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Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice

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ABSTRACT

Irrigation is an important measure for increasing grain production. Improving water use efficiency in agriculture is expected to play a very important role in ensuring food and water security in China, since there is a serious problem between food supply and limited water resources in China. The present state and future trend of water and food security in China were analyzed, while the importance of irrigation in ensuring China food security was highlighted based on the analysis of the evolution of irrigation water productivity in recent 60 years and its relationships with changes of crop yield, cropping pattern, fertilization and irrigation water use. Research progresses and practical application on high-efficient agricultural water use in China were introduced, and two successful cases of improving agricultural water productivity in China were presented, one was to improve crop water use efficiency by the novel irrigation method based on crop physiological responses, and the other was to improve the regional water productivity by the integrative methods in the Shiyang River Basin of Northwest China. The major research areas needed to focus on in the future were discussed, which include responses of crop water demand to changing environment and associated spatio-temporal optimization of water allocation, multi-processes hydrologic cycle of irrigated land under strong influences of human activities, integrated measures for improving multi-scale agricultural water use efficiency, and interactions between grain production, water resources and ecological system and its sustainability analysis in a systematic way.

1. Introduction

Increases in greenhouses gas concentrations have resulted in the increases in globally-averaged mean annual air temperature and variations in regional precipitation and these changes are expected to continue and intensify in the future (Solomon et al., 2007). Climate change poses serious threats to global food security due to changes in water supply and demand by altering the spatial and temporal distribution of rainfall, the availability of water, and other agricultural production factors (Alcamo et al., 2007; Hanjra and Qureshi, 2010). Sustainable use of water resources and food security are essential for ensuring sustainable social and economic development. Worsening resources and climate crises, water and soil resources scarcity, and extreme weather events such as severe drought and flooding have been affecting global agricultural production in a negative way (Turral et al., 2001). Ensuring food security has become the most important challenge the human society has ever faced.

Water security is the basis for food security. Water resource scarcity will lead to the variable grain production, which is considered as the source of real food crisis. Water management is the key to ensuring that more food can be produced for the growing population. “There is no food security without water security,” said José Graziano da Silva, Director-General, Food and Agriculture Organization of the United Nations. (Bertilsson, 2012).Agriculture is the sector responsible for most water use, consuming 70% of total water use in the world. Therefore, improving agricultural water productivity in is an important measure for ensuring global water safety and food security. Rosegrant and Cline (2003) stated in an article published in Science that “Although the economic and environmental costs of irrigation make many investment unprofitable, much could be achieved by water conservation and increased efficiency in existing systems and by increased crop productivity per unit of water used”. Norman Borlaug said in 2000, “how can we continue to expand food production for a growing world population within the parameters of likely water availability? The inevitable conclu-

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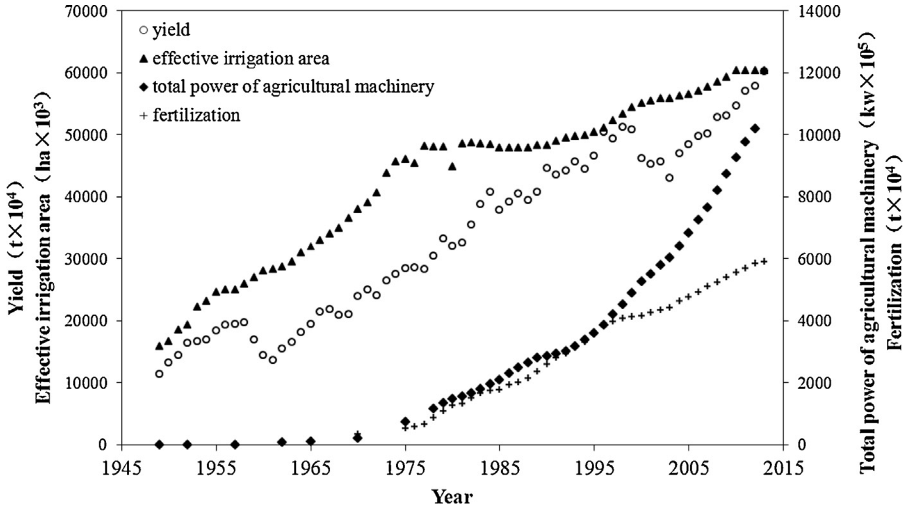

Fig. 1. Evolution of total grain crop yield and effective irrigation area, fertilization amount and total power of agricultural machinery in China during the period of 1949–2013. Source: The National Bureau of Statistics of China.

sion is that humankind in the 21st century will need to bring about a 'Blue Revolution-more crop for every drop' to complement the so called "Green Revolution" of the 20th Century. Water productivity must be wedded to land use productivity. Science and technology will be called upon to show the way" (Borlaug and Dowswell, 2000).

