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Article

A Holistic View of Global Croplands and Their Water Use for Ensuring Global Food Security in the 21st Century through Advanced Remote Sensing and Non-remote Sensing Approaches

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Abstract: This paper presents an exhaustive review of global croplands and their water use, for the end of last millennium, mapped using remote sensing and non-remote sensing approaches by world's leading researchers on the subject. A comparison at country scale of global cropland area estimated by these studies had a high R^2-value of 0.89–0.94. The global cropland area estimates amongst different studies are quite close and range between 1.47–1.53 billion hectares. However, significant uncertainties exist in determining irrigated areas which, globally, consume nearly 80% of all human water use. The estimates show that the total water use by global croplands varies between 6,685 to 7,500 $km^3 yr^{-1}$ and of this around 4,586 $km^3 yr^{-1}$ is by rainfed croplands (green water use) and the rest by irrigated croplands (blue water use). Irrigated areas use about 2,099 $km^3 yr^{-1}$ (1,180 $km^3 yr^{-1}$ of blue water and the rest from rain that falls over irrigated croplands). However, 1.6 to 2.5 times the blue water required by irrigated croplands is actually withdrawn from reservoirs or pumping of ground water, suggesting an irrigation efficiency of only between 40–62 percent. The weaknesses, trends, and future directions to precisely estimate the global croplands are examined. Finally, the paper links global croplands and their water use to a paradigm for ensuring future food security.

Keywords: croplands; remote sensing; water use; virtual water; food security; water productivity

1. Introduction

Global change is putting unprecedented pressure on global croplands, vital for ensuring future food security for all. Declining *per capita* agricultural production requires immediate policy responses to safeguard food security amidst global climate change and economic turbulence. The precise estimation of global croplands and their precise location are critical scientific tools for any policy response [1–3] at a time when most indicators point to worsening food security situation [4–6]. For instance, world food stocks are fast dwindling [7], cropland areas have nearly stagnated, yield per unit area have plateaued [8], world population is increasing at nearly 100 million per year [9], croplands are being lost to biofuel production [10], salinization [11], and urbanization [12,13], and nutritional transition is raising the calorie intake swiftly in emerging markets due to economic change [14]. Already, recent global trends suggest that grain production increases are becoming more difficult to achieve as a result of increasing population, and as the competition for water intensifies between agriculture, cities and the environment [15]. There is a need to reduce the environmental footprint of food production. Declining *per capita* agricultural production and warming oceans are emerging threats to global and regional food security [16]. The drop in grain production in the Northern China Plain, which produces over half of China's wheat and a third of corn, from its peak of 392 million tons in 1998 to 338 million tons in 2003 (a drop equivalent to Canada's entire harvest) has been attributed to the declining watertables and resulting loss of irrigated areas [17]. This is significant, since just a 3% drop in China's cereal production will claim 10% of the world export market and can potentially jeopardize global food security [18]. Also, in China's Yangtze Delta, for example, rice paddy areas have decreased by a dramatic 22% over the last six decades, while an increase has been seen for urban areas (8%) and aquaculture (14%) [19]. Global wheat stocks reached historic lows this decade and wheat prices increased by about 30% in 2008 [20], resulting in further structural changes in global grain markets, and increased rice prices in recent years have also endangered food security [14,21]. The global food outlook and price trends remains pessimistic and appear set to continue [22] over the medium term to 2015 [7], a year when the progress towards eradicating world hunger and other Millennium Development Goals will be judged by the United Nations [23]. Food commodity speculation and derivatives are a new cause of malnutrition [24]. Continuous food crisis will be new global norm unless international agricultural research and investment efforts are directed to find long term solution to the world food security crisis [25].

Increasing cropland areas for food security may not be feasible, due to potential negative environmental impacts of the area expansion [26]. For instance, land use land cover (LULC) changes, specifically deforestation for crop production, are shown to have a stronger influence on ecosystem carbon budgets than the projected climate change scenarios [27]. Cropland soils hold the key to terrestrial carbon (C) sequestration as well [28,29], accounting for 0.5–0.7 GtC yr^{-1} in mid-century [30]. The contribution from agricultural no-till soils by itself be about 40% by mid-century [30]. At current levels, agricultural croplands account for 50% of methane (CH_4) and 60% of nitrous oxide emissions [31]. Irrigated rice paddies are a major source of atmospheric CH_4 [32,33].

Above all, croplands are also water guzzlers [34], taking anywhere between 60% and 90% of all human water use. With increasing urbanization, industrialization, and other demands on water, there is increasing pressure to reduce agricultural water use. Conversion from natural vegetation to irrigated cropland also means greater water use. When large tracts of a river basin are converted from natural vegetation to irrigated croplands, they will result in a substantial reduction in the volume of water in streams. Recent research in Brazil using Landsat data showed that the regional mean ET for irrigated crops was 3.6 mmd^{-1}, being higher by an order of magnitude than for natural vegetation (1.4 mmd^{-1}) [35].

The above factors imply that there is a need to produce more food from existing or even reduced (a) areas of croplands (more crop per unit area); and (b) quantum of water (more crop per drop). More crop per unit area (crop productivity) along with crop intensification led to the Green Revolution during 1960–2000, that helped build food barriers against episodes of hunger [36] and lifted millions out of malnutrition and poverty [37]. But, the Green Revolution has more or less stagnated lately, and declining yield gains are failing to keep up with population growth. More crop per drop (water productivity) is a concept that has yet to take off, but holds much promise amid caution [38]. In order to produce more food from existing croplands and water resources, precise maps and data on croplands and their water use are needed.

Thereby, emerging strategies for feeding the growing population in spite of the stagnated and even decreasing cropland areas will be to [1]:

(A) grow less water consuming crops (e.g., more wheat and less rice);
(B) increase water productivity through better water management and increasing irrigation efficiency;
(C) educate people to eat less water consuming food (e.g., more vegetables and grains compared to meat; more local and seasonal foods); and
(D) emphasize rainfed crop productivity to reduce stress on water-intensive irrigated croplands.

For planning these strategies and related incentive measures, we need to know the precise spatial location of agricultural crops, their water source (e.g., irrigation and/or rainfed), land use changes (e.g., biofuel *vs*. food crops), and water use patterns (e.g., water productivity maps). Such an effort will help agricultural policy makers and managers to plan and implement strategic goals of food security through renewed investments in agriculture, education and markets [25,37] and direct involvement of local governments and farmers to enhance the future food security [39 this issue].

Given the above background, the overarching goal of this paper is to produce a holistic review of the current state-of-art on information pertaining to global croplands and their water use with the aim to work towards a strategy for a food secure world. The main purpose of the paper is to identify the weaknesses and trends in existing methods and approaches and provide future directions to precisely estimate the global croplands. More precise estimates of global croplands are essential for future food security.

2. Global Croplands

Global croplands include irrigated and rainfed lands, but do not include pasture and rangelands. Cropland mapping at the global level [40–42] has become feasible by integrating agricultural statistics and census data from the national systems with spatial mapping technologies involving geographic information systems (GIS). More recently, availability of advanced remote sensing data along with secondary data and recent advances in data access, quality, processing, and delivery have made remote sensing based cropland estimates at the global level possible [1,2]. The specific remote sensing advances enabling global cropland mapping and generation of their statistics include factors such as: (a) free access to well calibrated and guaranteed data such as Landsat and (Moderate Resolution Imaging Spectroradiometer) MODIS; (b) frequent temporal coverage of data such as MODIS backed by high resolution Landsat data; (c) free access to high quality secondary data such as long-term precipitation, evapotranspiration, surface temperature, soils, and Global Digital Elevation Model (GDEM); (d) global coverage of the data; (e) web-access to data and faster download; (f) advances in computer technology; and (g) advances in processing. Prior to this, irrigated and rainfed cropland areas were estimated, at large scale, in global land use classifications [43–47] derived from remote sensing, which usually focused on other objectives, such as LULC for forestry, rangelands and rain-fed croplands. Most remote sensing work at regional level produced LULC maps and not specific thematic maps like croplands. The Global Land Cover Map produced by USGS [43] using Advanced Very High-Resolution Radiometer (AVHRR) 1-km data had four irrigated classes: irrigated grassland, rice paddy and field, hot irrigated cropland, and cool irrigated cropland.

Currently, there are four main global cropland maps produced in recent times for the end of the last millennium. These are:

1. Thenkabail *et al*. [1]—Figure 1;
2. Ramankutty and Foley [48] —Figure 2;
3. Goldewijk *et al*. [42]—Figure 3; and
4. Portmann *et al*. [41] and Siebert and Döll [49]—Figure 4.

Globally, cropland areas increased from 265 Mha in 1700 to 1,471 Mha in 1990, while the area of pasture increased more than six fold from 524 to 3,451 Mha [50]. By these estimates, agriculture and pasture cover about 33% of the world's land area. Foley *et al*. [51] and Ramankutty and Foley [48] estimate cropland and pasture to be nearly 40% of the world's terrestrial surface (148,940,000 Km^2). The first remote sensing based global cropland estimate [1,2] for the nominal year 2000 showed global croplands as 1.53 billion hectares (Figure 1, Table 1). However, in all these studies, there is substantial scope for improvement in the precise spatial location of croplands, their characteristics (e.g., cropping intensity, crop calendar, type of crop grown), and their area estimates.

The four major global cropland studies [1,2,40–42,49] estimated total cropland areas between 1.30 to 1.53 Bha. Ramankutty *et al*. [40] (Figure 2) and Goldewijk [42] (Figure 3) do not differentiate between irrigated and rainfed cropland areas whereas Thenkabail *et al*. [1,2] (Figure 1) and Portsmann *et al*. [41] (Figure 4) and Siebert and Döll [49] (Figure 4) provide distinct irrigated and rainfed cropland statistics. A country-by-country comparison between cropland area estimates of different studies showed very high correlations. As shown in Figures 5a and 5b Ramankutty *et al*. [40] used a combination of agricultural statistics and remote sensing to determine cropland areas of 197 countries that were highly correlated (R^2 value of 0.89) with the remote sensing based estimates of Thenkabail *et al*. [1,2]. Similarly, even though Portsmann *et al*. [41] and Siebert and Döll [49] used non-remote sensing approaches involving agricultural statistics and GIS and Thenkabail *et al*. [1,2] used remote sensing approaches, a comparison of cropland areas derived using two products for the 197 countries showed remarkable correlation with R^2 value of 0.94 (Figure 5b). Nevertheless, various coarse resolution cropland area mappings have two highly significant differences: (A) Precise spatial location of these cropland areas; and (B) Estimates of irrigated areas *versus* rainfed areas.

Both of these are crucial for water use assessments and practical applications of the data including food security planning. In addition to cropland maps and statistics, there are two premier global irrigated area maps and statistics. These are:

5. Thenkabail *et al*. [1,2]—Figure 1; and
6. Siebert *et al*. [52]—Figure 4.

These two premier products on irrigated areas are also referred as: (1) The International Water Management Institute's (IWMI) global irrigated area map (GIAM), which is based on coarse resolution remote sensing [1,2,53,54]; and (2) Food and Agricultural Organization of the United Nations and the University of Frankfurt (FAO/UF's) global map of irrigated areas (GMIA), which is based on national statistics [52] (Figure 4, Table 1). The Siebert *et al*. [52] study provides estimates of global area "equipped" for irrigation (but not necessarily irrigated) as 278.8 Mha, which is about 19% of the total croplands (1.5 Bha) around the year 2000. The Thenkabail *et al*. [1,2] study provides two types of areas: (a) total area available for irrigation (TAAI), which does not consider cropping intensity, and (b) annualized irrigated areas (AIA) which considers the intensity. The TAAI, which is equivalent to FAO/UF's "areas equipped for irrigation" definition, was 399 Mha (Figure 1). This is nearly 120 Mha higher than FAO/UF estimates. The main differences occur in China and India. The AIA, which has no equivalent in FAO/UF statistics, was 467 Mha.

The importance of irrigation to global food security is highlighted in a recent study by Siebert and Döll [49] who show that without irrigation there would be decrease in production of various foods including dates (60%), rice (39%), cotton (38%), citrus (32%) and sugarcane (31%) from their current levels. Globally, without irrigation cereal production in irrigated areas will decrease by massive 43%, with overall cereal production, from irrigated and rainfed croplands, decreasing by 20%. As the world's population grew from 2.2 billion in 1950 to 6.1 billion in 2001, irrigation played a major role in tripling of the world grain harvest from 640 million tons to 1,855 million tons [17]. Irrigated agriculture currently meets about 40% of global food needs from just 20% of the area that is irrigated. Khan *et al*. [55] studied irrigation systems in Australia, China, and Pakistan to show that none of them were sustainable in the current operational conditions as a result of soil salinity [56], lack of adequate water resources, groundwater mismanagement, and the mismatch between water policy and environmental policy for agricultural sustainability [11]. In contrast, rainfed croplands meet 60% of the food and nutritional needs of the world's population from 80% of the global croplands. Irrigated lands are at least twice more productive than rainfed croplands though the latter are considered more environmentally friendly, and remain important to the food security of the marginal or subsistence farmers in many developing countries [1,2,57].

Figure 1. Global cropland map by Thenkabail *et al*. [1,2]. This includes irrigated and rainfed areas of the world as well as permanent crops. The product is derived using remotely sensed data. Total area of croplands is 1.53 billion hectares of which 399 million hectares is total area available for irrigation (without considering cropping intensity) and 467 million hectares is annualized irrigated areas (considering cropping intensity). The product is derived using 1–10 km base data. The output is given in nominal 1–km resolution. Also see: http://www.iwmigiam.org.

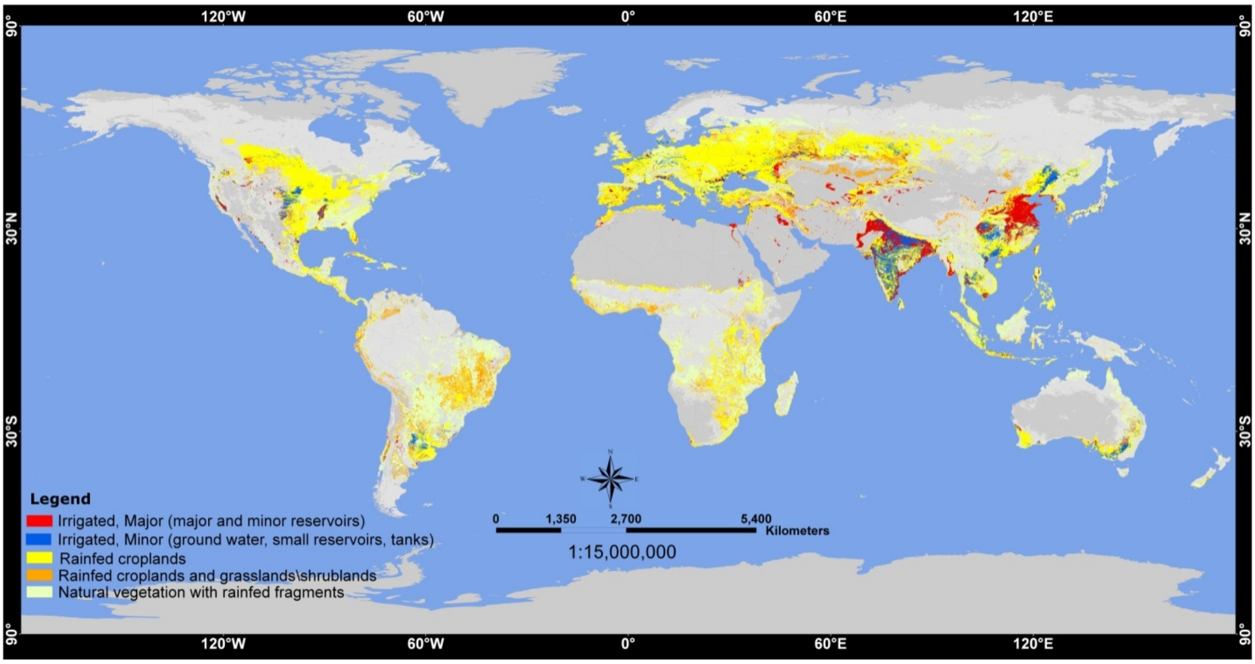


Figure 2. Global cropland map by Ramankutty *et al*. [40] and Ramankutty and Foley [48]. This includes irrigated and rainfed areas of the world as well as permanent crops. Total area of croplands is 1.47 billion hectares. The product is derived using national agricultural census data and remote sensing derived land use. The output is given in nominal 5-min (0.083333 decimal degrees) resolution.

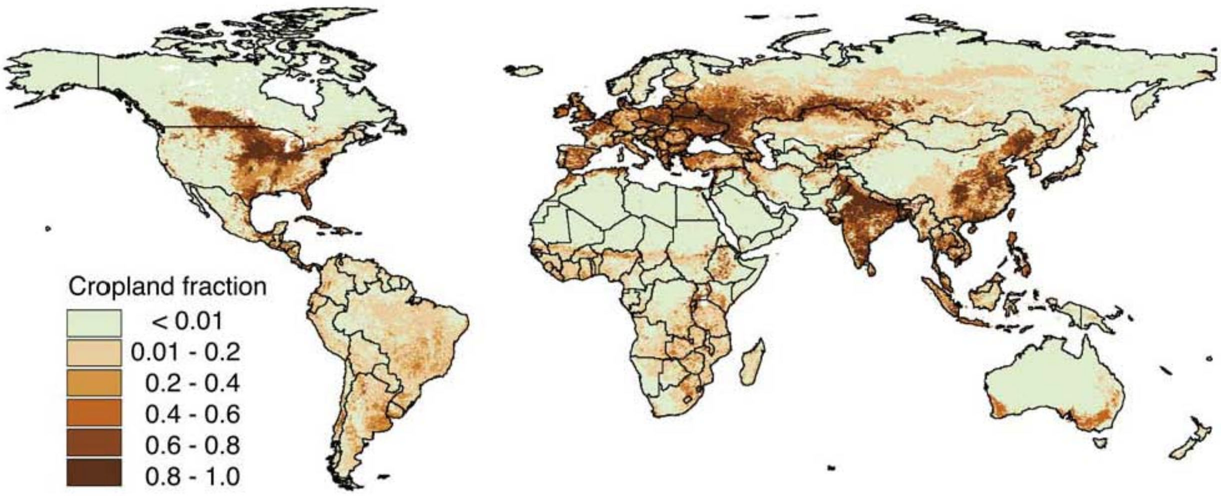


Figure 3. Global irrigated cropland area map by Goldewijk *et al*. [42]. This includes irrigated and rainfed areas of the world as well as permanent crops. Total area of croplands is 1.47 billion hectares. The product is derived using national agricultural census data and remote sensing land use. The output is given in nominal 5-min (0.083333 decimal degrees) resolution.

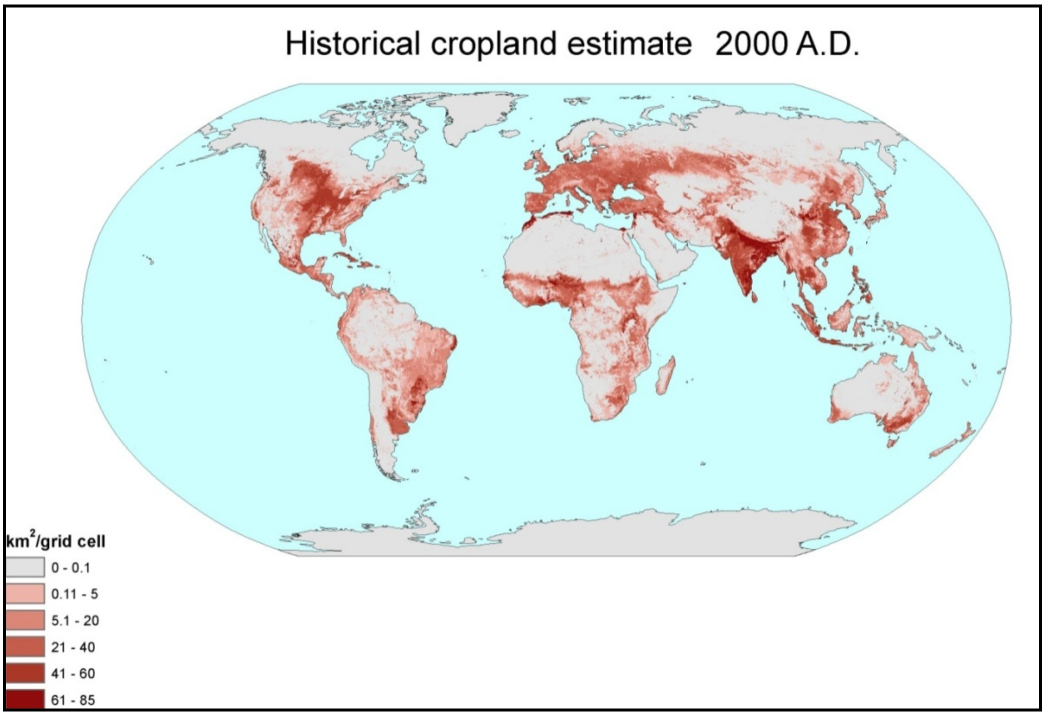
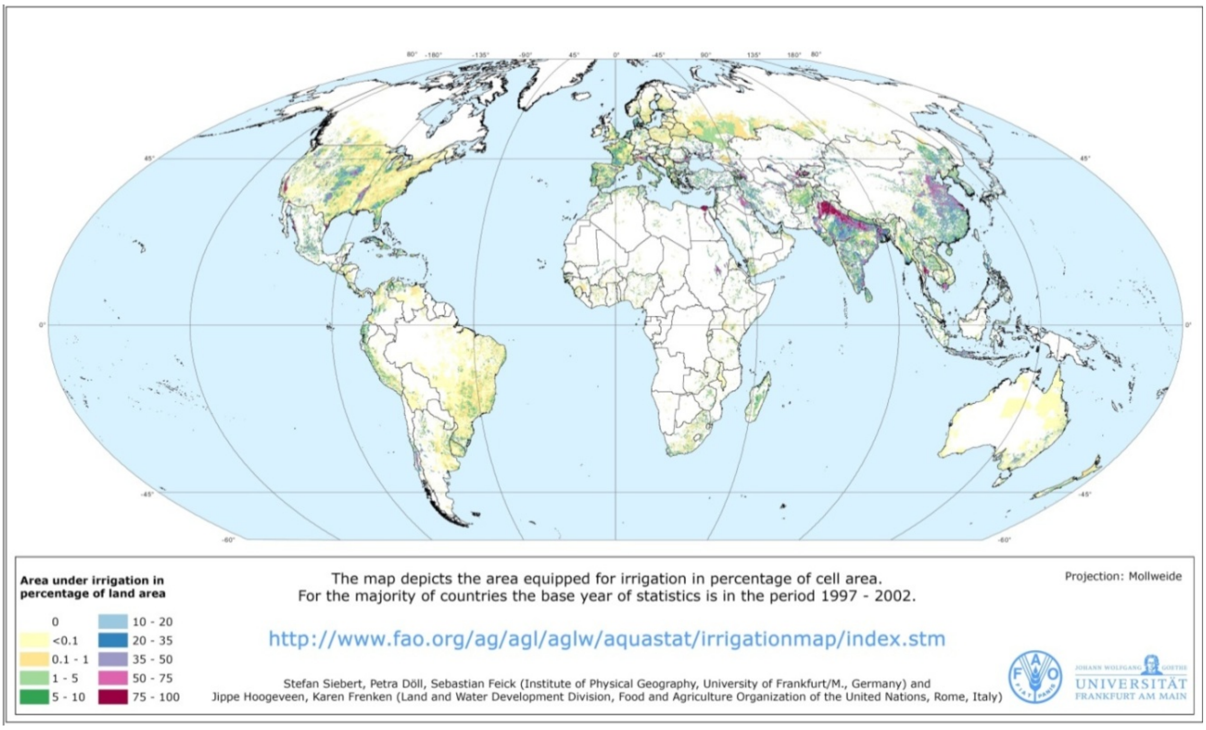


Figure 4. Global irrigated cropland area map [52]. This includes only areas "equipped" for irrigation in the world. Total area of irrigated croplands is 278 Mha. The product is derived using the national agricultural census data and GIS. The output is given in nominal 5-min (0.083333 decimal degrees) resolution.



