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Closing the yield gap while ensuring water sustainability

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Abstract

Water is a major factor limiting crop production in many regions around the world. Irrigation can greatly enhance crop yields, but the local availability and timing of freshwater resources constrains the ability of humanity to increase food production. Innovations in irrigation infrastructure have allowed humanity to utilize previously inaccessible water resources, enhancing water withdrawals for agriculture while increasing pressure on environmental flows and other human uses. While substantial additional water will be required to support future food production, it is not clear whether and where freshwater availability is sufficient to sustainably close the yield gap in cultivated lands. The extent to which irrigation can be expanded within presently rainfed cropland without depleting environmental flows remains poorly understood. Here we perform a spatially explicit biophysical assessment of global consumptive water use for crop production under current and maximum attainable yield scenarios assuming current cropping practices. We then compare these present and anticipated water consumptions to local water availability to examine potential changes in water scarcity. We find that global water consumption for irrigation could sustainably increase by 48% (408 km^3 H_2O yr^{-1})—expanding irrigation to 26% of currently rainfed cultivated lands (2.67×10^6 km^2) and producing 37% (3.38×10^{15} kcal yr^{-1}) more calories, enough to feed an additional 2.8 billion people. If current unsustainable blue water consumption (336 km^3 yr^{-1}) and production (1.19×10^{15} kcal yr^{-1}) practices were eliminated, a sustainable irrigation expansion and intensification would still enable a 24% increase in calorie (2.19×10^{15} kcal yr^{-1}) production. Collectively, these results show that the sustainable expansion and intensification of irrigation in selected croplands could contribute substantially to achieving food security and environmental goals in tandem in the coming decades.

1. Introduction

Steady increases in crop production have supported marked population growth while substantially reducing incidences of malnourishment globally (Pingali 2012). This Green Revolution was made possible through the proliferation of high-yielding crop varieties, increased pressures on land and water, substantial nutrient inputs, and rising greenhouse gas emissions, making agriculture one of humanity's most profound environmental burdens. A continuation of these practices is expected to be constrained by the limited water resources of the planet (Postel *et al* 1996, Gleick and Palaniappan 2010) and be insufficient to sustainably ensure future food security in the long term (Wackernager *et al* 2002, Rockström *et al* 2009, Galli *et al* 2014, Hoekstra and Wiedmann 2014, Steffen *et al* 2015).

Recent work has devoted substantial focus to examining the avenues by which humanity can feed more people and minimize the environmental impacts of agriculture, including reducing food waste, improving resource use efficiencies, and shifting diets (Rost *et al* 2009, Godfray *et al* 2010, Foley *et al* 2011, Tilman *et al* 2011, Cassidy *et al* 2013, Ray and Foley 2013). Receiving the bulk of the attention among these promising solutions is the opportunity to enhance crop yields on current croplands, thereby ensuring that agricultural inputs are used efficiently by a crop as well as preventing agricultural expansion into biodiversity-rich ecosystems (Phalan *et al* 2011, Pretty *et al* 2011, Mueller *et al* 2012, Garnett *et al* 2013, Davis *et al* 2017b). Known as 'agricultural intensification' such an approach entails closing (or at least narrowing) crop yield gaps—the difference between potential yield (or water-limited yield potential) and the actual yield that a farmer currently achieves (Cassman 1999, Lobell *et al* 2009, van Ittersum *et al* 2013, Gobbett *et al* 2017). A common benchmark used in studies estimating maximized crop production (e.g., Foley *et al* 2011, Mueller *et al* 2012), potential yield is defined as the yield of a crop cultivar when grown in an environment to which it is adapted, with non-limiting water and nutrient supplies, and with pests, weeds, and diseases effectively controlled (Evans 1993). While water and other inputs will likely be used more efficiently under higher yields (i.e., more crop per drop), additional irrigation will be needed in many places in order to close the yield gap and to maximize food production (Gerten *et al* 2011, Tilman *et al* 2011, Pfister *et al* 2011, Mueller *et al* 2012, Davis *et al* 2017a).

Global crop production depends on water received both as precipitation (or 'green water') and irrigation (or 'blue water') from surface water bodies and aquifers (Rockström *et al* 2009). Through irrigation, it is possible to reduce crop exposure to water stress, and therefore enhance productivity. Particularly in regions frequently affected by crop water stress, irrigation represents a major pathway to the intensification of crop production and yield gap closure (Mueller *et al* 2012). In some regions, the development of irrigation is limited by the availability of blue water resources. In other places, water withdrawals that exceed renewable water availability can affect environmental flows that support aquatic habitats (Poff *et al* 1997, Dudgeon *et al* 2006) and deplete groundwater resources (Konikow and Kendy 2005, Wada *et al* 2012). Recent work has assessed water scarcity under current levels of crop production (Brauman *et al* 2016, Mekonnen and Hoekstra 2016, Liu *et al* 2017), showing that many important agricultural regions maintain water consumptions that consistently exceed local freshwater availability. Yet it remains unclear where and to what extent local water resources will be sufficient to sustainably close the yield gap (i.e., achieve potential yields globally). Here we perform a global spatially distributed biophysical analysis of irrigation water demand under current and maximized crop production within the world's existing croplands. We then compare these demands to local renewable freshwater availability—accounting for environmental flows—to identify regions of the world where irrigation can be expanded into currently rainfed croplands without threatening freshwater ecosystems. We conclude our analysis by estimating the additional calories and protein that can potentially be produced while ensuring water sustainability. This study can ultimately help prioritize agricultural initiatives that can achieve food security and environmental goals together.