Irrigation water productivity (IWP), defined as the production per irrigation water amount (Molden, 1997), reflects the relationship between irrigating input and output, i.e. how much value is being obtained from irrigation water, and could be used as a useful indicator for assessing irrigation and crop management level (Zoebl, 2006). Improvement in IWP can reflect the comprehensive improvement in crop production and irrigation water use efficiency. Therefore, how to reduce the irrigation water use while maintaining or even increasing agricultural production with available irrigation water is essential for improving irrigation water productivity.

At present, agriculture in China encounters immense challenges. How to secure supply of agricultural products and improve the sustainability of agricultural development under the constraints of limited resources and environmental sustainability is the most important challenge that has to be overcome. Water is a vital factor in agricultural production, and water shortage has seriously affected China's agricultural production (Brown and Halweil, 1998; Oweis and Hachum, 2003). Owing to extensive use of irrigation, China is able to feed 21% of world population with only 6% of world freshwater resource and 9% of arable land. However, there is severe water shortage in China, with annual average water resource of 2100 m^3 per capita (28% of world average), and 21,000 m^3 ha^{-1} area (about 50% of world average). Water shortage is one prominent factor shaping the food security picture of China. The total water use in China was 618.34 billion m^3 in 2013, in which 63.4%, i.e. 392.03 billion m^3 was used by agriculture. To make things worse, irrigation water delivery efficiency in China is only 52%, far lower than that in the developed countries of 70–80%. To mitigate the water shortage problem, there is a great need to reduce irrigation water use. However, simply reducing irrigation water without diligent planning will lead to the reduction in local agricultural production, thus pose great risk to national food security. Consequently, how to improve irrigation water productivity becomes the key factor that strikes the balance between alleviating water shortage and maintaining high and stable agricultural production.

To solve the current water crisis and ensure agricultural sustainable development and food security in China, it is essential to (1) identify the key issues related to highly-efficient water utilization in agriculture (2) understand the mechanisms of water transformation and consumption in grain production at different scales, and (3) improve water use efficiency through scientific and technological advancements and management reform. Therefore, this paper has four main objectives: (1) to analyze the present state and future trend of water and food security in China (2) to analyze the evolution of irrigation water productivity in recent 60 years and its relationships with changes of crop yield, cropping pattern, fertilization and irrigation water use in China, and to demonstrate the importance of irrigation in ensuring China food security (3) to present the research progresses and practical experience on improving agricultural water use efficiency in China, and (4) to discuss the major research areas that need further study for improving agricultural water productivity in the future.

2. The state of water and food security under changing environment in China

Water security state is closely linked to sustainable development of human economic society and ecosystem. Rapidly increasing water consumption, worsening water pollution and excessive extraction of water resources due to competition of different sectors aggravated the water shortage problem and deteriorated water ecosystem around the world, threatening the development of social economy and human well-being (UNESCO, 2006). Ever-diminishing water supply poses great risks to national security, economic development and social stability and adversely affects human health, energy reserve, and food supply across the globe (UNESCO, 2012).

The normal annual total water resource of China is about 2840.5 billion m^3, the sixth highest of the world. However, average water resource per capita is less than one-third of the world average. Moreover, there is mismatch spatially between water resources and other social resources. For example, about 64% of total land area, 46% of cultivated land area, and 60% of population are in the northern part of China, where there is only 19% of total water resource of China. Groundwater in the Northern China Plain has been severely over-extracted. As a result, there are more than 160 regions with groundwater over-extracted for many years. Also groundwater depth in the Northern China Plain has declined from 10 m in 1970s to 32 m in 2001, and continues to decline annually at the rate of 1 m (Hu et al., 2010). Climate change has great impacts on water resources of China (Piao et al., 2010). Relative to the period of 1956–2000, surface water and total water resources during 2001–2009 was decreased by 5.2 and 3.2% respectively. Climate change also led to intensified drought incidents in China with more frequent drought occurrence and larger drought affected areas (Zhao et al., 2010). Climate change will threaten food security in China in the future.

