply than it has done in the past.[6] Given our calculated deficit in *either* food or water in key cereal-producing and -consuming countries (such as Bangladesh, China, and Pakistan), food trade will be essential [*Liu et al.*, 2014] to effectively respond to food risks out to 2050.

4.3. Crop Yield Improvements

As highlighted in our scenario results, which are consistent with top-down modeling [*Baldos and Hertel*, 2014], sufficiently high enough CYIs are required to feed the world by 2050. In particular, CYIs of 0.5% per annum, which we associate with the worst case scenario with climate change, will be inadequate to ensure that food supply satisfies food requirements. What is also needed are increases in crop yields without concomitant rises in agricultural inputs, such as fertilizer and water, and that collectively represents growth in agricultural total factor productivity (TFP).[7]

Encouragingly, [*Fuglie and Wang*, 2012] show that globally over the past five decades the source of growth in agricultural output has shifted from identifiable resources or inputs towards TFP growth. For instance, over the past 50 years TFP growth accounted for about 40% of the output growth, but over the period 2001–2009, they estimate that TFP growth accounted for about 75% of the global agricultural production increase.

Our findings indicate that much more is required, given the resource limits in water and other resources, than increases in the TFP of farmers. There must also be what we term “sustainable TFP” growth that is consistent with the sustainable intensification of agriculture [*Chartres and Noble*, 2015; *Rockström et al.*, 2017] where not only TFP growth occurs, but also in ways that reduce agriculture’s environmental impact [*Phalan et al.*, 2016]. Sustainable TFP growth requires multiple actions, locally adapted, to support the delivery of ecosystem services from the whole of the landscape perspective [*McKenzie and Williams*, 2015; *Rockström et al.*, 2017].

Possible approaches to promote sustainable TFP growth include precision agriculture whereby fertilizers, pesticides, and water are only applied when they are absolutely needed [*Bongiovanni and Lowenberg-DeBoer*, 2004], and in innovative ways to reduce water use [*Brauman et al.*, 2013] and nitrogen use [*Mueller et al.*, 2014]. To ensure such approaches are sustainably applied, along with precision agriculture [*Schimmelpfennig and Ebel*, 2011], relevant and effective agro-ecological practices at a local level will need to be up-scaled to a regional and national dimension [*Horlings and Marsden*, 2011]. This requires on-going research and development into the adoption, or otherwise, of precision agriculture technologies [*Tey and Brindal*, 2012], and also demand-driven research on innovation systems [*Harley et al.*, 2015], including on the incentives for farmers to adopt sustainable TFP practices.

4.4. Water Supply Infrastructure

As shown in Figures 4 and 6, we calculate water deficits in key food-producing countries should the irrigated land area increase or the water consumed for the existing irrigated land rise. While improvements in water productivity may help to bridge these gaps, it is also possible to increase the available water supply though investments in water infrastructure, and in particular water storages. Storages and water transfer projects already provide a response to either temporal or spatial variability in water availability and represent an important strategy in some countries, such as China, in response to water insecurity.

At a global level, additional or enlarged water storages could provide an increased water supply, in terms of increased reservoir capacity, equivalent to 600 km^3 [*Wada et al.*, 2014]. While the building of new water storages or the expansion of existing water storages poses environmental challenges [*Vörösmarty et al.*,

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[6] The *World Bank* [2012] observes that “If African farmers were to achieve the yields that farmers are attaining in other developing countries then output of staples would easily double or even triple. On top of this, barely a fraction of fertile agricultural land is being cultivated—just 10% of the 400 million hectares of agricultural land in the Guinea Savannah zone that covers a large part of Africa.”

[7] Growth in TFP represents the difference between the growth in outputs and the growth in inputs such that if the growth in the outputs is the same as the growth inputs, TFP remains unchanged. Thus, even if agricultural output were to double, but the amount of inputs used were to triple, agricultural TFP would have *declined*.

2010], it does offer greater security of water supply to farmers and may provide ancillary benefits, such as reduced risks of flooding [*Sadoff et al.*, 2015].