2. Methods

We evaluated the availability of freshwater resources for irrigation and the extent to which their consumption may affect environmental flows. We considered both current irrigation conditions and a possible scenario of yield gap closure on currently cultivated lands. Irrigation water use under yield gap closure accounts for both the intensification of irrigation and its expansion into rainfed croplands where yields are currently limited by precipitation availability in many places. This analysis allowed us to estimate where and to what extent water consumption for agriculture is sustainably accommodating local environmental needs and where crop production is or will be constrained by locally available renewable surface and groundwater resources. Our analysis examined only currently cultivated lands and did not consider cropland expansion, crop switching or increased cropping frequencies enabled by additional irrigation. Our hydrological analysis considers all renewable (blue) water resources (including both surface water and groundwater).

We used a process-based crop water model to estimate irrigation water consumption under current crop production and under yield gap closure for 16 major crops. This model was coupled with a daily soil water balance and integrated over each crop's growing season to determine spatially explicit, crop-specific irrigation water requirements (mm yr^{-1}) (Davis *et al* 2017b). These blue crop water requirements were then multiplied by their respective irrigated areas—and combined with estimates of local blue water consumption for other human activities (BWC) (i.e., municipal and industrial uses) (Hoekstra and Mekonnen 2012)—to determine total blue water consumption in each grid cell under current levels of crop production and under maximized crop production. Following Rosa *et al* (2018) we calculated the renewable blue water availability (BWA) using estimates of renewable blue water flow (Fekete *et al* 2002) and a flow accumulation algorithm (see section 2.3). Finally by combining estimates of the availability and consumption of renewable blue water resources (including both surface water and groundwater), we identified current and future areas of sustainable irrigation water consumption as those places where BWC < BWA.

2.1. Rainfed and irrigation water consumption assessment

We follow the methods in Davis *et al* (2017b) and Davis *et al* (2018) to calculate the crop water requirement at yield gap closure (see supplementary materials is available online at stacks.iop.org/ERL/13/104002/mmedia). A crop's water requirement is the amount of water needed by a crop to satisfy its evapotranspirative demand and to avoid a water-stressed condition. This demand can be satisfied by precipitation (i.e., green water) and supplemented through irrigation (i.e., blue water) if precipitation is insufficient. We considered 16 major crops (barley, cassava, groundnuts, maize, millet, oil palm, potatoes, rapeseed, rice, rye, sorghum, soybeans, sugar beet, sugar cane, sunflower, and wheat) which account for 73% of the planet's cultivated areas and 70% of global crop production (Food and Agricultural Organization of the United Nations 2017).

2.2. Current and yield gap closure water consumption

The current (year 2000) extent of crop-specific irrigated areas and planting and harvesting dates came from Portmann *et al* (2010). The current blue water consumption for a crop in a given pixel was then calculated as the product of the blue water requirement of that crop and its respective irrigated harvested area (Portmann *et al* 2010).

For each of the 16 major crops, we also calculated the additional volumes of blue water required to close the crop yield gap (i.e., to reach the maximum attainable yield) (Mueller *et al* 2012). In this yield gap closure scenario, given the uncertainty in determining where and to what extent cropping frequency can be increased through irrigation expansion, we assumed that current cropping practices will be implemented. This analysis was carried out for all cultivated lands around the world in which irrigation could substantially improve yields. In many humid areas where most of the crop water requirements can be met by precipitation, investments in irrigation infrastructures would not be justified by the modest increase in crop production induced by irrigation. Therefore, in these places we assume that farmers will likely continue to focus their efforts on rainfed agriculture. With this in mind, we assumed that a given crop and pixel will be irrigated under yield gap closure if the ratio between the blue and the total crop water requirements (units: mm yr^{-1}) was greater than a critical value of 0.10 (i.e., Blue Water/(Blue Water + Green Water) > 0.10) (Dell'Angelo *et al* 2018) (figure S1). This assumption is based on the rationale that in the wettest environments the development of irrigation infrastructure will not be economically justifiable given the marginal

Table 1. Sensitivity analysis of water consumption and harvested areas under yield potential scenario. We considered three ratios (0, 0.1, and 0.2) between the blue and the total crop water requirements (i.e., BW/(BW + GW)).

Ratio BW/(BW + GW)	WATER Irrigation (Rainfed) (km^3 per year)	LAND Irrigated (Rainfed) ($\times 10^6$ km^2)
0	1722 (6151)	9.66 (3.4)
0.1	1607 (6151)	7.35 (5.71)
0.2	1460 (6151)	5.29 (7.77)

increases in yield it would likely bring. We also used thresholds of 0.00 and 0.20 to examine the sensitivity of our results to this threshold assumption (table 1).

For each pixel (5 arcminute), current blue water consumption for irrigation was then summed with estimates of annual municipal and industrial freshwater consumption (Hoekstra and Mekonnen 2012) to determine the current total blue water consumption of humanity. This analysis was repeated for blue water consumption under yield gap closure—where we assumed constant consumption from municipal and industrial uses—to calculate the total blue water consumption of humanity under yield gap closure. The blue water consumption (BWC) of humanity at a 5 × 5 arcminute resolution was then aggregated to a 30 × 30 arcminute resolution, the resolution of the global renewable blue water availability (BWA) analysis (see following section of methods).