3. Uncertainties in Cropland Area Estimates

Uncertainties in cropland estimates (Table 1) are well established [1,58]. The greatest difficulty and differences in global cropland estimates is in differentiating between rainfed croplands *versus* irrigated croplands. This is also the most crucial difference because water use assessments and food production estimates depend heavily on whether an area is irrigated or rainfed.

A country-wise assessment of global irrigated areas using a remote sensing approach [1,2] (irrigated areas in Figure 1) and a non-remote sensing approach [52] (Figure 4) showed a clear trend with high correlations (R^2 value between 0.89 and 0.94; Figures 5a and 5b). However, there are highly significant differences for China and India—the two countries with nearly 60% of all annualized irrigated areas of the world.

Figure 5a. Cropland areas per year (annualized) compared for 197 countries [1,2, *versus* 40]. Cropland areas include irrigated and rainfed crops as well as permanent crops. Ramankutty *et al*. [40] used national agricultural statistics fused with remote sensing data whereas Thenkabail *et al*. [1,2] used advanced remote sensing approaches. There is remarkably high correlation (R^2 value of 0.89) for the 1:1 line for comparison, at countries scale, of cropland areas between the two approaches. However, large differences in areas for some countries are clear. Reasons for the differences are discussed in the paper.

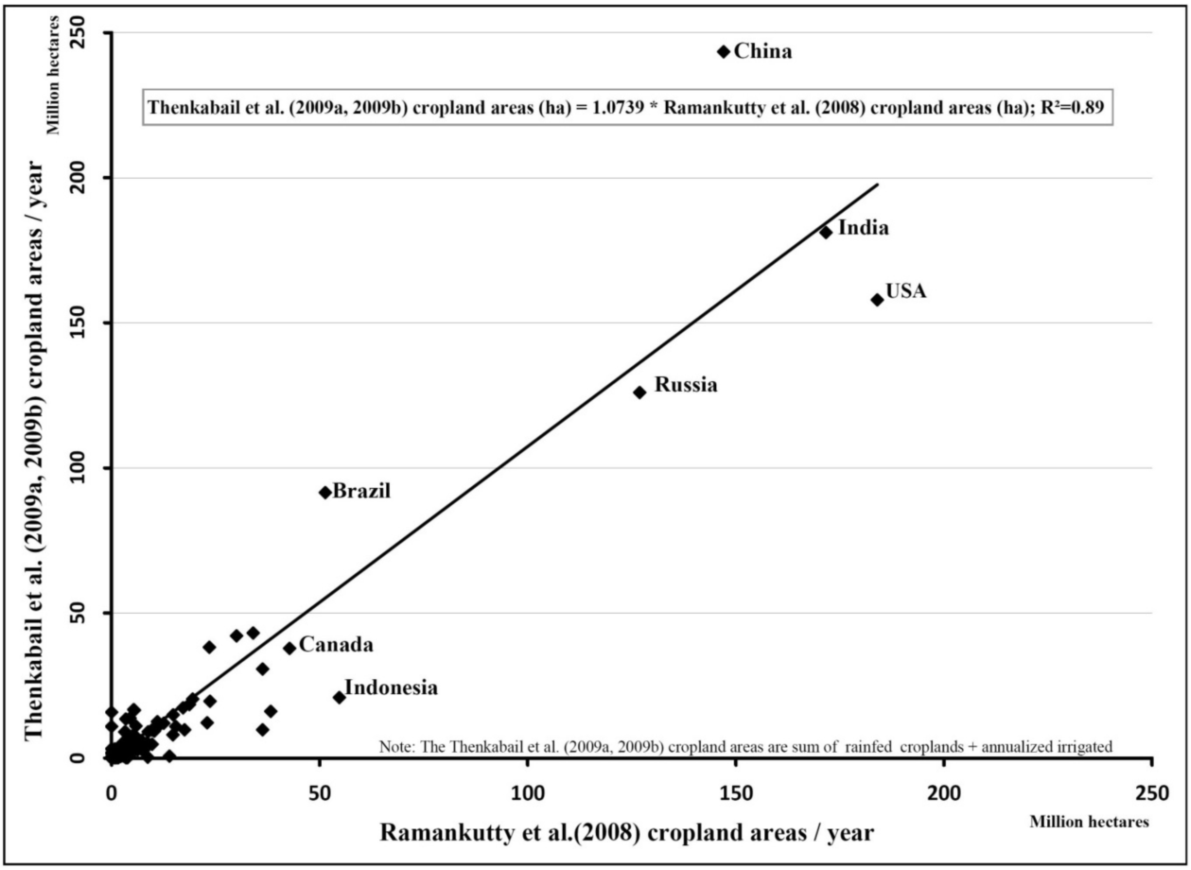
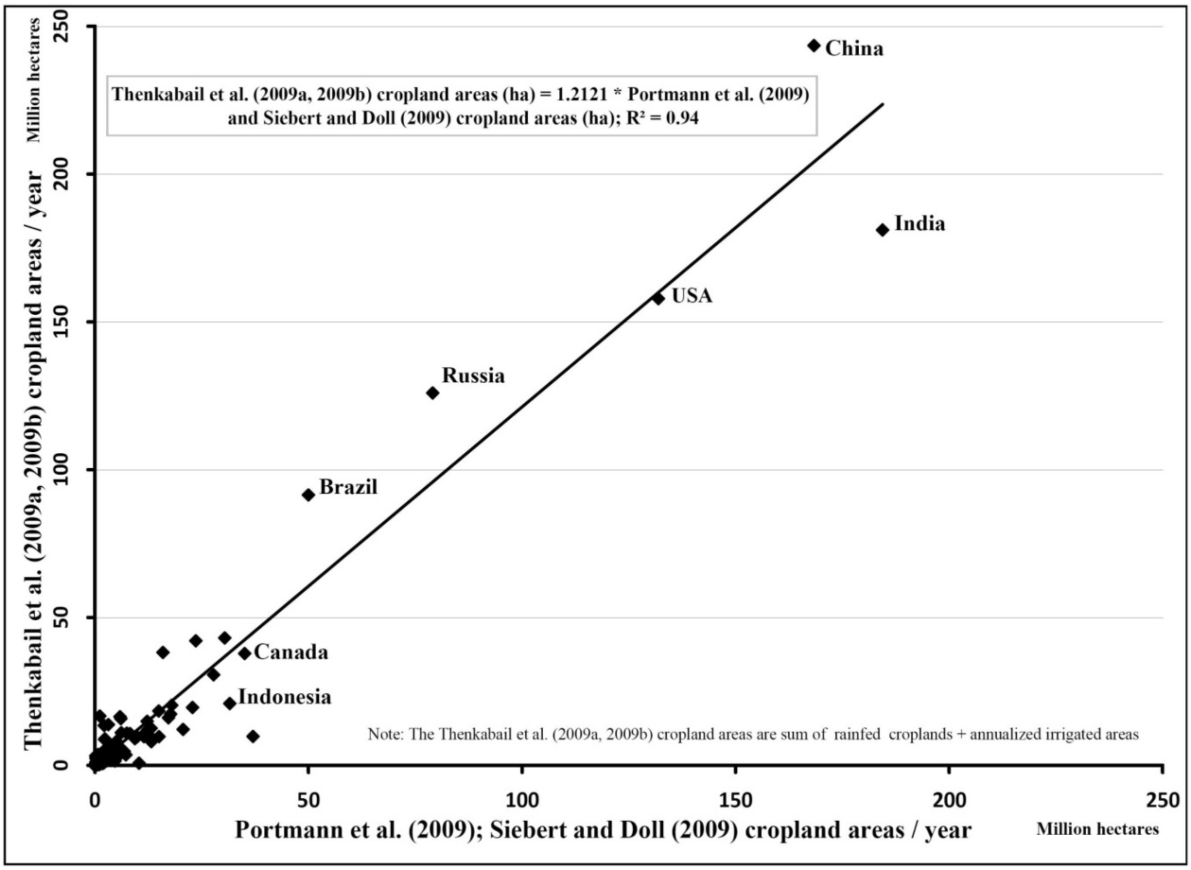


Figure 5b. Cropland areas per year (annualized) for 197 countries [1,2, *versus* 41,49]. Cropland areas include irrigated plus rainfed crops per year as well as permanent crops. Portmann *et al.* [41] and Siebert and Döll [49] use national agricultural statistics and geographic information systems (GIS) whereas Thenkabail *et al.* [1,2] use remote sensing approaches. There is remarkably high correlation (R^2 value of 0.94) for the 1:1 line for a country-by-country comparison of cropland areas between the two approaches. However, large differences in areas for some countries are clear. Reasons for differences are discussed in the paper.



The main causes of differences in areas reported in various studies can be attributed to [3,47,59], but not limited to: (a) reluctance on part of states to furnish irrigated census area data in view of their vested interests in sharing of water; (b) reporting of large volumes of census data with inadequate statistical analysis; (c) subjectivity involved in observation-based data collection process; (d) inadequate accounting of irrigated areas, especially minor irrigation from groundwater, in the national statistics; (e) definition issues involved in mapping using remote sensing as well as national statistics; (f) difficulties in arriving at precise estimates of area fractions (AFs) using remote sensing; (g) difficulties in separating irrigated from rainfed croplands; and (h) imagery resolution in remote sensing.

Even when cropland area estimates match reasonably well [1,40–42] (Figures 1–3, Table 1) (Figure 6a–6b) there are serious mismatches in their exact spatial location and distribution of crops. One of the biggest causes of uncertainty is inadequate accounting of minor irrigation (from groundwater, small reservoirs, and tanks). In India, for example, the number of tube-wells increased from a meager 100,000 in early 1960s to about 26 million by the year 2000 [60]. However, the irrigated area maps and statistics on groundwater irrigation are sketchy and/or missing [61]. Indeed, overwhelming evidence [59–62] shows that much of the potential is already exploited but these do not show up as irrigated area maps [63]. Massive exploitation of surface water from minor reservoirs and/or tanks is a missing link in many irrigated area statistics. Wide discrepancies exist in tank irrigation area, even in the States where tanks have historically been an important source of irrigation [64]. Often groundwater and small reservoir irrigation are mapped as rainfed croplands. Similarly, definition issue is another main factor for differences in the areas. The "supplemental" irrigated areas are croplands that can sustain a crop only with substantial irrigation, but they are often labeled as rainfed.

China is important to world food security [18]. Yet, China presents a cautionary tale regarding the generation and use of irrigation statistics, given their problems of measurement and bureaucratic construction [65]. Despite having the largest irrigated area worldwide [66], the key data issues include problems of measuring irrigated area, the principal categories used in China, the agencies that issue data and their biases, and the difficulties of interpreting increases and decreases in irrigated area over time [67]. For instance, 59.3 Mha of irrigated area by one measure, by others 55.0, 53.8, 48.0 or 40.2 Mha in the year 2000 [65].

Figure 6a. Comparison of irrigated areas of 197 countries in the world [1,2, *versus* 52]. Irrigated areas derived by Siebert *et al*. [52] based primarily on non-remote sensing approaches, are compared with Thenkabail *et al*. [1,2], based primarily on remote sensing approaches. The total areas by Thenkabail *et al*. [1,2] estimates were significantly higher than Siebert *et al*. [52] mainly as a result of higher estimates for India and China. Overall, there is remarkably high correlation (R^2 value of 0.94) for the 1:1 line for a country-by-country comparison of irrigated cropland areas between the two approaches. The differences are larger than Figure 6b. Reasons for differences are discussed in the paper.

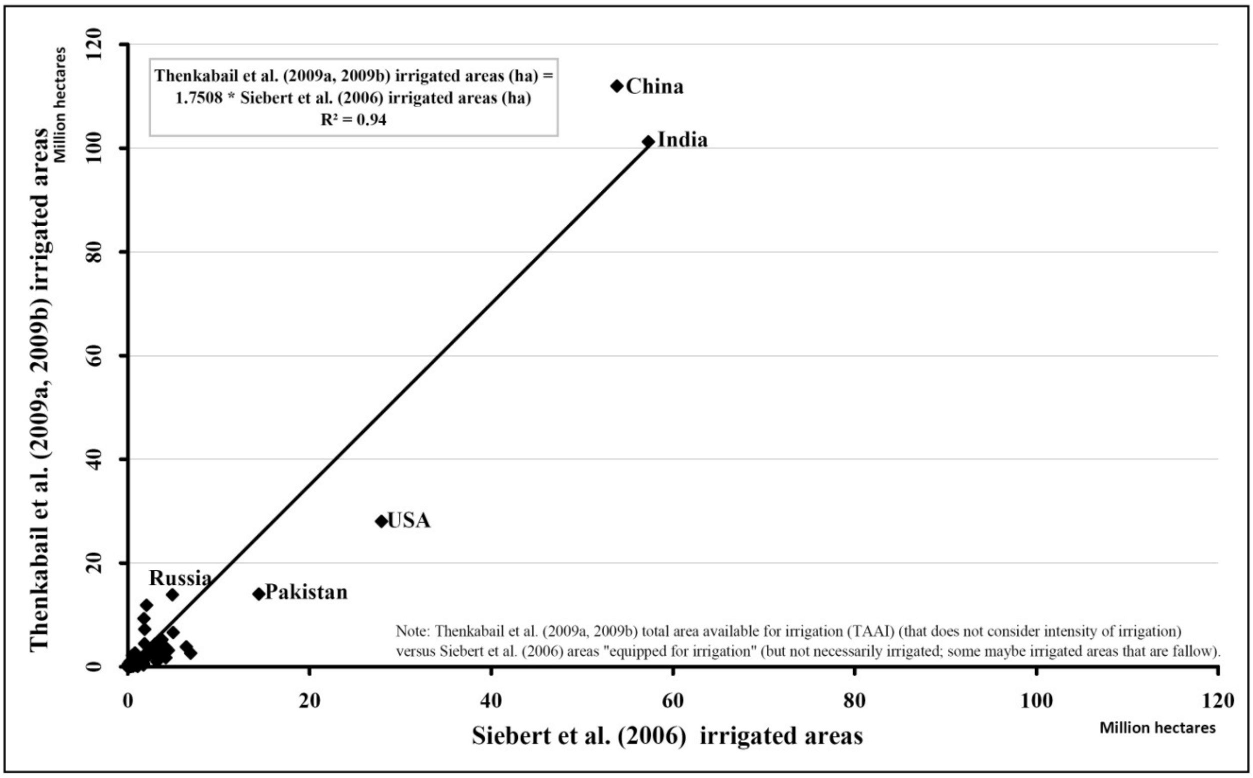
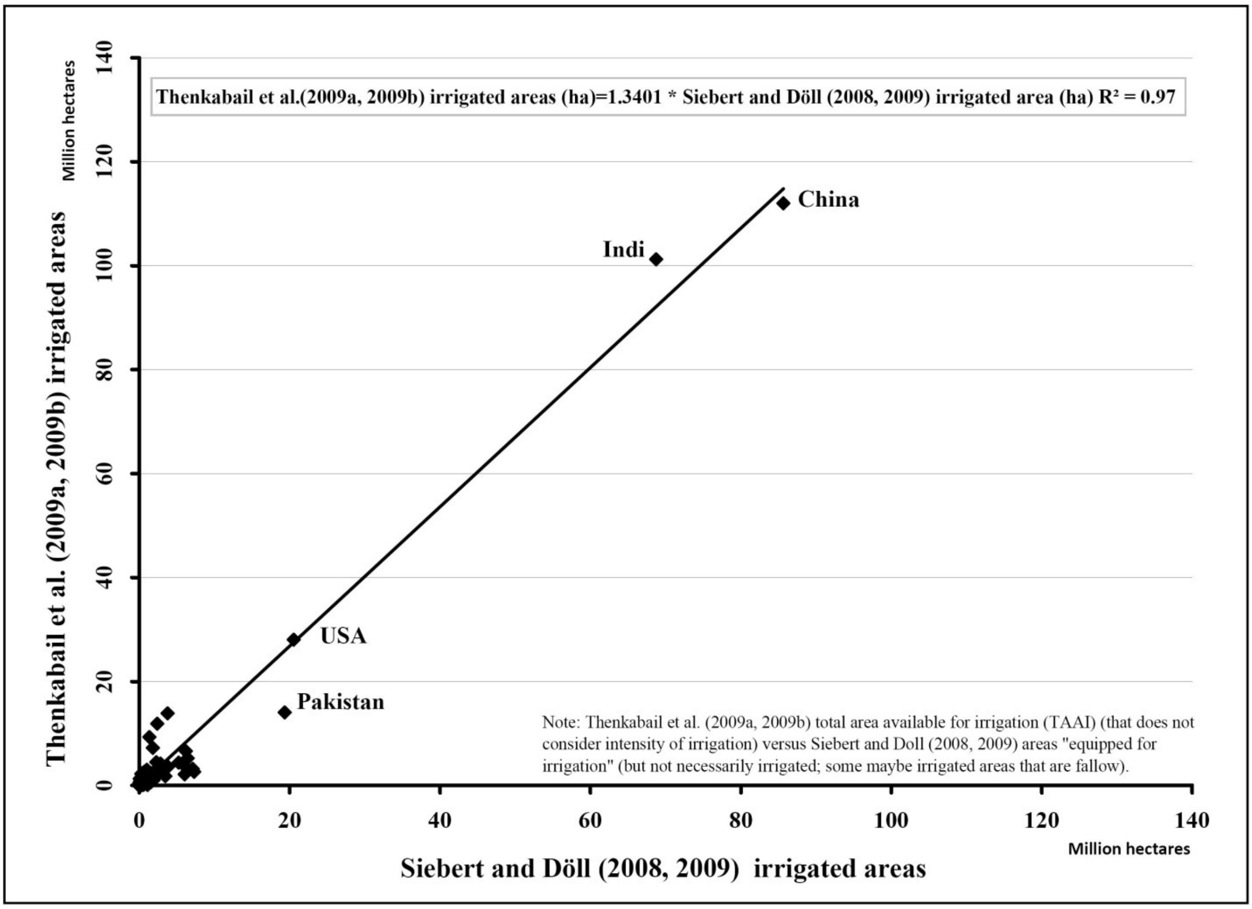
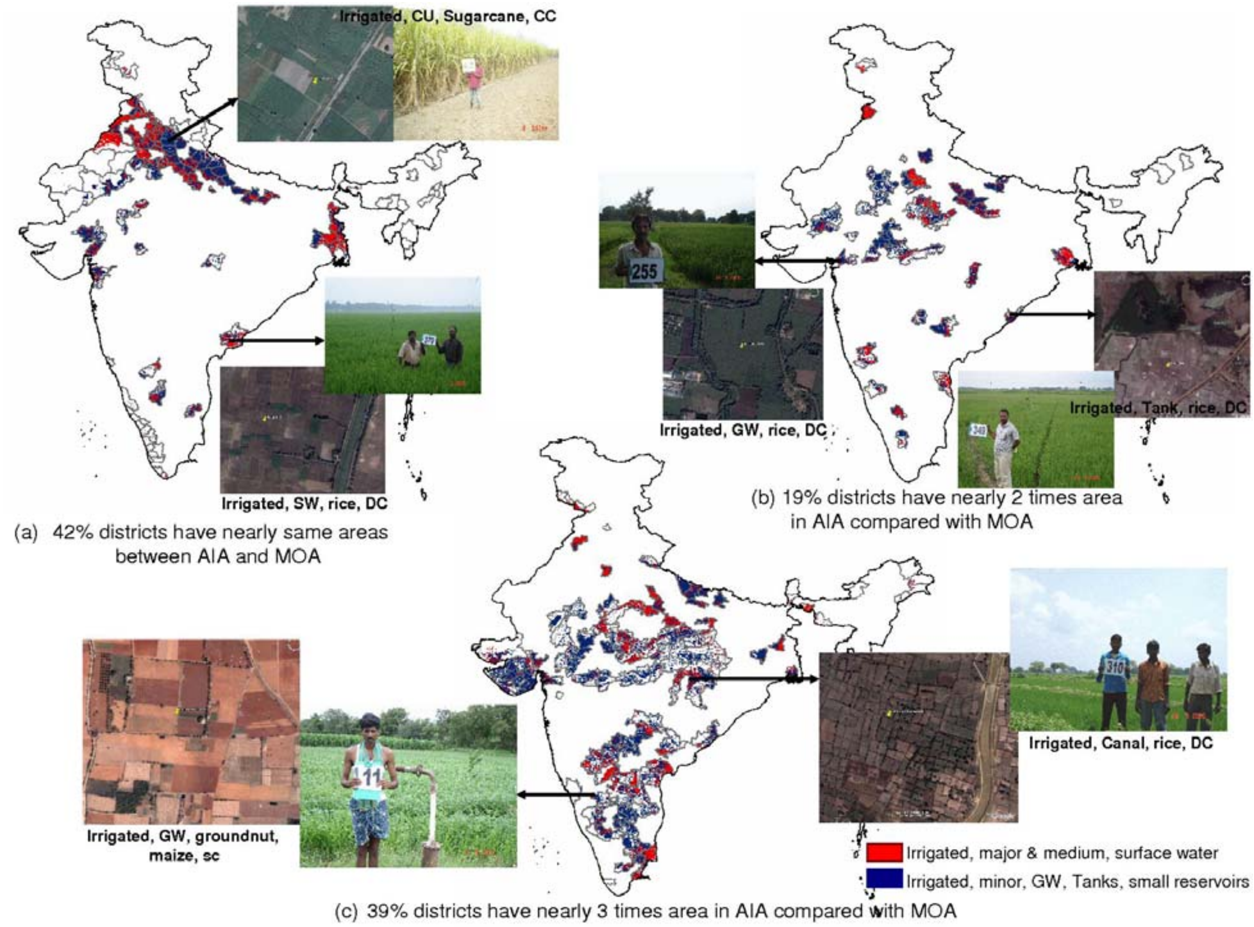


Figure 6b. Comparison of irrigated areas. Irrigated areas derived by Siebert and Döll [49] and national statistics provided by Ministry of Agriculture [68] based primarily on remote sensing approaches. The Thenkabail *et al*. [69] estimates were significantly higher than Siebert *et al*. [52] mainly as a result of the huge differences for India and China. Overall, there is remarkably high correlation (R^2 value of 0.97) for the 1:1 line for a country-by-country comparison of irrigated cropland areas between the two approaches. However, the differences are lower than Figure 6a mainly due to revised irrigated areas reported for China and India by Siebert and Döll [49] compared to Siebert *et al*. [52]. Reasons for differences are discussed in the paper.



In order to determine the magnitude of differences that occur between remote sensing and census based field data, we made a comparison of irrigated area statistics derived from MODIS 500 m [63] with that of the census based national statistics [68] (Figure 7). This resulted in 42% of the districts of India having a 1:1 or near 1:1 match between MODIS based areas and the census based areas, 19% of the districts had MODIS based areas nearly twice as the census based areas, and the rest 39% of the districts had MODIS based areas nearly thrice as the census based areas (Figure 7). Field evidence showed that, the perfect or near-perfect matches were in areas with irrigation from major reservoirs. The greatest differences were observed in areas where irrigation from groundwater, small reservoirs, and tanks were maximum; showing sufficient evidence that census based statistics may not fully account for these minor irrigation sources which are spread across large areas.

