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Water limits to closing yield gaps

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ABSTRACT

Agricultural intensification is often seen as a suitable approach to meet the growing demand for agricultural products and improve food security. It typically entails the use of fertilizers, new cultivars, irrigation, and other modern technology. In regions of the world affected by seasonal or chronic water scarcity, yield gap closure is strongly dependent on irrigation (blue water). Global yield gap assessments have often ignored whether the water required to close the yield gap is locally available. Here we perform a gridded global analysis (10 km resolution) of the blue water consumption that is needed annually to close the yield gap worldwide and evaluate the associated pressure on renewable freshwater resources. We find that, to close the yield gap, human appropriation of freshwater resources for irrigation would have to increase at least by 146%. Most study countries would experience at least a doubling in blue water requirement, with 71% of the additional blue water being required by only four crops – maize, rice, soybeans, and wheat. Further, in some countries (e.g., Algeria, Morocco, Syria, Tunisia, and Yemen) the total volume of blue water required for yield gap closure would exceed sustainable levels of freshwater consumption (i.e., 40% of total renewable surface and groundwater resources).

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1. Introduction

Agriculture is among the most environmentally impactful human activities. More than one third of the world's land surface is used for croplands or pastures (FAO, 2016b). Approximately 80% of humanity's consumptive water use is for growing crops (Falkenmark and Rockström, 2004). In addition, the use of fertilizers has roughly doubled the planet's available reactive nitrogen (Schlesinger, 2008). Moreover, farming practices typically entail substantial soil losses (e.g., Montgomery, 2007). Yet despite the rapid increases in crop production that these natural resources have supported over the past 50 years, many cultivated areas remain underproductive and have the potential to realize large increases in crop yields given additional inputs of fertilizer and irrigation water. With population growth and dietary changes expected to increase human food demand by 70%–120% by mid-century (Kastner et al., 2012; Ray et al., 2013), improving crop yields is among the most promising approaches for meeting future demand (Foley et al., 2011; Mueller et al., 2012). Indeed, re-

cent work has shown that by maximizing crop yields alone it is possible to feed an additional 2 to 3 billion people (Davis et al., 2014b). Although this is reassuring from a food security perspective, the large amount of resources required for current and future food production have led to recent calls for the 'sustainable intensification' of agriculture (Tilman et al., 2011; Garnett et al. 2013) – a concept that seeks to increase yields on existing croplands while simultaneously minimizing the environmental impacts of agriculture.

The proposition of defining what is 'sustainable' is a tenuous one. While certain agricultural resources (e.g. fertilizers, pesticides) can be traded, other resources like water and arable land remain heterogeneously distributed. As a result, some countries have adequate resources to support their populations while others must rely on food trade to meet demand (Allan, 1998; Hoekstra and Hung, 2005; D' et al., 2014). However, as growth in human demand continues, some countries in surplus may find that their domestic agricultural resources have become inadequate for continued self-sufficiency (Suweis et al., 2013; Fader et al., 2013) regardless of the level of intensification that can occur. Conversely, countries with relatively low demographic growth and sufficient arable land may find that they can increase their food self-sufficiency through

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intensification (e.g., Davis et al., 2015). In any case, determining the natural resources required for a country to maximize crop yields provides a tangible upper limit within which to begin the discussion surrounding a nation's sustainability.

Yield gap closure is typically achieved by applying industrial fertilizers and irrigation water. While the use of fertilizers and new cultivars are often limited by economic and environmental costs, the development of irrigation infrastructures also requires the availability of adequate (blue) water resources. With such geographic limitations in mind, we sought to address several questions in this study. First, how much water is required to close the yield gap in different countries around the world? Also, is that water locally available in each of these countries? And finally, to what extent would the increased use of irrigation induce or enhance water stress in those countries? To date little work has been done to quantify the impact of increased crop production on the water resources required to support intensification. Indeed, most estimates of yield gap closure do not account for inherent limitations to agricultural intensification resulting from water scarcity. We argue that in some regions of the world the available freshwater resources are simply not sufficient to sustain the demand for irrigation water required to close the yield gap. To this end, we focus on countries identified as having crop yields that are presently water-limited (Mueller et al., 2012). Using a crop water model, we calculate the additional irrigation (blue) water required to maximize crop production (i.e. close yield gaps) and compare this volume to estimates of each country's available renewable freshwater resources. In doing so, we examine whether adequate resources are locally available to support such an increase in crop production and, if so, whether the potential consequences of that additional resource use would be an acceptable trade-off for that country.

