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Water-scarcity footprints and water productivities indicate unsustainable rice-wheat production of sub-tropical eco-systems: A review

M Sharath Chandra, RK Naresh, Rahul Kumar, Shipra Yadav, Jana Harish, Pradeep Rajput, Akshay Ujjwal and Shakti Om Pathak

Abstract

Scare water resource or water shortage are one of the major constraint to sustaining and increasing the productivity of rice-wheat systems and limiting primary world issues, particularly India for food security and according to climate change projections, it will be more critical in the future. Since water availability and accessibility are the most significant constraining factors for crop production, addressing this issue is indispensable for areas affected by water scarcity. Saving water can be challenging in that minimizing field losses of precipitation, percolation, and runoff will not inevitably save water if it can be recovered at any other temporal or spatial scale, such as groundwater pumping. Many rice-wheat production technologies tend to save significant quantities of water by reducing the irrigation water demand, but it is unclear if these are real water savings although water balance components have not been quantified. For improving land as well as water productivity, the number of resource conservation technologies include laser levelling, direct drilling, raised beds, non-ponded rice cultivation, micro irrigation and scheduling for irrigation. To encourage the adoption of many water-saving technologies, rehabilitation and enhancement of channel and power systems in Asia, financed by charging according to usage, are needed. Based on awareness of the likely amount of irrigation water available each season and crop water usage requirement, they are able to schedule their plantings, and thus avoid wasting water and financial loss through overplanting and crop failure. These strategies have the potential to increase Asia's output of food and water, but the challenge will be to implement them in a way that benefits many millions of subsistence farmers. This compiled review literature comparing irrigation water productivities (IWPs) and water-scarcity footprints (WSFs) for rice-wheat production at high spatial resolution to provide evidence supporting environmentally safe water use and adoption of latest resource conservation technologies to improve water productivity by proposing potential solutions to address water scarcity for sustainable rice-wheat production.

Keywords: Water-scarcity footprints (WSFs), Water productivities (WP), Rice-wheat production

Introduction

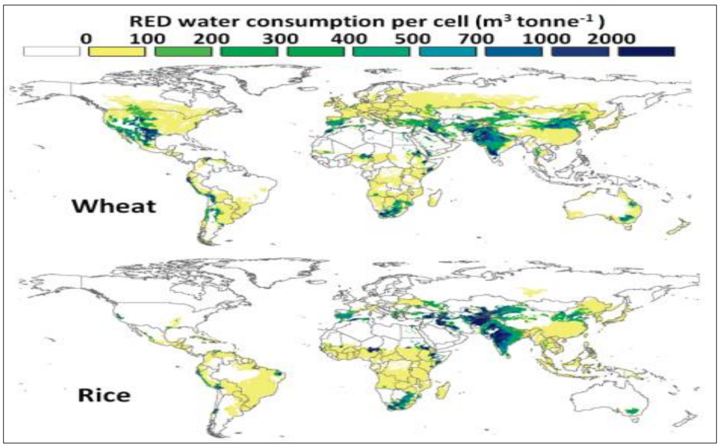
Water is a crucial core resource for the production of every human operation, and is becoming increasingly scarce due to population growth and agricultural intensification (Rijsberman. 2006) [56]. The available water supply and the uneven distribution of these services in time and space are pressing problems in many countries. It is estimated that water shortage will affect a significant proportion of the world's population, up to two-thirds, in the next few decades. Globally, agriculture is the main freshwater user (about 70%) accounting for 90% of intake of water (AQUASTAT. 2016; Siebert *et al.* 2010) [6, 60]. Twin challenges faced by the global food system are to feed a growing population while reducing global environmental impacts (Davis *et al.*, 2017; Foley *et al.*, 2011; Scherer *et al.*, 2018) [16, 21, 57]. Water availability for agriculture is a prerequisite for achieving adequate and sustainable yields, both in terms of unit yields and efficiency (Mancosu *et al.*, 2015) [44]. Of the main staple food crops (rice and wheat), is especially the most important crop in developing countries (Nguyen. 2002) [50]. Given its wide water footprint, practices such as deficit irrigation need to be explored that can increased water inputs for rice wheat production. Deficit irrigation is a technique used to reduce water losses and increase water output, especially in areas where the irrigation water supply is inadequate. Managing the irrigation deficit means inducing marginal tension, except in critical growth stages where crop yield could be negatively impacted (Geerts and Raes, 2009) [22]. The key strategy to increase food security of scarcity of land and water resources should be through the increase of production per unit resources, i.e., the combined increase of production per unit land (crop yield expressed in kg ha^{-1}) and the increase of production per unit water consumed (water productivity expressed in kg m^{-3}) (Bastiaanssen and Steduto, 2016) [7].

Nowadays, water scarcity affects many parts of the planet (Alcamo *et al*., 1997) [5], and threatens countries capacity to meet the increasing demand for food (Hanjra and Qureshi, 2010) [27]. The predicted increase in the world population growth rate (UNDESA, 2013) [68] indicates that higher demand for food would be anticipated in the future, with a direct impact on agricultural water use. In addition, due to the increased water scarcity and drought due to climate change (Cisneros *et al*., 2014) [15], it is predicted that substantial water usage for irrigation would occur in the light of increasing rivalry between agriculture and other economic sectors. Some other measures aimed at streamlining and optimizing the efficiency of water consumption in the agricultural sector are critical in view of the large volumes of water required for the production of crops. Irrigation is used to replace losses due to crop evapotranspiration and to achieve full production under the given growing environment (Doorenbos and Pruitt, 1977) [19]. Rapid socio-economic growth accompanied by a diversification of the global diets and rising water demand and increased meat consumption will continue to meet increased demands for water-limited resources (Cao *et al*. 2016) [13]. Moreover, for non-agricultural purposes, demand has been steadily increasing, including increased urbanization (Gordon *et al*., 2010) [24], industrialization (Liu *et al*., 2005) [42], ecosystem services and environmental flow (Gordon *et al*., 2008; Thenkabail *et al*., 2011) [25, 67]. This combined fresh water rivalry poses a challenge around the water use areas which will need to use water more effectively to prevent conflict (Foley *et al*., 2019) [20]. In order to cope with future estimates of water shortages, improving crop water productivity (WP), especially irrigation water productivity (IWP), water-scarcity footprints (WSP) has been an important measure for ensuring water and food security.

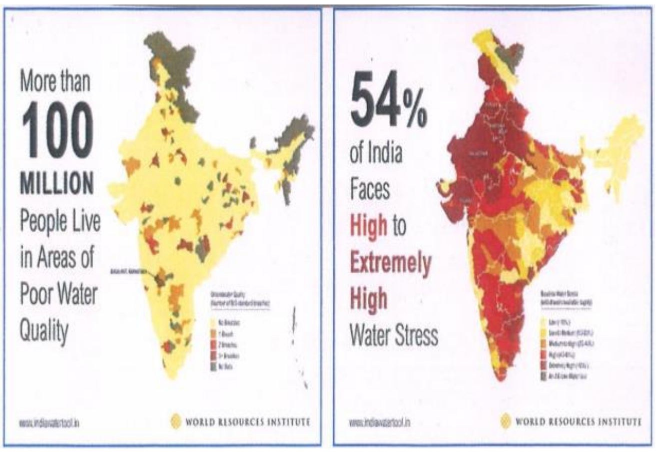
Rice and wheat are major staple food crops and also most water-intensive crops in the world; producing a kilogram of rice requires an average of 2,800 litres of water, while a kilogram of wheat takes 1,654 litres. Inefficient cropping patterns in the last four decades have affected the groundwater reserves according to NABARD and ICRIER, which have accounted for about 84% of the irrigated area (Abraham 2019) [2]. The area and productivity of Rice wheat systems in the IGP increased dramatically between the 1960s and 1990s due to the introduction of improved varieties, increased use of fertilizers and other chemicals, and the expansion of irrigation. However, during the past decade, yields have stagnated or possibly declined, and there are large gaps between potential yields, experimental yields and farmers' yields (Gill 1999; Ladha *et al*. 2003) [23, 40]. In India, top rice and wheat producers like Punjab, Haryana in the north west regions, which contribute almost 15 percent of India's entire rice production and western Uttar Pradesh in the Gangetic plain, are also among the world's top water-risk zones for agricultural production, the others being northeastern China and southwestern U.S., according to Water-Aid Report. By 2030, shifting the larger portion of rice production to central and eastern India including Chhattisgarh and Jharkhand could help India prevent the imminent water crises by 2030, while encouraging the cultivation of wheat through sustainable irrigation within rice-growing Punjab-Haryana regions (Abraham 2019) [2]. Therefore the sustainability of RW systems of the IGP and the ability to increase production in pace with population growth are major concerns. Symptoms of degradation of the resource base include declining soil organic matter content and nutrient availability, and increasing soil salinisation and weed, pathogen and pest populations. However, the biggest threat to sustaining or increasing the productivity of RW systems of South Asia and China is probably water shortage (Humphreys *et al*., 2004) [34].