Figure 7. Uncertainties in irrigated areas illustrated with an example of India (Dheeravath, 2009). A district-wise spatial comparison between the remotely sensed irrigated areas derived using MODIS 500m data [69] and national statistics provided by Ministry of Agriculture [68] in India. The 42% of the districts where there was near 1:1 match in areas were mainly irrigated from large reservoirs. In the areas where minor irrigation (groundwater, small reservoirs, and tanks) dominated, remote sensing based estimates [69] were either twice or thrice than those reported by MOA. This was mainly because minor irrigation is inadequately reported in MOA census data.



4. Cropland Areas at Finer Resolutions

The need for finer resolution (30 m or better) cropland maps are many fold. First, maps and statistics produced by coarser resolution remote sensing have uncertainties as a result of the issues discussed in Section 3.0, which clearly highlights the need for finer resolution products.

Second, is the lack of precise location of cropland areas in these maps. The coarser resolution products (e.g., Figures 1–4) provide cropland areas as proportion of a pixel. In a 10-km grid, for example, a < 5% croplands would mean the location of this 5% cropland area within an area of 10,000 hectares (10 km x 10 km) and may lay anywhere. This is a glaring limitation of these maps that can be overcome only with finer resolution mapping.

Table 1. Cropland areas and their water use for various countries of the World from a number of different sources.

Rank based on Total IWMI GIAM cropland areas	Country	Croplands: irrigated	Croplands: irrigated	Croplands: irrigated	Croplands: irrigated	Croplands: irrigated	Croplands: irrigated	Croplands: rainfed	Croplands: rainfed	Croplands (irrigated + Rainfed)	Croplands (irrigated + Rainfed)	Croplands (irrigated + Rainfed)	Croplands: rainfed + irrigated	Croplands: irrigated	Croplands: irrigated	Croplands: irrigated	Croplands: irrigated	Croplands: rainfed	Croplands: rainfed	Croplands: rainfed + irrigated
		Thenkabail *et al.,* 2009a,b [1,2]	Thenkabail *et al.,* 2009a,b [1,2]	Thenkabail *et al.,* 2009a,b [1,2]	Thenkabail *et al.,* 2009a,b [1,2]	Thenkabail *et al.,* 2009a,b [1,2]	Thenkabail *et al.,* 2009a,b [1,2]	Thenkabail *et al* ., 2009a [1]; Biradar *et al.,* 2008 [79]	Thenkabail *et al* ., 2009a [1]; Biradar *et al.,* 2008 [79]	Thenkabail *et al.,* 2009a [1]	Thenkabail *et al.,* 2009a [1]	Thenkabail *et al.,* 2009a [1]	Ramnkutty and Foley, 1998 [48]	Siebert *et al* ., 2006 [52]	Siebert and Döll, 2008, 2009 [49,97]	Portmann *et al.,* sumbitted [41]; Siebert and Döll, 2009 [49]	Portmann *et al.,* sumbitted [41]; Siebert and Döll, 2009 [49]	Portmann *et al.,* sumbitted [41]; Siebert and Döll, 2009 [49]	Portmann *et al.,* sumbitted [41]; Siebert and Döll, 2009 [49]	Portmann *et al.,* sumbitted [41]; Siebert and Döll, 2009 [49]
		Total area available for irrigation or Net irrigated areas	Season 1 irrigated areas	Season 2 irrigated areas	Continuous irrigated areas	Annualized irrigated areas or gross irrigated areas	% of total global annualized irrigated areas	Total rainfed cropland areas	% of total global rainfed cropland areas	Total NET cropland areas (irrigated TAAI+rainfed)	Total GROSS cropland areas (AIA+rainfed)	% of total global GROSS cropland areas	Harvested area of rainfed + irrigated crops	Area equipped for irrigation	Area equipped for irrigation	Harvested area of irrigated crops	Maximum monthly growing area of irrigated crops	Harvested area of rainfed crops	Maximum monthly growing area of rainfed crops	Harvested area of rainfed + irrigated crops
A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21
#	Name	Hectares	Hectares	Hectares	Hectares	Hectares	%	Hectares	%	Hectares	Hectares	%	Hectares/yr	Hectares	Hectares	Hectares/yr	Hectares	Hectares/yr	Hectares	Hectares/yr
1	China	111988772	75880320	68233355	7688411	151802086	32.52	91635702	8.10	203624474	243437788	14.33	147070700	53823000	85655033	85655000	50627000	82691500	72835500	168346500
2	India	101234893	72612189	53685066	5956598	132253854	28.34	48824269	4.31	150059162	181078123	10.66	171696820	57291407	68724872	68724900	44300300	115719000	108352000	184443900
3	USA	28045478	18182104	4006141	2120942	24309188	5.21	133571602	11.80	161617080	157880790	9.30	183979540	27913872	20548479	20548500	20071100	111394000	111394000	131942500
5	Russia	13886856	8865013	2113783	224734	11203530	2.40	114788560	10.14	128675416	125992090	7.42	126892130	4899900	3772922	3772920	3772920	75288900	75288900	79061820
14	Brazil	4195118	2165151	869365	1051327	4085844	0.88	87408556	7.72	91603674	91494400	5.39	51341076	3149217	2820954	2820970	2719070	47144500	45258500	49965470
6	Argentina	9304258	3601505	1605815	3559092	8766412	1.88	34318900	3.03	43623158	43085312	2.54	34010544	1767784	1352379	1352380	1352380	29024400	29027100	30376780
11	Australia	11865244	2991344	0	2382064	5373409	1.15	36758302	3.25	48623546	42131711	2.48	30030778	2056580	2384292	2384300	2286550	21219600	15950000	23603900
9	Kazakhstan	7227718	4625716	1760606	83362	6469685	1.39	31722986	2.80	38950704	38192671	2.25	23507754	1855200	1804753	1804750	1727760	14085200	13517600	15889950
20	Canada	2658297	1727915	1124721	21616	2874252	0.62	34944402	3.09	37602699	37818654	2.23	42773136	785046	707053	707056	707050	34353900	34146900	35060956
26	Ukraine	2995578	1631677	258515	491607	2381799	0.51	28290153	2.50	31285731	30671952	1.81	36282376	2395500	1005120	1005120	1005120	26733700	26733700	27738820
16	Indonesia	3172879	1221384	716038	1385021	3322443	0.71	17573608	1.55	20746487	20896051	1.23	54709968	4459000	7108333	7108330	4314020	24425300	21978300	31533630
21	France	2399518	1249368	829980	607806	2687153	0.58	17648821	1.56	20048339	20335974	1.20	19494778	2906081	1708020	1708020	1575620	16226300	16226300	17934320
4	Pakistan	14036151	7895566	7302243	761533	15959342	3.42	3642557	0.32	17678708	19601899	1.15	23634900	14417464	19344802	19344800	11591100	3471930	2998450	22816730
18	Spain	3421724	1516815	683698	825310	3025823	0.65	15392046	1.36	18813770	18417869	1.08	18712148	3575488	3423510	3423510	3167060	11499900	11499900	14923410
7	Thailand	6610586	3228550	2209523	1959295	7397368	1.59	9931747	0.88	16542333	17329115	1.02	17151778	4985708	6187300	6187300	3930080	11514700	11854100	17702000
164	Zambia	779	0	0	536	536	0.00	16677106	1.47	16677885	16677642	0.98	5338720	155912	55387	55387	48816	1071070	1091760	1126457
107	Tanzania	47022	33678	7852	5467	46998	0.01	16410652	1.45	16457674	16457650	0.97	5477548	184330	227000	227000	141564	5641460	4999840	5868460
15	Mexico	3854673	1818168	916083	874479	3608730	0.77	12497923	1.10	16352596	16106653	0.95	38267104	6435800	5958094	5958090	5316100	11246700	11157800	17204790
124	Congo, Dem. Rep.	21833	19326	191	857	20375	0.00	15815336	1.40	15837169	15835711	0.93		10500	7771	7771	6800	6061650	6323630	6069421
56	Poland	351514	268183	185150	779	454111	0.10	14424037	1.27	14775551	14878148	0.88	14790640	134050	83292	83292	83292	12150000	12150000	12233292
103	Mozambique	56415	39402	16753	4587	60742	0.01	13726544	1.21	13782959	13787286	0.81	4435618	118120	40063	40063	35026	3093520	3356670	3133583
112	Angola	23316	16671	14371	3116	34158	0.01	13454118	1.19	13477434	13488276	0.79	3404562	80000	42000	42000	35000	2123380	2372100	2165380
10	Myanmar(Burma)	4452997	3360330	2798234	148108	6306671	1.35	6257996	0.55	10710993	12564667	0.74	10997484	1841320	2263062	2263060	1320680	10890200	10052500	13153260
32	Turkey	1753382	882867	332404	362042	1577313	0.34	10603366	0.94	12356748	12180679	0.72	22992722	4185910	3476000	3476000	2390480	17142500	17142500	20618500
19	Germany	2197697	1642692	1318567	40415	3001674	0.64	8998878	0.80	11196575	12000552	0.71	12543913	496871	266827	266827	228889	12099400	12099400	12366227
102	Belarus	84088	60731	195	0	60926	0.01	10968114	0.97	11052202	11029040	0.65	5872892	115000	115000	115000	114185	6050970	6050970	6165970
43	South Africa	821040	574487	206929	47075	828491	0.18	10097803	0.89	10918843	10926294	0.64	15444497	1498000	1664300	1664300	1448040	5768150	5255740	7432450
13	Vietnam	4384022	1865074	1419401	1665058	4949533	1.06	5967528	0.53	10351550	10917061	0.64	0	3000000	5228400	5228400	2978400	6450190	6305110	11678590
74	Ethiopia	184239	62157	25604	75047	162808	0.04	10564343	0.93	10748582	10727151	0.63	11042325	289530	410557	410557	249461	7810690	6065960	8221247
70	Nigeria	197909	103154	61884	51115	216154	0.05	9572789	0.85	9770698	9788943	0.58	36278520	293117	164000	164000	124394	36852800	35808400	37016800
30	Sudan	1737118	1185252	643655	101685	1930592	0.41	7816063	0.69	9553181	9746655	0.57	17520156	1863000	1208110	1208110	883921	10245300	8499570	11453410
8	Bangladesh	5235050	3882847	3076494	206686	7166028	1.54	2536292	0.22	7771342	9702320	0.57	9707694	3751045	6431077	6431080	3595540	8571160	6692060	15002240
28	Romania	2375239	1128692	315485	605711	2049888	0.44	7563254	0.67	9938493	9613142	0.57	10143706	2149903	422724	422724	401795	9404020	9404020	9826744
31	Philippines	1542629	1024930	589003	175175	1789108	0.38	7479645	0.66	9022274	9268753	0.55	10265201	1550000	2067000	2067000	1162000	11243600	10692000	13310600
22	Italy	2829523	1342442	539802	761896	2644140	0.57	6436452	0.57	9265975	9080592	0.53	8788428	3892202	2670358	2670360	2471380	6671640	6671640	9342000
73	Bolivia	214091	28854	9777	124404	163036	0.04	8803829	0.78	9017920	8966865	0.53	3155506	128240	127001	127001	126999	2201000	2016080	2328001
146	Zimbabwe	4744	3234	299	0	3533	0.00	8781932	0.78	8786676	8785465	0.52	3544333	173513	202816	202816	135570	2057260	2075330	2260076

Table 1. *Cont.*

A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21
12	Uzbekistan	3601487	2733397	2427259	134859	5295515	1.14	2821987	0.25	6423474	8117502	0.48	5312912	4223000	3819097	3819100	3389710	1144480	1017500	4963580
24	Iran	2623336	1308727	679564	500268	2488558	0.53	5509694	0.49	8133030	7998252	0.47	14774583	6913800	7296524	7296520	5308790	5899260	5337800	13195780
37	United Kingdom	970733	810688	233603	15913	1060204	0.23	5014629	0.44	5985362	6074833	0.36	7140452	228950	183461	183461	183461	5674230	5674230	5857691
83	Kenya	85401	53025	37354	14148	104527	0.02	5944333	0.53	6029734	6048860	0.36	5094582	103203	76813	76813	59593	4199470	3892500	4276283
53	Colombia	546186	336538	176558	79399	592495	0.13	5359287	0.47	5905473	5951782	0.35	3660984	900000	645000	645000	617767	3017570	2931630	3662570
25	Japan	2525096	1157850	656470	654276	2468596	0.53	3428667	0.30	5953763	5897263	0.35	3771969	3129000	2167228	2167230	1523010	2189900	2169270	4357130
120	Paraguay	28582	12913	1670	10445	25029	0.01	5538996	0.49	5567578	5564025	0.33	2964544	67000	54000	54000	54000	4861040	4814890	4915040
94	Madagascar	72359	41627	19039	14490	75156	0.02	5345476	0.47	5417835	5420632	0.32	3723170	1086291	1105685	1105690	574486	1287310	1439370	2393000
66	Malaysia	258766	123739	66638	84189	274565	0.06	5042468	0.45	5301234	5317033	0.31	8588696	362600	501606	501606	284830	5310880	5247650	5812486
60	Peru	355956	189766	113945	71243	374954	0.08	4846774	0.43	5202730	5221728	0.31	4382453	1729069	1108999	1109000	781688	1494620	1198310	2603620
85	Ivory Coast	95138	79392	20756	1742	101890	0.02	4986024	0.44	5081162	5087914	0.30	7050554	72750	41618	41618	40743	6355950	5905470	6397568
113	Uganda	30017	26957	3447	183	30586	0.01	5012869	0.44	5042886	5043455	0.30	8363950	9150	2330	2330	2025	6288240	5898730	6290570
41	Cambodia	736318	480153	329683	128606	938441	0.20	3868166	0.34	4604484	4806607	0.28	4115292	284172	336992	336992	171665	2098280	2050380	2435272
36	Morocco	1045119	578582	460512	114723	1153817	0.25	3603724	0.32	4648843	4757541	0.28	9755383	1458160	1468600	1468600	1186830	5362090	5096880	6830690
33	Nepal	1251988	681267	530989	265047	1477303	0.32	3131060	0.28	4383048	4608363	0.27	2892683	1168349	1257984	1257980	775053	2950220	2779970	4208200
72	Hungary	241714	166069	14990	5162	186221	0.04	4358475	0.39	4600189	4544696	0.27	4793370	292147	103764	103764	97483	4786070	4786070	4889834
38	Bulgaria	1301804	579629	62782	369652	1012064	0.22	3416518	0.30	4718322	4428582	0.26	3678408	545160	50898	50898	37001	3164360	3164360	3215258
46	Venezuela	894880	499284	93686	214109	807078	0.17	3256971	0.29	4151851	4064049	0.24	8062588	570219	491000	491000	490997	1251740	1191990	1742740
23	Iraq	2220024	1242694	1254929	128942	2626564	0.56	1356711	0.12	3576735	3983275	0.23	5958466	3525000	2439000	2439000	2274790	36974	36974	2475974
34	Chile	1514922	703120	345867	396243	1445230	0.31	2412213	0.21	3927135	3857443	0.23	2457098	1900000	897274	897274	730165	831023	831022	1728297
49	Czech Republic	518036	380186	321296	245	701727	0.15	3068209	0.27	3586245	3769936	0.22	3141046	50590	16554	16554	16554	2593460	2593460	2610014
61	Uruguay	381403	311863	25602	22591	360055	0.08	3354348	0.30	3735751	3714403	0.22	1621174	217593	216979	216979	216978	551795	545327	768774
42	Afghanistan	1008138	403083	218706	301701	923490	0.20	2748082	0.24	3756220	3671572	0.22	8355130	3199070	1912917	1912920	1468090	1427810	1398810	3340730
78	Algeria	144349	90667	34731	11548	136946	0.03	3520819	0.31	3665168	3657765	0.22	6174593	569418	570447	570447	512517	2908470	2727970	3478917
27	Korea, Dem. Rep.	1467262	935934	923533	194157	2053625	0.44	1598207	0.14	3065469	3651832	0.22	2858257	1460000	1278000	1278000	1278000	1557170	1545920	2835170
17	Egypt	2144099	1635323	1491605	165798	3292726	0.71	281590	0.02	2425689	3574316	0.21	2494046	3422178	6027115	6027120	3248170	1199970	1199710	7227090
48	Greece	907739	271632	106151	388895	766678	0.16	2757498	0.24	3665237	3524176	0.21	2742187	1544530	1237967	1237970	1161030	2060890	2060890	3298860
35	Korea, Rep.	1192469	546413	432289	335053	1313755	0.28	1928760	0.17	3121229	3242515	0.19	1858862	880365	875415	875415	875415	1290420	1219390	2165835
142	Botswana	5417	3687	590	0	4278	0.00	3198620	0.28	3204037	3202898	0.19	778086	1439	620	620	620	166867	166866	167487
67	Serbia	171939	140266	92171	1910	234348	0.05	2947604	0.26	3119543	3181952	0.19		163311	60071	60071	60071	3099970	3099970	3160041
65	Ecuador	288581	127918	85157	68091	281166	0.06	2844430	0.25	3133011	3125596	0.18	2705382	863370	686000	686000	686000	1792480	1629470	2478480
63	Portugal	358865	133115	54464	126330	313908	0.07	2756177	0.24	3115042	3070085	0.18	2853130	792008	638947	638947	600314	1727700	1727700	2366647
96	Ghana	60647	28411	24173	19181	71764	0.02	2716307	0.24	2776954	2788071	0.16	6248967	30900	17138	17138	14519	5140830	5024290	5157968
47	Kyrgyzstan	700876	447852	247134	75288	770274	0.17	1990967	0.18	2691843	2761241	0.16	1159904	1075040	1140614	1140610	1064460	341595	337899	1482205
110	Lithuania	57272	41591	0	0	41591	0.01	2651512	0.23	2708784	2693103	0.16	3734526	4416	4416	4416	4416	2369650	2369650	2374066
51	Cuba	486898	342202	269666	25291	637159	0.14	2007424	0.18	2494322	2644583	0.16	4963997	870319	822225	822225	822225	1440130	1405960	2262355
106	Cameroon	52694	35415	5861	10852	52128	0.01	2591767	0.23	2644461	2643895	0.16	7437664	25654	45079	45079	25654	3243950	2981280	3289029
29	Turkmenistan	1522372	994264	904352	101368	1999984	0.43	542979	0.05	2065351	2542963	0.15	1878684	1744100	1402828	1402830	1193410	473466	382018	1876296
59	Mongolia	422332	265966	110413	0	376378	0.08	2136984	0.19	2559316	2513362	0.15	1823339	57300	57300	57300	57300	252370	250226	309670
62	Guinea	302633	153448	95459	71442	320350	0.07	2190800	0.19	2493433	2511150	0.15	1691191	94914	20386	20386	13523	1856450	1809260	1876836
158	Central African Republic	1155	1086	0	0	1086	0.00	2393214	0.21	2394369	2394300	0.14	2129445	135	69	69	43	776393	811591	776462
179	Congo	0	0	0	0	0	0.00	2386480	0.21	2386480	2386480	0.14	733403	2000	2000	2000	2000	211392	240616	213392
64	Senegal	211416	148318	129202	13052	290572	0.06	1980242	0.18	2191658	2270814	0.13	2475760	119680	83904	83904	53904	1693600	1571660	1777504
45	Sri Lanka	948029	169255	111161	529164	809579	0.17	1439246	0.13	2387275	2248825	0.13	2046457	570000	731700	731700	400850	1344560	1275970	2076260
44	Azerbaijan	835627	441335	218092	162553	821980	0.18	1398784	0.12	2234411	2220764	0.13	2054320	1453318	730129	730129	730010	734327	684343	1464456
99	Mali	56355	38220	26100	1559	65879	0.01	2051073	0.18	2107428	2116952	0.12	5015301	235791	180317	180317	106905	2424560	2234560	2604877
137	Latvia	12683	7260	65	0	7325	0.00	2040565	0.18	2053248	2047890	0.12	1838370	1150	833	833	833	917421	917421	918254
128	Burkina faso	15663	4539	4420	5702	14660	0.00	2025961	0.18	2041624	2040621	0.12	3914244	25000	20233	20233	14932	3483640	3314970	3503873