2.3. Renewable blue water availability

The global distribution of annual renewable BWA (at 30 arcminute resolution) was calculated following the methods by Mekonnen and Hoekstra (2016), whereby the value of BWA in a grid cell was expressed as the sum of the local BWA in that cell (BWA_{loc}) and the net blue water flow from the upstream grid cells defined as the local renewable water availability in the upstream cells (BWA_{up}) minus the blue water consumption BWC of human activities (i.e., agriculture, municipal, and industrial) in the upstream cells (BWC_{up}). Blue water consumption was calculated as explained in section 2.2 (see also supplementary materials). The net renewable blue water flows (combined surface and subsurface) were calculated using the upstream-downstream routing 'flow accumulation' function in ArcGIS®, where the subscript i denotes the cells upstream from the cell j under consideration:

$$BWA_j = BWA_{loc,j} + \sum_{i=1}^{n}(BWA_{up,i} - BWC_{up,i}). \quad (1)$$

Local renewable BWA (surface + groundwater) was calculated as the local blue water flows generated in that grid cell minus the environmental flow requirement. Local blue water flows are calculated in every grid cell as the difference between precipitation and evapotranspiration—using estimates by Fekete *et al*

(2002)—and therefore they account for surface and subsurface runoff generated in that cell as well as for aquifer recharge. We assumed that a fraction (y) of blue water flows is allocated to maintain environmental flows and that the remaining fraction ($1 - y$) is considered blue water locally available for human needs, BWA_{loc} (Pastor *et al* 2014, Steffen *et al* 2015). Environmental flow is defined as the minimum runoff that is required to sustain ecosystem functions. For irrigation to be sustainable, these minimum flow requirements need to be met even during dry season and low flow conditions (Richter *et al* 2012, Pastor *et al* 2014). Three flow regimes were considered: low, intermediate, and high corresponding to less than 25th percentile, between 25th and 75th percentile, and greater than 75th percentile of annual runoff, respectively (Rosa *et al* 2018). Following Steffen *et al* (2015) in each pixel the estimated blue water flow (Fekete *et al* 2002) was multiplied by the environmental flow fraction, y, associated with the corresponding flow regime (table S1, Pastor *et al* 2014) to calculate the environmental flows. Environmental flows were then subtracted from the local blue water flows to calculate the local BWA (BWA_{loc}). Thus, BWA_{loc} accounts only for renewable blue water resources that can be sustainably used for human activities and excludes both environmental flows and the (unsustainable) depletion of groundwater stocks.

To calculate the upstream to downstream water availability we used the flow direction raster (at 30 arc-minute resolution) from the World Water Development Report II (Vörösmarty *et al* 2000a, 2000b). Runoff estimates were obtained from the Composite Runoff V1.0 database (Fekete *et al* 2002). Finally, we defined unsustainable irrigation as occurring when BWC is equal to or exceeds BWA, a condition that would imply the depletion of either environmental flows or groundwater stocks (or both).

2.4. Calorie and protein production from cultivated lands

For each of the 16 crops, calorie and protein production under current (Monfreda *et al* 2008) and yield gap closure (Mueller *et al* 2012) scenarios were assessed as the product of the crop yield value (tonne ha^{-1}), the crop harvested area (ha) (Monfreda *et al* 2008), and the calorie or protein content (kcal $tonne^{-1}$; tonne protein $tonne^{-1}$). Caloric content for each crop was taken from D'Odorico *et al* (2014), and crop-specific protein content was assessed as the ratio of per capita protein supply (g protein cap^{-1} day^{-1}) to per capita food supply (g cap^{-1} day^{-1}) from FAOstat (Food and Agricultural Organization of the United Nations 2017) (table S2). The number of people that can be potentially fed was assessed according to a previous global average estimate of 3343 vegetal kcal cap^{-1} day^{-1} (Davis *et al* 2017b).

2.5. Uncertainties, limitations, and assumptions

Our results are based on the assumption that in the yield gap closure scenario a given crop and pixel will be irrigated if the ratio between the blue and the total crop water requirements is greater than a critical value of 0.10 (Dell'Angelo *et al* 2018). This assumption is based on the fact that, if blue water is needed to meet less than 10% of the crop water requirements, farmers will likely decide that the cost of improving irrigation systems will exceed the cost of reduced agricultural production from crops that are slightly water stressed. This ratio certainly depends on a host of factors including crop type, cost of irrigation infrastructure, access to water, farmer access to capital or credit, additional revenue from higher crop yields, market incentives, government policies, food needs, and interannual rainfall variability. The 10% threshold is here used as a conservative estimate, based on the fact that for major staple crops irrigation is found to be typically developed in areas in which green water consumption contributes to at most 80% of the total water consumption (i.e., irrigation infrastructure is found in areas where more than 10% of crop water requirements come from irrigation because it does not rain enough) (Rost *et al* 2008, Tuninetti *et al* 2015) (see table S7 for crop-specific values). Moreover, we found that the ratio between the blue and the total crop water requirements is less than 0.10 for only 6% (1.51×10^5 km^2) of currently irrigated lands (see table S7 for crop specific values of currently irrigated areas with a ratio $BW/(BW + GW) < 0.1$). We also performed a sensitivity analysis to analyze how our results would vary with different $BW/(BW + GW)$ threshold values and we found that there is only a modest ±10% change in blue water consumption in the yield gap closure scenario when this ratio is reduced to zero or increased to 0.20 (table 1). Thus our estimates of irrigation water use in the yield gap closure yield scenario are robust with respect to the assumption that irrigation is not performed in areas where rainfed agriculture undergoes a water deficit smaller than 10%.