Since 1949 and especially from 1980 when Reformation and Opening Policy was launched, food production capacity of China, as well as its ability to maintain stable food supply, has improved considerably. Total grain production has been increased from 0.1 billion ton in 1950s to current 0.6 billion ton while yield of major cereal crops also increased substantially (The State Council Information Office of the People's Republic of China, 1996). Increased food production is the result largely from breed improvement, extensive application of fertilizer, pesticide, and irrigation. Although total food production has increased from 0.305 billion ton in 1978 to 0.607 billion ton in 2014, there is no significant food surplus in China and food import dependency ratio was more than doubled during the 2005–2014 period, increased from 6.2 to 12.9%. Therefore, growth rate in food demand outgrows the growth rate in food supply. During the period of 2003–2011, food demand increased at a rate of 1.3 times of food supply. As a result, food supply-demand of China will remain tight balance for a long period of time.

Relative to the world average, the impact of climate change on food production is expected to be more pronounced in China. Some predict that in 2050 total food production of China might decrease by 13% on average due to climate change (Piao et al., 2010). Food supply has to increase by 30% in 2030 to meet the demand from growing population. However, resource shortage, especially water shortage limits the further growth of food production of China. In addition, the negative impact from climate change, more frequent extreme weather events in particular, on food production is getting graver, which could lead to the fluctuation of food production and shortage of food supply (FAO, 2010).

The problem between food demand and available water for agriculture is a global issue, and water shortage has become the main constraint on food security worldwide (Hanjra and Qureshi, 2010). The estimated water shortage is about 50 billion m^3 in 2030 for China to ensure food production increase by at least 30% so as to meet the food demand from growing population, given the irrigation water use will not change substantially during the period. Maintaining stable water supply for grain production is essential for ensuring food security. Improving agricultural water use efficiency is critical to increase total grain production considerably under the constraint of insufficient water supply for agriculture.

3. Contribution of irrigation to food security and evolution of irrigation water productivity in China

Irrigation is the main contributing factor to increased grain production worldwide. Irrigated land produced 40% of the total grain output with only 20% of total land acreage while rain-fed land produced 60% grain output with 80% of land acreage. Crop yield on irrigated fields is about 2.5 times yield on rain-fed fields (Shiklomanov, 2000). In China, more than 60 million ha cultivated land is irrigated, accounting for 49% of total cultivated area, which produces more than 75% of total grain production and 90% of cash crop production (Chen, 2012). Irrigation plays more prominent role in ensuring stable agricultural production and food security in China than other countries. Therefore, improving irrigation water productivity is the foundation and prerequisite to increase grain production of China under changing environment.

Fig. 1 shows the evolution of total grain production, effectively irrigated land acreage, total agricultural water use, fertilizer, and agricultural mechanic power of China from 1949 to 2013. During that period, total grain production and irrigated area displayed similar trend of continuous growth, while total water consumption remained flat after reaching peak in the 1980s. The fact that grain production continued to increase during that period while the total water consumption remained leveling off was the result mainly from the considerable increase in irrigation water productivity (Fig. 2). Total grain production in China was found increase exponentially with the change of effective irrigation area during the period of 1949–2013 (Fig. 3). In 2011, the percentage of grain production from irrigated area to the total production across China was 61.76%, i.e. 0.35 billion ton of 0.57 billion ton grain in total was from irrigated land, and national-average yield per unit area on irrigated land was about 2.31 times of the yield on rain-fed land. Therefore, food security of China relies heavily on irrigation, thus developing sustainable irrigation strategies remains an important measure for ensuring national food security in China.

Irrigation water productivity increased only from 0.2 to 0.5 kg m^{-3} during the period of 1950–1980 while after 1980, it increased rapidly from 0.8 kg m^{-3} in early 1990s to 1.1 kg m^{-3} in late 1990s and reached 1.58 kg m^{-3} in 2013 (Fig. 2). Main factors contributing to the great increase in irrigation water productivity were breed improvement (higher yield per unit area), crop pattern adjustment (reducing acreage of high water-demanding crops), and application of water-saving irrigation technologies (considerable decrease in irrigation water use per unit area). Fig. 4 demonstrated that national-average irrigation water productivity increased with