2. Methods

To start, we clearly state that this study examined consumptive water use through crop irrigation. We considered 14 major crops (Table A1) – covering 71% of the planet's cultivated area and accounting for 66% of global crop production (FAO, 2016b). Country-specific information on the extent to which crop yields are expected to increase in an irrigated agriculture scenario is available for six of these crops: barley, maize, oil palm, rice, sugarcane and wheat (Mueller et al., 2012). Sixty-six countries (Table A1) were identified by Mueller et al., (2012) as having irrigation-limited yields for at least one of these crops. If water limitation was reported for one of these 6 crops (excluding rice), we assumed that this water limitation would also affect the remaining 8 crops grown in the country of interest, as the purpose of this analysis is to identify countries in which water limitations may exist. Crop yield data came from Mueller et al., (2012) for current scenario (circa year 2000) as well as when closing the yield gap to 90% of maximum attainable yields. If a crop in a given country had already reached $\geq 90\%$ of its maximum attainable yield, we did not include this crop, as this study's focus was on the additional irrigation water required to close the yield gap.

For current cultivated areas only (IIASA/FAO, 2012), we estimated crop water requirement (CWR) every 10 km with the FAO's Cropwat 8.0 model (FAO, 2009b) for the time period 1996 to 2005 to allow for comparisons with other recent studies (e.g., Mekonnen and Hoekstra, 2011). Because of the large number of points involved in our calculations, the Cropwat model was automated and run for all grid cells within the currently cultivated lands of the study countries (IIASA/FAO, 2012). At each point, we determined soil type using the FAO's Harmonized World Soil database (FAO, 2012); if more than one soil type occupied the 10 km resolution of analysis, we selected the soil type occupying the largest percentage of the area. For consistency, all climatic and meteorological

data (precipitation, maximum and minimum temperatures, wind speed, relative humidity and hours of sunshine) were taken from the Climwat 2.0 station (FAO, 2009a) closest to each grid point. The dataset reports climatic and meteorological data for over 5000 stations around the world for the period 1971–2000, which is representative for the study period we analyzed. Crop data – crop coefficient (K_c), growing stage, and planting schedule – came from Chapagain and Hoekstra (2004a, b) and FAO (2016). The sensitivity of these model calculations to changes in planting date, length of the growing season and other model parameters depends on crop type and has been thoroughly assessed in recent work by Tuninetti et al., (2015). We then averaged the CWRs calculated at each of these points to determine the national CWR for a given crop. Because this model does not account for losses of irrigation water due to runoff and drainage (which depend on the irrigation technique and soil management), our estimates of the additional pressure placed by the enhancement/development of irrigation on the local renewable freshwater resources are conservative. Thus this analysis focuses only on consumptive water uses, which are independent of the irrigation technique. The way such consumptive water uses are partitioned into productive water losses (i.e., transpiration) and unproductive soil evaporation (which can be substantial; see e.g., Chukalla et al., 2015), of course depends on the irrigation technique. In this study, however, we do not distinguish between productive and unproductive losses of irrigation water.

As an output, the Cropwat model gives the CWR ($\text{m}^3 \text{H}_2\text{O ha}^{-1} \text{yr}^{-1}$), partitioned into precipitation (i.e. green water) and irrigation (i.e. blue water). Required blue water is simply the additional water (after accounting for precipitation's runoff, deep percolation and productive use) required to keep soil moisture levels above a crop's wilting point. Because this study was only concerned with consumptive irrigation water use, we do not evaluate the grey water footprint (i.e. the amount of water required to dilute concentrated nutrient runoff to an acceptable or standard level). After determining the average CWR for each irrigation-limited crop, the total volume of blue water BW ($\text{m}^3 \text{H}_2\text{O yr}^{-1}$) required in each country – either with current yields or with yield gap closure – was calculated as:

$$BW = \sum (r_i * l_i * CWR_{blue,i} * A_{cult,i})$$

where r_i is the fraction of cultivated area equipped for irrigation (FAO, 2016a), l_i is the fraction of area equipped for irrigation that is actually irrigated (FAO, 2016a), $CWR_{blue,i}$ is the irrigation water requirement for crop i , and $A_{cult,i}$ is the harvested area for crop i . Due to missing data and differences in reporting years, r_i and l_i were necessarily calculated in different ways for the current irrigation situation. r_i was calculated as the average of three time periods (1993–1997, 1998–2002, 2003–2007), and l_i was the value with the reporting year closest to the 1996–2005 time period of this study (Table A2). Also due to data limitations, r_i and l_i were assumed to be the same for all crops. This calculation is limited to a certain extent as r and l are not reported as a crop-specific value. Thus, our study necessarily assumed that irrigated area was proportionally distributed amongst the crops considered here. Under yield gap closure, we assume $r_i = 1$ and $l_i = 1$ for all crops.

Lastly, following Fader et al., (2013), available freshwater resources (ARWR) in each country were calculated as 40% of the country's total renewable freshwater resources (RWR) (FAO, 2016a); the remaining 60% is assumed to be necessary for maintaining environmental flows. While this national-scale comparison ensures that our estimates of water stress are conservative, this approach is limited to a certain extent as we do not consider the timing and spatial distribution of water availability and crop water demand throughout the year.

Table 1
Major human appropriations of freshwater resources.

	Annual flow ($\text{m}^3 \text{ yr}^{-1}$)	Year	Source
Additional irrigation water for yield gap closure	1.31×10^{12}	2000	This study
Irrigation water used for current agricultural production	0.90×10^{12}	1996–2005	Hoekstra and Mekonnen (2012)
Groundwater used for irrigation	0.54×10^{12}	2000–2010	Siebert et al. (2010)
Virtual blue water associated with agricultural trade	0.28×10^{12}	1996–2005	Mekonnen and Hoekstra (2011)

Fig. 1. Blue water demand for current crop production and crop production at yield gap closure. Countries are ordered from left to right based on the additional volume of irrigation water required for yield gap closure.

3. Results

We estimate that the water-limited countries considered here will require 1315 km^3 of additional consumptive irrigation water use to close the crop yield gap. This volume is comparable in magnitude to several other important water uses associated with the global food system (Table 1). In particular, this additional required water would mean a 146% increase over the current blue water requirement for global crop production (Hoekstra and Mekonnen, 2012) and a 4.9-fold increase for the study countries. Alone, six countries – the United States, India, China, Nigeria, Australia, and Brazil – comprise 68% of this increased demand (Fig. 1; Table A3). While nearly all countries would experience at least a doubling in blue water requirement, several countries would not experience such dramatic increases – a result of either a high fraction of current crop water demand met by irrigation (e.g., Pakistan, Tajikistan) or an ability to continue relying largely on green water supply (e.g., Azerbaijan) (Table A3).

In addition, we find that enhancing the yields of certain crops will contribute disproportionately to the increase in blue water demand. We estimate that 71% of the required blue water at yield gap closure will be for only four crops – maize, rice, soybeans, and wheat – in large part because these crops are some of the most extensively cultivated (Table A4). In particular, countries seeking to enhance rice yields (e.g., China, India, Pakistan) will require large volumes of additional blue water (Table A3).

Finally, to evaluate the impact of yield gap closure on freshwater systems, we compared current and future blue water demand to the renewable freshwater resources available in each country. Presently in Yemen, blue water appropriation for crop production exceeds available freshwater resources (Fig. 2a). As such, the existing freshwater resources are not sufficient to sustain yield gap closure through enhanced irrigation, unless the country rely on groundwater mining or desalination. For five countries – Algeria, Morocco, Syria, Tunisia, and Yemen – we found that local water resources will be insufficient to support complete yield gap closure under current technologies. Further, many more countries will experience substantial increases in pressure on water resources if they close yield gaps domestically (Fig. 2b). These results highlight how, because of the heterogeneous distribution of freshwater resources, the impact of yield gap closure on water stress will vary across different regions of the world (e.g., more evident in North Africa and the Middle East).