'Irrigation Water Productivity' (IWP) refers to total crop yield divided by the total amount of irrigation water used for crops, i.e. if crop yields are high and irrigation is low, this is high. IWP shall help to understand where each unit of irrigation water applied would be most efficient across states (Huang *et al*., 2019) [31]. In India, Punjab and Haryana states reported the highest land productivity for rice (4 tonnes per hectare), the IWP for these states is relatively low at 0.22 kg/m^3, even though they have almost 100 percent irrigation coverage, which reflects inefficient irrigation water use, encouraged by Punjab's free electricity policy that enables farmers to pump up groundwater through borewells. Rainfed states like Chhattisgarh and Jharkhand, in contrast, display higher levels of IWP at 0.68 kg/m^3 and 0.75 kg/m^3, even though they had substantially lesser irrigation coverage at 32 percent and 3 percent, respectively. Land productivity here is also lesser because of low irrigation levels, although the region is hydrologically suited for rice cultivation. While in wheat, however, Punjab has the highest level of IWP of 1.22 kg/m^3, followed by Haryana at 1.05 kg/m^3 and is suitable for cultivation in the region. The dry regions of Madhya Pradesh, Maharashtra and Gujarat have low IWP (0.53 kg/m3, 0.63 kg/m^3 and 0.71 kg/m^3, respectively) and wheat cultivation in these states would add to water crisis (Abraham 2019) [2]. In developing countries where 80 percent of the population is projected to rise, Increasing crop water productivity (CWP) is also important to balance the decreased availability of water and soil for the production of food, which include water use and efficiency (Brauman *et al*., 2013 [10]; Cai and Rosegrant, 2003) [11]. This would allow us to produce 'more crops per decline' and thus help to improve food production by reducing the allocation of land and water. The enhanced CWP is a big part of the increased availability of water for urbanization uses as both social and economic developments (Molle and Berkoff 2006; Molden *et al*. 2010) [47, 46]. Each of these was compared with land productivity to determine if the existing cropping pattern was in line with naturally available water resources of various regions and if these were hydrologically sustainable (Abraham 2019) [2].

Globally, Spatial variability of RED water varies largely as both irrigation intensity and water stress fluctuate substantially among different climatic regions. The spatially explicit RED water per tonne for wheat and rice (Fig.1a). Wheat production in central and northern Europe, for instance, is mostly rainfed and therefore has almost no blue and RED water consumption, whereas large environmental impacts may result from wheat production in arid regions, such as Texas or northern India. Similarly, rice, which is almost irrigation-free in South-East Asia, features high RED water in central Asia. Spatial variability is not bound to country boundaries, but rather to climatic and hydrological conditions (Pfister *et al*., 2011) [52]. The availability and demand for water resources in India show significant variations from one area to another. The usage and distribution of water is inefficient and inequitable. Nearly 90% of India's population lives in areas with some form of water stress or food production deficit. Ground water was fairly plentiful in most parts of India. However, in some areas, this is becoming one of the most important resource problems. The low water quality and water stress conditions in India are shown in Fig. 1b (Dhawan. 2017) [18].



(a)



(b)

Fig. 1a: Specific RED water consumption of the globally most important crops: wheat and rice [Pfister *et al*., 2011] [52].

Fig. 1b: Conditions of poor water quality and water stress in India [Dhawan. 2017] [18].

In this context, the aim of this collected literature review article is to provide a broad review of several water-related issues, including irrigation water productivities (IWPs), water-scarcity footprints (WSFs) of rice-wheat production and implementing latest resource conservation technologies for improving water productivity to propose potential solutions to cope with water scarcity for sustainable rice- wheat production.

Rice-Wheat production and Irrigation water consumption

Naturally, this is largely because rice and wheat are the most common crops grown around the world, and therefore provide a significant pay-off for their water usage, by feeding more of the world's population than any other type of food. In India, the production of rice and wheat reported a food grain production of 284.95 million tonnes, which fell slightly short of the target of 290.25 million tones in 2019, according to the fourth advance estimate released by the Ministry of Agriculture. There is, however, a large amount of rice and wheat in 2018-19, though rice production increased from 112.76 million tons in 2017-18 to 116.42 million tons this year, wheat production also increased from 99.87 million tons to 102.19 million tonnes. (The Economic times, 2019) [66].

Huai *et al*. (2019) reported that the production of both rice in Northeast China increased substantially from 2000 to 2010 (Fig. 2). The total production of rice increased from 1.4 × 107 ton in 2000 to 2.2 × 107 ton in 2010, which shows an increase of 60% (Fig. 2a,b). While rice production slightly decreased in some northern regions of Northeast China, the main increase happened in the middle-lower western and eastern regions (Fig. 2b).

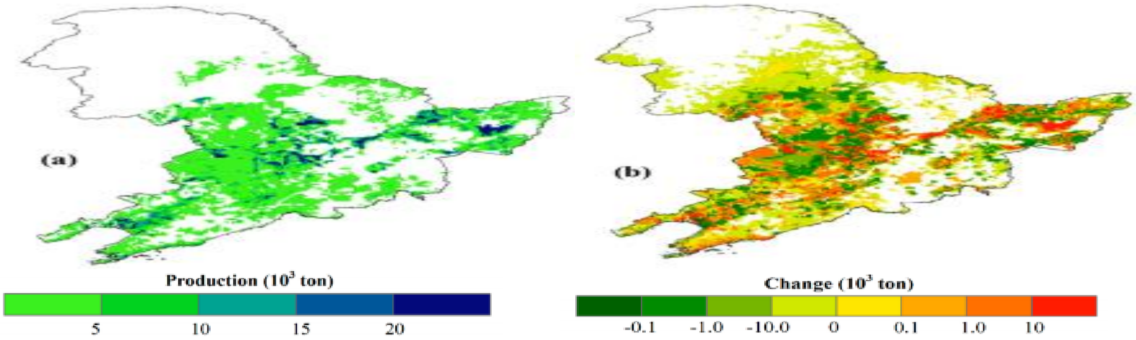
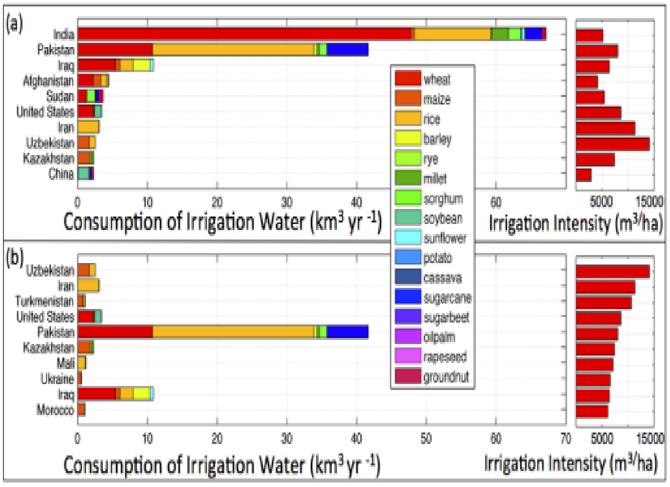


Fig 2: The change in rice production in Northeast China. (a) rice production in 2010, and (b) the change of rice production between 2010 and 2000 [Huai *et al*. 2020] [30].

Brauman *et al*. (2013) [10] stated that they evaluated the irrigation water use on cultivated land with the lowest 20 percent of water productivity in precipitation environment (fig. 3a) to identify countries where water savings on irrigated cropland will be most beneficial. More than 40% of total water irrigation use for this area is in India, 67 km^3 yr^{-1}, primarily in cultivation of wheat and rice. As there are so many croplands in India, however, irrigation intensity (consumption per hectare) is around 520 mm yr^{-1}. In Uzbekistan, by comparison, food crops use just 3 km^3 yr^{-1} in similar climates. However, irrigation intensity (∼1400 mm yr^{-1}) is nearly three times greater, due to the low overall water consumption, improving the irrigation efficiency of food crops in Uzbekistan is unlikely to reduce water shortages across the basin, although the impact on the farm may be dramatic. Water consumption by crops varies considerably across the globe, reflecting differences in crop density, crop choice, soil characteristics, availability of irrigation and agricultural management, as well as climate evapotranspiration. The distribution of crop water consumption between climate zones (Fig. 3b) shows that crops are likely to make a significant contribution where water resources are scarce. Rainwater consumption is dominated by millet and sorghum in arid climates ($P / PET < 0.2$), while irrigation water is mainly used for wheat and rice. In semi-arid and dry sub-humid climates ($0.2 < P / PET < 0.7$) rainwater consumption is dominated by wheat, rice and maize, while irrigation water use is dominated by wheat, rice, sugarcane, and maize. For the 16 crops studied, 52% of rainwater consumption (irrigated and rainfed) and 82% of irrigation water consumption occur in regions where precipitation is potentially limiting ($P < PET$) (Brauman *et al.*, 2013) [10].