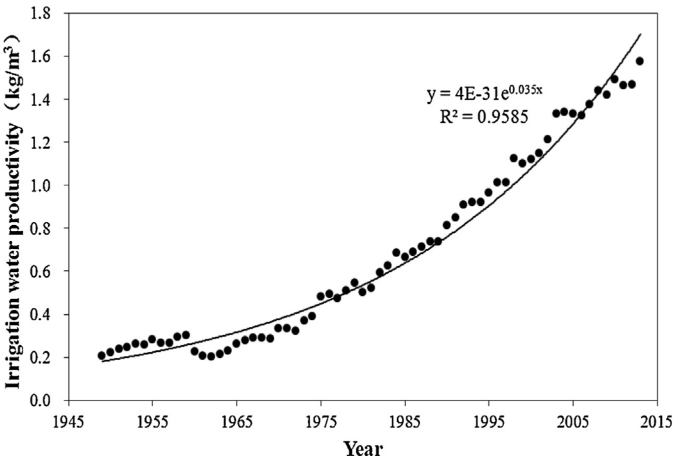

Fig. 2. Evolution of irrigation water productivity for grain crops in China during 1949–2013. Irrigation water productivity equals to the total grain crop yield divide by the total irrigation water use for grain crops.

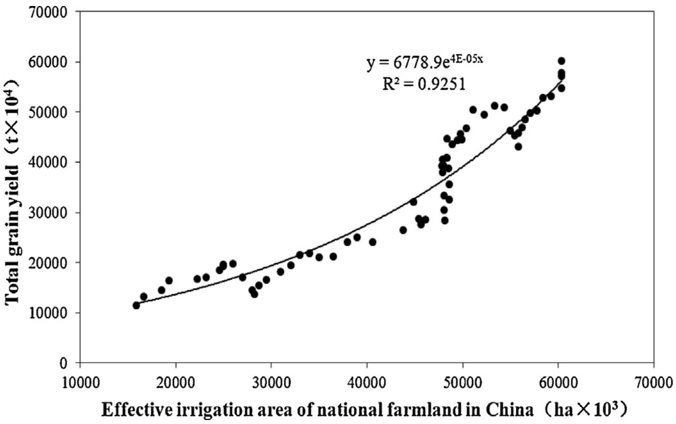

Fig. 3. Relationship of total grain crop production with the total effective irrigation area of China during 1949–2013.

Source: the National Bureau of Statistics of China.

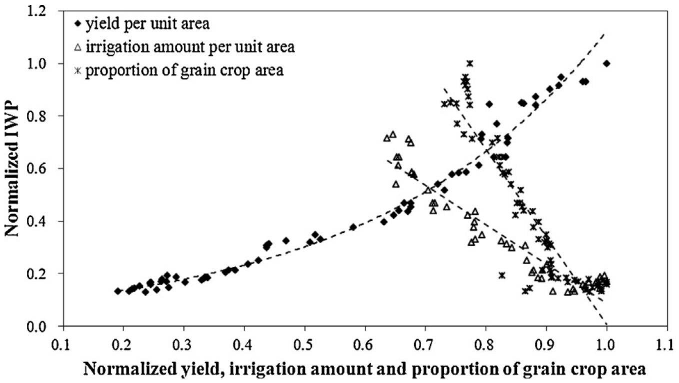

Fig. 4. Variation of irrigation water productivity with yield per unit area, proportion of grain crops planting area, and irrigation water amount per unit area.

the yield increase, and the decrease of both water consumption per unit area and acreage of grain crops. Improving irrigation water productivity through a variety of measures, such as increasing grain yield through agronomic practices that can help better use of soil, fertilizer, water and breed, implementing advanced irrigation technologies and systems on the field, adjusting crop pattern and optimizing water delivery is an important step to ensure food security of China without significant increase of agricultural water use.

4. Integrative strategies for improving irrigation water productivity in China

Facing the serious problem between global food security and scarce water resources, how to make the efficient use of limited water resources has become a great concern to international organizations, governments, and scientists around the world. Water cycle in irrigation agriculture involves three major processes, i.e. water distribution in a canal system, water transport in soil-plat-atmosphere continuum, and water uptake by plants (Fig. 5), thus improving water productivity is basically to reduce the water loss in those processes while maintain certain yield level, which has to be done across wide scales from molecule to region (Kang et al., 2004a). Water productivity potential can be improved through three major pathways: (1) to select drought-tolerant and water-saving varieties to increase crop generic yield potential while reducing water consumption; (2) to adopt appropriate agronomic measures, irrigation technologies, and other management practices for achieving higher yield with low water use; (3) to develop capabilities to monitor and predict regional water resources dynamics, improve water delivery efficiency, and coordinate water resources allocation at regional (watershed or irrigation district) scale for higher use efficiency and lower water loss. In the recent decade, great progresses have been achieved in fields related to single technology or combination of various technologies for improving agricultural water productivity (Du et al., 2014; Du et al., 2015).