Lastly, these results are conservative for several reasons. First, our approach only accounts for crop water requirements and does not include direct evaporative losses from the field, irrigation ponds and irrigation ditches. Second, we only consider crops in irrigation-limited countries; countries with yield gaps that are nutrient-limited will still likely require large additional volumes of irrigation water to enhance crop yields. Third, altered precipitation patterns, elevated temperatures, and increased frequency of extreme events (e.g., drought) are all anticipated under future

Fig. 2. Ratio of blue water demand to AWR. Ratio is shown for (a) current levels of crop production and (b) production if crop yields are maximized using current irrigation technologies. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

climate change, which may increase crop stress and lead to greater irrigation inputs to meet crop water requirements. Fourth, our calculation of current irrigation water demand (including consumptive water losses only and without accounting for the entire amount of water withdrawals for irrigation) is likely high to a certain extent, as irrigated areas – represented by variables ri and li – may undergo periods during which available surface and groundwater resources are insufficient to meet CWR (Mekonnen and Hoeksma, 2011).

4. Discussion

Our results clearly show that closing crop yield gaps through irrigation will result in unsustainable water demands given the current distribution of technologies and cropping practices. Thus while closing yield gaps locally can increase the food self-sufficiency (i.e., the ratio of domestic crop production to local demand) of a country and reduce its reliance on imports, doing so will likely entail significant environmental tradeoffs as well as increased competition for water use with other sectors (e.g., energy),

and may still fall short of domestic food demand (e.g., Davis et al., 2015). From our study, it also appears that diminishing returns on water use may also occur in the near future, where many places will require large volumes of water to realize a relatively small gain in crop productivity. Specifically for the countries studied here, we found that blue water demand will more than triple (Fig. 1) while closing the yield gap to within 90% of maximum attainable yields will lead to a 42% increase in crop production (Mueller et al., 2012). A similar trend has already been observed for nitrogen use in cereal production (Tilman et al., 2002; FAO, 2016b). The potential for declining water productivity portends yet greater reliance by many countries on food imports in the coming decades (Fader et al., 2013) and suggests that many countries will likely need to adopt policies aimed at maximizing water productivity as opposed to closing yield gaps.

Indeed, many places have the possibility to greatly increase water productivity and in turn substantially reduce water stress resulting from crop production. A recent study by Jägermeyr et al., (2016) quantified this synergy, showing that – through transitions towards more efficient sprinkler and drip irrigation

systems – it is possible to increase calorie production by 26% while simultaneously reducing non-productive water consumption by 48%. In addition, numerous other studies (Sinclair and Muchow, 2001; Hamdy et al., 2003; Zwart and Bastiaanssen, 2004; Passioura, 2006; Ali and Talukder, 2008; Chukalla et al., 2015) have examined the potential for reductions in water requirement through techniques such as shifting planting dates and modified tillage practices and crop traits. All of these solutions offer promise for minimizing the consumptive water demand of future food production and are especially important for areas experiencing chronic groundwater depletion (e.g., California; India) and unsustainable surface water use (e.g., Colorado River; Murray-Darling Basin). While promising, efforts to do so would require considerable capital to be realized and should ensure that any investment does not jeopardize local livelihoods or the environment (Rulli et al., 2013; D'Odorico and Rulli, 2013, 2014; Davis et al., 2014a).

Several recent studies have also examined consumer-side solutions, showing that it is possible to modify diets towards less water-demanding choices and, as a result, feed more people with the same amount of water resources (Davis et al., 2014b, 2016 Jalava et al., 2014; Gephart et al., 2016). One way to effect these consumer-side changes is through influencing individual consumer behaviors through public awareness and food labeling schemes (e.g., Leach et al., 2016). There are also economic solutions that incorporate the true environmental cost of producing a food item or that allow the market to set the price (e.g., carbon tax vs. car-

bon credits). For instance, in areas of water scarcity, water markets have provided an effective mechanism for allocating and capping water use (Debaere et al., 2014).

The solutions summarized here require greater attention and urgency from policy makers, as water scarcity has already been shown to have important social and political consequences (e.g., Kelley et al., 2015). Future analyses should also focus on watershed scales at monthly intervals to assess in greater detail when and where water stress from yield gap closure may occur and to prioritize areas where irrigation improvements can sustainably occur (e.g., Braumann et al., 2016).