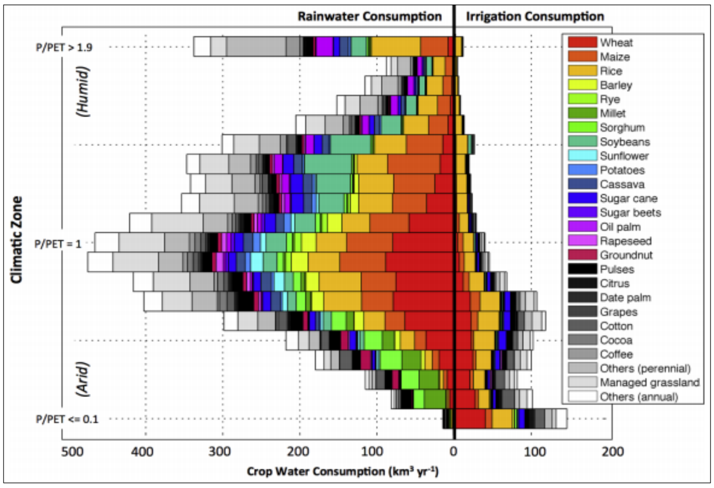
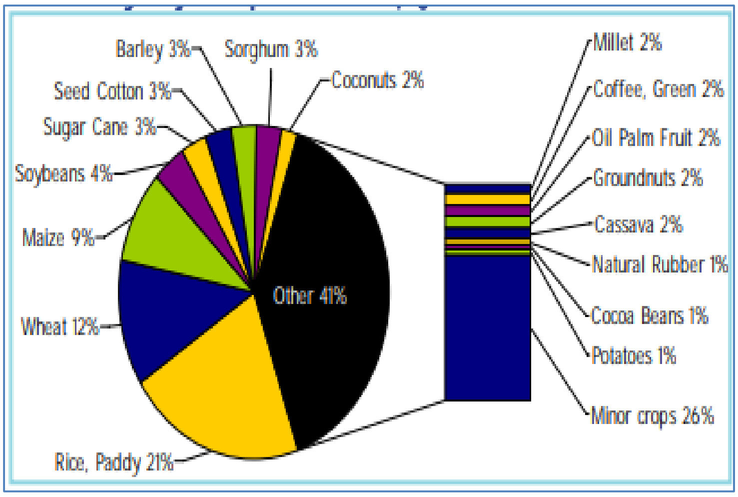


Fig 3a: Annual water consumption per country for 16 food crops in precipitation-limited areas with low water productivity. Countries are ranked by (a) irrigation water consumption as well as (b) irrigation intensity (consumption per hectare). We limited the analysis of countries with high irrigation intensity to those where irrigation consumption on precipitation-limited, low water productivity cropland was at least 0.5 $km^3 yr^{-1}$.

Fig 3b: Annual water consumption across climatic zones. Rainwater (left of centre line) and irrigation water (right of centre line) consumption by all crops, including those (in greys) that are not included in this analysis. For the 16 food crops analyzed, the majority (83 per cent) of the water originates as rainfall on the cropland. Climate zones, most arid at the bottom and most humid at the top, are based on P / PET and are evenly distributed in the climate. Cropland in climatic zones where P / PET > 1.9 is compressed into a single zone [Source: Brauman *et al.*, 2013] [10].

Chapagain and Hoekstra (2004) have shown that the proportion of crop water used by major foreign crops reflects both blue and green water, and that irrigation losses are not accounted for. These estimates often presume complete fulfillment of the crop water requirements. Some may indicating (Fig. 4a) implies that rice, wheat, and maize have the highest content of embedded water: this would be incorrect. Just because these crops use much of the total water, that doesn't mean they use the most water per kilogram. Between 2005 and 2014, cereal cultivated irrigated land area increased from 51.4 to 58.2 Mha (+ 13.4%). Total annual cereal production increased by 26.4% from 188.2 Mt to 237.9 Mt (Fig. 4b). The average annual total water consumption for cereal production was 377.9 km3 over the period 2005–2014 and decreased from 393.2 to 367.1 (−6.6%). Wheat and rice production consumed the greatest amount of water (80.6% of total water use) and the highest consuming states Uttar Pradesh, Punjab and Rajasthan, accounted for 20.0%, 8.4% and 8.4% of total Indian water consumption for cereal production, respectively (Kayatz *et al.*, 2019) [38].



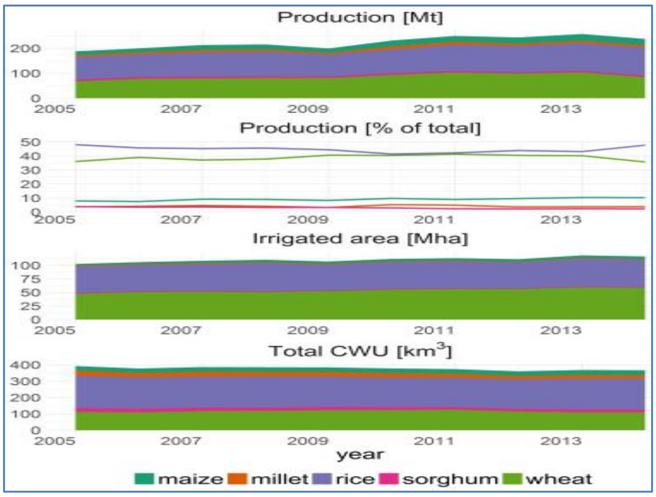


Fig 4a: Percent of global crop water (green and blue) consumed by major crops.

Fig 4b: Irrigated area, total production and overall water use for rice, wheat and other cereal crops in India [Kayatz *et al.*, 2019] [38].

Water-scarcity footprints (WSF) and Irrigation water productivities (IWP) of Rice-Wheat Production

The environmental impact of water usage depends not only on the amount of water used, but also on the water stress situation in the region where the water was extracted. The water deprivation potential, or referred to as "water scarcity footprint," is therefore proposed as a measure for assessing and comparing the possible effect of water usage in terms of the amount of water depletion to downstream human users and ecosystems (Pfister and Bayer, 2014 [51]; Lovarelli *et al*., Hoekstra, 2016) [43]. However, according to the Taub (2016) [65] reported that rice, wheat and tea are the three most water-intensive commodities needing the most hydration per tonne. As a result, the study encourage farmers and scientists around the world to continue developing more water-efficient production techniques, while also creating drought-resistant strains of key crops. As seen in the graphs and infographics below, the production of these two important foodstuffs guzzles constitutes an enormous proportion of all global water consumption. For example, Rice uses up to 40% of all irrigation water in the world (Fig. 5a & 6b).

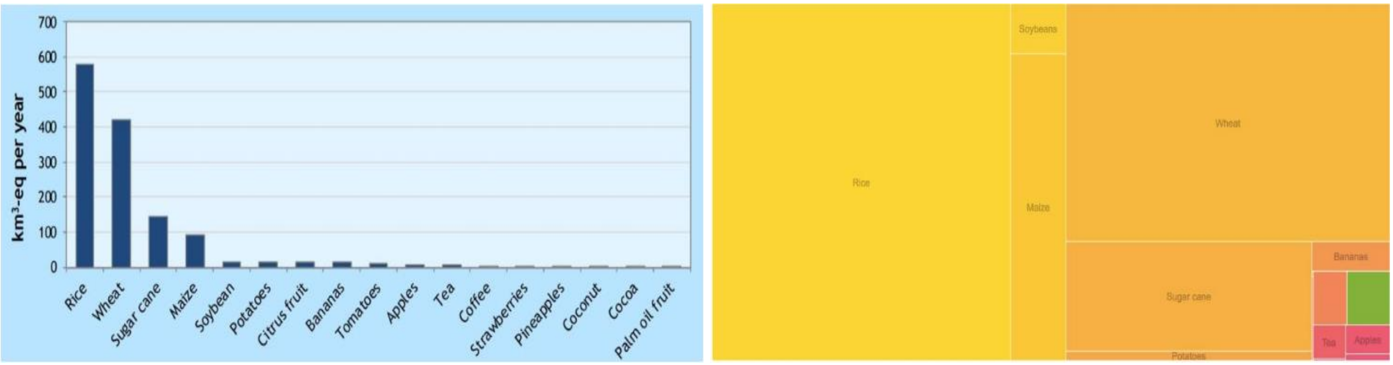


Fig. 5: a) Graph showing the water scarcity footprint of various crops. **b)** Annual global water scarcity footprint by commodity. Cubic meters of water equivalents. Water scarcity is a factor of water used in irrigation and regional water scarcity indicators [Taub (2016) [65]].

Huai *et al*. (2020) [30] indicated that the total Water-Scarcity Footprint (WSF) of both rice in Northeast China increased substantially from 2000 to 2010 (Fig. 6). The total WSF of rice was 6.4 × 109 m^3 H_2Oe in 2010, which was almost triple as high as the WSF in 2000 (Fig. 6a, 6b). He also found that based on the one-at-a-time sensitivity analysis, the change in production (P_1) and WSI (P_2) substantially increased the total WSF of the rice, whereas the change in the irrigation intensity decreased the total WSF of the rice (Fig. 6a). As the production in 2010 was 1.6 times that in 2000, the increase in the total WSF (increased by 60%) under P_1 kept pace with the increase in the production. The total WSF under P_2, which had increased by 168%, was the highest among all the parameter perturbations. That result occurred because the WSIs of most regions in 2010 were higher than those in 2000 (Fig. 7). The rice production-weighted average WSI in the northeast was 0.50 in 2010, whereas it was 0.19 in 2000. The total WSF under P_3 was 25% lower than that in 2000, which was caused by lower irrigation intensity (Fig. 10). For example, the average irrigation intensity in 2010 was 0.53 m3 kg^{-1}, whereas that in 2000 was 0.71 m3 kg^{-1}.