In recent years, the Ministry of Water Resources of China has put forward an improving irrigation water productivity initiative which set up different goals for different regions of China: for 'increasing grain yield and water-saving' in Northeast China, 'limiting groundwater exploitation for water-saving' in the North China Plain, 'Water-saving and improving water use efficiency' in Northwest China, and 'Water-saving with drainage reduction' in South China. Research and the practical applications of water-saving technologies have been developed rapidly in China (Cui et al., 2008; Du et al., 2010, 2013; Kang et al., 2000a, 2002; Kang and Cai, 2002; Tang et al., 2005, 2010; Zhang et al., 2005). Planting varieties that are drought-tolerant and able to use water efficiently can achieve high yield with less water, thus achieve higher water use efficiency. Wheat is the second largest grain crops of China, and the total planted acreage is 23 million hm^2. Wheat is planted mostly in northern China, where the climate tends to be dry and timing of precipitation does not match the timing of water demand of wheat. Therefore, breeding and application of drought-tolerance and water-saving crop varieties is very important for wheat production of China. Breeding wheat varieties that can resist severe drought has achieved great success during the recent decade. For example, to alleviate the excess groundwater extraction problem, Agricultural Science Research Institute of Shijiazhuang City, Hebei Province successfully developed a series of drought-tolerant high-yield varieties, such as Shijiazhuang 8, Shimai 15, Shimai 18, Shiyou 17, Shimai 13, Shimai 21, etc. For Shijiazhuang 8, water use efficiency could get as high as 2.113 $kg\,m^{-3}$, yield with no irrigation 7.8 $Mg\,hm^{-2}$, and yield with two irrigation events 9.7 $Mg\,hm^{-2}$; For Shimai 15, water use efficiency could get as high as 2.418 $kg\,m^{-3}$, yield with no irrigation 7.7 $Mg\,hm^{-2}$, and yield with one irrigation 9.7 $Mg\,hm^{-2}$ (water use efficiency record of Hebei Province); For Shimai 18, yield with two irrigation events could reach 10 $Mg\,hm^{-2}$. In recent decades, sprinkling irrigation, micro-irrigation, drip irrigation under plastic film mulch, and subsurface irrigation have also rapidly gained popularity in China. One good example is the drip irrigation under plastic film mulch on cotton in Xinjiang Uygur Autonomous Region, where more than one-third of the country's cotton, or one-eighth of world's cotton, is grown. Nearly half of the irrigated water can be saved with this new irrigation method in comparison to the traditional surface irrigation. Experiments conducted at the Shanqian Plain of Hai River basin showed that microspray irrigation method resulted in significantly higher winter wheat yield, relative to conventional irrigation methods, with the similar irrigation water use of 3600 $m^3\,hm^{-2}$. Water use efficiency under microspray irrigation method was 1.7 $kg\,m^{-3}$, higher than 1.5 $kg\,m^{-3}$ of conventional border irrigation method (Zhang et al., 2013). With drip irrigation under mulch, corn yield in northeast part of China has achieved as high as 15000 $kg\,hm^{-2}$, 6000–7500 $kg\,hm^{-2}$ more than the conventional irrigation method did. Drip irrigation under mulch also was shown to be able to save 50% and 86% of total irrigation water use, relative to sprinkler and border irrigation respectively. The new method also shows great advantageous in terms of financial benefit to local farms, with net income about 1000 $ hm^{-2} higher than the conventional irrigation methods after accounting for equipment, mulch, and other related costs. The following are the two successful examples of improving irrigation water productivity in China achieved through different approaches, one is the novel irrigation method based on crop physiological responses, and the other is the integrative methods at basin scale.