5. Conclusions

The lack of adequate irrigation infrastructure currently imposes limits on crop yields. Our study showed that enhancing crop yields through irrigation will require large volumes of additional irrigation water. Further, we demonstrated that available freshwater resources will likely be insufficient in many countries to sustainably close crop yield gaps under the current assortment and distribution of irrigation technology. Various solutions already exist that can help countries to conserve water resources and better meet future food demand, but only if concerted efforts are made towards sustainable production and consumption.

Appendix

Table A1

Irrigation crop water requirement by crop and by country [mm]. Crops are abbreviated as follows: B-Barley, G-Groundnut, M-Maize, ML-Millet, O-Oilpalm, P-Potato, RA-Rapeseed, R-Rice, RY-Rye, SO-Sorghum, SY-soybean, SC-Sugarcane, SF-Sunflower, W-Wheat. Empty cells indicate that a crop is not grown in a particular country. Values of 0 indicate that irrigation is not needed.

Country	B	G	M	ML	O	P	RA	R	RY	SG	SY	SC	SF	W
Afghanistan	309			641		884								333
Algeria	349	564				685	570			427				357
Angola		324	354	266		354						768	220	
Argentina		118	122	132		115	175		115	126		436		251
Armenia	84					311			387					
Australia	469	256		282			282		317	287	217	1137	271	543
Azerbaijan	0					289			319		296		267	0
Belarus						83	77		161				102	
Bolivia		145	102			131					115	384	79	
Brazil		128	175			126		353		164	109	492		
Bulgaria		176	228	248		256	220		270	163	267		230	82
Burkina Faso		260	147	86		310				109	230			
China	234	107	142			140		226	220	254	173	337	198	237
Congo		96			66	66						203		
Croatia			283			265	239		268	223	316		93	
DRC		85	0	0	76	64				0	79	171		
Ecuador		108			434	127		227		145	337	521	226	159
El Salvador		354	0							0	240	149	261	
Eritrea	873	479		383		695				367				
Ethiopia	379	340	171	128		407			416	145				422
Finland							0		76					
France						168			98		179			
Georgia			239			241			286		295		268	
Germany											116			
Ghana		293	128	75	494					70		475		
Guatemala		241	0							0				
Guinea		482		0	968					79				
Honduras		342				412		407	19	0	241	313		
Hungary			115	0		178	125		170	0	154		90	
India		219	166	115		294	274	292		122	220	758	256	396
Indonesia			120		243	169		36			111	177		
Iran	367	620		585		825					821	1311	658	374

(continued on next page)

Table A1 (continued)

Country	B	G	M	ML	O	P	RA	R	RY	SG	SY	SC	SF	W
Italy	166					240	225	297	274					176
Kazakhstan	171					332	352		398		354		262	183
Kenya		159	200	131		171				138		737	247	
Latvia						78	0		165					
Lebanon		485								300		837		0
Lithuania						109	0		159					
Madagascar		157	173			215				127		486		
Mexico	411	277						364		193	301	932	303	
Morocco	362	494	580	481		622	508		637	375	627	1219	314	369
Mozambique		209	292	175		207				198		817	144	
Nicaragua						419		101		0	226	146		
Nigeria		481	197	119		594		581		109	375	1383		
Pakistan		328	336	233		457	322	733		187	434	997	319	356
Paraguay		133				96		157		0	73	308	83	
Peru		176	207			252					237			
Philippines		62	0			131		82				0		
Poland						72	0		102					
Portugal	53					296			322				0	50
Romania			199	151		249	144		269	151	267		157	
Russia	70			114		126	112		188	103	151		105	67
Senegal		330	597	487		494				384				
S. Africa	301	244	212	154					258	152	231	904	175	366
Spain	149	394				498	431		516		530	772	406	155
Syria	253	680		644		901				549	907		660	
Tajikistan	126	581				519			520				0	
Tanzania		154	258	135		158				169	193		164	
Tunisia	303					669	502			366			485	324
Turkey	111	391		375		412	320		389				328	102
Ukraine			123	135		129	120		187	127	142		130	
Uruguay		94	105			85				47	102	280	113	
USA	220	291	347	282			367		457	276	425	745	325	250
Yemen	762			537		806				491				
Zambia		352	434	246		403				317	467		119	
Zimbabwe		397	359	206		425				258	397		205	

Table A2

Country-specific values for r_i and l_i . Values with an asterisk represent the percentage of area equipped for *full control* irrigation actually irrigated. For Australia, the percentage of area equipped for irrigation actually irrigated was not reported and was assumed to be 100%.