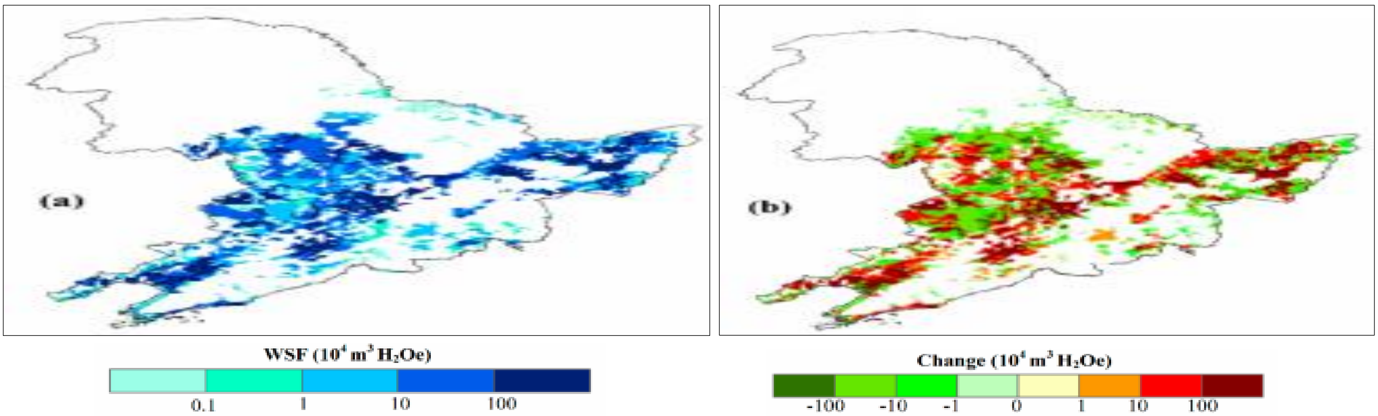


Fig 6: The change in the water-scarcity footprint (WSF) of rice in Northeast China. (a) is the WSF of rice in 2010, and (b) is the change of rice WSF between 2010 and 2000.

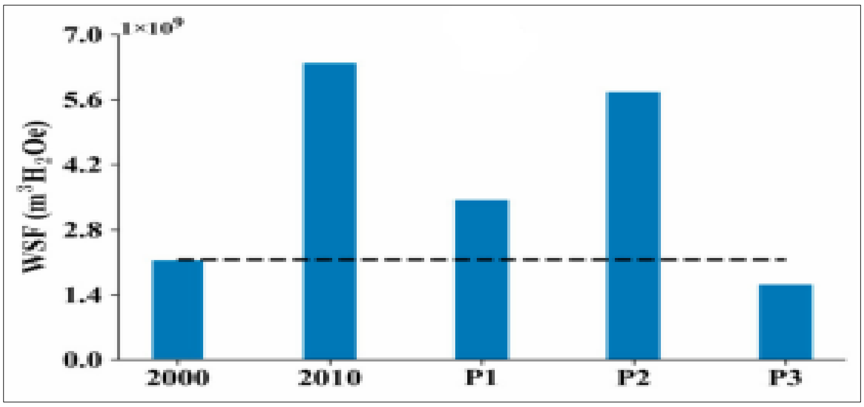
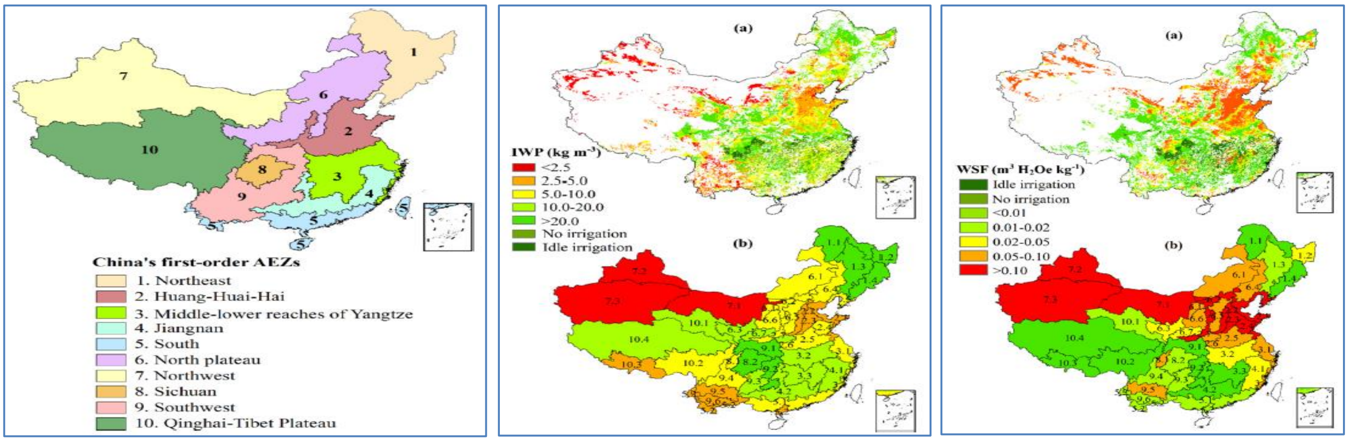


Fig 7: Sensitivity analysis of the water-scarcity footprint (WSF) for rice. P_1: change in the total production; P_2: change in the WSI from; P_3: change in the irrigation intensity (the average irrigation amount per kilogram grain) under irrigated conditions; and P_4: change in the irrigated fraction (the ratio of irrigated area to the total arable land) from 2000 to 2010. Note: P_4 was not performed for rice, because the irrigated fractions of rice were always 100% [Huai *et al*. 2020] [30].

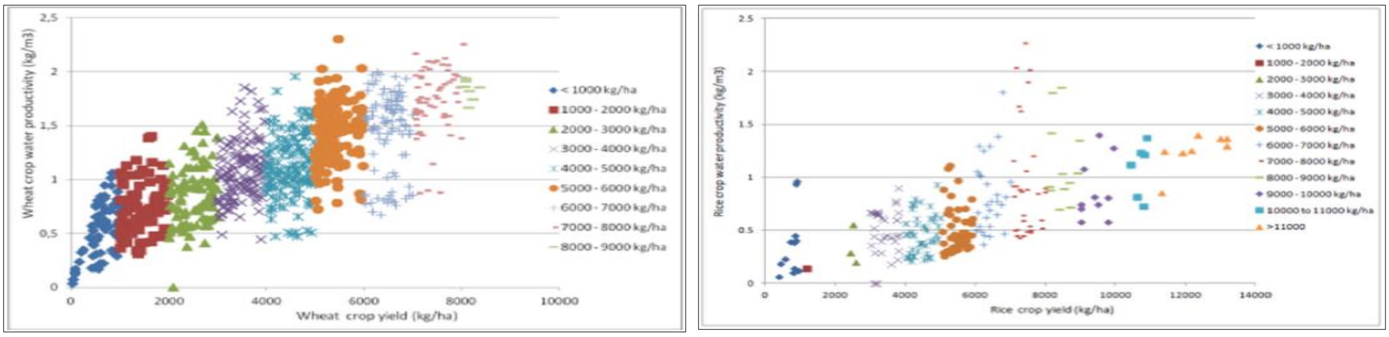
Huang *et al*. (2019) [31] reported that IWPs vary largely across AEZ regions of china (Fig. 8A), in line with differences in wheat yield and irrigation intensity. Most of the rainfed wheat production areas were located in the water-rich southern region (Fig. 8B(a)). Low irrigation water consumption in some southern and northeastern regions resulted in much higher IWPs (> 20.0 kg m^{-3}) compared to wheat grown in some northern, northwestern and southwestern regions (< 2.5 kg m^{-3}). According to the AEZ scale (Fig. 8B(b)), the Northwest AEZs had much lower IWPs (< 2.5 kg m^{-3}), while some Southwest, Sichuan Basin and Northeast AEZs had much higher IWPs (> 20.0 kg m^{-3}). If idle irrigation was avoided, most AEZs in the southern regions could have higher IWPs, e.g., the IWP of the Southwest AEZ encoded as 9.2 may increase from 31.3 to 35.6 kg m^{-3}. He also found larger environmental impacts resulted from irrigation in water-scarce regions, such as the Huang-Huai-Hai and northwestern regions (Fig. 8C(a)). The WSFs of wheat in these regions were higher than 0.10m3 H_2Oe kg^{-1}. In contrast, the WSFs of wheat produced in some southern and northeastern regions were less than 0.01m^3 H_2Oe kg^{-1}. At the AEZ scale (Fig. 8C(b)), the Northwest AEZs as well as some Huang-Huai-Hai AEZs had much higher WSFs (> 0.10 m^3 H_2Oe kg^{-1}), while most Northeast AEZs and most AEZs in southern China had much lower WSFs (< 0.02 m^3 H_2Oe kg^{-1}) respectively.