Table 1. *Cont.*

A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21
81	Lao Dem.Rep.	105585	78350	21795	7589	107734	0.02	1917269	0.17	2022854	2025003	0.12	1137818	295535	354642	354642	211641	637728	608301	992370
149	Malawi	3293	2794	0	0	2794	0.00	1996142	0.18	1999435	1998936	0.12	1440040	56390	56515	56515	53709	1541930	1589460	1598445
87	Austria	116456	69017	19025	10509	98551	0.02	1822194	0.16	1938650	1920745	0.11	1569707	97480	41076	41076	34230	1331250	1331250	1372326
50	Taiwan, Prov. China	499043	282608	314359	80910	677877	0.15	1111947	0.10	1610990	1789824	0.11		525528	588798	588798	368552	363675	315310	952473
93	Slovakia	109904	71826	1044	2618	75488	0.02	1690815	0.15	1800719	1766303	0.10	1339293	15643	104560	104560	104560	1324930	1324930	1429490
68	Moldova	294070	161373	20311	47749	229433	0.05	1533012	0.14	1827082	1762445	0.10	2046245	307000	256377	256377	223406	1530200	1530200	1786577
57	Tajikistan	383243	277736	156376	15040	449153	0.10	1190392	0.11	1573635	1639545	0.10	1091111	719200	637213	637213	549562	347061	301498	984274
55	Belgium	324796	294221	204916	8293	507430	0.11	1101425	0.10	1426221	1608855	0.09		35170	10378	10378	6484	416387	416387	426765
192	Papua New Guinea	0	0	0	0	0	0.00	1607752	0.14	1607752	1607752	0.09	2024525	0		0	0	923169	820222	923169
77	New Zealand	125390	68146	58034	15505	141686	0.03	1459699	0.13	1585089	1601385	0.09	660818	577882	383236	383236	383236	372708	271042	755944
168	Liberia	237	201	100	0	300	0.00	1598806	0.14	1599043	1599106	0.09	379859	2100	2100	2100	2100	399802	409810	401902
109	Croatia	35202	28102	15511	1018	44630	0.01	1551680	0.14	1586882	1596310	0.09	1992810	5790	5000	5000	5000	1138000	1138000	1143000
58	Somalia	372476	162324	117817	123434	403574	0.09	1189487	0.11	1561963	1593061	0.09	1093790	200000	206000	206000	200000	340769	344951	546769
39	Netherlands	870243	681847	299991	29502	1011340	0.22	564102	0.05	1434345	1575442	0.09	833890	476315	153650	153650	146333	737499	737499	891149
89	Guatemala	69373	47776	40864	2673	91313	0.02	1440867	0.13	1510240	1532180	0.09	2630816	129803	139788	139788	129803	1479390	1398810	1619178
40	Denmark	1164705	976705	2835	0	979539	0.21	517119	0.05	1681824	1496658	0.09	3197374	476000	204071	204071	180740	2450940	2450940	2655011
52	Syria	566990	302293	235219	58751	596263	0.13	879249	0.08	1446239	1475512	0.09	4837218	1266900	1507867	1507870	1156250	3160120	3160120	4667990
92	Honduras	70584	51034	21071	5623	77729	0.02	1384346	0.12	1454930	1462075	0.09	1623373	73210	100000	100000	65739	852399	674025	952399
86	Tunisia	109144	30355	23663	46628	100647	0.02	1284882	0.11	1394026	1385529	0.08	2444246	394063	367000	367000	367000	1690130	1658470	2057130
115	Sierra Leone	21807	16343	12481	213	29037	0.01	1336205	0.12	1358012	1365242	0.08	582745	29360	30000	30000	20500	477979	417570	507979
130	Bosnia and Herzegovina	10766	6696	5445	2062	14203	0.00	1303620	0.12	1314386	1317823	0.08	995513	4630	3000	3000	3000	633413	633413	636413
122	Nicaragua	16439	12165	9941	614	22720	0.01	1241957	0.11	1258396	1264677	0.07	2542479	61365	75222	75222	57406	867862	812828	943084
97	Sweden	83918	69968	1140	0	71108	0.02	1040821	0.09	1124739	1111929	0.07	2804305	188470	53440	53440	53440	2227520	2227520	2280960
69	Albania	223777	117469	55223	53172	225864	0.05	864549	0.08	1088326	1090413	0.06	677557	340000	180000	180000	180000	264223	264223	444223
181	Gabon	0	0	0	0	0	0.00	1084861	0.10	1084861	1084861	0.06	315822	4450	8450	8450	4239	205735	210814	214185
108	Panama	49069	21997	6477	16574	45048	0.01	1037572	0.09	1086641	1082620	0.06	826045	34626	30811	30811	30811	278973	230981	309784
129	Estonia	24637	14476	0	0	14476	0.00	1052562	0.09	1077199	1067038	0.06	897736	1363	600	600	600	765029	765028	765629
116	Chad	25234	15932	8020	3747	27698	0.01	925287	0.08	950521	952985	0.06	3831578	30273	26804	26804	22754	2082790	1932290	2109594
76	Georgia	128538	96950	46285	2907	146141	0.03	796878	0.07	925416	943019	0.06	1138420	300000	196702	196702	173943	547279	519852	743981
79	Macedonia	169843	113105	9610	8905	131620	0.03	695920	0.06	865763	827540	0.05	717538	127800	42500	42500	42500	360056	360056	402556
136	Burundi	11793	534	36	7921	8490	0.00	798743	0.07	810536	807233	0.05	588748	21430	20130	20130	10907	1125320	1073810	1145450
95	Finland	125307	71961	0	0	71961	0.02	721148	0.06	846455	793109	0.05	2447813	103800	20000	20000	20000	1991230	1991230	2011230
126	Costa rica	12628	9730	5448	613	15791	0.00	772096	0.07	784724	787887	0.05	697421	103084	123030	123030	100518	349366	333138	472396
100	Rwanda	80067	64806	0	0	64806	0.01	710557	0.06	790624	775363	0.05	777961	8500	5500	5500	2417	1349640	1286550	1355140
121	Togo	21727	9624	7433	6786	23843	0.01	725130	0.06	746857	748973	0.04	3045446	7300	2557	2557	2400	1376440	1107000	1378997
111	Switzerland	29523	21079	15897	0	36976	0.01	690849	0.06	720372	727825	0.04	374221	40000	14500	14500	10500	428373	428373	442873
141	Niger	4129	3121	1196	0	4317	0.00	703697	0.06	707826	708014	0.04	13904998	73663	96125	96125	55479	10238200	10238700	10334325
127	Benin	15173	4383	3797	7235	15415	0.00	668742	0.06	683915	684157	0.04	2880695	12258	2823	2823	2505	1787270	1428470	1790093
135	Namibia	10526	7508	1795	0	9303	0.00	672697	0.06	683223	682000	0.04	819824	7573	8806	8806	6389	185874	185874	194680
185	Ireland	0	0	0	0	0	0.00	630766	0.06	630766	630766	0.04	1348463	1100	1100	1100	1100	586198	586198	587298
90	Dominican Republic	70876	45462	25851	8335	79648	0.02	550415	0.05	621291	630063	0.04	1667190	269710	220000	220000	164500	687649	688183	907649
71	Libya	230656	67173	60076	82773	210022	0.05	412158	0.04	642814	622180	0.04	805312	470000	316000	316000	316000	357915	336287	673915
54	Saudi Arabia	678677	143187	89073	318806	551066	0.12	63518	0.01	742195	614584	0.04	2148407	1730767	1280725	1280720	1022940	122034	120988	1402754
145	Lesotho	5675	3681	0	0	3681	0.00	571627	0.05	577302	575308	0.03	417547	2638	203	203	203	188366	170530	188569
88	Swaziland	149274	97004	0	0	97004	0.02	446942	0.04	596216	543946	0.03	128573	49860	45482	45482	45482	134479	134295	179961
165	Slovenia	439	293	217	0	510	0.00	542220	0.05	542659	542730	0.03	254712	0	10324	10324	8952	183915	183912	194239
104	Haiti	50848	29974	15438	8490	53903	0.01	486161	0.04	537009	540064	0.03	1567588	91502	89000	89000	67500	1048170	855320	1137170
80	Armenia	106695	73185	37092	8047	118324	0.03	415591	0.04	522286	533915	0.03	410979	286027	172806	172806	120981	333254	294465	506060

Table 1. *Cont.*

A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21
155	Norway	2072	1323	130	0	1453	0.00	485336	0.04	487408	486789	0.03	569607	134396	36200	36200	36200	604876	604876	641076
131	Montenegro	10331	6940	5604	1364	13908	0.00	364360	0.03	374691	378268	0.02	0	0	2109	2109	2109	347634	347634	349743
75	Guinea Bissau	108042	84650	66770	3969	155389	0.03	191959	0.02	300001	347348	0.02	546406	22558	8562	8562	8232	369965	365026	378527
134	El Salvador	11592	7839	2508	54	10401	0.00	294667	0.03	306259	305068	0.02	1036444	44993	50710	50710	44019	738223	736480	788933
84	Guyana	96276	61736	30935	10259	102930	0.02	184027	0.02	280303	286957	0.02	438246	150134	178029	178029	114733	53756	42819	231785
91	Yemen	91688	42912	16073	20203	79188	0.02	206310	0.02	297998	285498	0.02	8690437	388000	399668	399668	254862	661291	583094	1060959
101	Gambia	39872	34993	28422	0	63415	0.01	197119	0.02	236991	260534	0.02	540746	0	7000	0	0	0	0	0
132	Eritrea	17017	11467	2309	0	13776	0.00	232850	0.02	249867	246626	0.01	523471	21590	5969	5969	4554	501042	373184	507011
147	Belize	3887	2919	306	286	3510	0.00	228077	0.02	231964	231587	0.01	102505	3000	3000	3000	2350	82274	76685	85274
143	East Timor	3800	3257	804	0	4061	0.00	222063	0.02	225863	226124	0.01	0	14000	0	7000	7000	179410	163146	186410
82	Israel	99806	39883	37020	27639	104542	0.02	101665	0.01	201471	206207	0.01	407057	183408	184072	184072	164701	76797	76797	260869
157	Bhutan	997	796	600	0	1396	0.00	154068	0.01	155065	155464	0.01	226391	38734	43507	43507	38734	77788	65103	121295
139	Cyprus	7099	2751	129	1983	4863	0.00	148942	0.01	156041	153805	0.01	0	55813	36210	36210	35410	5342	5342	41552
119	Lebanon	24747	11240	8170	5859	25268	0.01	126708	0.01	151455	151976	0.01	264201	117113	139292	139292	104384	137695	129000	276987
133	Puerto Rico	11964	7082	1582	2588	11253	0.00	138701	0.01	150665	149954	0.01	0	37079	17465	17465	17465	49918	48476	67382
105	Jordan	72717	574	568	51399	52541	0.01	75548	0.01	148265	128089	0.01	595772	76912	100105	100105	68811	42477	42477	142582
125	Mauritania	15124	9814	10007	214	20036	0.00	100469	0.01	115593	120505	0.01	745161	45012	23084	23084	14423	272066	175249	295150
187	Luxembourg	0	0	0	0	0	0.00	111041	0.01	111041	111041	0.01	1051585	27	24	24	16	34221	34221	34245
123	Suriname	19845	14491	5070	1213	20774	0.00	88593	0.01	108438	109367	0.01	77794	51180	51180	51180	51180	9400	8440	60580
114	Oman	17853	15247	14898	0	30145	0.01	66449	0.01	84302	96594	0.01	98737	72630	72461	72461	71013	3143	3143	75604
160	Brunei Darussalam	799	481	369	152	1002	0.00	86509	0.01	87308	87511	0.01	57747	1000	1000	1000	1000	15028	9775	16028
98	United Arab Emirates	93810	10249	4867	55487	70603	0.02	0	0.00	93810	70603	0.00	180144	280341	204951	204951	186479	19453	19453	224404
140	Jamaica	4881	3058	492	1006	4556	0.00	61139	0.01	66020	65695	0.00	0	25214	24666	24666	23780	171191	156788	195857
154	West Bank	1612	538	533	471	1542	0.00	64136	0.01	65748	65678	0.00	3801523	0	0	0	0	0	0	0
150	Equatorial guinea	2812	2644	0	0	2644	0.00	57260	0.01	60072	59904	0.00	130423	0	0	0	0	127208	122608	127208
117	Qatar	38509	0	0	27596	27596	0.01	0	0.00	38509	27596	0.00	0	12520	9544	9544	6176	0	0	9544
118	Kuwait	37333	0	0	26753	26753	0.01	0	0.00	37333	26753	0.00	15704	6968	8509	8509	5937	719	719	9229
148	French Guiana	2860	2217	351	254	2822	0.00	18869	0.00	21729	21691	0.00	15752	2000	6007	6007	5865	9658	6895	15665
153	Trinidad and Tobago	1859	1672	0	48	1720	0.00	8590	0.00	10449	10310	0.00	167262	3600	3600	3600	3310	57308	54015	60908
195	Singapore	0	0	0	0	0	0.00	8941	0.00	8941	8941	0.00	102300	225310	0	0	0	405	209	405
138	Gaza Strip	5909	3192	3223	375	6790	0.00	693	0.00	6602	7483	0.00	0	0	0	0	0	0	0	0
175	Andorra	0	0	0	0	0	0.00	5776	0.00	5776	5776	0.00	20558	150	150	150	150	0	0	150
186	Liechtenstein	0	0	0	0	0	0.00	4839	0.00	4839	4839	0.00	0	0	0	0	0	0	0	0
144	Mauritius	5312	2381	0	1528	3910	0.00	0	0.00	5312	3910	0.00	0	21222	20919	20919	20441	67663	64642	88582
162	San Marino	1102	0	0	797	797	0.00	2060	0.00	3162	2857	0.00	0	0	0	0	0	1957	1957	1957
151	Antigua and Barbuda	2270	1378	706	384	2468	0.00	0	0.00	2270	2468	0.00	0	130	130	130	130	3478	3187	3608
152	Guadeloupe	1894	1498	342	183	2022	0.00	0	0.00	1894	2022	0.00	0	2000	5697	5697	5642	20111	18707	25808
156	St. Kitts and Nevis	1650	1314	84	48	1445	0.00	0	0.00	1650	1445	0.00	0	18	0	18	18	7831	7440	7849
159	Virgin Islands	827	563	361	91	1015	0.00	0	0.00	827	1015	0.00	1516774	185	0	185	185	0	0	185
161	Reunion	651	517	329	0	846	0.00	0	0.00	651	846	0.00	0	13000	7584	7584	7142	46469	43173	54053
163	Djibouti	905	587	0	0	587	0.00	0	0.00	905	587	0.00	1092	1012	388	388	388	707	707	1095
166	Comoros	241	218	199	0	417	0.00	0	0.00	241	417	0.00	0	130	85	85	85	75698	79698	75783
167	Anguilla	489	404	0	0	404	0.00	0	0.00	489	404	0.00	0	0	0	0	0	0	0	0
173	Monaco	73	0	0	53	53	0.00	132	0.00	205	185	0.00	0	0	0	0	0	0	0	0
169	Turks and Caicos Islands	214	117	0	53	170	0.00	0	0.00	214	170	0.00	0	0	0	0	0	0	0	0
170	Montserrat	69	51	65	0	115	0.00	0	0.00	69	115	0.00	0	0	0	0	0	554	334	554

Table 1. *Cont.*

A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21
171	St. Pierre and Miquelon	70	59	0	0	59	0.00	0	0.00	70	59	0.00	0	0	0	0	0	0	0	0
172	Cayman Islands	66	55	0	0	55	0.00	0	0.00	66	55	0.00	0	0	0	0	0	440	411	440
174	Seychelles	66	44	0	0	44	0.00	0	0.00	66	44	0.00	0	260	224	224	224	0	0	224
176	Bahrain	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	4060	3113	3113	3113	488	488	3601
177	Barbados	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	1000	1000	1000	1000	13175	12220	14175
178	Cape Verde	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	3109	2578	2578	2578	46964	47049	49542
180	Fiji	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	3000	3000	3000	3000	154135	151525	157135
183	Grenada	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	219	218	219	212	15440	14515	15659
184	Guam	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	312	312	312	312	13715	13602	14028
188	Malta	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	2300	3540	3540	2130	12330	12330	15870
189	Martinique	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	3000	6730	6730	6730	15595	13765	22325
190	Northern Marianna Islands	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	60	60	60	60	0	0	60
193	Pitcairn Islands	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	0	0	0	0	0	0	0
194	Sao Tome and Principe	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	9700	9700	9700	9700	15415	14871	25115
196	St. Lucia	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	297	0	297	297	24167	22817	24464
197	St. Vincent and the Grenadines	0	0	0	0	0	0.00	0	0.00	0	0	0.00	0	0	0	0	0	17261	14313	17261
198	Vatican city	0	0	0	0	0	0.00	0	0.00	0	0	0.00	3525306	0	0	0	0	0	0	0
	TOTAL	398526952	251760119	173553844	41443717	466757677	99.99	1131552272	100	1530079224	1598309949	94.11179331	1537977307	278803473	312384000	312384543	217730879.9	992349053.4	949425049.3	1304733596

Note: Cropland areas based on Thenkabail *et al.*, 2009b, 2009b [1,2]

A1 = Ranking based on total cropland (irrigated + rainfed) areas of the world reported by IWMI GIAM estimates;

A2 = Countries listed based on the ranking of total cropland (irrigated + rainfed) areas of the world reported by IWMI GIAM estimates;

A3 = TAAI or total area available for irrigation as determined by IWMI GIAM; A4 = Season 1 (June-October) irrigated areas as determined by IWMI GIAM;

A5 = Season 2 (November-February) irrigated areas as determined by IWMI GIAM;

A6 = Continuous (June-May) irrigated areas as determined by IWMI GIAM; A7 = annualized irrigated areas which is sum of season 1 + season 2 + continous year-round irrigated areas of IWMI GIAM;

A8 = % global annulaized (season 1 + season 2 + continuous) irrigated areas; A9 = total rainfed cropland areas (Note: rainfed cropland areas are assumed as only 1 crop per year);

A10 = % global rainfed cropland areas; A11 = total NET cropland areas (net irrigated areas or TAAI + rainfed areas);

A12 = total GROSS cropland areas (annualized irrigated areas taking areas of season 1, season 2, and continuous + rainfed cropland areas); A13 = % of GROSS cropland areas

Cropland areas based on Siebert et al., 2006 and Siebert *et al.* , 2008

A15 = area equipped for irrigation by FAO\UF (Siebert *et al., [52]* ; A16 = area equipped for irrigation by Siebert *et al.,* [49,97];

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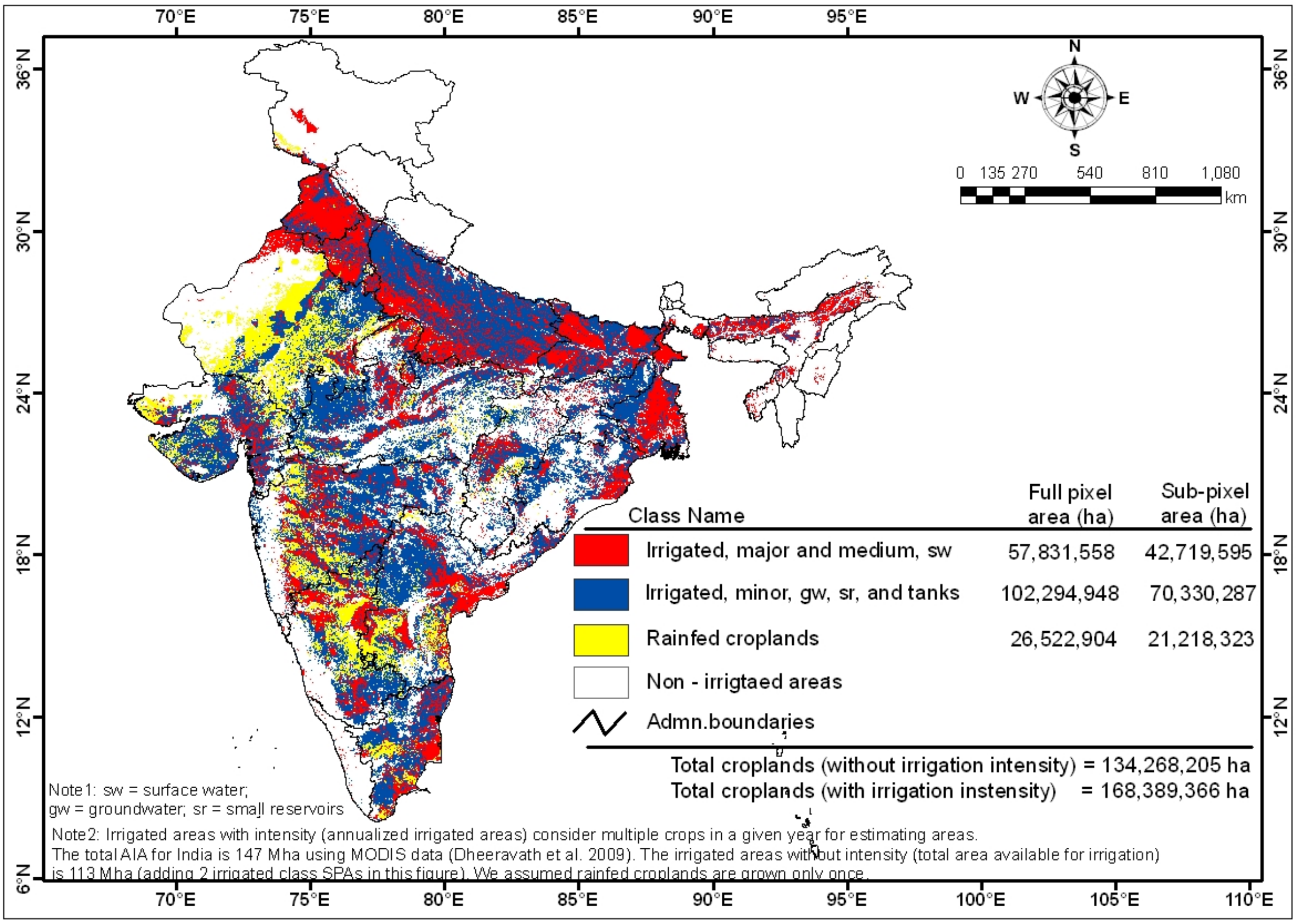
52 Siebert, S.; Hoogeveen, J.; Frenken, K. Irrigation in Africa, Europe and Latin America - Update of the Digital Global Map of Irrigation Areas to Version 4; Institute of Physical Geography, University of Frankfurt: Frankfurt am Main, Germany and Rome, Ital

97 Siebert, S.; Döll, P. The Global Crop Water Model (GCWM): Documentation and first results for irrigated crops, University of Frankfurt: Frankfurt am Main, Germany, 2008.

Third, is the absence of crop types in the coarse resolution products reported in Figures 1–4. Crop type information is crucial for water use assessment, productivity assessments, and many other practical applications of data and maps at local levels. Accurate crop classification is the key to determining many other crop specific parameters [70] such as water use by crops, water productivity, biomass, yield, and carbon sequestration [19,71].

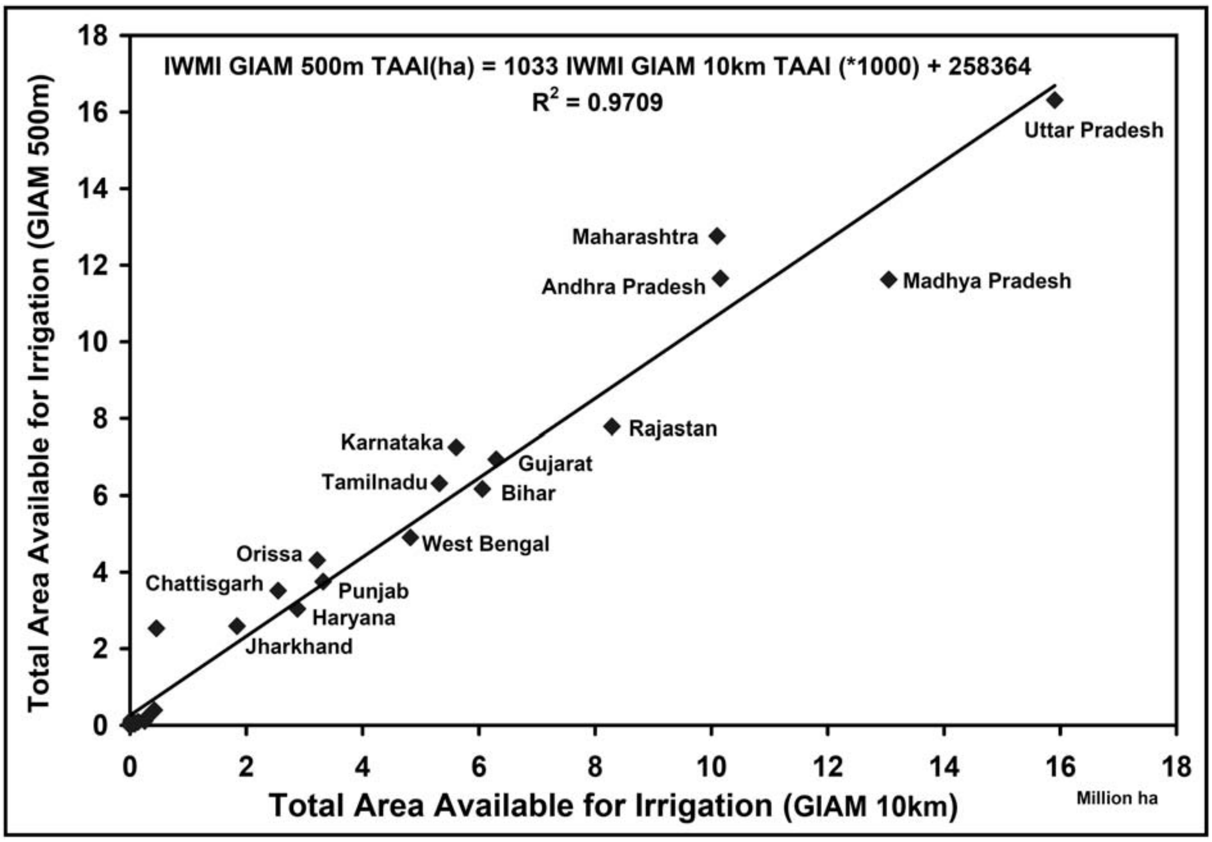
Fourth, the need to provide irrigated and rainfed cropland area products (maps, area statistics, precise location, local specific data) at a finer resolution is crucial for accurate assessment and study of global water use trends, food production trends, land use change patterns, investment targeting, and policy simulation and future scenario modeling. Given the climate change scenarios that are expected to accelerate negative impact on cropland areas, food production, and water use in the future [16] and make agriculture less resilient to natural shocks [72] the global food security studies demand precise knowledge of global irrigated and rainfed croplands in readily usable digital formats covering the entire world at a finer resolution.