Apart from the high capital costs and possible negative environmental consequences, another key challenge to investing in water storages is that it does not increase the overall water resource available, but simply changes the inter-temporal availability or where the water supply is delivered. Thus, in countries with already high levels of water stress where the ratio of water use to the renewable fresh water resource is already high, or in excess of 0.4 [*Vörösmarty et al.*, 2000], the ability of water infrastructure to overcome large water deficits will remain a challenge.

4.5. Integrative Polices and Decision Processes

A key pathway to respond to the food–water nexus are changes in institutions or the "rules of the game" so as to better align short- and long-term goals [*Guerry et al.*, 2015] and to make better decisions about what food gets produced, and where, and what water is extracted and for what purposes. Any changes to promote both food and water security, however, must be locally adapted to both the bio-physical and socio-economic circumstances and constraints. Whatever the chosen policy or decision approach, there is also a need to consider a range of other issues such as equity in food and water use, the links to sustainability and ecosystem services, and the incentives to promote desired behaviors and practices in the production of food and extraction and application of fresh water [*Zeitoun et al.*, 2016].

Given the consequences of either food or water deficits, as identified in our results, a risk-based approach to institutional change is required. Key to such an approach are participatory processes [*Brouwer et al.*, 2016], given the atomistic nature of farming, and also causal risk assessment [*World Economic Forum*, 2011; *Grafton et al.*, 2016] so as to improve decisions and promote sustainable outcomes at multiple scales. A "soft" approach [*Gleick*, 2002] to resolving challenges in the food–water nexus should also consider tools such as retrospective analysis, monitoring, and strategic risk management [*Cai et al.*, 2015], in addition to systems modeling [*World Economic Forum*, 2011]. Further, to ensure private and social incentives align, and where relevant, signals need to be provided to reflect water scarcity such as in the form of water pricing [*OECD*, 2015].

5. Conclusions

Using "bottom-up" field-based, crop-hydrological models that include both blue and green water, and with no growth in water use for domestic and industrial purposes, our results show that while there may be sufficient land there will be inadequate fresh water supplies for irrigated agriculture to satisfy national food requirements in key food-producing countries. This poses key food–water nexus tensions given that world food requirements are, according to the FAO, likely to increase by at least 60% to 2050 and that irrigation currently accounts for 70% of global water extractions, and some 40–50% of food production.

To manage the interplay of issues at the global food–water nexus, we propose five possible interconnecting pathways that include: (1) increased water productivity; (2) food trade; (3) improvements in both crop yield increases and sustainable TFP; (4) investments in water infrastructure; and (5) integrative policies and decision processes. These possible pathways, when appropriately combined and locally adapted to bio-physical and socio-economic circumstances, offer the potential to increase food production, while avoiding the deterioration of water quality, increased water stress, and the diminishment of ecosystem services.

6. Author Contributions

The funding and concept for the GFWS platform was due to R.Q.G. while Q.J. was responsible for model construction, development, and operation. The framing of the research questions, application of the model, its execution, and the analysis of results was jointly conducted by J.W. and R.Q.G. The text for the paper was jointly written by R.Q.G. and J.W. All authors read and also approved the final manuscript.

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References

Addams, L., G. Boccaletti, M. Kerlin, and M. Stuchtey (2009), Charting our water future: Economic frameworks to inform decision-making, *Rep.*, 2030 Water Resour. Group, New York, N. Y.

Baldos, U. L. C., and T. W. Hertel (2014), Global food security in 2050: The role of agricultural productivity and climate change, *Aust. J. Agric. Resour. Econ.*, *58*(4), 554–570. https://doi.org/10.1111/1467-8489.12048.

Bondeau, A., P. C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, and M. Reichstein (2007), Modelling the role of agriculture for the 20th century global terrestrial carbon balance, *Global Change Biol.*, *13*(3), 679–706. https://doi.org/10.1111/j.1365-2486.2006.01305.x.

Bongiovanni, R., and J. Lowenberg-DeBoer (2004), Precision agriculture and sustainability, *Precis. Agric.*, *5*(4), 359–387. https://doi.org/10.1023/b:prag.0000040806.39604.aa.