(A) (B) (C)

Fig. 8: A) China's first-order agro-ecological zones (AEZs). The number of the AEZs represents codes linked to their names [Source: Liu and Chen, 2005] [42]. Each first order AEZ includes several sub-order AEZs. B) Irrigation water productivities (IWP, kg m^{-3}) and **C)** Water-scarcity footprints (WSFs, m^3 H_2Oe kg^{-1}) with a resolution of 5 arc minutes (a) and (b) at the scale of agro-ecological zones (AEZs). White indicates no data or no wheat production [Source: Huang *et al*., 2019] [31].

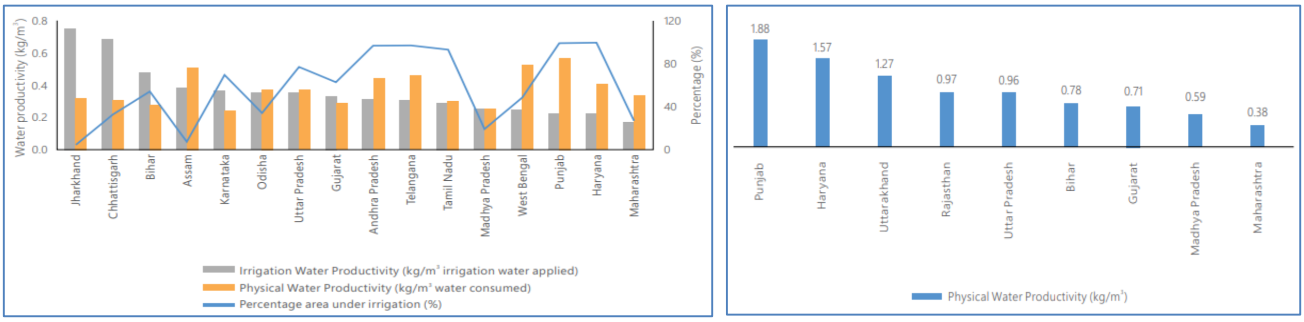
Bastiaanssen and Steduto (2016) [7] indicates the width of band of crop water productivity (CWP) values of wheat and rice crops appears to be a wide variability in the yield zone of b1000 kg ha^{-1} according to estimates, while the yield zone of N9000 kg ha^{-1} and higher shows a small spatial variation due to consistent and optimal on-farm practices (Fig 9).



(a) (b)

Fig 9: Crop water productivity variability by crop yield zones for (a) wheat and (b) rice based on experimental research from 17 different countries [Bastiaanssen and Steduto, 2016] [7]

Sharma *et al.* (2018) [59] stated that the irrigation-water productivity and physical water productivity values of the rice crop are plotted in each state along with the percentage area under irrigation (Fig. 10a). The states are organized in a descending order of irrigation water productivity, with Jharkhand having the highest irrigation water productivity at just three percent irrigation level, followed by Chhattisgarh with 32% irrigated rice field. Bihar with 0.48 kg/m^3 irrigation water productivity and 54% irrigation area and Assam with 0.38 kg/m^3 IWP and 6 % irrigation area. All these states have significant water requirements for irrigation. Increasing irrigation and growing areas and using available irrigation water efficiently will help to significantly boost rice production in those regions. In wheat, there is a huge difference in water productivity among the lowest and best performing districts (ranging between 0.24 and 2.03 kg/m^3). A large number of districts in Maharashtra and Gujarat had low PWP rates. Punjab has the highest level of physical water productivity for wheat (1,88 kg/m^3) when Haryana (1,57 kg / m3) is considered to be state wide (Fig. 10b). The eastern UP and Bihar districts also showed low PWP rates when compared with the western UP area. Although it is a matter of serious concern at one point, at another it presents a good opportunity for efficient use of water and improved productivity in India's vast wheat agri-scape. This is mainly due to the high levels of land productivity in Punjab achieved by using improved varieties, optimum fertilization, agronomic methods, laser field levelling and large-scale groundwater pumping to meet the high irrigation water requirements of the crop.



(a) (b)

Fig. 10: a) Applied irrigation water productivity and proportion of rice irrigated area in different states of India. **b)** Physical water productivity (kg/m3) for dominant wheat growing states in India [Source: Sharma *et al*., 2018] [59].

Foley *et al*. (2019) [20] opined that meta-analysis helped us understand the spatial distribution of Crop Water Productivity in countries for irrigated wheat and rice (Fig. 11a and 11b). In each case, the mean CWP of crop growing sites within each country was derived by crop type and categorized into low, medium, and high based on global averages. The categories for wheat were: low CWP ($\leq$0.75 kg/m^3), medium CWP (>0.75 to $\leq$1.10 kg/m^3), and high CWP ($\geq$1.10 kg/m^3). For wheat, countries that had: (1) high CWP were China, Egypt, Israel, Mexico, Netherlands, Turkey, and USA; (2) medium CWP were Argentina, Australia, Bangladesh, India, Iran, Pakistan, and Syria; and (3) low CWP were Algeria, Morocco, Niger, and Uzbekistan. The categories for rice were: low CWP ($\leq$0.70 kg/m^3), medium CWP (>0.70 to$\leq$1.25 kg/m^3), and high CWP (>1.25 kg/m^3). For rice, countries that had: (1) high CWP were China, Philippines, and USA; (2) medium CWP were Australia, Cambodia, Egypt, India, Mali, and Senegal; and (3) low CWP were Ghana, Malaysia, Morocco, Nigeria, Pakistan, Turkey, and Uzbekistan.

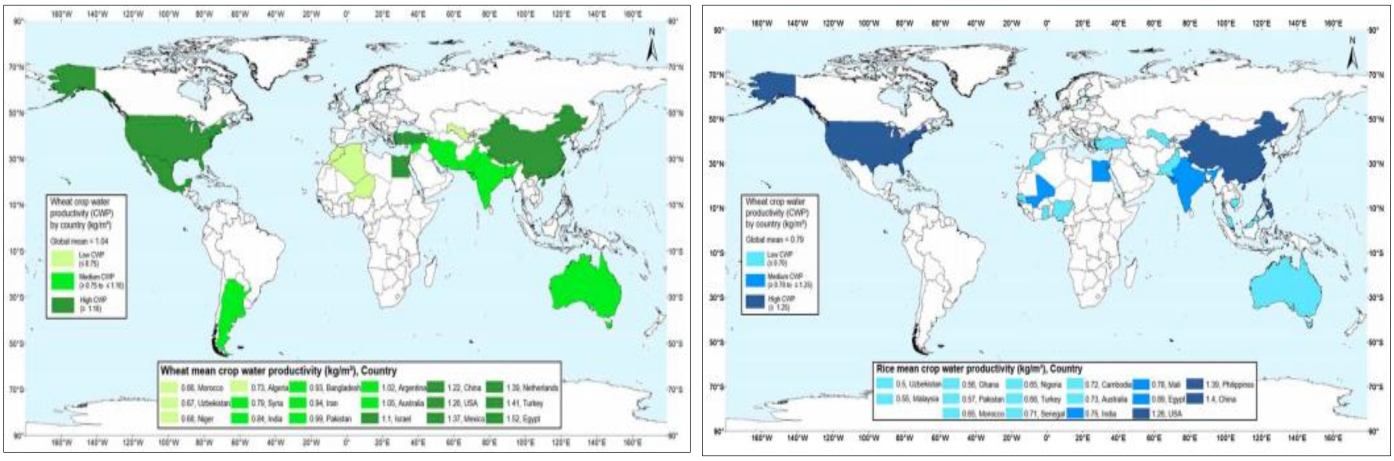


Fig 11: Spatial variability of mean crop water productivity (CWP) for irrigated a) wheat and b) rice by country analyzed in this study. Broadly, CWP, can be grouped into countries with three levels: Low CWP (≤0.75 kg/m³), medium CWP (>0.75 to <1.10 kg/m³), and high CWP (≥1.10 kg/m³) [Foley *et al*., 2019] [20].

Resource conservation technologies for saving water and Improving water productivity in sustainable rice- wheat production

Water productivity can be increased by increasing yield and/or reducing water use. There have been substantial increases in irrigation and total water productivity of Rice wheat systems in Asia over the past thirty years, largely due to increased yields of both rice and wheat as a result of improved varieties and management of water, nutrients, weeds, pests and diseases (Hobbs and Gupta 2000 [28]; Kahlown *et al*. 2002 [37]; Alam *et al*. 2003 [4]; Humphreys and Robinson 2003 [32]; Dawe 2004) [17]. Some of the technologies for saving irrigation water and increasing irrigation water productivity in rice- wheat production systems.

A) Raised Beds

Kukal *et al*. (2010) [39] reported that raised beds for rice-wheat (RW) cropping systems in the Indo-Gangetic Plains as increasing irrigation water productivity, among many other potential benefits. The amount of irrigation water applied to rice on permanent beds and puddled transplanted rice (PTR) was similar in the small plots on the sandy loam. However, on the loam, irrigation applications to the permanent beds were always higher than the puddled plots, by 16 to 21%. Over 4 years, WP_{IW} of transplanted rice on permanent beds decreased with time on both soils, mainly due to declining grain yield as the beds aged. Irrigation applications to fresh beds were lower than to the puddled flats (by 11% on the sandy loam, and 20-24% on the loam) while yields were only 7 and 15% lower, resulting in similar WP_{IW} on fresh beds and PTR. Reducing irrigation application from full-furrow to half-furrow depth in the farmers' field reduced the irrigation amount on both permanent and fresh beds by 40-50%, but also reduced yield by about 20% respectively. Singh *et al*. (2005) indicated that in the IGP, wheat grows successfully on raised beds, with similar or higher yields and about 18% to 30- 50% less irrigation water than conventional tillage on the flat but usually these beds are destroyed after wheat for successful puddling operations for paddy establishment.