Our assessment is based on temporal averages and does not account for interannual and seasonal variability in river discharge and crop water requirements. For example, some irrigated areas might only experience unsustainable irrigation water demand in dry years or during dry periods of the year (Brauman *et al* 2016). Our model considers only short-range transport (~50 km) of freshwater, without accounting for interbasin freshwater transfer projects like the South-to-North Water Diversion Project in China (Zhao *et al* 2017), the California State Water Project, and the Great Man Made River Project in Libya (Sternberg 2016). It also does not consider large water supply networks within the same basin that distribute water across hundreds of kilometers (at distances greater than the 50 km resolution of our model) such as the Nile and Indus basin channel networks. Moreover, because information on actual irrigation water use is limited, our model may produce instances where blue water demand in current irrigated lands cannot be fully met as a result of inadequate infrastructure or insufficient irrigation pumping capacity. The goal of this study is to provide biophysical estimates of crop water requirements that can be used to understand a farmer's average water needs. Our model also does not account for future potential changes in cropping frequency and crop types that could be enabled by additional irrigation infrastructure (Ray and Foley 2013, Rufin *et al* 2018).

Crop choice and cropping frequency are decisions primarily driven by economics, and farmers will likely decide to produce the most profitable crop under a change to irrigated conditions. Indeed, it remains difficult to estimate where and to what extent cropping frequency can be increased. Because we assume current cropping patterns and frequencies, our estimates of water consumption for certain areas may be conservative, as the expansion of irrigation may allow for an additional cropping season. On the other hand, our assumption of 100% yield potential in non-water-stressed conditions might overestimate water consumption under yield gap closure. Indeed, producers do not necessarily attempt to avoid water stress, but maximize their profit. This is usually not achieved by fully removing water and nutrient limitations to crop growth (i.e., maximum yield) because it may require an inefficient application of inputs (including water) that are not compensated by yield increases (Cassman 1999). Moreover, our biophysical model does not consider potential additional water demand from losses from irrigation infrastructure (e.g., losses from irrigation canals) and water use to control soil salinity. Future water consumption in agriculture will also be affected by climate change, which will alter both water availability and crop evapotranspiration (e.g., Katul *et al* 2012, Elliott *et al* 2014).

Lastly, the dataset on crop production under yield gap closure (Mueller *et al* 2012) relied on a statistical climate-binning approach to estimate the extent to which crop yields could be increased under improved management practices and inputs. Following the approach of Monfreda *et al* (2008)—the data we used to estimate current (circa 2000) crop production—Mueller *et al* (2012) developed gridded crop-specific maps of current crop yields and controlled for rainfall and temperature in order to develop yield distributions and estimate attainable yields. Because this yield gap closure dataset—which we also used here—relies on year 2000 yield data to estimate potential yields, it is likely that our estimates of potential crop production are conservative to a certain extent, as yields have been (slowly) increasing since the turn of the century because of new crop cultivars and improved management (Ray *et al* 2013), though, climate change could have a negative impact on potential yield growth in many regions of the world (Urban *et al* 2017).

3. Results

3.1. The status of current irrigation

We estimate that the current irrigation water consumption for major crop production is 847 $km^3\ yr^{-1}$ (table 2). This agrees well with previous estimates by Siebert and Döll (2010) (1180 $km^3\ yr^{-1}$) and Hoekstra and Mekonnen (2012) (899 $km^3\ yr^{-1}$). Our assessment shows that 40% of this volume of irrigation water is currently consumed at the expense of environmental flows (i.e., the minimum flows needed to sustain ecosystem functions in streams and rivers) (Jägermeyr *et al* 2017) or groundwater stocks. Not surprisingly, some of the world's major agricultural baskets such as the US High Plains and California's Central Valley, the North China Plain, the Murray-Darling Basin of Australia, and the Indo-Gangetic Basin consistently exhibit unsustainable water use, where blue water consumption exceeds its local availability (see figure 1(a)). In these regions, irrigation is depleting groundwater stocks (Konikow and Kendy 2005, Wada *et al* 2010, Gleeson *et al* 2012, Scanlon *et al* 2012, Famiglietti 2014, Rodell *et al* 2018) and diminishing environmental flows (Brauman *et al* 2016, Mekonnen and Hoekstra 2016, Jägermeyr *et al* 2017).