Brauman, K. A., S. Siebert, and J. A. Foley (2013), Improvements in crop water productivity increase water sustainability and food security—A global analysis, *Environ. Res. Lett.*, *8*(2), 024030. https://doi.org/10.1088/1748-9326/8/2/024030.

Brouwer, H., J. Woodhill, M. Hemmati, K. Verhoosel, and S. van Vugt (2016), *The MSP Guide, How to Design and Facilitate Multi-Stakeholder Partnerships*, Pract. Action Publ.; Wageningen Univ. and Res., Wageningen; The Netherlands.

Cai, X., X. Zhang, P. H. Noël, and M. Shafiee-Jood (2015), Impacts of climate change on agricultural water management: A review, *Wiley Interdiscip. Rev.: Water*, *2*(5), 439–455. https://doi.org/10.1002/wat2.1089.

Carberry, P. S., W.-l. Liang, S. Twomlow, D. P. Holzworth, J. P. Dimes, T. McClelland, N. I. Huth, F. Chen, Z. Hochman, and B. A. Keating (2013), Scope for improved eco-efficiency varies among diverse cropping systems, *Proc. Natl. Acad. Sci. U. S. A.*, *110*(21), 8381–8386. https://doi.org/10.1073/pnas.1208050110.

Chartres, C. J., and A. Noble (2015), Sustainable intensification: Overcoming land and water constraints on food production, *Food Secur.*, *7*(2), 235–245. https://doi.org/10.1007/s12571-015-0425-1.

Comprehensive Assessment of Water Management in Agriculture (2007), Water for food, water for life: A comprehensive assessment of water management in agriculture – Summary report, *Rep.*, Int. Water Manage. Inst., Earthscan, and Colombo, London, U. K.

Dalin, C., H. Qiu, N. Hanasaki, D. L. Mauzerall, and I. Rodriguez-Iturbe (2015), Balancing water resource conservation and food security in China, *Proc. Natl. Acad. Sci. U. S. A.*, *112*(15), 4588–4593. https://doi.org/10.1073/pnas.1504345112.

Elliott, J., D. Deryng, C. Müller, K. Frieler, M. Konzmann, D. Gerten, M. Glotter, M. Flörke, Y. Wada, and N. Best (2014), Constraints and potentials of future irrigation water availability on agricultural production under climate change, *Proc. Natl. Acad. Sci. U. S. A.*, *111*(9), 3239–3244. https://doi.org/10.1073/pnas.1222474110.

Fischer, R. A., D. Byerlee, and G. O. Edmeades (2014), *Crop Yields and Global Food Security: Will Yield Increase Continue to Feed the World?* Aust. Cent. for Int. Agric. Res., Canberra, Australia.

Food and Agriculture Organization of the United Nations (2006), World agriculture: Towards 2030/2050 – Interim report, *Rep.*, Food and Agric. Organ., Rome, Italy.

Food and Agriculture Organization of the United Nations (2011), Database collection of the Food and Agriculture Organization of the United Nations. Food balance sheets.

Food and Agriculture Organization of the United Nations (2016), *Save and Grow in Practice: Maize, Rice, Wheat. A Guide to Sustainable Cereal Production*, Food and Agric. Organ. of the United Nations, Rome, Italy.

Fuglie, K., and S. L. Wang (2012), Productivity growth in global agriculture shifting to developing countries, *Choices 4th Quarter*, *27*(4).

Gerten, D., J. Heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha (2011), Global water availability and requirements for future food production, *J. Hydrometeorol.*, *12*(5), 885–899. https://doi.org/10.1175/2011jhm1328.1.

Gleick, P. H. (1993), *Water in Crisis: A Guide to the World's Fresh Water Resources*, Oxford Univ. Press, Inc., New York, N. Y..

Gleick, P. H. (2002), Water management: Soft water paths, *Nature*, *418*(6896), 373. https://doi.org/10.1038/418373a.