Figure 8. Cropland areas at higher spatial resolution of 500 m, which is adopted from Dheeravath *et al*. [63]. Cropland areas of India are determined using MODIS 500 m resolution time-series data of years 2001–2003. Generally, most studies agree that about 50% (or 164 Mha) of India's geographic area (328.7 Mha) are croplands around year 2000.



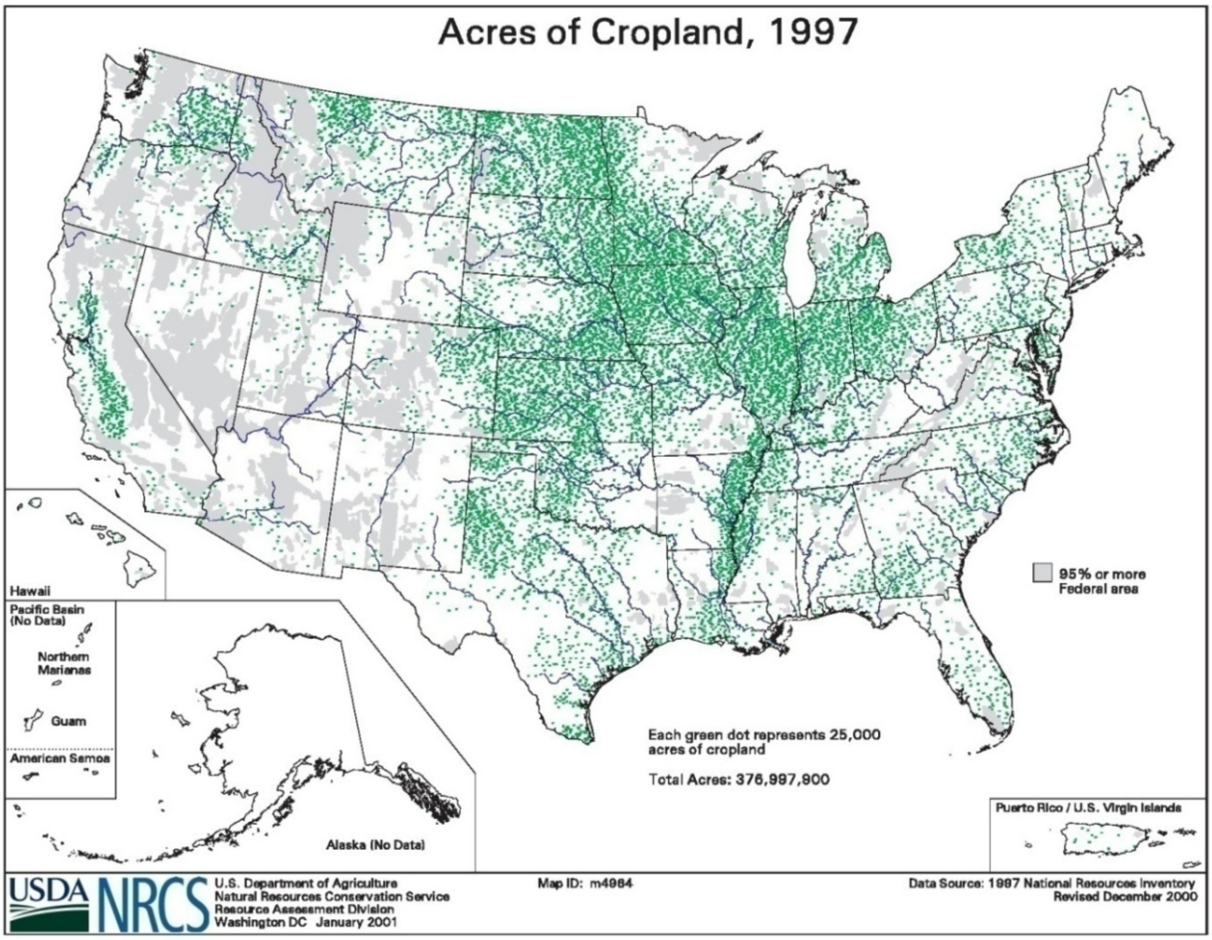
Fifth, there are several studies in mapping croplands using improved resolutions of 500 m MODIS [16,63,73] , or conventional agricultural statistics [74] but none of these are at the global level. These products continue to propagate uncertainties in cropland areas. These studies are mostly limited to the national or subnational level. Dheeravath *et al*. [63] produced a cropland (irrigated and rainfed) map of India (Figure 8) for 2001–2003 using MODIS 500 m time-series data along with a suite of secondary data and field-plot data. Thenkabail *et al*. [1,2] estimated total cropland areas of India as 150 Mha at 10-km, comparable to this 500 m finer resolution product. However, most studies [1,52] disagree on the (a) proportions of irrigated to rainfed croplands and (b) precise location of croplands. The total area available for irrigation or TAAI (cropping intensity not considered) was 113 Mha whereas the annualized irrigated areas or AIA (the intensity considered) was 147 Mha. There is a high correlation between areas derived from the MODIS 500 m product [63] and AVHRR 10-km product [1,2] (Figure 9).

Figure 9. Irrigated croplands at two resolutions in India [63]. There is a remarkable correlation (R^2 value of 0.97) in irrigated areas mapped at nominal 10-km [1,2] *versus* irrigated areas mapped at MODIS 500 m [63]. However, areas estimated by MODIS 500 m were significantly higher for a few Indian states. This resulted in higher area estimates from MODIS 500 m data compared to the 10km product. Using MODIS 500 m, the total area available for irrigation or TAAI (the intensity not considered) was 113 Mha whereas the annualized irrigated areas or AIA (the intensity considered) was 147 Mha. These figures are significantly higher than Thenkabail *et al*. [1,2] estimated figures at 10-km of TAAI at 101 Mha and AIA at 132 Mha.



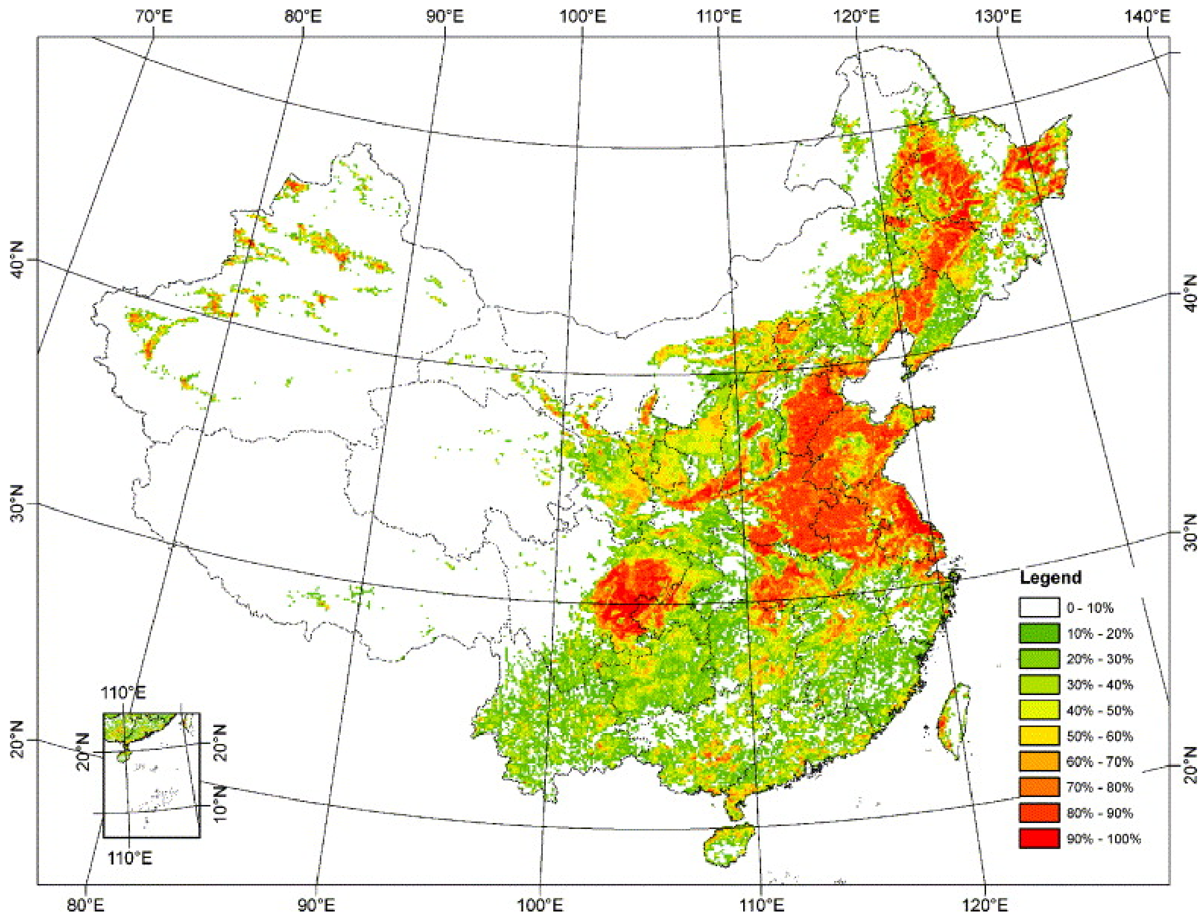
However, the MODIS derived areas were significantly higher than Thenkabail *et al*. [1,2] estimated areas at 10-km grid, TAAI of 101 Mha and AIA of 132 Mha. The cropland areas of India estimated using 10-km data were 203 Mha of TAAI and 243 Mha of AIA (Table 1), significantly higher figures than census based cropland statistics reported in the FAOSTAT as 168 Mha for year 2000 or 184 Mha reported by Portmann *et al*. [41] and Siebert and Döll [49]. The cropland statistics of 152 Mha reported by NRI (1997) for USA (Figure 10) are very close to Thenkabail *et al*. [1,2] reported 158 Mha but significantly higher than Portmann *et al*. [41] and Siebert and Döll [49] reported 131 Mha (Table 1). These results show that there is a need for more rigorous and consistent approach to overcome these limitations.

Figure 10. Cropland areas using non-remote sensing approaches with each dot representing 25,000 acres [74]. Cropland areas of USA are determined using various statistical data by NRI. Total cropland areas of USA is 152.56 Mha [74]. Thus about 15.86% of USA's geographic area (963.1 Mha) are croplands around the year 2000. Thenkabail *et al*. [1,2] estimates 161.6 Mha. Irrigation intensity actually reduces this area to 157.8 Mha because there is overwhelmingly only one irrigated crop and during this period some of the land is left fallow. Map available at: http://www.nrcs.usda.gov/technical/nri/maps/meta/ m4964.html.



Sixth, Liu *et al*. [58] even used Landsat 30 m data to produce a cropland map of China (Figure 11). Their estimated cropland area of China for nominal year 2000 was 141 Mha—a figure lower than the FAOSTAT estimate of 160 Mha and Portmann *et al*. [41] and Siebert and Döll [49] reported 168 Mha (Table 1). It is difficult to say which estimate is more accurate. Liu *et al*. [58] study relied solely on one time Landsat data, which again can be a limitation. This implies that, we will not only need finer spatial resolution, but also higher temporal frequency (e.g., MODIS) to narrow the range of uncertainty and increase the reliability of estimates.

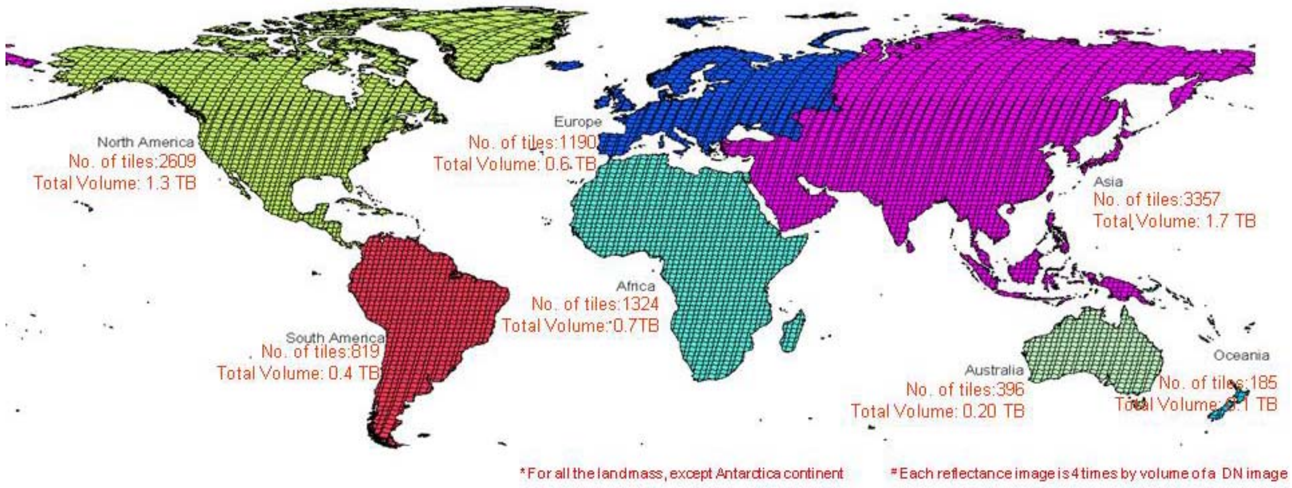
Figure 11. A cropland distribution map of China at 30 m resolution adopted from [58]. Cropland areas of China are determined using Landsat TM 30 m resolution data for 1990–2000. Total cropland areas of China is 141.1 Mha [58]. Thus about 14.35% of China's geographic area (982.6 Mha) are croplands around the year 2000. This estimate by Liu *et al*. [58] is lower than 203.8 Mha estimated by Thenkabail *et al*. [1,2]. This does not include the intensity of irrigated areas which will add an additional 40 Mha [1,2].



5. Way Forward in Cropland Mapping

Given the above issues with existing maps of global croplands and specifically irrigated and rainfed areas, the way forward will be to produce global irrigated and rainfed areas at finer Landsat 30 m resolutions. Research has shown that at finer spatial resolution the accuracy of irrigated and rainfed area class delineations is better because more fragmented and smaller patches of irrigated and rainfed cropland can be delineated [75,76]. Further, crop types can be determined using finer spatial resolution. This is crucial for determining crop water use, crop productivity, water productivity, biomass yield, and carbon assimilation and sequestration potential in agriculture as well as a number of other applications at local, regional, continental, and global scales, making these products invaluable for research and development purposes. Since the sophisticated orthorectified Landsat Geocover images for the entire world [77] are available for free for the nominal years 1975s, 1990s, 2000s, and 2005s, global irrigated and rainfed cropland area maps at 30-m resolution are possible for these epochs. However, the Landsat images will have to be fused with Moderate Resolution Imaging Spectroradiometer (MODIS) 500-m time-series images in order to obtain time-series spectra that are so crucial for monitoring crop growth dynamics and cropping intensity (e.g., single crop, double crop, continuous year round crop).

Figure 12. Illustrating the challenges of global mapping at higher spatial resolution. Distribution of Landsat 30 m images for the world. About 9,500 images are required to cover the terrestrial world, with a total data volume of about 20 TB. With advanced compression techniques this can be reduced to about 4 TB. Yet, single shot Landsat images need to be fused with time-series imagery such as MODIS 250 m or 500 m for a realistic analysis of croplands or other land use. This further adds to data volume. Further, processing such high volume data brings its own challenges. This will require us to use super computer facilities. Image Credit: Mr. Manohar Velpuri, South Dakota State University, South Dakota, USA.



However, there are significant challenges in terms of data volume as well as data processing that need to be addressed. For instance, the uncompressed volume of the 9,770 Landsat Geocover reflectance images (Figure 12) of the entire world is about 20 terabytes, which must be compressed to a more manageable size. Some compression techniques include: (a) JPEG2000 lossless compression using ERMapper software [78]; (b) principal component analysis (PCA); (c) vegetation indices; and (d) focus on irrigated areas mapped by IWMI GIAM 10-km [2]. The JPEG2000 lossless compression, retaining all six nonthermal Landsat bands, reduces the volume for the global mosaic from about 20 TB to 4.8 TB, yet retaining the integrity of original reflectance values. Further, a massive reduction in global data volume is possible by several different approaches. First, taking only the irrigated and rainfed areas of the world as mapped in GIAM 10 km and in the global map of rainfed cropland areas (GMRCA 10 km)—both produced by IWMI (the statistics of which are also available at http://www.iwmigiam.org). The greatest confusion for irrigated areas comes from rainfed croplands. Putting the GIAM and GMRCA maps together, a total of about 1,500 Mha are covered, but often as blocks of fragments and not all contiguous areas. The GIAM and GMRCA areas are covered by roughly 1,000 Landsat images (down from the global coverage of 9,770 images), which reduced the data volume of the world to about 1.5 TB for 6-band reflectance images and a very manageable 360 gigabyte compressed JPEG2000 6-band image mosaic.

There is growing literature on global cropland (irrigated and rainfed) mapping across resolutions [1,2,43,76,79–85]. Based on these experiences, an ensemble of methods that is considered most efficient includes: (a) spectral matching techniques (SMTs) [1,2]; (b) decision tree algorithms [46]; (c) Tassel cap brightness-greenness-wetness [86–88]; (d) Space-time spiral curves, Change Vector Analysis (CVA) [54]; (e) Phenology [43,82]; and (f) fusing climate data with MODIS time-series spectral indices and using algorithms such as decision tree algorithms, and subpixel calculation of the areas [73].

The advanced and finer irrigated and rainfed croplands products at 30 m will: (1) define more precisely the actual area and spatial distribution of irrigated and rainfed cropland areas of the world; (2) develop methods and techniques for consistent and unbiased estimates of irrigated and rainfed cropland areas over space and time for the entire world; (3) elaborate on the extent of multiple cropping over a year, particularly in Asia, where two or three crops may be grown in one year, but where cropping intensities are not accurately known or recorded in secondary statistics; and (4) account for: (a) irrigation and rainfed cropping intensity; (b) irrigation source; (c) irrigated and rainfed crop types; and (d) precise location of irrigated and rainfed cropland areas. This will be a significant advance since irrigated and rainfed cropping intensity and their crop types have a huge influence on the quantum of water consumed by crops and associated indicators of agricultural productivity, crop diversification and food security. The irrigation and rainfed source is a must to determine patterns of land and water use and environmental impacts from factors such as major *versus* minor irrigation, and in determining the quantum of groundwater use and its overdraft issues that are critical to the food security and wellbeing of millions around the world, particularly in India and China. These two countries are home to largest number of poor and food insecure people worldwide; they are also the countries that encounter greatest gaps in data on cropping intensity and precise location of irrigated *versus* rainfed croplands. Precise and finer delineation of crop types, irrigation types and cropping intensities can greatly support global food security assessment and planning.

6. Global Cropland Water Requirements and Withdrawal: Blue, Green, and White Water

Croplands have resulted in changes in land use and cover through land clearing, specialization in production such as crop monoculture as well as deforestation and reforestation, deriving redistribution of evapotranspiration, decreasing it in areas of large-scale deforestation and increasing it in many irrigated areas with associated impacts on microclimate and regional climate impacts [89]. Continued increase in demand for water and recent water shortages have intensified the need for better utilization of our water resources; its has also forced us to think more innovatively about different components of water available in the hydrological cycle, including white, green, and blue water [90–92]. The blue, green and white water metaphor has enhanced policy discussion regarding water scarcity and food security.

Blue water: water in lakes, reservoirs, rivers, ice caps, and ground-water (saturated zone) are called "blue water". However, the proportion of the water that evaporates back without being used by humans is called "white water". Blue water is typically associated with crop production under irrigated conditions. The distinction between blue and white water has many implications for water management for food security. For instance, the lesser the blue water used for producing food and fiber the greater will be the water productivity and water use efficiency; however the implications for the environment may not always be straightforward.

Green water (productive green water or effective rainfall): water in the soil moisture that transpirates through crops and vegetation is termed "green water" since this water is available for crop productivity and vegetation. This water is in the unsaturated zone and readily available for consumptive use by crops. Green water is typically associated with crop production under rainfed conditions and constitutes bulk (70%) of the water used by croplands. The lesser the "green water" used for producing food and fiber crops the greater will be the water productivity. Strategies that improve green water management offer potential to enhance food production even in places with serious water scarcity issues [93].

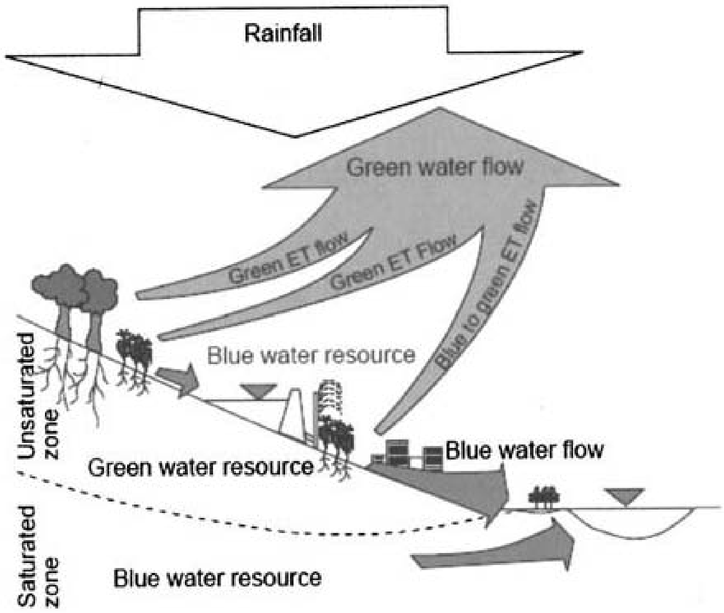
White water (nonproductive green water or noneffective rainfall): Water that evaporates straight back to atmosphere from soil, water surfaces, and intercepted water from plant and other surfaces is termed as "white water". This water is "not available" for human uses and recycles back into hydrological cycle, without being used.

Siebert and Döll [49] proposed a global crop water model (GCWM) to compute green water and blue water use of crops (Table 2, Figure 13). Basing their calculations on MIRCA2000 dataset [94] that provides monthly growing areas of 26 crops for 1998–2002 period, they estimated that the global total crop water use for the above mentioned period was 6,685 km^3 $yr–^1$; of which blue water use was 1,180 km^3 yr^{-1}, green water use of irrigated crops was 919 km^3 yr^{-1} and green water use of rainfed crops was 4,586 km^3 yr^{-1} (Table 2).

These data are comparable to the estimates of Falkenmark and Rockström [91]. Total crop water use was largest for rice (941 km^3 yr^{-1}), wheat (858 km^3 yr^{-1}) and maize (722 km^3 yr^{-1}). The largest amounts of blue water use were for rice (307 km^3 yr^{-1}) and wheat (208 km^3 yr^{-1}) [49]. Postel [95] estimated the total volume of water consumed for food production, roughly at the end of the last millennium as 13,800 km^3/yr of which 7,500 km^3/yr goes for food crops and their associated biomass (higher than Siebert and Döll, [49] and Falkenmark and Rockström [91] estimates, but it includes "associated biomass") and the rest 5,800 km^3/yr for pasture and natural grazing lands. This is about 20% of the total evapotranspiration per year from Planet Earth [95].

Falkenmark and Rockström [91] suggest that much of the water for food security in next few decades will have to come from green water, with irrigation withdrawal plateauing or even exceeding annual fresh water recharge in some areas such as parts of Yellow River Basin in China and Indo-Gangetic Basin and also becoming increasingly unacceptable due to severe impacts on environments and ecologies [14].