4.1. Development of regulated deficit irrigation (RDI) and alternate partial root-zone irrigation (APRI) to improve irrigation water productivity based on crop physiological responses

The low cost and convenient way of improving water productivity is to develop a water saving irrigation method or mode, which can reduce crop water consumption without apparent yield reduction based on understanding physiological mechanisms. Regulated deficit irrigation (RDI) and alternate partial root-zone irrigation (APRI) are two examples of the irrigation methods broadly adopted in China (Kang and Cai, 2002). For RDI, water stress is regulated to occur in a given specific growth stage to control the reproductive and vegetative growth, with irrigation applied in the whole root zone (Goodwin and Jerie, 1992; Boland et al., 1993). For APRI, irrigation is performed alternatively in the different parts of root zone by keeping some part dry and the remaining part wet, which was derived from the findings of split-root research by Blackman and Davies (1985). APRI is a new irrigation technique to improve water

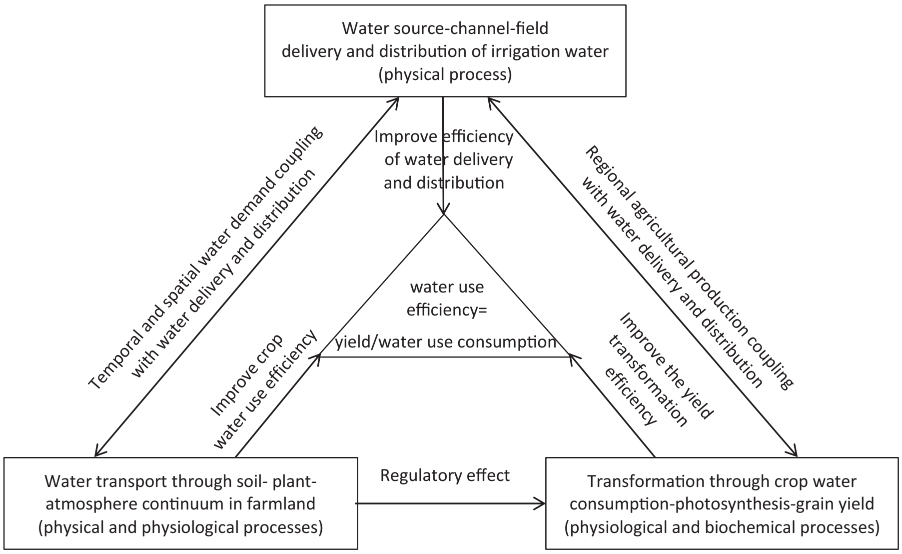

Fig. 5. The diagramof three processes that are important to water use in agriculture for improving irrigation water productivity, and their interrelationships.

use efficiency (WUE) without significant crop yield reduction, and requires that part (approximately half) of the root zone would be always in a dry or drying state while the remainder is irrigated as in full irrigation. For APRI, the wetted and dried sides of the root system are alternated according to the demand of crops (Kang et al., 1997; Kang and Zhang, 2004; Dry and Loveys, 2000; Gu et al., 2000; Loveys et al., 1997).

In China, many previous studies have showed that RDI decreased crop water consumption without apparent drop of yield, thus improved water use efficiency for field crops, fruit trees and greenhouse vegetables, as shown in Tables 1–3 . On average, RDI could improve WUE (or water productivity) of field crops by 25%, and in one case for rice, WUE was actually more than doubled while yield reduction under RDI was averagely less than 1%. For fruit trees greenhouse vegetables, the reported WUE under RDI was 26 and 32% higher respectively on average than full irrigation with yield reduction under RDI less than 3%. Indeed, averagely yield was found higher under RDI than full irrigation for fruit trees (Table 2). Moreover, other studies suggested that RDI could affect shoot and fruit growth of fruit trees and greenhouse crops, leading to better quality of fruits and vegetables and higher benefit to farmers. For example, RDI improved WUE and increased V_c and total soluble solid content (TSSC) of the pear-jujube fruit, relative to conventional irrigation methods, with the similar yield (Cui et al., 2008). One study has shown that applying 2/3 of full irrigation amount at the flowering and fruit development stages while imposing no water stress in other growth stages was the optimal irrigation practices for achieving high yield and better quality of greenhouse tomato in Hexi Corridor of Northwest China.