Naresh *et al*. (2011) [49] revealed that conventional puddled transplanted rice consumed about 9% more water (2,950 mm) than dry-seeded rice (2,575 mm) with zero conventional tillage, and 18% more water than with beds (2,420 mm). Similarly, the water use in wheat on PB-DSW was 15–26% lower than with other tillage / crop establishment practices with the same rice-residue management. The higher irrigation water use in wheat with residue retention resulted from one good rainfall just before an irrigation was due in the residue removed treatments, saving one irrigation. The total system water input was least with PB- DSW and about 16% less than with CT TPR-ZT- DSW. There were no significant differences in input water productivity between any treatments for rice or the total system. However, input water productivity of wheat on PB- DSW was significantly higher than in all other treatments, with and without rice mulch (Table 1). There was also a consistent trend for higher wheat input water productivity with rice-residue retention.

Table 1: Water application and water productivity in rice and wheat with various tillage and crop establishment techniques [Source: Naresh *et al*., 2011] [49]

Crop establishment		Irrigation water applied(mm ha^{-1})			Water productivity (kg grain m^{-3})		
Rice	Wheat	Rice	Wheat	RW system	Rice	Wheat	RW system
CT-TPR+S	ZT-DSW+R	2760	365	3125	0.20	1.49	0.35
CT- TPR	ZT- DSW	2950	395	3345	0.19	1.28	0.35
ZTDSR+S	ZT- DSW+R	2490	315	2805	0.19	1.83	0.37
ZTDSR	ZT- DSW	2575	385	2960	0.18	1.36	0.33
CTDSR+S	RT- DSW+R	2625	390	3015	0.17	1.45	0.33
CTDSR	RT- DSW	2675	415	3090	0.17	1.28	0.32
PBDSR+S	PB-DSW+R	2315	310	2625	0.18	1.73	0.36
PBDSR	PB- DSW	2385	325	2710	0.17	1.62	0.35
PBTPR+S	PB- DSW+R	2395	315	2710	0.18	1.71	0.36
PBTPR	PB- DSW	2420	330	2750	0.18	1.56	0.35
CT- TPR	CT- BCW	2950	445	3395	0.19	0.91	0.29

CT- TPR- conventional till puddle transplanted rice, ZTDSR-zero till direct seeded rice, CTDSR-conventional till direct seeded rice, PBDSR-Direct seeded rice on permanent raised beds,PBTPR-Transplanted rice on permanent raised beds, +S-with Sesbania as groundcover, ZT-DSW-zero till wheat, CT-BCW-Conventional till broad cast wheat, +R-with rice residue,RTW-Reduced till wheat.

Choudhury *et al*. (2007) [14] reported that rice yields on raised beds that were kept around field capacity were 32–42% lower than under flooded transplanted conditions and 21% lower than under flooded wet-seeded conditions. While, Water inputs were reduced by 32–42% compared with flooded rice, but could also be accomplished with dry seeding on flat land with the same water management. The reduced water inputs and yield reductions balanced each other so that water productivity was comparable among most treatments. Both dry-seeded and transplanted rice on beds yielded less, by 8–25%, than conventional puddled transplanted rice. There was no effect of tillage and establishment method on wheat yield. Total system productivity (rice equivalent yield) of the permanent raised beds (PRB) systems was lower than productivity of the conventional system by 2–16% (Ladha *et al*., 2008) [41].

B) Land Levelling

Flood irrigation is most adopted practice in rice-wheat cropping system in the IGP because of which a significant amount of water lost (10-25%) because of uneven fields (Kahlown *et al* 2002) [37] which further results in poor resource use efficiency (Jat *et al*., 2009) [35]. Land levelling will minimize the loss of wheat evaporation and percolation by allowing for faster irrigation times and by reducing depression in depression. This also eliminates problems with water logging, in particular in densely textured soils. Average wheat irrigation savings of 25 percent in Pakistan in comparison to non laser fields resulted in a 20-35% increase in yield and a decreasing labor costs and land preparation (Kahlown *et al*. 2002 [37]; Alam *et al*. 2003) [4]. Land levelling also reduces the water depth needed for highest areas and ponding in rice for weed control and thus loss of percolation on more permeable soils. In Rickman (2002) [55], rice yield was found to be 24 per cent higher in rainfed lowland laser-level fields than in non-lasered fields in Cambodia, growing with uniformity of levelling.

Jat *et al*. (2011) [36] reported that higher grain yield of wheat and less water use in raised bed planting and precision land leveling compared to other treatments resulted in higher irrigation water productivity (kg·grain·m^{-3} irrigation water). The water productivity of precision leveling with raised beds was 31% and 35% higher yr. 1 (2002-2003) and yr. 2 (2003-2004), respectively compared to precision leveling with flat sowing and the corresponding increase in WP under traditional leveling with raised beds over traditional leveling with flat planting was 40% and 37% respectively. laser leveling results in improved crop stand because of uniform distribution of water along with improved crop productivity and lower labour requirement. LL improved the farm income by improving system productivity to 7% and by saving irrigation water upto 14% in rice and upto 13% in wheat (Jat *et al*., (2009) [35].

C) Direct seeding rice

Direct seeded rice come out with a hope as no puddling operations are required here which further means lower use of irrigation water and good soil health, which is free from the plough pan and offers no restrictions to the wheat roots (Yadav *et al*., 2015) [69]. Input water savings 35-57 percent in dry seeded rices seed to soils not puddled with soil held near saturation or field potential have been recorded in NW India (Singh *et al*. 2002; Sharma *et al*. 2002) [61, 58] as opposed to continuously flooded PTRs (~5 cm). However, yields were decreased due to iron or zinc inadequacy by comparable amounts and increased nematodes incidence. The experimental findings in the farm fields in the NW Indian and Punjab's Pakistan indicate a marginal increase or a ten per cent decrease in flat DSR levels compared with puddled transplanted rice water use (Gupta *et al*. 2002; Qureshi *et al*. 2004) [26, 54], increasing water productivity.

Bhushan *et al*. (2007) [9] reported that the yields of rice in the conventional puddled trans-planting and direct-seeding on puddled or nonpuddled (no-tillage) flatbed systems were equal and wheat yields either the puddled-transplanted or no-tillage direct-seeded rice were also equal. Normally,puddled transplanting required 35 to 40% more irrigation water than no-tillage direct-seeded rice. Compared with conventional puddled trans-planting, direct seeding of rice onraised beds had a 13 to 23% savings of irrigation water, but with an associated yield loss of 14 to 25%.Nevertheless, water use efficiency (WUE) in the rice–wheat system was higher with direct-seeded rice (0.45 g L^{-1}) than with transplanted rice (0.37–0.43 g L^{-1}).

D) Irrigation scheduling for wheat

Irrigation of wheat after rice should be scheduled to maximise use of stored soil water and winter rain while maintaining yield. Prihar *et al*. (1978) [53] established guidelines for irrigation scheduling for wheat on the coarse textured soils of northwest India. Singh-Malik (1983) [62] concluded that, in order to avoid a loss of yield, wheat should be irrigated at approximately 60 and 70 percent depletion of plant water, at a lower yield value, compared with a 50 percent deficit in a sandy loam in Haryana. In some situation was different for wheat under varying climate change scenario, where water productivity was increased under sowing wheat 3 wk earlier and irrigation was applied every 21 d in both seasons. Under this scenario, both yield improvement and irrigation water saving could occur resulting that wheat yield could improve by 2% under saving 3% of the irrigation water in the first season. Whereas, in the second season, 8% improvement in wheat yield could happen with less than 1% increase in the applied irrigation water (Afandi *et al*., 2010) [3].

Singh *et al*., (2017) [63] revealed highest water use efficiency under irrigation levels CRI+100 mm and CRI+150 mm respectively. However, WUE was also different for treatments with the same irrigation amount but at different times, because grain production was affected by both the duration and the time of water stress.

E) Micro-Irrigation methods

Micro-irrigation methods like drip and sprinkler irrigation systems are efficient and could be adopted for irrigation in rice and wheat crops for improving the water use efficiency (Meena *et al*., 2015) [45]. Pressurized irrigation systems (sprinkler, surface and subsurface drip) can improve irrigation water efficiency in line with crop needs, decrease runoff and low drainages, and generally maintain a more stable soil environment that decreases soil evaporation and increases the capacity of soils to receive rainfall (Camp 1998) [12].