Figure 13. Blue water-green water approach [91]. About 20% of all water used for crops comes from the blue water diversions (from water in lakes, reservoirs, rivers, and ground water in aquifers) irrigating 278–399 Mha (without intensity) and 467 Mha (with intensity) annually. There is an additional 10% of water from direct rainfall (green water) over irrigated croplands. The rest, about 70%, of water used by crops is the green water (water in soil moisture in unsaturated zone) used by about 1.13 billion hectares of rainfed croplands. Management strategies for blue and green water are not the same and the impacts on food security depend synergistically on how blue and green water is managed and for what crops and where.



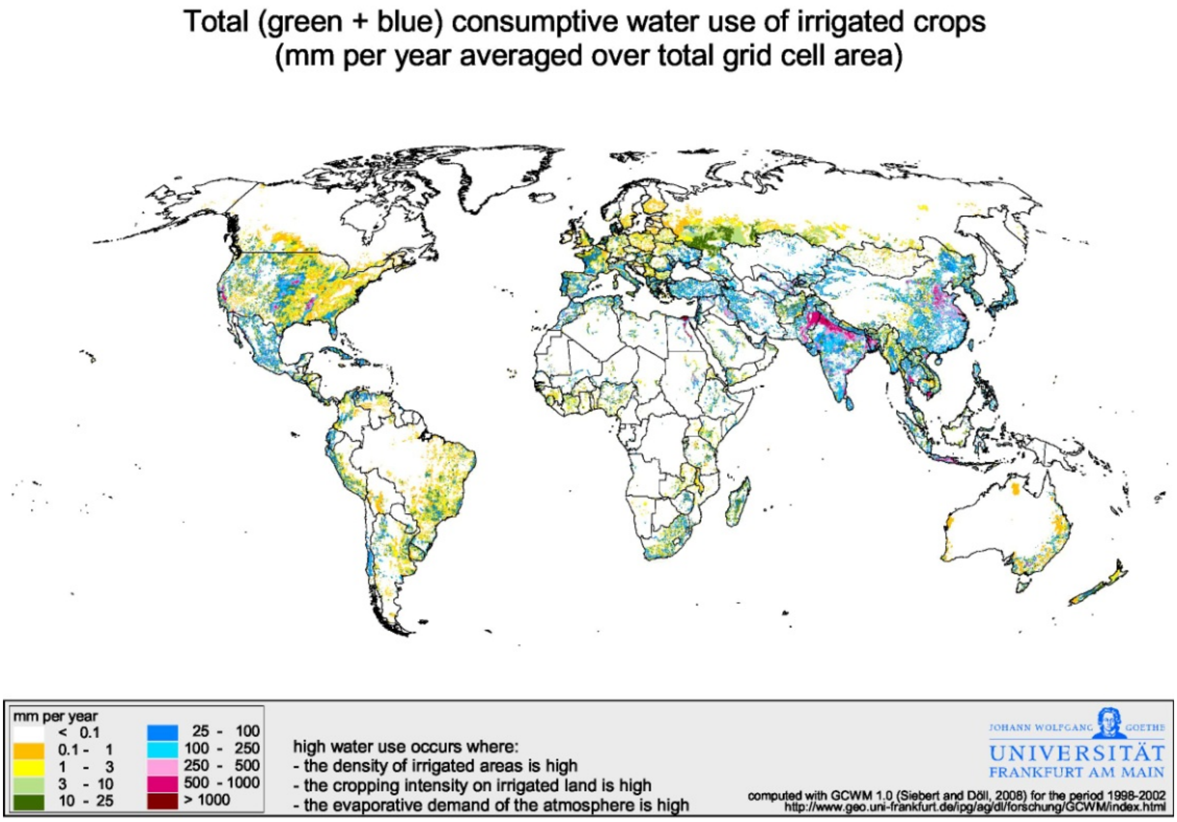
Note: about 80% of all blue water diversions for human water use goes to produce food by irrigated croplands. The 278.4 Mha is the global irrigated area determined by Siebert *et al.* [52] and 399 Mha is the global irrigated area determined by Thenkabail *et al.* [1,2]. The 20% blue water use by irrigated lands is based on Siebert *et al.* [52].

Table 2. Global blue water and green water use by agricultural crops roughly at the end of the last millennium.

Blue water use by irrigated crops km^3/yr	Green water use by irrigated crops km^3/yr	Green water use by rainfed crops km^3/yr	Total water use by irrigated crops rainfed crops km^3/yr	Reference
1,180	919	4,586	6,685	Siebert and Döll [49]
1,800	–	5,000	6,800	Falkenmark and Rockström [91]
–	–	–	7,500	Postel [95]

Irrigated areas consume nearly 80% of all human blue water use by humans. A country by country irrigated crop water requirement is computed by Siebert and Döll [49] (Table 3). They first compute the direct rainfall (green water) over irrigated areas and then compute the additional irrigation requirements (blue water) to sustain the crop during its growing period. Water required is the evapotranspiration of crops assuming optimal crop growth and no water limitation [49]. Green water is just the part of evapotranspiration that is provided by direct rainfall and blue water required is the additional evapotranspiration that occurs on irrigated fields as compared to rainfed conditions (assuming optimal growth and no water limitation on irrigated fields) (Siebert, personal communication). Adding these two water components over irrigated areas, gives the total irrigated crop water requirement, presented for 197 countries by Siebert and Döll [49] (Table 3).

Figure 14. Water required by crops [49,97]. Water required by irrigated croplands shown here includes green water (direct precipitation over the irrigated areas) plus additional blue water required (water from lakes, rivers, reservoirs, and ground water from aquifers) for sustaining crops. The highest water use (500 mm or more) is in the Ganges basin (India), Indus basin (Pakistan), areas near Beijing (China), and California valley (USA). High water use occurs in areas with high irrigation density, cropping intensity, and evaporative demand as noted in the figure. The irrigated areas used to compute water required are from MIRCA2000 data set (www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/ index. html) which is derived from Siebert *et al*. [52].



In contrast, Wisser *et al*. [96] determined a country-wise "water withdrawal". Typically, much more water is withdrawn for irrigation than crop water requirements, leading to poor irrigation efficiency. As a result water productivity (WP) can vary widely based on how water use is determined. Water input through canals is often far higher than water used by crops due to evaporative losses during supply and through direct evaporation from standing water in the field and percolation or infiltration. So, if we calculate WP based on water supplied it is likely to be 2–3 times lesser than the WP calculated based on water use by crops. To fully account for various components of water withdrawals, a basin perspective is required to analyze water productivity.

A country-wise comparison of water withdrawals for irrigation per year [96] is made with the corresponding country-wise water requirements estimated by Siebert and Döll [49] (Figure 14 and Table 3). Siebert and Döll [49] used irrigated areas reported in Siebert *et al*. [52] to estimate water required for optimal cropping conditions. Wisser *et al*. [96] used irrigated areas reported in Siebert *et al*. [52] (Figure 4, Table 1) and Thenkabail *et al*. [2]. The results in Figure 15 and Figure 16 indicate that, on an average, 1.6 to 2.5 times more water is withdrawn than required for irrigation, thus achieving irrigation efficiency of just 40% to 62%.

Figure 15. Water withdrawal [96] *versus* water required [49,97] by irrigated crops for 197 countries in the World. Water withdrawals are, of course, always much higher than water required. Here the trend shows withdrawal, on average, to be about 1.6 times than the water required for irrigation. The irrigated areas used to compute water withdrawal and water required are both from Siebert *et al*. [52].

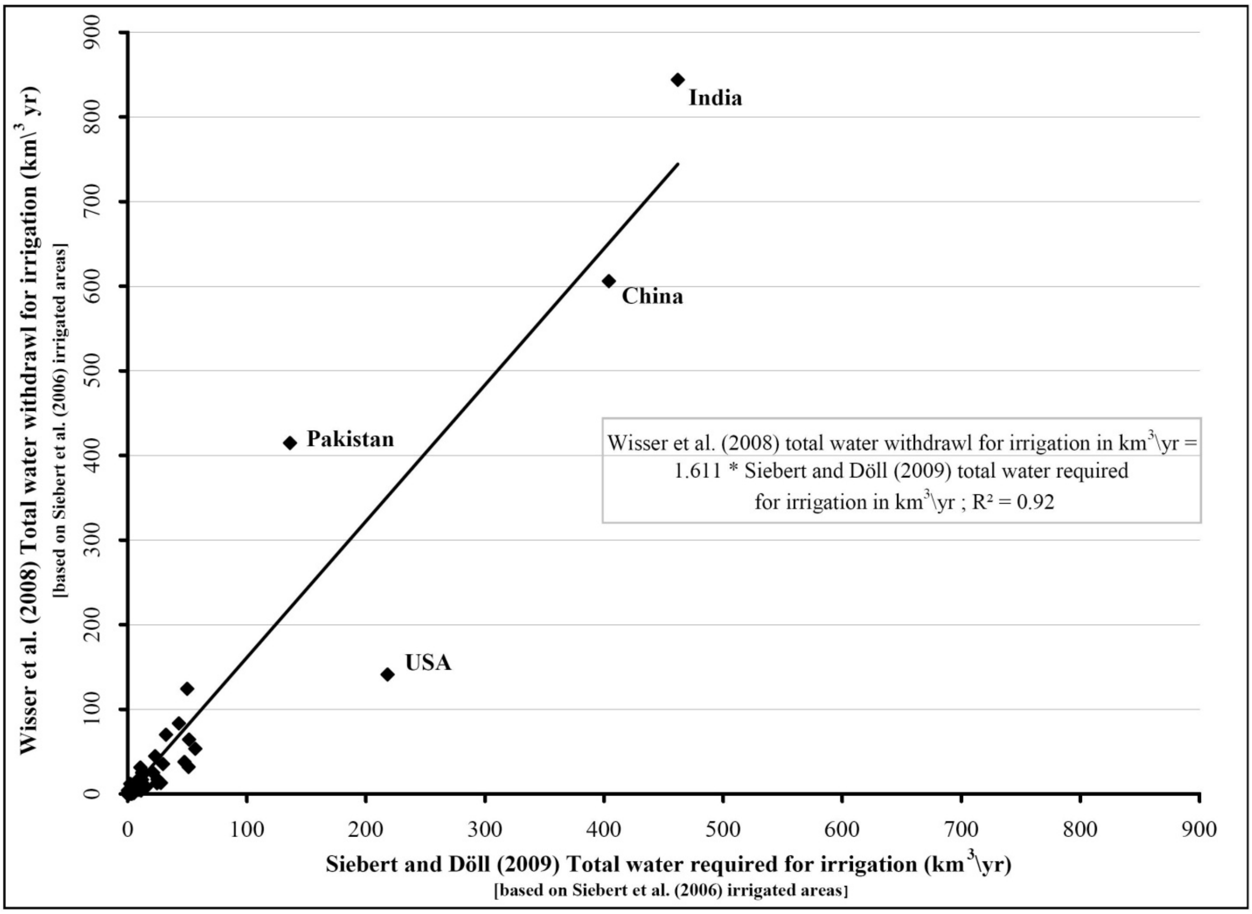
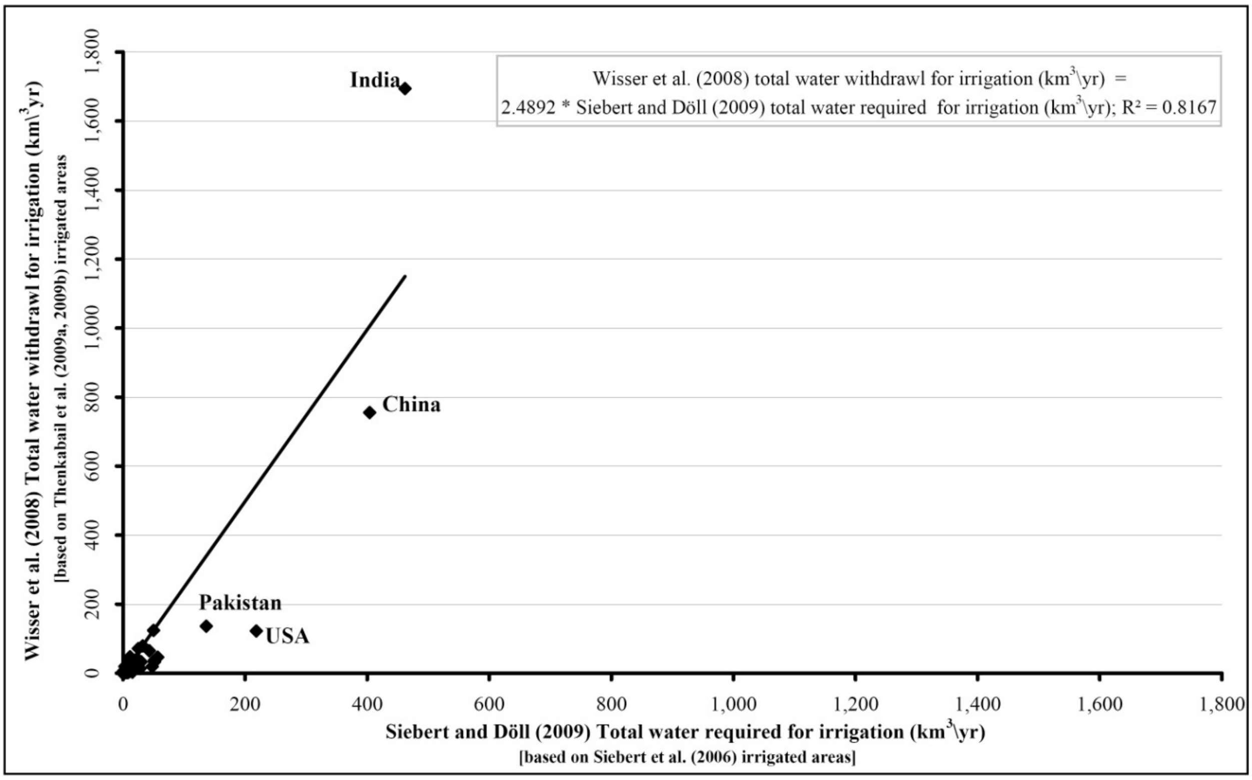


Figure 16. Water withdrawal [96] *versus* water required [49,97] by irrigated crops for the 197 countries in the World. Water withdrawals always much higher than water required. Here the trend shows withdrawal, on average, to be about 2.5 times the water required for irrigation. The irrigated areas used to compute water withdrawal are from Thenkabail *et al*. [1,2] and water required are from Siebert *et al*. [52].



7. Virtual Water Use

There is an increasing trend to regard water as a commodity that can be traded across basins, regions, nations, and continents. Virtual water use describes the water used to produce food crops that are traded [98,99]. Several authors [100–104] have described how water short countries can enhance their food security by importing water intensive food crops. Thus water surplus countries can produce food and export to water scarce countries, to the comparative advantage of both. Virtual water use improves the physical and economic access to food by increasing food availability and reducing food prices for domestic consumers. It also enables the global exchange of surplus food. In other words, it improves entitlements through exchange and, in so doing, widens the range of food available for consumption, improving diets and satisfying food preferences. Van Hofwegen [105] observed that virtual water trade is already a silent alternative for most water-scarce countries as it could be used as an instrument to achieve water security but also because of its increasing importance for food security in many countries with a continuous population growth. The virtual water trade addresses resource endowments but it does not address production technologies or opportunity costs of trade [98,99]. Optimal trading positions are therefore not always consistent with expectations based solely on resource endowment. The trading positions are determined by geopolitical and economic factors and some nations may not have the economic capacity to pay for virtual water food imports.

Table 3. Global water withdrawals *versus* water use by croplands—a country by country assessment. Also, blue water and green water use of irrigated croplands.

Rank based on Total IWMI GIAM cropland areas	Country	Water: renewable	Water: withdrawl for all purposes	Water: withdrawl for irrigation	Water: withdrawl for irrigation	Water: withdrawl for irrigation	Water: withdrawl for irrigation	Water: requirement (ET) for irrigation	Water Green: requirement (ET) for irrigation	Water blue: requirement (ET) for irrigation	Population	Area of Country	Access	Access	Access
		Glieck *et al.*, 2009 [133]	Glieck *et al.*, 2009 [133]	FAO AQUASTAT, 2009 [134]	Gliek *et al.;* FAO, 2009 [133,134]	Wisser *et al.*, (2008) [96]	Wisser *et al.*, (2008) [96]	Siebert and D鰈l, 2008, 2009 [49,97]	Siebert and D鰈l, 2008, 2009 [49,97]	Siebert and D鰈l, 2008, 2009 [49,97]	Glieck *et al.*, 2009 [133]	Ramankutty and Foley, 1998 [48]	Glieck *et al.*, 2009 [133]	Glieck *et al.*, 2009 [133]	Glieck *et al.*, 2009 [133]
		Annual renewable water resources	Total water withdrawl for all purposes	Total water withdrawl for irrigation from FAO AQUASTAT statistics	Total Irrigated water use as % of total water withdrawl	Total water withdrawl for irrigation based on IWMI GIAM irrigated areas	Total water withdrawl for irrigation based on FAO/UF V4.0 irrigated areas	Blue Water requirement for irrigation based on irrigated areas of FAO/UF V4.0	Green Water availability over irrigated areas based on FAO/UF V4.0	Total (blue + green) water requirement for irrigation based on FAO/UF V4.0	Population	Area	Population with access to improved water: URBAN	Population with access to improved water: RURAL	Population with access to improved water: TOTAL
A1	A2	A22	A23	A24	A25	A26	A27	A28	A29	A30	A31	A32	A33	A34	A35
#	Name	km3 /yr	km3 /yr	km3 /yr	%	km3 /yr	km3 /yr	km3 /yr	km3 /yr	km3 /yr	Millions	Hectares	%	%	%
1	China	2830	550	427	77.67	755	606	147	257	404	1323	959974780	93	67	77
2	India	1908	646	558	86.40	1694	844	287	175	462	1103	309375230	95	83	86
3	USA	3069	477	198	41.51	122.3	141.2	139.1	79.1	218.3	298	944148610	100	100	100
5	Russia	4498	76.7	13.6	17.74	71.3	17.1	11.6	13.4	25.0	143	1689619300	100	88	97
14	Brazil	8233	59.3	36.6	61.72	28.1	14.2	8.3	18.0	26.4	186	852846140	96	57	90
6	Argentina	814.0	29.2	21.5	73.66	47.4	11.1	5.8	5.7	11.5	39	281208900	98	80	96
11	Australia	398.0	24.1	18.0	74.81	25.0	12.8	13.6	10.9	24.5	20	784884030	100	100	100
9	Kazakhstan	109.6	35.0	28.6	81.71	40.0	12.7	8.9	3.2	12.1	15	272919390	97	73	86
20	Canada	3300	44.7	5.4	12.10	5.1	2.2	2.7	2.3	5.1	32	992791680	100	99	100
26	Ukraine	139.5	37.5	19.7	52.49	8.5	11.4	3.5	3.6	7.1	46	62823012	99	91	96
16	Indonesia	2838	82.8	75.6	91.33	46.3	53.4	13.6	43.2	56.8	223	179527940	87	69	77
21	France	189.0	33.2	3.9	11.82	5.6	4.9	3.2	6.0	9.2	61	55032184	100	100	100
4	Pakistan	233.8	169.4	163.0	96.23	136.2	414.7	117.0	19.3	136.3	158	87530040	96	89	91
18	Spain	111.1	37.2	24.2	65.02	13.7	13.1	18.6	9.2	27.8	43	50116908	0	0	0
7	Thailand	409.9	82.8	82.8	100.06	123.9	124.3	19.1	30.8	49.9	64	51464260	98	100	99
164	Zambia	105.2	1.7	1.3	75.86	0.0	0.1	0.4	0.2	0.6	12	74768256	90	40	58
107	Tanzania	91.0	5.2	4.6	89.38	0.2	0.8	1.0	0.8	1.8	38	91471488	85	49	62
15	Mexico	457.2	78.2	60.3	77.09	36.9	32.0	26.8	24.2	51.0	107	201567600	100	87	97
124	Congo, Dem. Rep.	1283.0	0.4	0.0	0.00	0.0	0.0	0.0	0.1	0.1	58	0	82	29	46
56	Poland	63.1	11.7	1.4	11.51	0.7	0.3	0.1	0.3	0.4	39	31557156	0	0	0
103	Mozambique	216.0	0.6	0.6	87.30	0.2	0.8	0.2	0.2	0.4	20	79790960	72	26	43
112	Angola	184.0	0.4	0.2	60.00	0.2	0.2	0.2	0.1	0.3	16	127110540	0	0	0

Table 3. *Cont.*

A1	A2	A22	A23	A24	A25	A26	A27	A28	A29	A30	A31	A32	A33	A34	A35
10	Myanmar (Burma)	1045.6	33.2	32.6	98.10	40.0	25.3	5.9	6.5	12.4	51	69936696	80	77	78
32	Turkey	234.0	39.8	27.9	70.14	14.6	25.0	14.6	6.6	21.3	73	80188848	98	93	96
19	Germany	188.0	38.0	9.3	24.49	4.5	1.9	0.2	0.9	1.1	83	36576396	0	0	0
102	Belarus	58.0	2.8	0.0	0.00	0.0	0.0	0.2	0.5	0.6	10	19086704	0	0	0
43	South Africa	50.0	12.5	7.8	62.72	3.1	8.3	8.8	6.5	15.3	47	124640750	99	73	88
13	Vietnam	891.2	71.4	48.6	68.08	78.9	70.0	7.4	24.7	32.1	84	27613914	99	80	85
74	Ethiopia	110.0	5.6	5.2	93.56	1.7	1.9	1.2	1.4	2.6	77	115511000	81	11	22
70	Nigeria	286.2	8.0	5.5	68.79	2.3	1.5	0.9	0.6	1.5	132	88327408	67	31	48
30	Sudan	154.0	37.3	36.1	96.73	17.7	11.2	10.1	2.9	13.0	36	252052980	78	64	70
8	Bangladesh	1210.6	79.4	76.4	96.22	65.0	83.3	18.7	24.3	43.0	142	15334228	82	72	74
28	Romania	42.3	17.0	13.2	77.65	8.1	11.9	0.9	1.3	2.2	22	24189514	91	16	57
31	Philippines	479.0	28.5	21.1	73.98	17.6	25.1	3.8	10.4	14.2	83	29995618	87	82	85
22	Italy	175.0	42.0	20.0	47.64	8.7	8.3	6.5	8.8	15.2	58	29358244	0	0	0
73	Bolivia	622.5	1.4	1.2	80.56	2.2	0.4	0.4	0.3	0.8	9	109194380	95	68	85
146	Zimbabwe	20.0	4.2	3.3	78.86	0.0	0.5	0.9	0.7	1.6	13	40475536	98	72	81
12	Uzbekistan	72.2	58.3	54.4	93.25	32.9	35.5	24.1	5.5	29.7	27	44443476	0	0	0
24	Iran	137.5	72.9	66.2	90.83	32.7	64.2	40.8	10.7	51.5	70	165938300	99	84	94
37	United Kingdom	160.6	11.8	0.3	2.38	2.1	0.3	0.2	0.6	0.9	60	26428910	100	100	100
83	Kenya	30.2	1.6	1.0	63.92	0.6	0.4	0.5	0.3	0.8	34	57352652	83	46	61
53	Colombia	2132.0	10.7	4.9	45.94	3.3	10.6	1.0	3.7	4.6	46	118348200	99	71	93
25	Japan	430.0	88.4	55.2	62.42	21.1	31.4	1.7	9.1	10.7	128	39937976	100	100	100
120	Paraguay	336.0	0.5	0.4	71.43	0.1	0.4	0.1	0.5	0.6	6	40165220	99	68	86
94	Madagascar	337.0	15.0	14.3	95.59	0.4	5.7	2.8	4.4	7.2	19	61659564	77	35	50
66	Malaysia	580.0	9.0	5.6	62.08	1.3	2.8	0.6	2.8	3.5	25	35897676	100	96	99
60	Peru	1913.0	20.1	16.4	81.47	3.7	11.5	5.1	1.4	6.5	28	132232860	89	65	83
85	Ivory Coast	81.0	0.9	0.0	0.00	0.0	0.0	0.1	0.3	0.5	18	35343676	97	74	84
113	Uganda	66.0	0.3	0.1	40.00	0.1	0.0	0.0	0.0	0.0	29	21084474	87	56	60
41	Cambodia	476.1	4.1	4.0	98.04	19.5	10.6	1.0	1.8	2.8	14	19058936	64	35	41
36	Morocco	29.0	12.6	11.0	87.30	5.5	4.1	9.0	2.2	11.2	31	43195264	99	56	81
33	Nepal	210.2	10.2	9.8	96.46	14.2	16.1	4.2	4.0	8.2	27	14762371	96	89	90
72	Hungary	120.0	21.0	2.5	11.65	0.8	1.4	0.2	0.4	0.6	10	9271688	100	98	99
38	Bulgaria	19.4	6.9	2.0	28.47	4.9	4.2	0.1	0.1	0.2	8	11155221	100	97	99
46	Venezuela	1233.2	8.4	4.0	47.43	7.0	8.1	2.0	3.4	5.4	27	30606504	85	70	83
23	Iraq	96.4	42.7	39.4	92.27	42.0	44.6	20.9	2.1	23.0	29	44132328	97	50	81
34	Chile	922.0	12.6	8.0	63.51	7.1	3.6	3.0	2.1	5.1	16	85476488	100	58	95