Gleick, P., H. Cohen, M. Morikawa, M. Morrison, and M. J Palaniappan (2009), The world's water 2008–2009: The biennial report on freshwater resources, *Rep. 1597265055*, Pac. Inst. for Stud. in Dev., Environ., and Secur., Washington, DC (EUA), Washington, D. C.

Grafton, R. Q., et al. (2013), Global insights into water resources, climate change and governance, *Nat. Clim. Change*, *3*(4), 315–321. https://doi.org/10.1038/nclimate1746.

Grafton, R. Q., J. Williams, and Q. Jiang (2015), Food and water gaps to 2050: Preliminary results from the global food and water system (GFWS) platform, *Food Secur.*, *7*(2), 209–220. https://doi.org/10.1007/s12571-015-0439-8.

Grafton, R. Q., M. McLindin, K. Hussey, P. Wyrwoll, D. Wichelns, C. Ringler, D. Garrick, J. Pittock, S. Wheeler, and S. Orr (2016), Responding to global challenges in food, energy, environment and water: Risks and options assessment for decision-making, *Asia Pac. Policy Stud.*, *3*(2), 275–299. https://doi.org/10.1002/app5.128.

Guerry, A. D., S. Polasky, J. Lubchenco, R. Chaplin-Kramer, G. C. Daily, R. Griffin, M. Ruckelshaus, I. J. Bateman, A. Duraiappah, and T. Elmqvist (2015), Natural capital and ecosystem services informing decisions: From promise to practice, *Proc. Natl. Acad. Sci. U. S. A.*, *112*(24), 7348–7355. https://doi.org/10.1073/pnas.1503751112.

Gustavsson, J., C. Cederberg, U. Sonesson, R. van Otterdijk, and A. Maybeck (2011), Global food losses and food waste: Extent, causes and prevention, *Rep.*, Food and Agric. Organ. of the United Nations, Rome, Italy.

Hall, J., D. Grey, D. Garrick, F. Fung, C. Brown, S. Dadson, and C. Sadoff (2014), Coping with the curse of freshwater variability, *Science*, *346*(6208), 429–430. https://doi.org/10.1126/science.1257890.

Harley, A. G., N. M. Holbrook, and W. C. Clark (2015), Workshop report: Innovation for vulnerable farmers: Drought and water scarcity adaptation technologies, *Rep.*, Sustainability Sci. Prog., Harvard Kennedy School.

Horlings, L. G., and T. K. Marsden (2011), Towards the real green revolution? Exploring the conceptual dimensions of a new ecological modernisation of agriculture that could 'feed the world', *Global Environ. Change*, *21*(2), 441–452. https://doi.org/10.1016/j.gloenvcha.2011.01.004.

Jägermeyr, J., D. Gerten, S. Schaphoff, J. Heinke, W. Lucht, and J. Rockström (2016), Integrated crop water management might sustainably halve the global food gap, *Environ. Res. Lett.*, *11*(2), 025002. https://doi.org/10.1088/1748-9326/11/2/025002.

Keating, B. A., P. S. Carberry, G. L. Hammer, M. E. Probert, M. J. Robertson, D. Holzworth, N. I. Huth, J. N. Hargreaves, H. Meinke, and Z. Hochman (2003), An overview of APSIM, a model designed for farming systems simulation, *Eur. J. Agron.*, *18*(3), 267–288. https://doi.org/10.1016/S1161-0301(02)00108-9.

Keating, B. A., M. Herrero, P. S. Carberry, J. Gardner, and M. B. Cole (2014), Food wedges: Framing the global food demand and supply challenge towards 2050, *Global Food Sec.*, *3*(3), 125–132. https://doi.org/10.1016/j.gfs.2014.08.004.

Korzun, V. I. (1974), *World Water Balance and Water Resources of the Earth*, Hydrometeoizdat, Leningrad, Russia.

Lesk, C., P. Rowhani, and N. Ramankutty (2016), Influence of extreme weather disasters on global crop production, *Nature*, *529*(7584), 84–87. https://doi.org/10.1038/nature16467.