Many studies showed that APRI could reduce crop water consumption while maintaining crop yield for different crops (Tables 4–6). Based on published studies, WUE under APRI was 64, 49, and 41% higher than full irrigation for field crops, fruit trees, and greenhouse vegetables with no apparent yield reduction. The physiological mechanism leading to water-saving of APRI was proposed that when part of roots are exposed to soil drying, a root-sourced chemical signal (abscisic acid) might be transported to shoots, which induces stomatal closure and reduction of stomatal conductivity. Meanwhile, plant is not in real water stress since there is water available to the other part of roots. Consequently, transpiration is reduced and water productivity is improved under APRI (Kang et al., 1997; Kang and Zhang, 2004). Other studies also showed that APRI increased root hydraulic conductivity and root activity in the irrigated root zone, suggesting that there is considerable increase in compensatory root water uptake under APRI (Hu et al., 2011b). APRI was also shown to have significant compensatory effect on root N uptake. Under APRI, the non-irrigated root-zone also contributed to the total N uptake, while for fixed partial root-zone irrigation (FPRI), there exists persistent non-irrigated root-zone where N uptake decreased or even stopped (Hu et al.,2006). Significant compensation effect of root function occurred when nitrogen and osmotic stresses were localized in part of the root system (Hu et al., 2006). A series of research conducted at northwest China has shown that APRI could improve water use efficiency, relative to conventional irrigation method, of pear-jujubi, spring maize, cotton, and table grape while also improving fruit quality with increased V_c and total soluble solid content in pear-jujubi fruit and higher lint quality of cotton (Kang et al., 2000b; Hu et al., 2006; Cui et al., 2008; Du et al., 2008a,b).

4.2. Integrative Methods for Improving Water Productivity in a Basin: an example from Northwest China

Integrative measures carried out from water supply to plant root uptake are essential to improve water productivity at basin scale. This involves water allocation and delivery optimization, cropping structure adjustment, efficient irrigation and fertilization, and water policies reform. As a pilot project, an integrative approach for water-saving agriculture has been implemented in the Shiyang River Basin, and achieved promising results.

The Shiyang River Basin is an inland river basin in the Hexi Corridor of Northwest China, which is a typical example of excessive exploitation and utilization of water resources because of continuous population increase in the last 50 years of the 20th century. The region suffers the most serious water shortage in China, which constrains its social and economic developments and led to the worst ecological and environmental deteriorations in China (Kang et al., 2004b; Kang et al., 2008). It lies on the northern part of the Qilian mountain, and ends at the Minqin oasis, sandwiched between Badanjilin Desert and Tenggeli Desert, with a total population of 2.4 millions and an area of 41,600 km^2, and has 8 tributaries from east to west (Fig. 6). A large 'desert' reservoir Hongyashan is located on the flatland of Minqin, and the river terminates at its lower reach. In average the total water resources added into the basin is estimated as 1.661×10^9 m^3 which includes streamflow of 1.561×10^9 m^3 and groundwater recharge of 0.100×10^9 m^3.

Table 1

Comparison of yield and water use efficiency (WUE) for regulated deficit irrigation (RDI) and full irrigation (FI) on different field crops in China.