3.2. Sustainable yield gap closure through irrigation

To enhance crop yields, irrigation will need to expand into primarily rainfed agricultural areas where productivity is constrained by access to water resources. Investments in irrigation infrastructure, however, can only be justified if they induce a substantial increase in production, a condition that can be expressed by ratios between irrigation water and total water requirements greater than a critical value, typically taken equal to 0.10 (Dell'Angelo *et al* 2018). We estimate that this condition is met in 44% (i.e., $4.53 \times 10^6\ km^2$) of the cultivated lands currently used for rainfed agriculture (figure 1). To expand and intensify irrigation over these lands, global blue water consumption for agriculture would need to increase by 760 $km^3\ yr^{-1}$. Doing so would enhance global food calorie production by 54% (5.00×10^{15} kcal yr^{-1})—consistent with earlier estimates (Foley *et al* 2011)—and increase vegetal protein production by 51% (121×10^6 tonnes yr^{-1}) (table 2, table S3).

In many places, however, these irrigation water requirements and the associated increases in food production can be sustainably met without depleting environmental flows and groundwater stocks. For only those rainfed areas with adequate freshwater resources, sustainable irrigation expansion would require an additional 408 $km^3\ yr^{-1}$. Though more limited in extent, this sustainable yield gap closure would still realize large increases in calorie (+37%, or 3.38×10^{15} kcal yr^{-1}) and protein (+34%, or 82×10^6 tonnes protein yr^{-1}) production—enough to feed an additional 2.77 billion people. Overall, this

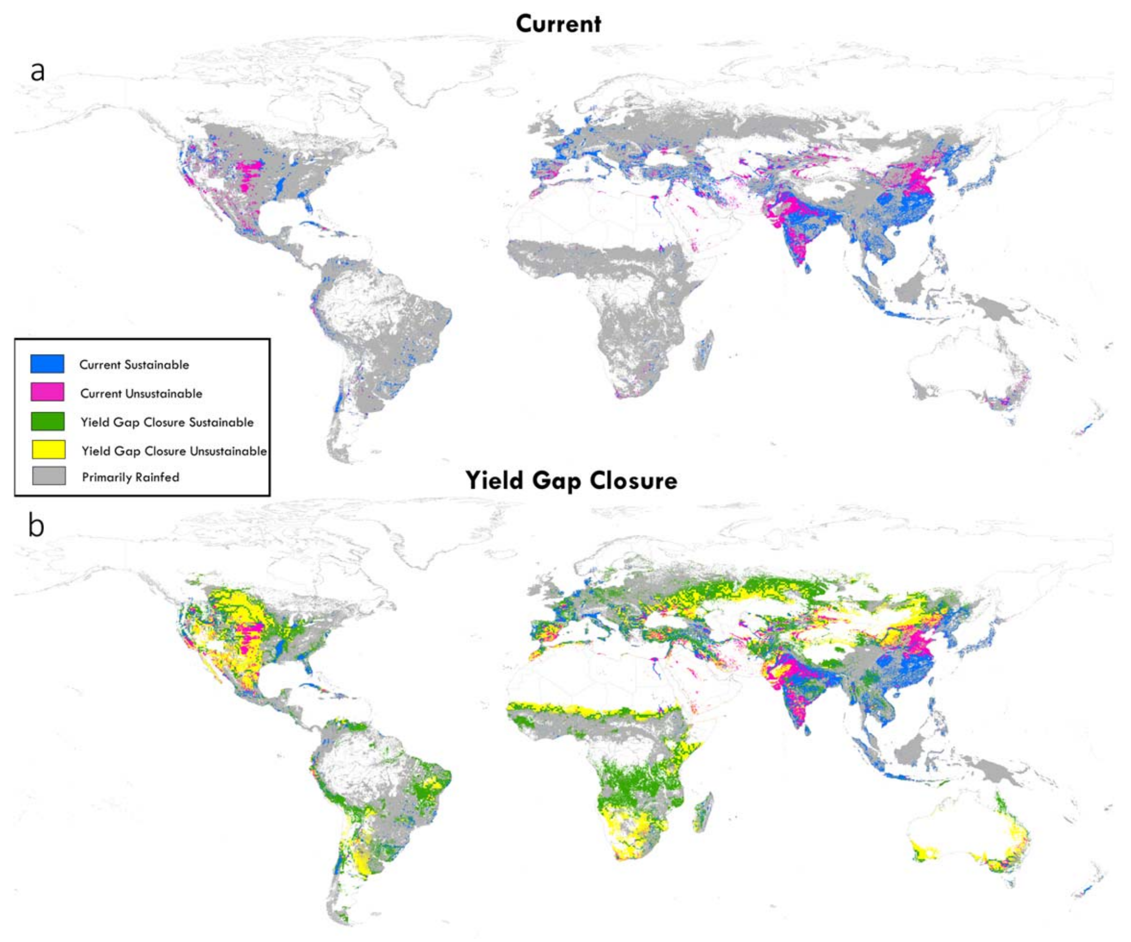

Figure 1. The extent of sustainable irrigation over cultivated lands. We define sustainable irrigation when water consumption for human activities remains below the limit imposed by environmental flow requirements (BWC < BWA). Blue (fuchsia) areas represent sustainable (unsustainable) irrigation water consumption over current (year 2000) irrigated lands. In the yield gap closure scenario green (yellow) areas show the potential for the sustainable (unsustainable) expansion and intensification of irrigation water consumption over currently underperforming cultivated lands (rainfed or irrigated). For current production, unsustainable irrigation consumption occurs on 40% of irrigated lands (1.13×10^6 km^2). In the yield gap closure scenario we estimate that irrigation needs to be expanded by 4.53×10^6 km^2 and that only half (56%) of this additional area has the potential for sustainable crop yield gap closure (see table 2).