Liu, J., T. W. Hertel, F. Taheripour, T. Zhu, and C. Ringler (2014), International trade buffers the impact of future irrigation shortfalls, *Global Environ. Change*, *29*, 22–31. https://doi.org/10.1016/j.gloenvcha.2014.07.010.

Lobell, D. B., and S. M. Gourdji (2012), The influence of climate change on global crop productivity, *Plant Physiol.*, *160*(4), 1686–1697. https://doi.org/10.1104/pp.112.208298.

McCown, R., G. Hammer, J. Hargreaves, D. Holzworth, and D. Freebairn (1996), APSIM: A novel software system for model development, model testing and simulation in agricultural systems research, *Agric. Syst.*, *50*(3), 255–271. https://doi.org/10.1016/0308-521x(94)00055-v.

McKenzie, F. C., and J. Williams (2015), Sustainable food production: Constraints, challenges and choices by 2050, *Food Secur.*, *7*(2), 221–233. https://doi.org/10.1007/s12571-015-0441-1.

Mueller, N. D., P. C. West, J. S. Gerber, G. K. MacDonald, S. Polasky, and J. A. Foley (2014), A tradeoff frontier for global nitrogen use and cereal production, *Environ. Res. Lett.*, *9*(5), 054002. https://doi.org/10.1088/1748-9326/9/5/054002.

Nelson, G. C., H. Valin, R. D. Sands, P. Havlík, H. Ahammad, D. Deryng, J. Elliott, S. Fujimori, T. Hasegawa, and E. Heyhoe (2014), Climate change effects on agriculture: Economic responses to biophysical shocks, *Proc. Natl. Acad. Sci. U. S. A.*, *111*(9), 3274–3279. https://doi.org/10.1073/pnas.1222465110.

Organization for Economic Co-operation and Development (2015), *Water Resources Allocation*, OECD Publ., Paris, France.

Payero, J. O., D. D. Tarkalson, S. Irmak, D. Davison, and J. L. Petersen (2008), Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate, *Agric. Water Manage.*, *95*(8), 895–908. https://doi.org/10.1016/j.agwat.2008.02.015.

Perry, C., P. Steduto, R. G. Allen, and C. M. Burt (2009), Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities, *Agric. Water Manage.*, *96*(11), 1517–1524. https://doi.org/10.1016/j.agwat.2009.05.005.

Phalan, B., R. E. Green, L. V. Dicks, G. Dotta, C. Feniuk, A. Lamb, B. B. Strassburg, D. R. Williams, E. K. zu Ermgassen, and A. Balmford (2016), How can higher-yield farming help to spare nature? *Science*, *351*(6272), 450–451. https://doi.org/10.1126/science.aad0055.

Pingali, P. L. (2012), Green Revolution: Impacts, limits, and the path ahead, *Proc. Natl. Acad. Sci. U. S. A.*, *109*(31), 12302–12308. https://doi.org/10.1073/pnas.0912953109.

Pohlner, H. (2016), Institutional change and the political economy of water megaprojects: China's south–north water transfer, *Global Environ. Change*, *38*, 205–216. https://doi.org/10.1016/j.gloenvcha.2016.03.015.

Postel, S. L., G. C. Daily, and P. R. Ehrlich (1996), Human appropriation of renewable fresh water, *Science*, *271*(5250), 785–787. https://doi.org/10.1126/science.271.5250.785.

Rockström, J., et al. (2017), Sustainable intensification of agriculture for human prosperity and global sustainability, *Ambio*, *46*, 4–17.

Sadoff, C., et al. (2015), Securing water, sustaining growth: Report of the GWP/OECD task force on water security and sustainable growth, *Rep.*, 180 pp., Univ. of Oxford, Oxford, U. K.

Schimmelpfennig, D., and R. Ebel (2011), On the doorstep of the information age: Recent adoption of precision agriculture, in *Economic Research Service, Paper No. EIB-80*, US Dept. of Agric., Washington, D. C.

Schlenker, W., and M. J. Roberts (2009), Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(37), 15594–15598. https://doi.org/10.1073/pnas.0906865106.