Country	% of cultivated area equipped for irrigation	% of the area equipped for irrigation actually irrigated	Reporting year
Afghanistan	41.23	53.99	2002
Algeria	6.94	79.61	2001
Angola	2.32	13.47	2005
Argentina	5.47	91.73	2011
Armenia	55.62	60.67	1997
Australia	5.55	100.00	No year reported
Azerbaijan	69.41	94.81	2002
Belarus	2.03	100.00	2011
Bolivia	6.51	100.00	2011
Brazil	5.13	96.81	2006
Bulgaria	3.20	69.45	2007
Burkina Faso	0.52	72.58	2001
China	44.92	84.42	1996
Congo	0.37	100.00	1993
Croatia	0.74	66.82	2007
DRC	0.14	76.19	1995
Ecuador	32.82	72.64	2000
El Salvador	5.51	74.82	2012
Eritrea	5.49	62.48	1993
Ethiopia	2.76	100.00	2001
Finland	3.79	21.90	2010
France	13.36	57.23	2007
Georgia	59.57	63.00	1996
Germany	4.11	45.49	2006
Ghana	0.30	90.32	2000
Guatemala	9.61	100.00	1997
Guinea	3.06	99.99	2001
Honduras	6.02	92.92	2007
Hungary	3.83	31.92	2002
India	34.69	93.90	2001
Indonesia	14.85	100.00*	2005

(continued on next page)

Table A2 (continued)

Country	% of cultivated area equipped for irrigation	% of the area equipped for irrigation actually irrigated	Reporting year
Iran	42.74	77.41*	2006
Italy	36.54	63.62*	2000
Kazakhstan	8.11	61.23	2010
Kenya	1.90	88.69	2003
Latvia	0.06	74.70	2007
Lebanon	32.78	86.54	1998
Lithuania	0.30	22.40	2007
Madagascar	30.59	50.64	2000
Mexico	24.51	88.00	1997
Morocco	16.06	97.51	2000
Mozambique	2.55	33.92	2001
Nicaragua	3.63	83.00	1997
Nigeria	0.70	76.30	2000
Pakistan	55.89	100.00*	2008
Paraguay	2.03	100.00	2012
Peru	36.16	64.14	1994
Philippines	16.97	95.00	1993
Poland	1.01	62.28	2007
Portugal	31.77	72.21	2007
Romania	23.46	28.18	2007
Russia	1.93	39.53	2006
Senegal	3.13	96.64	1997
S. Africa	9.83	100.00	2000
Spain	20.63	89.14	2011
Syria	22.35	95.50	2001
Tajikistan	80.03	90.88	2009
Tanzania	1.65	99.75*	2001
Tunisia	8.63	86.69	2006
Turkey	17.80	30.32	2002
Ukraine	7.11	100.00	2002
Uruguay	13.90	83.10	2002
USA	15.52	100.00	1998
Yemen	35.04	100.00	2004
Zambia	5.96	100.00	2002
Zimbabwe	3.93	71.41	1999

Table A3

Summary of blue water requirement under current and yield gap closure scenarios.