Table 2. Water consumption, irrigated extent, and calorie production under current and yield potential scenarios. Sustainable irrigation is practiced in areas where BWC does not exceed renewable BWA, which accounts also for environmental flows. Irrigation is 'unsustainable' when BWC $\geqslant$ BWA (i.e., it sacrifices environmental flows, requires non-renewable groundwater resources, or interbasin water transport). Values in parentheses correspond to rainfed croplands.

	WATER Irrigation (Rainfed) (km^3 per year)	LAND Irrigated (Rainfed) ($\times 10^6$ km^2)	CALORIES Irrigated (Rainfed) ($\times 10^{15}$ kcal per year)
Current			
Sustainable	511	1.69	1.69
Unsustainable	336	1.13	1.19
Total current	847 (6151)	2.82 (10.24)	2.88 (6.35)
Additional at yield gap closure			
Sustainable (expansion of irrigation)	336	2.67	2.33
Sustainable (intensification of irrigation)	72	−0.14	1.05
Unsustainable (expansion of irrigation)	261	1.86	0.91
Unsustainable (intensification of irrigation)	91	0.14	0.71
Total yield gap closure	1607 (6151)	7.35 (5.71)	7.88 (6.35)

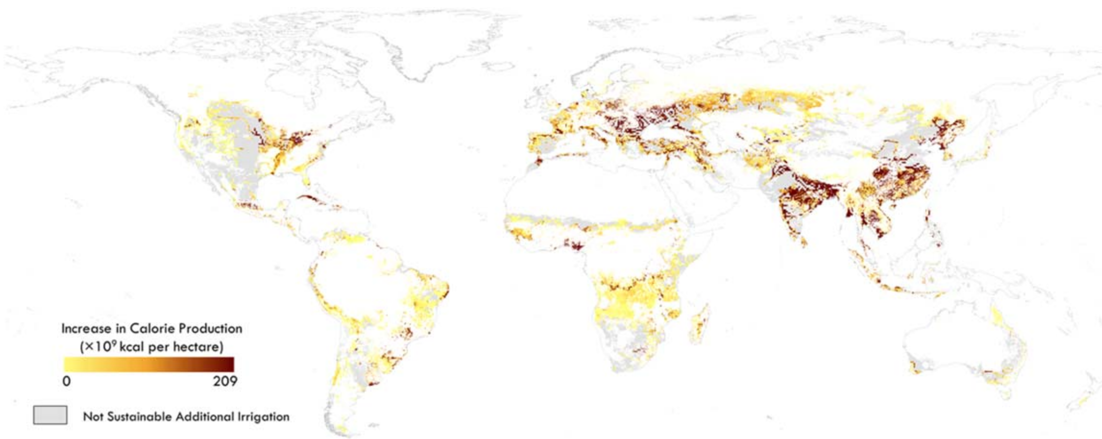

Figure 2. Sustainable increases in calorie production. The map represents the additional calories that can be produced through sustainable irrigation intensification (blue areas where additional irrigation is sustainable in figure 1) and expansion (green areas in figure 1). These additional calories would be enough to feed 2.77 billion more people.

means that 54% of the water needed to expand and intensify irrigation and 68% of the associated increase in calorie and protein production could be attained sustainably within the limits of renewable BWA (table 2). In this scenario of sustainable yield gap closure, half of the calorie production would rely on irrigation water. In addition, we find that opportunities to close the yield gap by sustainably expanding irrigation exist only in 26% of currently rainfed cultivated lands (green areas in figure 1(b)). Maximizing yields by sustainably expanding irrigation into these primarily rainfed lands (as opposed to intensifying irrigation in currently irrigated croplands) would require 82% of the sustainable additional blue water consumption, while contributing to 69% of the potential increase in calorie and protein production (table 2; table S3).

If current unsustainable blue water consumption (336 km^3 yr^{-1}) and crop production (1.19×10^{15} kcal yr^{-1}) practices were eliminated, sustainable irrigation expansion and intensification (336 km^3 yr^{-1} and 72 km^3 yr^{-1}, respectively) would still enable a substantial net increase in sustainable calorie (+24%, or 2.19×10^{15} kcal yr^{-1}) and protein (+22%, or 53×10^6 tonnes protein yr^{-1}) production (table 2). In this scenario, total sustainable blue water consumption for irrigation would reach 919 km^3 yr^{-1} (551 km^3 yr^{-1} from current irrigation with additional 408 km^3 yr^{-1} from irrigation intensification and expansion). Moreover, an intensification of irrigation over currently irrigated lands would shift 0.14×10^6 km^2 of irrigated croplands from sustainable to unsustainable water consumption practices.