Siebert, S., and P. Döll (2010), Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation, *J. Hydrol.*, *384*(3), 198–217. https://doi.org/10.1016/j.jhydrol.2009.07.031.

Tey, Y. S., and M. Brindal (2012), Factors influencing the adoption of precision agricultural technologies: A review for policy implications, *Precis. Agric.*, *13*(6), 713–730. https://doi.org/10.1007/s11119-012-9273-6.

Tilman, D., and M. Clark (2014), Global diets link environmental sustainability and human health, *Nature*, *515*(7528), 518–522. https://doi.org/10.1038/nature13959.

Tilman, D., C. Balzer, J. Hill, and B. L. Befort (2011), Global food demand and the sustainable intensification of agriculture, *Proc. Natl. Acad. Sci. U. S. A.*, *108*(50), 20260–20264. https://doi.org/10.1073/pnas.1116437108.

Vörösmarty, C. J., P. Green, J. Salisbury, and R. B. Lammers (2000), Global water resources: Vulnerability from climate change and population growth, *Science*, *289*(5477), 284–288. https://doi.org/10.1126/science.289.5477.284.

Vörösmarty, C. J., P. B. McIntyre, M. O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S. E. Bunn, C. A. Sullivan, and C. R. Liermann (2010), Global threats to human water security and river biodiversity, *Nature*, *467*(7315), 555–561. https://doi.org/10.1038/nature09440.

Wada, Y., T. Gleeson, and L. Esnault (2014), Wedge approach to water stress, *Nat. Geosci.*, *7*(9), 615–617. https://doi.org/10.1038/ngeo2241.

Wada, Y., M. Flörke, N. Hanasaki, S. Eisner, G. Fischer, S. Tramberend, Y. Satoh, M. Van Vliet, P. Yillia, and C. Ringler (2016), Modeling global water use for the 21st century: The Water Futures and Solutions (WFaS) initiative and its approaches, *Geosci. Model Dev.*, *9*(1), 175–222. https://doi.org/10.5194/gmd-9-175-2016.

Ward, F. A., and M. Pulido-Velazquez (2008), Water conservation in irrigation can increase water use, *Proc. Natl. Acad. Sci. U. S. A.*, *105*(47), 18215–18220. https://doi.org/10.1073/pnas.0805554105.

Welling, R. (2015), *Unseen and unrecognised: Allocating water to nature in river systems*, CGIAR, Research Prog. on Water, Land and Ecosyst.

Wichelns, D. (2015), Water productivity and food security: Considering more carefully the farm-level perspective, *Food Secur.*, *7*(2), 247–260. https://doi.org/10.1007/s12571-015-0426-0.

Wichelns, D., and J. Oster (2006), Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial, *Agric. Water Manage.*, *86*(1), 114–127. https://doi.org/10.1016/j.agwat.2006.07.014.

World Bank (2012), Africa can help feed Africa: Removing barriers to regional trade in food staples, *Rep.*, Poverty Reduct. and Econ. Manage. Africa Reg., Washington, D. C.

World Economic Forum (2011), *Water Security: The Water-Food-Energy-Climate Nexus: The World Economic Forum Water Initiative*, Island Press, Washington, D. C..

Zeitoun, M., B. Lankford, T. Krueger, T. Forsyth, R. Carter, A. Y. Hoekstra, R. Taylor, O. Varis, F. Cleaver, and R. Boelens (2016), Reductionist and integrative research approaches to complex water security policy challenges, *Global Environ. Change*, *39*, 143–154. https://doi.org/10.1016/j.gloenvcha.2016.04.010.

Zhuo, L., M. M. Mekonnen, and A. Y. Hoekstra (2016), Consumptive water footprint and virtual water trade scenarios for China—With a focus on crop production, consumption and trade, *Environ. Int.*, *94*, 211–223. https://doi.org/10.1016/j.envint.2016.05.019.

Zwart, S. J., and W. G. Bastiaanssen (2004), Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize, *Agric. Water Manage.*, *69*(2), 115–133. https://doi.org/10.1016/j.agwat.2004.04.007.