Table 3. *Cont.*

A1	A2	A22	A23	A24	A25	A26	A27	A28	A29	A30	A31	A32	A33	A34	A35
49	Czech Republic	16.0	1.9	0.1	3.14	0.8	0.1	0.0	0.1	0.1	10	8017978	0	0	0
61	Uruguay	139.0	0.0	3.0	0.00	4.1	1.7	0.6	1.0	1.6	0	19021774	100	100	100
42	Afghanistan	65.0	23.3	22.8	98.02	9.8	25.1	9.4	2.6	12.0	30	66708280	63	31	39
78	Algeria	14.3	6.1	3.9	64.91	0.8	1.1	4.3	1.0	5.2	33	228937980	88	80	85
27	Korea, Dem. Rep.	77.1	9.0	8.9	98.89	8.5	7.9	1.1	5.6	6.7	22	12353767	100	100	100
17	Egypt	86.8	68.3	59.0	86.38	19.0	37.8	46.9	0.8	47.7	74	100336120	99	97	98
48	Greece	72.0	8.7	6.3	71.84	3.9	5.8	6.9	2.5	9.4	11	12705944	97	93	95
35	Korea, Rep.	69.7	18.6	5.0	26.68	5.3	5.7	0.8	4.0	4.9	48	9495020	97	71	92
142	Botswana	14.7	0.2	0.1	42.11	0.0	0.0	0.0	0.0	0.0	2	58570900	100	90	95
67	Serbia	0.0	0.0	0.0	0.00	0.0	0.0	0.2	0.2	0.4	11	0	99	86	93
65	Ecuador	432.0	17.0	14.0	82.45	2.1	9.6	2.7	2.1	4.8	13	24803418	97	89	94
63	Portugal	73.6	11.1	8.8	79.44	1.3	2.4	3.2	1.9	5.1	11	10976086	0	0	0
96	Ghana	53.2	1.0	0.7	66.53	0.5	0.1	0.1	0.1	0.1	22	23036762	88	64	75
47	Kyrgyzstan	46.5	10.1	9.5	93.75	2.6	4.1	3.1	2.6	5.7	5	16312056	98	66	77
110	Lithuania	24.5	3.3	0.0	0.60	0.1	0.0	0.0	0.0	0.0	3	8306550	0	0	0
51	Cuba	38.1	8.2	5.6	68.78	5.9	11.5	1.6	6.2	7.8	11	12108422	95	78	91
106	Cameroon	285.5	1.0	0.7	73.74	0.4	0.4	0.2	0.2	0.4	16	48120400	86	44	66
29	Turkmenistan	60.9	24.7	24.0	97.36	16.8	17.0	10.6	1.3	11.9	5	46019548	93	54	72
59	Mongolia	34.8	0.4	0.2	52.27	0.6	0.1	0.3	0.1	0.4	3	153666640	87	30	62
62	Guinea	226.0	1.5	1.4	90.07	2.8	1.5	0.1	0.1	0.2	9	25321418	78	35	50
158	Central African Republic	144.4	0.0	0.0	3.33	0.0	0.0	0.0	0.0	0.0	4	63468144	93	61	75
179	Congo	832.0	0.0	0.0	13.33	0.0	0.0	0.0	0.0	0.0	4	36886096	84	27	58
64	Senegal	39.4	2.2	2.1	92.79	3.2	0.6	0.6	0.2	0.8	12	20425072	92	60	76
45	Sri Lanka	50.0	12.6	12.0	95.16	19.4	11.2	2.2	3.0	5.2	21	7072204	98	74	79
44	Azerbaijan	30.3	17.3	11.6	67.25	7.5	10.9	3.8	1.2	5.0	8	8509874	95	59	77
99	Mali	100.0	6.6	5.9	90.08	0.9	5.1	1.3	0.4	1.7	14	127994250	78	36	50
137	Latvia	49.9	0.3	0.0	16.00	0.0	0.0	0.0	0.0	0.0	2	6441168	100	96	99
128	Burkina faso	17.5	0.8	0.7	86.25	0.2	0.5	0.1	0.1	0.2	13	23639698	94	54	61
81	Lao, Dem.Rep	333.6	3.0	2.7	90.00	1.3	2.6	1.3	1.4	2.7	6	25241708	79	43	51
149	Malawi	17.3	1.0	0.8	80.20	0.0	0.1	0.3	0.4	0.7	13	10247228	98	68	73
87	Austria	84.0	3.7	0.0	0.54	0.3	0.1	0.0	0.2	0.2	8	8159030	0	0	0
50	Taiwan, Province of China	67.0	0.0	0.0	0.00	0.0	0.0	0.7	2.6	3.3	0	0	92	48	59
93	Slovakia	80.3/50.1	1.0	0.0	0.00	0.0	0.0	0.2	0.4	0.6	5	4905294	100	99	100

Table 3. *Cont*.

A1	A2	A22	A23	A24	A25	A26	A27	A28	A29	A30	A31	A32	A33	A34	A35
68	Moldova	11.7	2.3	0.8	32.90	0.9	1.1	0.7	0.6	1.3	4	3166654	95	94	94
57	Tajikistan	99.7	12.0	11.0	91.97	2.7	4.7	3.3	1.0	4.3	7	14549783	0	0	0
55	Belgium	20.8	7.4	0.1	1.48	0.8	0.3	0.0	0.0	0.0	10	0	0	0	0
192	Papua New Guinea	801.0	0.1	0.0	1.00	0.0	0.0	0.0	0.0	0.0	6	41579064	88	32	39
77	New Zealand	397.0	2.1	0.9	42.18	0.1	0.9	0.7	2.1	2.8	4	31252526	100	0	0
168	Liberia	232.0	0.1	0.1	54.55	0.1	0.0	0.0	0.0	0.0	3	9555961	72	52	61
109	Croatia	105.5	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	5	6356546	0	0	0
58	Somalia	15.7	3.3	3.3	99.70	3.0	1.9	1.0	0.7	1.6	8	64049144	32	27	29
39	Netherlands	89.7	8.9	2.7	30.36	1.3	1.0	0.1	0.8	0.9	16	3220241	100	100	100
89	Guatemala	111.3	2.0	0.0	0.00	0.0	0.0	0.7	1.2	1.9	13	12239412	99	92	95
40	Denmark	6.1	0.7	0.5	80.60	2.0	1.2	0.0	0.5	0.6	5	5215516	0	0	0
52	Syria	46.1	20.0	18.9	94.74	6.9	7.6	9.5	2.2	11.7	19	19801656	98	87	93
92	Honduras	95.9	0.9	0.7	80.23	0.3	0.4	0.4	0.6	0.9	7	12591915	95	81	87
86	Tunisia	4.6	2.6	2.2	81.82	0.7	2.3	2.6	0.7	3.3	10	15911228	99	82	93
115	Sierra Leone	160.0	0.4	0.4	92.11	0.2	0.2	0.1	0.1	0.2	6	7669371	75	46	57
130	Bosnia and Herzegovina	37.5	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	4	5131768	99	96	97
122	Nicaragua	196.7	1.3	1.1	83.08	0.2	0.5	0.3	0.4	0.7	5	12699630	90	63	79
97	Sweden	179.0	2.7	0.3	9.70	0.1	0.3	0.0	0.2	0.3	9	45342812	0	0	0
69	Albania	41.7	1.7	1.1	61.99	0.9	0.8	0.7	0.6	1.4	3	2804224	99	94	96
181	Gabon	164.0	0.1	0.1	41.67	0.0	0.0	0.0	0.0	0.0	1	24811990	95	47	88
108	Panama	148.0	0.8	0.0	0.00	0.0	0.0	0.1	0.3	0.4	3	8898913	99	79	90
129	Estonia	21.1	1.4	0.0	0.57	0.0	0.0	0.0	0.0	0.0	1	4681222	100	99	100
116	Chad	43.0	0.2	0.2	82.61	0.3	0.2	0.1	0.1	0.2	10	129845730	41	43	42
76	Georgia	63.3	3.6	2.1	59.00	0.8	1.6	0.5	0.6	1.1	4	8037330	96	67	82
79	Macedonia	6.4	2.3	0.0	0.00	0.0	0.0	0.2	0.1	0.3	2	2779304	0	0	0
136	Burundi	3.6	0.3	0.2	76.55	0.1	0.1	0.1	0.1	0.1	8	2477599	92	77	79
95	Finland	110.0	2.3	0.1	2.83	0.2	0.2	0.0	0.1	0.1	5	34689660	88	71	84
126	Costa rica	112.4	2.7	1.4	53.36	0.2	1.0	0.4	0.9	1.3	4	6416118	100	92	97
100	Rwanda	5.2	0.2	0.1	68.00	0.3	0.0	0.0	0.0	0.0	9	2480528	92	69	74
121	Togo	14.7	0.2	0.1	44.71	0.1	0.0	0.0	0.0	0.0	6	7057118	80	36	52
111	Switzerland	53.3	2.5	0.1	1.98	0.0	0.0	0.0	0.0	0.0	7	4036908	0	0	0
141	Niger	33.7	2.2	2.1	95.41	0.0	0.6	0.6	0.2	0.8	14	120584560	80	36	46
127	Benin	25.8	0.1	0.1	45.38	0.4	0.1	0.0	0.0	0.0	8	11917741	78	57	67
135	Namibia	45.5	0.3	0.2	71.00	0.0	0.1	0.1	0.0	0.1	2	83173288	98	81	87
185	Ireland	46.8	1.2	0.0	0.02	0.0	0.0	0.0	0.0	0.0	4	7992032	0	0	0

Table 3. *Cont*.

A1	A2	A22	A23	A24	A25	A26	A27	A28	A29	A30	A31	A32	A33	A34	A35
90	Dominican Republic	21.0	4.0	2.2	56.00	0.8	3.1	0.9	1.5	2.4	0	4988026	97	91	95
71	Libya	0.6	4.3	3.5	82.90	1.8	4.3	2.7	0.3	3.0	6	164917920	0	0	0
54	Saudi Arabia	2.4	17.3	15.4	88.91	16.9	25.7	12.4	0.7	13.1	25	197678690	97	0	0
145	Lesotho	5.2	0.1	0.0	20.00	0.0	0.0	0.0	0.0	0.0	2	3240211	92	76	79
88	Swaziland	4.5	1.0	1.0	97.12	0.5	0.3	0.3	0.3	0.6	1	1110600	87	54	62
165	Slovenia	32.1	0.9	0.0	0.00	0.0	0.0	0.0	0.0	0.1	2	2363816	0	0	0
104	Haiti	14.0	1.0	0.9	93.94	0.5	0.6	0.2	0.5	0.7	9	4108348	52	56	54
80	Armenia	10.5	3.0	1.9	65.76	1.1	2.3	0.6	0.3	0.9	3	2367831	99	80	92
155	Norway	381.4	2.4	0.2	9.58	0.0	0.1	0.0	0.1	0.2	5	35193748	0	0	0
131	Montenegro	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0
75	Guinea Bissau	31.0	0.2	0.1	80.00	1.7	0.2	0.1	0.0	0.1	2	3337240	79	49	59
134	El Salvador	25.2	1.3	0.8	59.38	0.1	0.2	0.2	0.3	0.5	7	2412104	94	70	84
84	Guyana	241.0	1.6	1.6	97.56	0.5	1.1	0.3	1.2	1.6	1	20705946	83	83	83
91	Yemen	4.1	6.6	6.3	95.32	0.9	2.6	2.9	0.5	3.4	21	235407810	71	65	67
101	Gambia	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.1	0	1810676	0	0	0
132	Eritrea	6.3	0.3	0.3	96.67	0.1	0.5	0.0	0.0	0.1	4	12558357	74	57	60
147	Belize	18.6	0.2	0.0	20.00	0.0	0.0	0.0	0.0	0.0	0	2370216	100	82	91
143	East Timor	0.0	3.4	0.0	0.00	0.0	0.0	0.0	0.0	0.0	9	0	77	56	58
82	Israel	1.7	2.1	1.3	62.44	1.1	0.9	1.5	0.2	1.7	7	2653467	100	100	100
157	Bhutan	95.0	0.4	0.4	93.02	0.1	0.2	0.1	0.2	0.3	2	3581824	86	60	62
139	Cyprus	0.4	0.2	0.2	83.33	0.1	0.3	0.3	0.1	0.4	1	0	100	100	100
119	Lebanon	4.8	1.4	0.9	66.67	0.2	0.6	1.0	0.2	1.2	4	1030317	100	100	100
133	Puerto Rico	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.2	0.2	0	0	0	0	0
105	Jordan	0.9	1.0	0.8	75.25	1.0	0.8	0.8	0.1	0.9	6	9541204	99	91	97
125	Mauritania	0.0	0.6	0.0	0.00	0.0	0.0	0.2	0.0	0.2	1	102892310	59	44	53
187	Luxembourg	1.6	0.1	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	3543657	0	0	0
123	Suriname	122.0	0.7	0.6	92.54	0.2	0.3	0.1	0.3	0.4	0	15777050	98	73	92
114	Oman	1.0	1.4	1.2	90.44	0.5	2.3	1.1	0.1	1.1	3	31054446	0	0	0
160	Brunei	8.5	0.1	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	1237159	0	0	0
98	United Arab Emirates	0.2	2.3	1.6	68.26	1.8	4.7	3.3	0.1	3.4	5	8506388	100	100	100
140	Jamaica	9.4	0.4	0.2	48.78	0.0	0.0	0.1	0.3	0.3	3	0	98	88	93
154	West Bank	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	9601513	0	0	0
150	Equatorial guinea	26.0	0.1	0.0	0.91	0.0	0.0	0.0	0.0	0.0	1	1860838	45	42	43
117	Qatar	0.1	0.3	0.2	72.41	0.8	0.2	0.1	0.0	0.1	1	1122404	100	100	100
118	Kuwait	0.0	0.4	0.2	52.27	0.8	0.1	0.1	0.0	0.1	3	2164154	0	0	0

Table 3. *Cont*.

A1	A2	A22	A23	A24	A25	A26	A27	A28	A29	A30	A31	A32	A33	A34	A35
148	French Guiana	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	8977087	0	0	0
153	Trinidad and Tobago	3.8	0.3	0.0	6.45	0.0	0.0	0.0	0.0	0.0	1	610102	92	88	91
195	Singapore	0.6	0.2	0.0	0.00	0.0	0.0	0.0	0.0	0.0	4	310175	100	0	100
138	Gaza Strip	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	94	88	92
175	Andorra	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	229652	75	40	53
186	Liechtenstein	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0
144	Mauritius	2.2	0.0	0.5	0.00	0.0	0.0	0.1	0.2	0.3	0	0	100	100	100
162	San Marino	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	90	87	88
151	Antigua and Barbuda	0.1	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	95	89	91
152	Guadeloupe	0.0	0.0	1.6	0.00	0.9	0.8	0.0	0.1	0.1	0	0	98	93	98
156	St. Kitts and Nevis	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	99	99	100
159	Virgin Islands	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	43877180	0	0	0
161	Reunion	5.0	0.0	0.0	0.00	0.0	0.0	0.0	0.1	0.1	0	0	0	0	0
163	Djibouti	0.3	0.0	0.0	15	0.0	0.0	0.0	0.0	0.0	1	2125626	76	59	73
166	Comoros	1.2	0.0	0.0	47	0.0	0.0	0.0	0.0	0.0	1	0	92	82	86
167	Anguilla	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	60	0	60
173	Monaco	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0
169	Turks and Caicos Islands	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	100	100	100
170	Montserrat	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	100	100	100
171	St. Pierre and Miquelon	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0
172	Cayman Islands	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0
174	Seychelles	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	100	75	88
176	Bahrain	0.1	0.3	0.2	56.67	0.0	0.0	0.0	0.0	0.0	1	0	100	0	0
177	Barbados	0.1	0.1	0.0	22.22	0.0	0.0	0.0	0.0	0.0	0	0	100	100	100
178	Cape Verde	0.3	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	1	0	86	73	80
180	Fiji	28.6	0.1	0.1	71.43	0.0	0.0	0.0	0.0	0.0	1	0	43	51	47
183	Grenada	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0
184	Guam	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	100	100	100
188	Malta	0.1	0.0	0.0	50.0	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0
189	Martinique	11.4	1.7	1.5	88.24	0.3	0.9	0.0	0.1	0.1	3	0	0	0	0
190	N/Marianna Islands	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0	0	0

Table 3. *Cont.*

A1	A2	A22	A23	A24	A25	A26	A27	A28	A29	A30	A31	A32	A33	A34	A35
194	Sao Tome and Principe	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.1	0.1	0	0	89	73	79
196	St. Lucia	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	98	98	98
197	St. Vincent and the Grenadines	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	0	0	93	0
198	Vatican city	0.0	0.0	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0	92272568	0	0	0
	TOTAL	54,695	3,725	2,658	9,257	3,798	3,091	1,180	919	2,099	6,445	13,317,869,385	13,736	10,652	11,947

Note: **Water use by crops by Glieck *et al.*, 2009, Siebert *et al.*, 2006, 2008**

A22 = renewable water every year (compiled by Glieck *et al.*, 2009 from multiple sources); A23 = total water withdrawl for all purposes; A24 = total water withdrawl for irrigation purposes;

A23 = total water withdrawl for all purposes; A24 = total water withdrawl for irrigation purposes; A25 = Total water withdrawl for irrigation as % of total water withdrawl for all purposes;

A26 = total water withdrawl for irrigation purposes based on IWMI GIAM irrigated cropland areas; A27 = total water withdrawl for irrigation purposes based on FAO/UF irrigated cropland areas;

A28 = blue water requirement for FAO/UF V4.0 irrigated areas; A29 = green water requirement for FAO/UF V4.0 irrigated areas; A30 = Total water (blue water + green water) requirement for FAO/UF V4.0 irrigated areas;

Population

A31 = population for nominal year 2000 compiled by Glieck *et al.*, 2009 from various sources;

Access to improved water

A32 = area of a Country (Ramankutty *et al.*, 2008; Ramankutty and Foley, 1998); A33 = % of urban population with access to improved water for nominal year 2000 compiled by Glieck et al. 2009 from various sources;

A34 = % of rural population with access to improved water for nominal year 2000 compiled by Glieck *et al.*, 2009 from various sources;

A35 = % of total population (urban + rural) with access to improved water for nominal year 2000 compiled by Glieck *et al.*, 2009 from various sources;

References: For column A22-A25, A31, A33-A35:

1 Gleick, P.H.; Cooley, H., and others Statistics compiled by Gleick P.H., and Cooley, H., and others of the Pacific Institute, **2009**, Statistics available at: http://www.worldwater.org/data.html.

2 United Nations Food and Agricultural Organization's Aquastat (FAO AQUASTAT). Source: http://www.fao.org/NR/WATER/AQUASTAT/water_use/index.stm, **2009**.

For column A26-A27:

3 Wisser, D.; Frolking, S.; Douglas, E.M.; Fekete, B.M.; Vo¬o´marty, C.J.; Schumann, A.H., Global irrigation water demand: Variability and uncertainties arising from agricultural and climate data sets. *Geophys. Res. Lett.* **2008**, *35* , doi:10.1029/2008GL035296.

For column A28-A30:

49 Siebert, S.; D鰈, P., Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation. *J. Hydrol.* **2009**, doi:10.1016/j.jhydrol.2009.1007.1031.

52 Siebert, S.; Hoogeveen, J.; Frenken, K. Irrigation in Africa, Europe and Latin America - Update of the Digital Global Map of Irrigation Areas to Version 4; Institute of Physical Geography, University of Frankfurt: Frankfurt am Main, Germany and Rome, Italy, **2006**.

97 Siebert, S.; D鰈, P. The Global Crop Water Model (GCWM): Documentation and first results for irrigated crops, University of Frankfurt: Frankfurt am Main, Germany, **2008**.

For column A32:

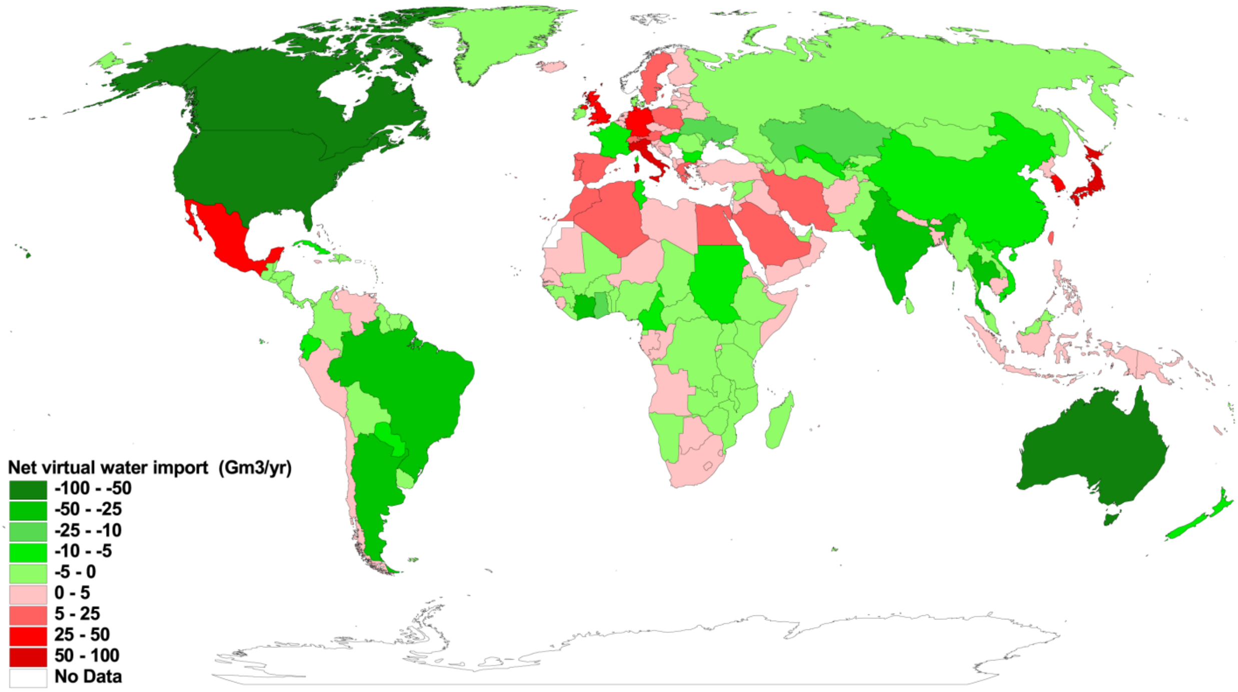
40 Ramankutty, N., EvanA. T, Monfreda, C and Foley, J. A., Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000, Global Biogeochem. Cycles, **2008**, 22, GB1003, doi:10.1029/2007GB002952.