Under sustainable yield gap closure, we found at least a doubling of calorie production for 50 countries, 29 of which are in Africa (e.g., Nigeria, Ethiopia, Eritrea, Democratic Republic of Congo, Tanzania, and Mozambique) (figure 2). We also found at least a doubling of protein production for 54 countries—most of which occur in the developing world (examples include 30 African countries, Mongolia, Cambodia, and Afghanistan) (table S3 and S6). Collectively, China, the United States, India, Russia, Brazil, and Nigeria can contribute to about 46% of the global increase in food calorie production associated with the sustainable intensification and expansion of irrigation (figure 3). China, the world's top food calorie producer, has the greatest potential to sustainably increase crop production by intensifying and expanding irrigation, thereby feeding an additional 382 million people. India and Russia also have great opportunities to sustainably increase calorie production to feed 261 and 222 million people, respectively (figure 3). Africa, currently only sparsely irrigated (Burney *et al* 2013), currently produces enough calories to feed 400 million people—making it the continent with the largest gap between crop production and demand (van Ittersum *et al* 2016). An increase in yields through investments in irrigation expansion could sustainably feed an additional 450 million people and substantially reduce the continent's dependence on food imports.

Sustainable irrigation could increase national food self-sufficiency in countries that today meet large fractions of their domestic food demand through international trade (D'Odorico *et al* 2014). For example, net food importing countries (such as Mexico, Iran, Germany and Italy), would experience a greater than 15% increase in calorie production. This in turn could reduce their exposure to economic and environmental shocks to the global food system that occur beyond their borders (Suweis *et al* 2015, Oki *et al* 2017).

4. Discussion

Our study identifies where and to what extent crop production can be sustainably intensified through irrigation expansion in currently cultivated lands without inducing major losses of aquatic habitat, groundwater depletion, or changes in other (nonagricultural) water uses. This increase in food production

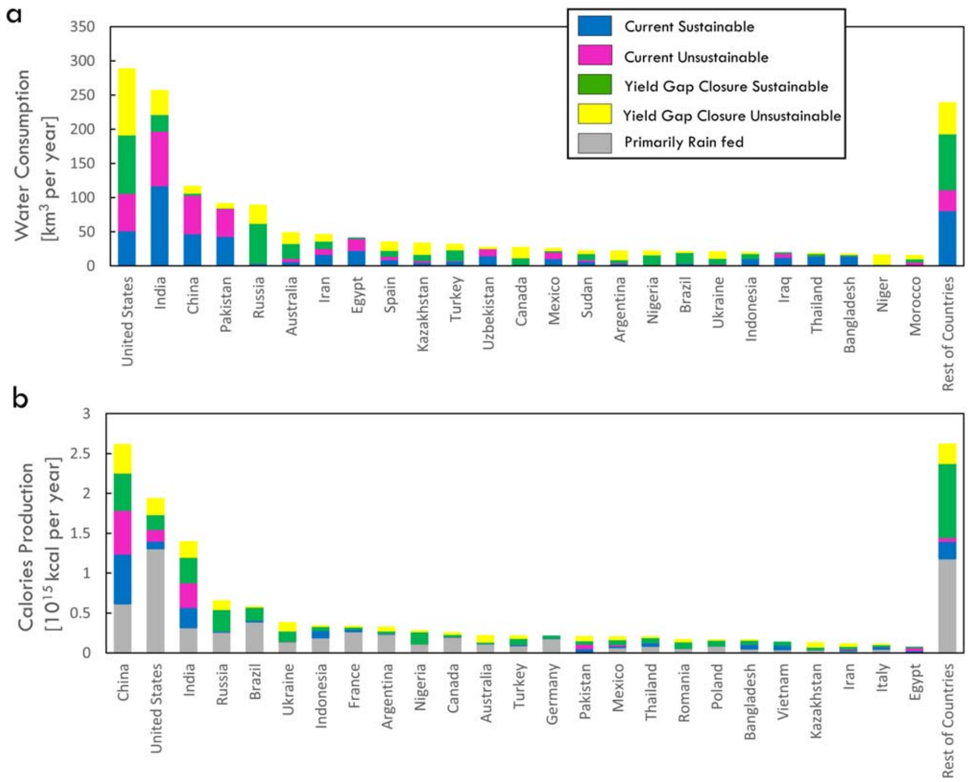

Figure 3. Potential increases in freshwater demand and calorie production. Panels show the extent to which (a) irrigation water consumption, and (b) calorie production can sustainably occur under current and maximized levels of crop production. Note that countries are listed in descending order based on potential irrigation water consumption, and calorie production at yield gap closure, respectively. Detailed country-specific values for irrigation water consumption and calorie and protein production values are shown in supplementary tables S4–S6.

Table 3. Planetary boundary of freshwater, current and projected blue water consumptions. Planetary boundary of freshwater is defined as the consumptive water left to be used for human activities (Rockström *et al* 2009).

	Blue water (km^3 per year)	Source
Planetary boundary of freshwater	1100–4500	Gerten *et al* (2013)
Current total blue water consumption	1800–2270	Shiklomanov and Rodda (2004) Hanasaki *et al* (2010) Wada *et al* (2011)
Blue water consumption for irrigation		
Current	847	This study
Additional for sustainable yield gap closure	408	

would also aid in minimizing the expansion of agriculture into land that is presently not cultivated, thereby avoiding human appropriation of water resources (both green and blue) that are currently used by natural systems.

In the case of irrigation intensification and expansion, the current dominance of rainfed calorie production would be superseded by irrigated production (table 2). However, the green water volumes would remain almost four times greater than those of irrigation water consumption, showing not only the huge water savings potential from making green water more productive in agriculture (Rockström *et al* 2009, Molden *et al* 2010, Davis *et al* 2017b) but also the importance of green water in global food production and international food trade (Aldaya *et al* 2010).