Country	Current		Yield gap closure		
	Blue water requirement (km ³ yr ⁻¹)	% of ARWR	Blue water requirement (km ³ yr ⁻¹)	% of ARWR	% increase from current
Afghanistan	2.057	7.9	9.243	35.4	349
Algeria	0.492	10.5	8.898	190.6	1710
Angola	0.013	0.0	4.165	7.0	31,927
Argentina	1.830	0.5	36.474	10.4	1893
Armenia	0.081	2.6	0.241	7.8	196
Australia	5.163	2.6	92.991	47.3	1701
Azerbaijan	0.150	1.1	0.228	1.6	52
Belarus	0.045	0.2	2.221	9.6	4818
Bolivia	0.128	0.1	1.965	0.9	1436
Brazil	3.959	0.1	79.704	2.3	1913
Bulgaria	0.078	0.9	3.530	41.4	4407
Burkina Faso	0.015	0.3	3.883	71.9	26,189
China	84.002	7.4	221.499	19.5	164
Congo	0.000	0.0	0.066	0.0	26,702
Croatia	0.008	0.0	1.602	3.8	20,229
DRC	0.001	0.0	0.666	0.1	94,872
Ecuador	0.747	0.4	3.132	1.8	319
El Salvador	0.004	0.0	0.102	1.0	2324
Eritrea	0.061	2.1	1.769	60.4	2813
Ethiopia	0.386	0.8	13.992	28.7	3525
Finland	0.000	0.0	0.032	0.1	11,941
France	0.666	0.8	8.715	10.3	1208
Georgia	0.368	1.5	0.981	3.9	166
Germany	0.093	0.2	4.978	8.1	5246
Ghana	0.009	0.0	3.188	14.2	36,296
Guatemala	0.069	0.1	0.721	1.4	941
Guinea	0.207	0.2	6.764	7.5	3169
Honduras	0.023	0.1	0.417	1.1	1689
Hungary	0.025	0.1	2.044	4.9	8076
India	116.577	15.3	357.884	46.8	207
Indonesia	2.448	0.3	16.489	2.0	574
Iran	10.974	20.0	33.173	60.5	202

(continued on next page)

Table A3 (continued)

Country	Current		Yield gap closure		
	Blue water requirement (km ³ yr ⁻¹)	% of ARWR	Blue water requirement (km ³ yr ⁻¹)	% of ARWR	% increase from current
Italy	2.292	3.0	9.862	12.9	330
Kazakhstan	1.242	2.9	25.018	57.7	1914
Kenya	0.077	0.6	4.568	37.2	5837
Latvia	0.000	0.0	0.127	0.9	212,053
Lebanon	0.022	1.2	0.078	4.4	253
Lithuania	0.000	0.0	0.293	3.0	147,260
Madagascar	0.134	0.1	0.866	0.6	546
Mexico	7.018	3.8	32.541	17.6	364
Morocco	3.321	28.6	21.212	182.9	539
Mozambique	0.048	0.1	5.541	6.4	11,477
Nicaragua	0.008	0.0	0.256	0.4	3220
Nigeria	0.494	0.4	92.852	81.1	18,678
Pakistan	36.074	36.5	64.545	65.4	79
Paraguay	0.033	0.0	1.650	1.1	4838
Peru	0.541	0.1	2.332	0.3	331
Philippines	0.526	0.3	3.261	1.7	520
Poland	0.018	0.1	2.892	11.9	15,839
Portugal	0.253	0.8	1.103	3.6	336
Romania	0.841	1.0	12.720	15.0	1413
Russia	0.292	0.0	38.430	2.1	13,041
Senegal	0.248	1.6	8.216	52.7	3206
S. Africa	1.582	7.7	16.089	78.3	917
Spain	2.812	6.3	15.292	34.3	444
Syria	1.823	27.1	8.543	127.1	369
Tajikistan	0.429	4.9	0.590	6.7	37
Tanzania	0.126	0.3	7.616	19.8	5948
Tunisia	0.355	19.2	4.122	223.3	1062
Turkey	3.012	3.6	19.520	23.1	548
Ukraine	0.198	0.3	9.201	13.1	4539
Uruguay	0.057	0.1	0.408	0.6	619
USA	39.175	3.2	303.753	24.7	675
Yemen	1.376	163.8	3.927	467.4	185
Zambia	0.207	0.5	3.479	8.3	1578
Zimbabwe	0.216	2.7	7.708	96.4	3461
Total	335.531	...	1650.363	...	392

Table A4

Crop-specific irrigation water demand under yield gap closure.

Crop	Irrigation water demand under yield gap closure (km ³ H ₂ O yr ⁻¹)	% of total irrigation water demand	% of production under yield gap closure
Barley	80.13	4.9	3.5
Groundnut	41.78	2.5	0.8
Maize	271.81	16.5	18.0
Millet	35.23	2.1	0.6
Oil Palm	57.47	3.5	2.1
Potato	31.25	1.9	9.6
Rapeseed	42.46	2.6	0.8
Rice	248.21	15.0	12.1
Rye	15.20	0.9	0.7
Sorghum	48.66	2.9	1.5
Soybean	188.29	11.4	4.0
Sugar cane	95.03	5.8	28.3
Sunflower	35.89	2.2	0.7
Wheat	458.98	27.8	17.1

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