48 Ramankutty, N.; Foley, J.A., Characterizing patterns of global land use: An analysis of global croplands data. *Global Biogeochem. Cycles* **1998**, *12* , 667-685.

For instance, virtual water trade increases with increase in cropped area; access to croplands must increase to help utilize available blue water for irrigation. This means that many of the humid, water-rich countries will not be in a position to produce surplus food and feed the water scarce nations. Others empirically argue that virtual water trade increase only with increase in gross cropped area and what is often achieved through virtual water trade is "global land use efficiency". Accordingly, for a water-poor, but land-rich country, virtual water import offers little scope as a sound water management strategy [106]. Global croplands remain critical even for the virtual water use strategies.

Globally, there is sufficient fresh water to meet human needs, including for food production, for foreseeable future. However, its distribution is uneven and timing of precipitation is concentrated in few months in many parts of the world. The virtual water concept is expected to help in better water management by taking the globe as a unit. Estimates suggest that some 695 Gm^3 yr^{-1} [one Gm^3 or giga-cubic meter is one billion cubic meters or one trillion (1×10^{12}) liters] or about 11% of the water used by crops (6,685 Gm^3 yr^{-1}; Table 1) was virtually traded at the end of the last millennium [107].

Figure 17. Virtual water balance per country over the period 1997–2001 [107]. The balances are drawn based on an analysis of international virtual-water flows associated with trade in both agricultural and industrial products. The red-colored countries have net virtual-water import; the green-colored countries have net virtual-water export.



The countries with the largest net virtual water export are Australia, United States, Canada, Thailand, Argentina and India [108] (Table 4a). The largest net importers are Japan, Italy, Germany, South Korea, China and Indonesia [108] (Table 4b). For example, Germany alone, with current policy on biofuel importation, will require an additional 2.5–3.4 Mha of cropland by 2030, possibly through land use conversions in Brazil or Indonesia [109]. This in turn will result in an additional 23–37 Tg of CO_2.

Table 4a. Top-15 of gross virtual water exporters and top-15 of gross virtual water importers for the period: 1997–2001 [Source: Hoekstra, A.Y.; Chapagain, A.K. Globalization of water: Sharing the planet's freshwater resources: Blackwell Publishing, Oxford, UK, 2008].

Top gross exporters		Rank	Top gross importers	
Countries	Gross export (Gm^3/yr)		Countries	Gross import (Gm^3/yr)
USA	229	1	USA	176
Canada	95	2	Germany	106
France	79	3	Japan	98
Australia	73	4	Italy	89
China	73	5	France	72
Germany	71	6	Netherlands	69
Brazil	68	7	United Kingdom	64
Netherlands	58	8	China	63
Argentina	51	9	Mexico	50
Russia	48	10	Belgium-Luxembourg	47
Thailand	43	11	Russia	46
India	43	12	Spain	45
Belgium-Luxembourg	42	13	Korea Rep.	39
Italy	38	14	Canada	35
Cote d'Ivoire	35	15	Indonesia	30

Note: One Gm^3 or giga-cubic metre is one billion cubic metres. This contains one trillion (1,000,000,000,000 or 1×10^{12}) litres.

Table 4b. Top-10 of net virtual water exporters and top-10 of net virtual water importers for the period 1997–2001. [Source: Hoekstra, A.Y., Chapagain, A.K., Globalization of water: Sharing the planet's freshwater resources: Blackwell Publishing, Oxford, UK, 2008].

Countries with net export	Virtual water flows (Gm^3/yr)			Rank	Countries with net import	Virtual water flows (Gm^3/yr)		
	Export	Import	Net export			Import	Export	Net import
Australia	73	9	64	1	Japan	98	7	92
Canada	95	35	60	2	Italy	89	38	51
USA	229	176	53	3	U/Kingdom	64	18	47
Argentina	51	6	45	4	Germany	106	70	35
Brazil	68	23	45	5	South Korea	39	7	32
Ivory Coast	35	2	33	6	Mexico	50	21	29
Thailand	43	15	28	7	Hong Kong	28	1	27
India	43	17	25	8	Iran	19	5	15
Ghana	20	2	18	9	Spain	45	31	14
Ukraine	21	4	17	10	Saudi Arabia	14	1	13

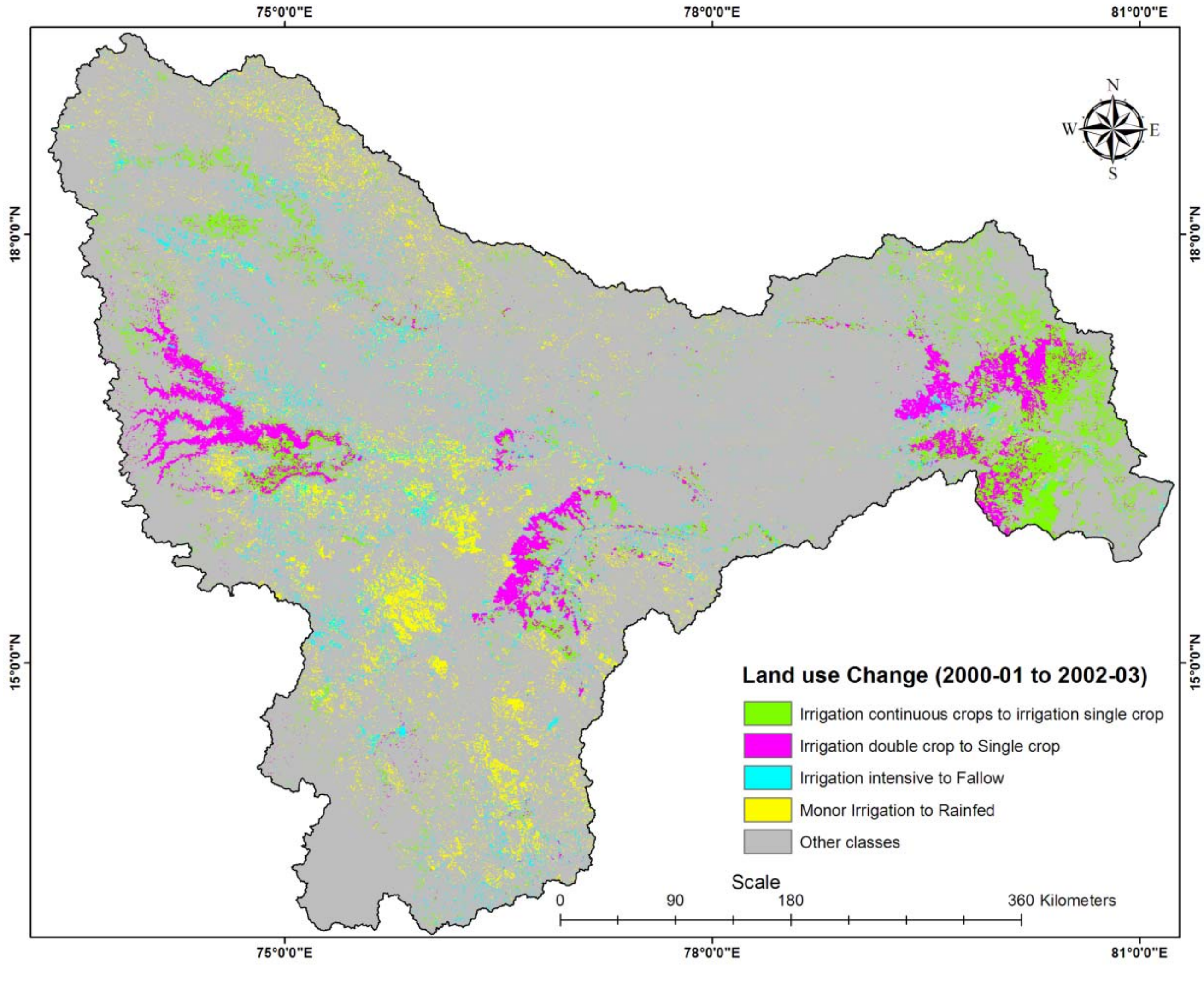
Note: One Gm^3 or giga-cubic metre is one billion cubic metres. This contains one trillion (1,000,000,000,000 or 10^{12}) litres.

8. Croplands, Crop Water Availability, Climate Change, and Food Security

Global climate change is a serious threat to world food security. Declining per capita global food production and warming oceans threaten food security [16]. Climate change also challenges our scientific understanding of the existing hydrological and biophysical relationships of water and food production and requires costly adaptation of core water programs and policies to unprecedented changes, impairing human capacity to respond to climate change. Adequate cropland supported by adequate water availability is essential for food security. What is "adequate" depends on how much we can produce per unit of land (crop productivity expressed in kg/m^2; CP) and how much we can produce by a unit of water (water productivity expressed in kg/m^3; WP). The Green Revolution (from 1960–2000) was made possible by the four main factors: (a) continued increase in crop productivity; (b) expansion in cropland areas; (c) intensification of cropping (more than one crop in a year); and (d) irrigation expansion at a rapid rate [110], all supported by pro-food government policy and assistance from international donors [111]. However, all these factors have now stagnated or are increasing at a rate almost insignificant compared to the Green Revolution period. The donor assistance and lending to agricultural research have faded and hit all times low. Population growth and economic growth continue to derive income transition for a far wider segment of society particularly in China and India, raising demand for calorie intake per person, influencing dietary changes and transforming the way the global cropland and water resources must be used to produce food. This compounds the perplexing climate change challenges.

A serious threat to future food security comes from a changing climate and related uncertainties in water availability. This is illustrated for the case example of Krishna river basin in India (Figure 18) by considering a water water-surplus year (2000-01) and comparing it to a water-deficit year (2002-03). The change in the net area irrigated was modest with an irrigated area of 8,669,881 hectares during the water-surplus year when compared with 7,718,900 hectares during the water-deficit year [112]. However, this is quite misleading as it does not show most of the major changes that occur in the cropping intensity, changing from a higher to lower intensity (e.g., from double crop to single crop). The changes in cropping intensity of the agricultural cropland areas that took place in the water-deficit year (2002-03) when compared with the water-surplus year (2000-01) in the Krishna basin were [112] highly significant (see Figure 18) and have strong impact on food security. Thus significant adjustments in irrigated area, crop mix, crop productivity, and land use are likely under wet-dry conditions that occur in most river basins, including the Colorado River basin in US [113], Mekong Basin countries [114], Murray Darling Basin [115,116] and the Yellow River Plain in China [117], with implications for economic wellbeing of agricultural communities. Such changes may be expected in many parts of the world in a changing climate.

Figure 18. Food security in a changing water and climate scenario [112]**.** Irrigated cropland change map from 2000-01 (water-surplus year) when compared with 2002-03 (water-deficit year). Changes that occurred in a water-deficit year relative to a water-surplus year are shown in the map, including: (a) 1,078,564 hectares changed to single crop from double crop; (b) 1,461,177 hectares changed from continuous crop to single crop; (c) 704,172 hectares changed from irrigated single crop to fallow; and (d) 1,314,522 hectares from minor irrigation (e.g., tanks, small reservoirs) to rainfed.



9. A New Paradigm for Future Food Security

The Malthusian model of "Population, when unchecked, increases in a geometrical ratio while subsistence increases only in an arithmetical ratio" [118] is certainly not true for the Green Revolution period (1960–2000) when, actually, foodgrain production nearly tripled to just above two billion tons whereas population doubled from about 3 billion to about 6 billion; even though croplands decreased from about 0.43 ha/capita to 0.26 ha/capita [7]. This was mainly as the result of: (a) expansion in irrigated areas which increased from 130 Mha in 1960s to 278.4 Mha in year 2000 [52] or 399 Mha when you do not consider cropping intensity [1,2] or 467 Mha when you consider cropping intensity [1,2]; (b) increase in yield and per capita food production (e.g., cereal production from 280 kg/person to 380 kg/person and meat from 22 kg/person to 34 kg/person [119]; (c) new cultivar types (e.g., hybrid varieties of wheat and rice, biotechnology); and (d) modern agronomic and crop management practices (e.g., fertilizers, herbicide, pesticide applications).

However, the Malthusian vision comes back into sharp focus in the new millennium with continued population growth [9] and stagnated crop yield growth [120], diversion of croplands to biofuels [10], limited water resources for irrigation expansion [121], limits on agricultural intensifications, loss of croplands to urbanization [14], increasing meat consumption (and associated demands on land and water) [122], environmental infeasibility for cropland expansion [123], and changing climate. Indeed, some of the factors that lead to the Green Revolution have stressed the environment to limits leading to salinization and decreasing water quality. For example, from 1960 to 2000, the phosphorous use doubled from 10 million tons to 20 MT, pesticide use tripled from near zero to 3 MT, and nitrogen use as fertilizer increased to a staggering 80 MT from just 10 MT [14,124]. Further, diversion of croplands to biofuels is already taking water away from food production; the economics, carbon sequestration, environmental, and food security impacts of biofeul production are net negative [125], leaving us with a carbon debt [126,127].

Future security is threatened by the complex factors. The new food security paradigm must extend beyond current definition that includes food production/availability, access, affordability, and utilization and must encompass various drivers of global change, including climate change, as well as the outcomes of global change processes including impacts on global croplands and water resources, and global policy and institutional solutions afforded by the challenges ahead such as global carbon trading schemes and reducing emissions from deforestation and degradation (REDD) – an emerging strategy with big potential for mitigating the climate change but serious consequences for taking water away from food production to commercial forest plantations. It must consider croplands and associated agricultural arrangements in the context of a quest for a low carbon economy as well as the potential inclusion of agriculture into the carbon pollution reduction schemes worldwide [39]. Strengthening global and local governance is the key and food security must be closely connected with economic growth and social progress as well as political stability and peace. In addition, future food security agenda must also focus on:

Improving water productivity (operationalize the concept of more crop per drop). Recent research by Platanov *et al*. [128] demonstrated that as high as 87% of all croplands in the intensively irrigated areas of Central Asia have low WP (e.g., Figure 19). Their research implied that there is an overwhelming proportion of cropland areas where better land and water management practices can help to improve WP, thus leading to food security without having to increase allocations of land and water resources [129].

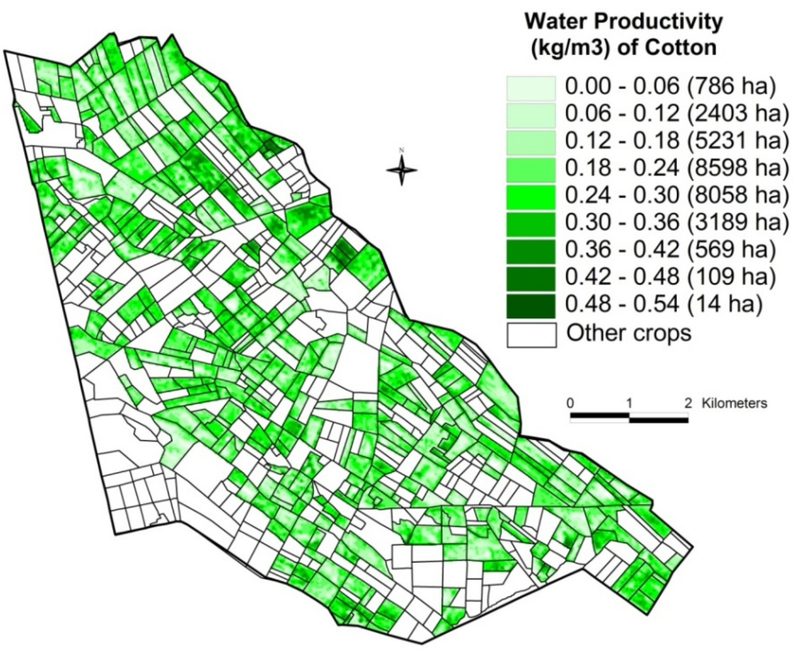
Better agricultural technologies and cropping systems. The change in cropping pattern (e.g., more wheat than rice) can deliver significant gains in food security. For example, rice crop requires about 2,000 liters to produce 1kg of rice where as wheat requires half that amount. Currently, India produces about 93 million tons of rice per year requiring 178 $km^3$of water. Investments to convert 50% of rice area to wheat, will save about 45 km^3 (or 45 trillion liters of water) every year.

Conserving water, preserving land resources. Enhancing the productivity of existing croplands and available blue and green water resources is the main pathway to future food security. This can be achieved through a suite of measures and approaches such as: (a) protecting croplands against salinization; (b) precision farming and resource conservation practices; (c) low-cost water saving irrigation innovations (e.g., drip, sprinklers); (d) reducing food waste from farm to fork that ranges anywhere between 20%–35% of all food produced [130], nutrient recovery and reuse; (e) desalination to augment water shortages (for urban water use is economically viable, but too costly for irrigation); (f) wastewater recycling (water reuse); and (g) and adopting organic farming that is more sustainable and also maintains the quality of land and water (thus, for example, increasing fish population).

Harnessing the potential of biotechnology. Genetically modified and non-GM crops that give better yields, are resistance to drought and are cold tolerant, can grow with less water, less number of growing days, and have better social acceptance can enhance food security. It has huge potential but the risks to environment and human health should be carefully assessed to safeguard the food security [131].

Policy planning and support for virtual water use/trade. Policy processes and WTO negotiations must create a level playing field for all stakeholders, particularly the poor countries heavily dependent on agriculture and unable to afford recurring food imports. For example, cotton will require 5,404 m^3 of water per ton if produced in China whereas it requires 21,563 m^3 per ton if produced in India (http://www.waterfootprint.com). Does that mean that we should grow some crops in some countries and have a global trade agreement? This is debatable as the issues of food security conflict with food sovereignty [132].

Figure 19. Water productivity map (WPM) illustrated for an irrigated area in Uzbekistan [128]. The the water productivity maps (WPMs) are derived by dividing the crop productivity maps (CPMs) with water use maps (WUMs). Nearly 87% of the areas is in the low water productivity (WP; <0.30 kg/m^3). This shows the opportunity that exists to grow more food from existing croplands and existing water allocated for crops by just improving WP.



10. Conclusions and Policy Implications

This paper provided a comprehensive overview of the estimates of global cropland areas and their water use assessment for 197 countries; summarizing and comparing findings by world's leading researchers on the subject. It argued that, global croplands remain key to ensuring future water and food security. At the end of the last millennium, world had between 1.47–1.53 billion hectares of croplands as per major remote sensing [1,2] and non-remote sensing studies [40–42,49,52]. Major cropland studies converge on these figures. A comparison of cropland areas of 197 countries between different studies had a high R^2-value between 0.89–0.94. Further, a comparison of irrigated cropland areas of 197 countries by different studies showed even a higher R^2-value between 0.94–0.97. These results indicate a presence of a strong trend between two products. However, there are significant differences in total cropland areas and/or their precise geographic locations for many individual countries between products that are not apparent in R^2-values. For example, irrigated croplands are variously estimated as 278 Mha [52], 312 Mha [41], 399 Mha (without cropping intensity) [1,2], and 467 Mha (with the intensity) [1,2]. The differences in irrigated area estimates between different studies [1,2,41,52] were especially significant in major irrigated area countries like China and India. The causes of these differences were as a result of definitions used in mapping, data types used, methodologies used, resolution of the imagery, uncertainties in sub-pixel area computations, inadequate accounting of statistics on minor irrigation (groundwater, small reservoirs and tanks), and data sharing issues.

Global cropland's water use vary between 6,685–7500 km^3 yr^{-1} [4,95,96]; with 70% as the green water used by about 1.13 billion hectares of rainfed croplands, 20% as the blue water used by about 278–399 Mha of irrigated croplands, and the 10% as the green water use by irrigated croplands from the rain that falls directly on these lands.

The croplands estimated by various approaches are still too coarse for appropriate planning of water use by crops. Thereby, the need for higher spatial resolution remote sensing products that offer numerous advantages including: (a) precise location of croplands; (b) delineation of crop types; (c) determining cropping intensity; (d) information on watering method (irrigation or rainfed); and (e) potential applications for food security planning and targeting investment to the food security hotspots. These facts clearly imply a need for high spatial resolution cropland mapping (and determination of associated water use) using advanced remote sensing. An ideal solution will be to produce a cropland map by fusing Landsat ETM+ 30 m data with MODIS time-series 250/500 m data. Knowledge of all these factors can have a huge impact on the quantum of water used and is also essential for improved climate change models. Such information becomes even more critical for water trade (virtual water) assessments and negotiating agricultural policy positions in a global change scenario and emerging global carbon trading regime.

A new paradigm for food security has been articulated. Global climate change, population growth, nutritional transition, and global environmental change are placing unprecedented pressure on global croplands and water use. A paradigm central for ensuring global food security in the 21st century, when land and water become more limiting factors as populations and economies grow, have been articulated. First, a country-by-country comparison showed about 1.6 to 2.5 times the water required for irrigation is actually withdrawn from fresh water sources; making irrigation efficiency only 40%–62%. This is one area where huge potential to improve efficiency exists. Second, irrigated areas generally have low water productivity (WP; crop productivity per unit of water). Indeed, in heavily irrigated parts of Central Asia, about 80% of croplands are in low WP range. Generally, WP is low or very low in over 50% of World's irrigated croplands. This is an area where large quanta of water can be saved by improving WP of low productivity areas. Third, a big water saving strategy could be to change crop types (e.g., grow more wheat than rice). For example, if we convert 50% of rice area of India to wheat, we could save about 45 km^3 (45 trillion liters) of water every year. Fourth, is to improve crop productivity of rainfed croplands, through improved green water management which have received scant attention to-date. Fifth, reuse of wastewater and marginal quality water in agriculture and purifying water through reverse osmosis can also save large quanta of fresh water. Sixth, desalination is already becoming economically viable solution for urban and industrial water use. However, it is not yet economical for agriculture. Seventh, trading water as a commodity (e.g., virtual trade) within and between countries also offers potential to boost food security but issues involving food security *versus* food sovereignty require balancing. As per current water scenario, uneven water distribution globally is the real issue than real physical water scarcity. Eight, a number of other management measures (e.g., precision farming, waste reduction, organic forming that will preserve our soils and enrich alternative food chain like fish), and new biotechnology (e.g., crops with less growing period, improved seeds) must all be considered by the new food security paradigm. Ninth, above all, it must respond to the global climate change challenges. For example, the paper illustrates serious decrease in food production during a water-deficit year compared with a water-excess year for a key river basin. This is likely to exasperate under a climate change scenario and numerous competing demands on croplands and water use in the context of global environmental and economic change. It must also respond to the potential inclusion of agriculture into the global carbon trading regime and associated impacts on croplands, water use, food production and food entitlements under the emerging global social contract.

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