An increase in irrigation would also draw humanity closer to the planetary boundary for freshwater (Rockström *et al* 2009), estimated to be on average 2800 $km^3\ yr^{-1}$ of freshwater (with a range of uncertainty estimated to be between 1110 and 4500 $km^3\ yr^{-1}$) (table 3) (Gerten *et al* 2013). With current (1995 to 2000 period) blue water consumption estimated to be around 1800–2270 $km^3\ yr^{-1}$ (Shiklomanov and Rodda 2004, Hanasaki *et al* 2010, Wada *et al* 2011), a sustainable expansion and intensification of irrigation would require an additional 408 $km^3\ yr^{-1}$ of freshwater, and may in some places increase competition for freshwater resources with other human activities, such as the industrial and energy sectors (Rosa *et al* 2017, Chiarelli *et al* 2018, D'Odorico *et al* 2018, Rosa *et al* 2018). Therefore, there is an urgent need to adopt water conservation strategies (Rost *et al* 2009, Jägermeyr *et al* 2016, Davis *et al* 2017b, Davis *et al* 2018) and to reassess where irrigated agriculture currently occurs (figure 1(a))—especially in water-stressed areas—in tandem with sustainable irrigation expansion in order to increase the water productivity of food systems.

Our biophysical modeling results show that if current unsustainable blue water consumption and production practices were eliminated, sustainable irrigation expansion and intensification would still enable a net increase in food production while keeping a safe distance from the planetary boundary for freshwater, restoring environmental flows, and reducing reliance on irrigation from non-renewable freshwater resources. Our results show that targeted policy and farming decisions could achieve important reductions in unsustainable irrigation demand in many regions of the world, while sustainably increasing calorie production of 24% globally.

However, additional irrigation infrastructure availability needs to be accompanied by other changes in management practices in order to achieve maximum yields. Indeed, Mueller *et al* (2012) showed that in many regions of the world achieving yield gap closure requires an improvement in nutrient supply through fertilizer application. Other practices that might be changed in response to the expansion of irrigation infrastructure are a switch to crops with higher productivity, the introduction of an additional cropping season, or the storage of water from the rainy to allow for its use during the dry seasons.

While the sustainable irrigation yield gap closure scenario investigated in this study accounts for the need to protect environmental flows that are crucial to the health of freshwater ecosystems, it does not evaluate other environmental and economic impacts associated with the irrigation of cultivated lands (e.g., changes in microclimate, habitat, and land use (Sacks *et al* 2009), energy costs and associated greenhouse emissions (Burney *et al* 2010), and infrastructure development (Blanc and Strobl 2013)) which require further investigation. Future research is also required to analyze in which areas additional irrigation water can exacerbate water stress and intensify a competition for water between food and energy production (Scanlon *et al* 2017, Rosa *et al* 2018). Our results are based on a biophysical model and on assumptions that are always necessary in any global modeling study. There are many factors that our model cannot predict (change in cropping patterns and harvest frequencies, rates of yield increase, rates of implementation of expanded irrigation, the influence of climate change, and changes in management practices such as improved fertilizer application) that depend on economic, institutional, and other non-biophysical factors that will need to be examined in much greater depth in future studies.

Ultimately, while the biophysical capacity of irrigation expansion to increase food production is an essential consideration, this is only one of the factors that influence governments' decisions to invest in agricultural infrastructure. Our results show that there is a great potential for the sustainable expansion of irrigation infrastructure in China, India, and Iran among many other places (figure 1). This study does not however account for socioeconomic factors that will determine whether irrigation expansion will occur and to what extent it will change cropping practices (e.g., the use of multiple cropping seasons, their length, and type of crops). For example, in India irrigation water use and crop choice is largely driven by state-level economic incentives (Davis *et al* 2018) and states with very similar climates and water availability may have very different irrigation water demands. Targeted, location-specific analyses are therefore required to fully understand the potential for sustainable irrigation expansion to meet future food demand.

5. Conclusions

This study investigated the extent to which irrigation can be expanded within presently rainfed cultivated lands without depleting environmental flows. This question is central to the debate on water use in agriculture, food security, and sustainability policies. Our analysis shows where and whether available freshwater resources can accommodate a sustainable increase in irrigation for crop production. A sustainable expansion of irrigation into cultivated areas that are presently rainfed would allow for major increases (+37%) in food production (table 2). Our results also confirm previous literature findings about the urgent need to adopt water management strategies to restore environmental flows and reduce the reliance on irrigation from non-renewable freshwater resources. Our results show that adequate and informed investments in irrigation infrastructure can help to feed billions more people, avoid agricultural expansion into natural habitats, and safeguard local boundaries of freshwater allocation for human and natural systems. In addition to investments, comprehensive policies that support the construction and maintenance of irrigation infrastructure and that implement monitoring systems for responsible and transparent water use will be essential. By examining food demand and resource availability together, our approach establishes a framework to assess the water sustainability of future crop production decisions in the coming decades.

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Author contributions

LR and PD conceived the study, LR, KFD, MCR, and PD designed the research; LR performed the research, collected, and analyzed the data; LR, MCR, DC, and CP carried out the simulation to assess water consumption on cultivated lands; and all authors wrote the paper.

Conflict of interest

The authors declare no conflict of interest.

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