There are few reports of the evaluation of these technologies in Rice-Wheat systems. In Australia sprinkler irrigation of rice to replace evaporative loss reduced irrigation water use by 30-70% (Humphreys *et al*. 1989) [48], however, even at frequencies of up to 3 times per week, yield declines of 35-70% occurred (Muirhead *et al*. 1989) [33]. Irrigation water use was reduced by about 200 mm in rice with subsurface drip commencing two weeks prior to panicle initiation compared with conventional flooded rice culture; however, yields with drip also decreased and there was no increase in irrigation water productivity (Beecher *et al*. 2006) [8] Supplemental irrigation depths at three phonological stages of wheat crop in Pakisthan, using small quantities of water through sprinkler irrigation system, significantly promoted the crop growth and the highest water productivity of 0.97 kg/m^3 was achieved with 25 mm supplemental irrigation depth when applied at tillering and anthesis stages (Abbas *et al*., 2014) [1].

Conclusion

This review paper concluded that the significance of putting regional problems of freshwater into a national context. The results of the water indicator obtained in many strategic implications for rice-wheat production. As this has led to greater irrigation area, this strategy is of limited use in solving water crises in subtropical ecosystem while sustaining crop production. Reducing pressure on freshwater resources, alleviating unsustainable groundwater use and securing rice-wheat production for food achieving food security. First, attempts to tackle environmental impacts benefit from recommendations from Water Scarcity Footprints (WSFs) instead of other volumetric measures. High water scarcity Footprint values underline the need for more urgent action. Second, national cropping adjustment has a high potential to ease regional water stress. Opportunities can be explored to increase production of rice-wheat in subtropical ecosystems. Third, regional decisions by combining national water, food, and socio-economic factors could avoid unintended negative consequences. It is critical that land- and water-use policies understand the wider consequences of meeting national food demands.

Globally, rice-wheat is the predominant cropping system and it contributes more than 70% of food grain production in India, but the potential for increasing crop water productivity (CWP) plays significant role in rice- wheat production. Both crops (wheat and rice) had a nominally higher low and medium CWP, their contribution to the global production of food and water would be significantly huge. However, major problem in this system is depletion and deterioration of water resources. Therefore, efforts must be focussed on reversing the trend in water resources depletion by adopting efficient irrigation technologies. In response to these strategic recommendations, it is recommended that further research with a narrower scope assess the specific managerial options. It can be difficult to save water in rice-wheat production systems because that filling, percolation and runoff losses on the field scale does not automatically save water if it can be recovered at any other temporal or spatial scale. Many innovations seem to save large quantities of water in rice-wheat systems, but it is not clear if these are real water savings because the water balance components have not been quantified. For improving both land as well as water productivity, number of latest resource conservation technologies include laser levelling, direct drilling, raised beds, non-ponded rice cultivation, micro-irrigation and irrigation scheduling of wheat. In order to achieve food safety and water security in the global context of rising demands on both, rising crop water productivity is a key strategy by reducing the amount of water required for sustainable rice – wheat crop production.

References

1. Abbas SH, Bhatti AA, Asif M, Islam Z, Sohail M, Din RU, *et al*. Effect of supplemental irrigation on wheat water productivity under rainfed ecology of pothohar, Pakistan. Innovare Journal of Agri. Sci 2014;3:10-13.
2. Abraham N. India Must Shift Rice Growing East From Punjab, Haryana To Prevent Desertification 2019. (Press news: https://www.bloombergquint.com/economy-finance/india-must-shift-rice-growing-east-from-punjab-and-haryana-to-prevent-desertification).
3. Afandi GE, Khalil FA, Ouda SA. Using irrigation scheduling to increase water productivity of wheat-maize rotation under climate change conditions. Chilean Journal of Agricultural Research 2010;70(3):474-484.
4. Alam MM, Asim JM, Raza ZI. Economic Evaluation of Resource Conservation Technologies in Rice-Wheat Cropping System. MREP Publication No. 255 (WAPDA, Pakistan) 2003.
5. Alcamo J, Doll P, Kaspar F, Siebert S. Global Change and Global Scenarios of Water Use and Availability: An Application of Water GAP 1.0; University of Kassel: Kassel, Germany 1997.
6. AQUASTAT. Water Resources Development and Management Service; Food and Agriculture Organization of the United Nations: Rome, Italy 2010.
7. Bastiaanssen WGM, Steduto P. The water productivity score (WPS) at global and regional level: Methodology and first results from remote sensing measurements of wheat, rice and maize. Science of the Total Environment 2016, 17p.
8. Beecher HG, Dunn BW, Thompson JA, Humphreys E, Mathews SK, Timsina J. Effect of raised beds and irrigation management on growth, yield and water use of rice in south-eastern Australia. Australian Journal of Experimental Agriculture 2006;46:1363-1372.
9. Bhushan L, Ladha JK, Gupta RK, Singh S, Tirol-Padre A, Saharawat YS *et al*. Saving of water and labor in a rice–wheat system with no-tillage and direct seeding technologies. Agron. J 2007;99:1288-1296.
10. Brauman KA, Siebert S, Foley JA. Improvements in Crop Water Productivity Increase Water Sustainability and Food Security: A Global Analysis. Environmental Research Letters 2013;8(2):1-7.
11. Cai X, Rosegrant MW. 10 World Water Productivity: Current Situation and Future Options. Water Productivity in Agriculture: Limits and Opportunities for Improvement 2003;1:163-178.
12. Camp CR. Subsurface drip irrigation: a review. Transactions of the American Society of Agricultural Engineers 1998;45:1353-1367.
13. Cao X, Chen X, Zhang W, Liao A, Chen L, Chen Z *et al*. Global Cultivated Land Mapping at 30 m Spatial Resolution. Science China Earth Sciences 2016;59(12):2275-2284.
14. Choudhury BU, Bouman BAM, Singh AK. Yield and water productivity of rice–wheat on raised beds at New Delhi, India. Field Crops Research 2007;100:229-239.
15. Cisneros BEJ, Oki T, Arnell NW, Benito G, Cogley JG, Döll P, *et al*. Freshwater resources. In Climate Change: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II

to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., *et al*. Eds.; Cambridge University Press: Cambridge, UK and New York, NY, USA 2014, 229-269p.

16. Davis KF, Rulli MC, Seveso A, D'Odorico P. Increased food production and reduced water use through optimized crop distribution. Nat. Geo Sci 2017;10:919-924.
17. Dawe D, Frolking S, Li C. Trends in rice-wheat area in China. Field Crops Research 2004;87:89-95.
18. Dhawan V. Water and Agriculture in India. Background paper for the South Asia expert panel during the Global Forum for Food and Agriculture (GFFA) 2017.
19. Doorenbos J, Pruitt WO. Crop water requirements. In FAO Irrigation and Drainage Paper 24, 2nd ed.; FAO: Rome, Italy 1977.
20. Foley DJ, Prasad S, Thenkabail, Itiya P, Aneece Pardhasaradhi Teluguntla G, Oliphant AJ. A meta-analysis of global crop water productivity of three leading world crops (wheat, corn, and rice) in the irrigated areas over three decades, International Journal of Digital Earth 2019. DOI: 10.1080/17538947.2019.1651912.
21. Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M *et al*. Solutions for a cultivated planet. Nature 2011;478:337-342.
22. Geerts S, Raes D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agric. Water Manag 2009;96:1275-1284.
23. Gill MA. Promotion of Resource Conservation Tillage Technologies in South Asia-An Overview of Rice-Wheat Consortium Activities in the Indo-Gangetic Plains (Directorate General Agriculture – Water Management, Lahore, Pakistan) 1999.
24. Gordon LJ, Finlayson CM, Falkenmark M. Managing Water in Agriculture for Food Production and Other Ecosystem Services. Agricultural Water Management 2010;97(4):512–519.
25. Gordon LJ, Peterson GD, Bennett EM. Agricultural Modifications of Hydrological Flows Create Ecological Surprises. Trends in Ecology & Evolution 2008;23(4):211-219.
26. Gupta RK, Naresh RK, Hobbs PR, Zheng Jiaguo, Ladha JK. Sustainability of post-green revolution agriculture: the rice-wheat cropping systems of the Indo-Gangetic Plains and China. In 'Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts' (Eds Ladha JK, Hill JE, Duxbury JM, Gupta RK and Buresh RJ). ASA Special Publication 65 (ASAInc, CSSAInc, SSSAInc, Madison, USA) 2002, 1-25p.
27. Hanjra MA, Qureshi ME. Global water crisis and future food security in an era of climate change. Food Policy 2010;35:365-377.
28. Hobbs PR, Gupta RK (Eds). Soil and Crop Management Practices for Enhanced Productivity of the Rice-Wheat Cropping System in the Sichuan Province of China'. Rice-Wheat Consortium Paper Series 9. (RWC, New Delhi, India) 2000.
29. Hoekstra AJ. A critique on the water-scarcity weighted water footprint in LCA. Ecol. Indic 2016;66:564-573.
30. Huai H, Chen X, Huang J, Chen F. Water-Scarcity Footprint Associated with Crop Expansion in Northeast China: A Case Study Based on AquaCrop Modeling. Water 2020;12:125. Doi:10.3390/w12010125.
31. Huang J, Ridoutt BG, Thorp KR, Wang X, Lan K, Liao J, *et al*. Water-scarcity footprints and water productivities indicate unsustainable wheat production in China. Agric. Water Manag 2019;224:105744.
32. Humphreys E, Robinson D. Increasing water productivity in irrigated rice systems in Australia: institutions and policies. In 'Rice Science: Innovations and Impact for Livelihood' (Eds Mew TW, Brar DS, Peng S., Dawe D and Hardy B) pp. 885-900. Proceedings of the International Rice Research Conference, 16-19 September 2002, Beijing, China 2003.
33. Humphreys E, Muirhead WA, Melhuish FM, White RJG, Blackwell JB. The growth and nitrogen economy of rice under sprinkler and flood irrigation in south-east Australia. II. Soil moisture and mineral N transformations. Irrigation Science 1989;10:201-213.
34. Humphreys E, Meisner C, Gupta RK, Timsina J, Beecher HG, Lu TY, *et al*. Water saving in rice-wheat systems. "New directions for a diverse planet". Proceedings of the 4th International Crop Science Congress, Brisbane, Australia. Published on CDROM 2004. Web site www.cropscience.org.au.
35. Jat ML, Gathala MK, Ladha JK, Saharawat YS, Jat AS, Vipin *et al*. Evaluation of precision land leveling and double zero-till systems in the ricewheat rotation: Water use, productivity, profitability and soil physical properties. Soil Till Res 2009;105:112-21.
36. Jat ML, Gupta R, Saharawat YS, Khosla R. Layering Precision Land Leveling and Furrow Irrigated Raised Bed Planting: Productivity and Input Use Efficiency of Irrigated Bread Wheat in Indo-Gangetic Plains. American Journal of Plant Sciences 2011;2:578-588.
37. Kahlown MA, Gill MA, Ashraf M. Evaluation of Resource Conservation Technologies in Rice-Wheat System of Pakistan. Pakistan Council of Research in Water Resources (PCRWR), Research Report-1, PCRWR, Islamabad, Pakistan 2002.
38. Kayatz B, Harris F, Hillier J, Adhya T, Dalin C, Nayak D, *et al*. More crop per drop: Exploring India's cereal water use since 2005. Science of the Total Environment 2019;673:207-217.
39. Kukal SS, Humphreys E, Yadav S, Yadvinder-Singh. Irrigation water productivity of rice grown with resource conservation technologies. 19th World Congress of Soil Science, Soil Solutions for a Changing World, Brisbane, Australia 2010.
40. Ladha JK, Pathak H, Tirol-Padre A, Dawe D, Gupta RK. Productivity trends in intensive rice-wheat cropping systems in Asia. In 'Improving the Productivity and Sustainability of Rice-Wheat Systems: Issues and Impacts' (Eds Ladha JK, Hill JE, Duxbury JM, Gupta RK and Buresh RJ). ASA Special Publication 65 ASAInc, CSSAInc, SSSAInc, Madison, USA 2003, 45-76p.
41. Ladha K, Bhushan L, Gupta RK, Pathak H. Performance of furrow-irrigated raised beds in rice–wheat cropping systems of the Indo-Gangetic Plain. Conference: Permanent beds and rice-residue management for rice-wheat systems in the Indo-Gangetic Plain. At: Ludhiana ACIAR Proceedings No 2008;127:108-110.
42. Liu XH, Chen F. Farming Systems in China. China Agriculture Press, Beijing, China 2005.
43. Lovarelli D, Bacenetti J, Fiala M. Water Footprint of crop productions: A review. Sci. Total Environ 2016, 236-251.

44. Mancosu N, Snyder RL, Kyriakakis G, Spano D. Water Scarcity and Future Challenges for Food Production. Water 2015;7:975-992.
45. Meena RP, Sharma RK, Chhokar RS, Chander S, Tripathi SC, Kumar R, *et al*. Improving water use efficiency of rice-wheat cropping system by adopting micro-irrigation systems. International Journal of Bio-resource and Stress Management 2015;6(3):341-345.
46. Molden D, Oweis T, Steduto P, Bindraban P, Hanjra MA, Kijne J. Improving Agricultural Water Productivity: Between Optimism and Caution. Agricultural Water Management 2010;97(4):528-535.
47. Molle F, Berkoff J. Cities Versus Agriculture: Revisiting Intersectoral Water Transfers, Potential Gains and Conflicts, Comprehensive Assessment of Water Management in Agriculture. Research Report, 10. Colombo: International Water Management Institute 2006.
48. Muirhead WA, Blackwell JB, Humphreys E, White RJG. The growth and nitrogen economy of rice under sprinkler and flood irrigation in south-east Australia. I. Crop response and N uptake. Irrigation Science 1989;10:183-199.
49. Naresh RK, Gupta, Raj K, Prakesh, Satya, Kumar *et al*. Permanent beds and rice-residue management for rice–wheat systems in the North West India. Internat. J agric. Sci 2011;7(2):429-439.
50. Nguyen NV (Ed.). Global Climate Changes and Rice Food Security; FAO: Rome, Italy 2002,24-30p.
51. Pfister S, Bayer P. Monthly water stress: Spatially and temporally explicit consumptive water footprint of global crop production. J. Clean. Prod 2014;73:52-62.
52. Pfister S, Bayer P, Koehler A, Hellweg S. Environmental Impacts of Water Use in Global Crop Production: Hotspots and Trade-Offs with Land Use. | Environ. Sci. Technol 2011;45:5761-5768.
53. Prihar SS, Sandhu BS, Khera KL, Jalota SK. Water use and yield of winter wheat in northern India as affected by timing of last irrigation. Irrigation Science 1978;1:39-45.
54. Qureshi AS, Masih I, Turral H. Comparing land and water productivities of transplanted and direct dry seeded rice for Pakistani Punjab. Paddy and Water Environment (in press) 2004.
55. Rickman JF. Manual for laser land levelling. Rice-Wheat Consortium Technical Bulleting Series 5. RWC-CIMMYT, New Delhi, India 2002.
56. Rijsberman FR. Water scarcity: Fact or fiction? Agric. Water Manag 2006;80:5-22.
57. Scherer LA, Verburg PH, Schulp CJE. Opportunities for sustainable intensification in European agriculture. Glob. Environ. Change 2018;48:43-55.
58. Sharma PK, Bhushan Lav, Ladha JK, Naresh RK, Gupta RK, Balasubramanian BV *et al*. Crop-water relations in rice-wheat cropping under different tillage systems and water-management practices in a marginally sodic, medium-textured soil. In ‘Water-wise Rice Production’ (Eds Bouman BAM, Hengsdijk H, Hardy B, Bindraban B, Toung TP and Ladha JK). Proceedings of the International Workshop on Water-wise Rice Production, Los Baños, Philippines, IRRI, Los Baños, Philippines 2002, 223-235.
59. Sharma BR, Gulati A, Mohan G, Manchanda S, Ray I, Amarasinghe U. Water productivity mapping of major Indian crops 2018.
60. Siebert S, Burke J, Faures JM, Frenken K, Hoogeveen J, Doll P *et al*. Groundwater use for irrigation—A global inventory. Hydrol. Earth Syst. Sci 2010;14:1863-1880.
61. Singh AK, Choudhury BU, Bouman BAM. Effects of rice establishment methods on crop performance, water use, and mineral nitrogen. In ‘Water-wise Rice Production’ (Eds Bouman BAM, Hengsdijk H, Hardy B, Bindraban B, Toung TP and Ladha JK, Proceedings of the International Workshop on Water-wise Rice Production, Los Baños, Philippines (IRRI, Los Baños, Philippines) 2002, 237-246.
62. Singh Tej, Malik DS. Effect of water stress at three growth stages on the yield and waer-use efficiency of dwarf wheat. Irrigation Science 1983;4:239-245.
63. Singh V, Naresh RK, Kumar R, Singh A, Shahi UP, Kumar V *et al*. Enhancing Yield and Water Productivity of Wheat (Triticum aestivum) Through Sowing Methods and Irrigation Schedules under Light Textured Soil of Western Uttar Pradesh. Int. J Curr. Microbiol. App. Sci 2017;6(4):1400-1411.
64. Singh Y, Singh G, Johnson D, Mortimer M. Changing from transplanted rice to direct seeding in the rice–wheat cropping system in India. In: Rice is Life: Scientific Perspectives for the 21st Century, Tsukuba, Japan: Proceedings of the World Rice Research Conference 2004, 198-201p.
65. Taub B. Rice And Wheat Production Use More Water Than All Other Crops Put Together. Press note 2016.
66. The Economic times. Rice-wheat at new high, Food grains output falls short of target. Press note 2019.
67. Thenkabail PS, Hanjra MA, Dheeravath V, Gumma M. Global Croplands and Their Water Use From Remote Sensing and Nonremote Sensing Perspectives, Milton Park: CRC Press 2011, 383-419.
68. United Nations Department of Economic and Social Affairs (UNDESA). Population Division. World Population Prospects: The 2012 Revision, Volume II, Demographic Profiles (ST/ESA/SER.A/345); United Nations: New York, NY, USA 2013.
69. Yadav M, Tripathi J, Rawal N, Yadav BP, McDonald A, Humphreys E *et al*. Direct Seeded Rice Productivity as Influenced by Establishment Methods, Seed Rate and Weed Management. IN Proceedings of the 28th National Summer Crops Workshop. 17-18 March 2015. Published by Government of Nepal, Nepal Agricultural Research Council 2015, 347-352.