Crop	Study No.	Location and time	Rainfall in growing season (mm)	Irrigation volume (mm)		Yield (t ha^{-1})		WUE (kg m^{-3})		Reference
				RDI	FI	RDI	FI	RDI	FI	
Maize	1	Changwu, Shaanxi, 1996	74.2	384.0[c]	502.0[c]	12.02	13.08	3.13	2.61	Kang et al.(2000a)
	2	Xinxiang, Henan, 2007	–	343.9[c]	382.4[c]	6.22	6.70	1.81	1.75	Du et al. (2010)
	3	Wuwei, Gansu, 2010–2011	–	270.0	360.0	12.77	12.96	2.51	2.01	Xue et al. (2013)
	4	Fuxin, Liaoning, 2009	–	288.8[c]	342.7[c]	11.94	12.24	4.13	3.57	Yin et al. (2013)
Wheat	5	Changwu, Shaanxi, 1995–1998	214.7	356.7	383.0	4.84	4.33	1.38	0.98	Kang et al.(2002),Cai et al. (2000)
	6	Zhangye, Gansu, 2003–2004	41.1	302.5	392.5	7.00	5.90	1.58	1.15	Zhang et al. (2006)
	7	Wuwei, Gansu, 2004	24.0	300.0	315.0	6.10	6.29	1.93	1.72	Kang et al. (2009)
	8	Yanzou, Shandong, 2007–2008	228.0	43.8	200.8	8.84	8.87	2.08	2.08	Han et al. (2009)
	9	Luancheng, Hebei, 2003–2012	113.3	196.5	225.9	6.83	6.81	1.69	1.55	Du et al. (2010), Liu et al. (2013b)
	10	Xinxiang, Henan, 2006–2007	–	358.8[c]	418.3[c]	7.61	8.10	2.12	1.94	Du et al. (2010)
Rice	11	Qingan, Heilongjiang, 2011	–	–	–	9.74	9.59	1.89	1.74	Yu et al. (2012)
	12	Xuzhou, Jiangsu, 1999	493.7	427.0	860.0	9.32	9.52	1.46	0.70	Liang et al. (2002)
Sorghum	13	Daan, Jilin, 2005–2006	280.9	175.0	218.5	6.41	6.81	3.66	3.24	Li et al. (2005)
Potato	14	Zhangye, Gansu, 2009, 2012	140.8	457.5[c]	540.0[c]	30.59	27.03	7.04	5.95	Zhuang et al. (2010), Wang et al. (2014)
	15	Jianping, Liaoning,2009	–	379.7[c]	417.3[c]	34.48	27.68	9.08	6.63	Liu et al.(2010c)
Bean	16	Qinwangchuan, Gansu, 2006	284.8	473.0	531.0	6.60	6.05	1.40	1.14	Ding et al. (2007)
Soybean	17	Shihezi, Xinjiang, 2007	–	345.0	445.0	4.21	4.91	1.22	1.10	Mao (2007)
Peanut	18	Qingdao, Shandong, 2005	–	323.0	387.0	4.78	5.08	1.47	1.31	Liu et al. (2009)
Cotton	19	Shihezi, Xinjiang, 1992–1993	–	285.0	405.0	1.17[a]	1.31[a]	0.41	0.32	Li et al. (1999)
	20	Tarim, Xinjiang, 2004, 2012–2013	70.8	425.4	697.6	2.77[b]	2.97[b]	0.38	0.25	Liu and Tian (2007), Wang et al.(2015)
	21	Bayingolin Mongol, Xinjiang, 2010	–	332.6	420.0	4.48[b]	4.37[b]	1.35	1.04	Wang et al. (2013)
	22	Urumqi, Xinjiang, 2007, 2009	109	331.5	435.0	5.01[b]	4.99[b]	1.52	1.16	Shen et al. (2012)
	23	Wusuwunong, Xinjiang, 1998	–	195.0	225.0	1.70[a]	1.38[a]	0.48	0.34	Zhang and Cai (2001)
	24	Yuncheng, Shanxi, 2006–2008	384.7	150.0	225.0	0.92[a]	1.37[a]	0.28	0.29	Wang et al. (2010)
	25	Xi'an, Shaanxi, 1999	–	–	–	1.60[a]	1.76[a]	0.46	0.39	Shi et al. (2004)
	26	Xinxiang, Henan, 2012	–	220.0	320.0	3.44[b]	3.14[b]	1.00	0.71	Shen et al. (2014)

[a] Means seed yield.
[b] Means lint yield.
[c] Means that the value is evapotranspiration because irrigation volume was not available.

Table 2

Comparison of yield and water use efficiency (WUE) for regulated deficit irrigation (RDI) and full irrigation (FI) on different fruit trees in China.

Crop	Study No.	Location and time	Rainfall in growing season (mm)	Irrigation volume (mm)		Yield (t ha^{-1})		WUE (kg m^{-3})		Reference
				RDI	FI	RDI	FI	RDI	FI	
Peach	1	Beijing, 1997–1998	433.3	169.3	250.6	15.38 kg/tree	16.56 kg/tree	12.75	8.70	Li et al. (2001)
	2	Yangling, Shaanxi, 2001	–	205.3	299.5	216.00	234.75	10.50	7.90	Gong et al. (2004)
Apple	3	Changping, Beijing, 1999–2000	453.3	257.8	314.1	46.19	47.09	8.62	7.85	Huang et al. (2001)
	4	Shexian, Hebei, 2004	528.1	120.0	180.0	24.94	25.30	20.78[a]	14.05[a]	Cheng et al. (2008)
Pear	5	Bayingolin, Xinjiang, 2009–2010	22.6	562.9	636.4	22.30	19.21	3.96[a]	3.02[a]	Zhao et al. (2015)
	6	Handan, Hebei, 1998–2001	–	390.2	464.9	43.08	42.90	11.07[a]	9.12[a]	Cheng et al. (2003)
	7	Korla, Xinjiang, 2009–2010	22.7	561.2	645.0	22.30	19.21	3.98[a]	2.98[a]	Wu et al. (2013)
Pear-jujube	8	Dali, Shanxi, 2005	212.7	270.0	360.0	44.22	35.40	9.31	6.23	Cui et al. (2008)
Grape	9	Zhangye, Gansu, 2011	–	634.5	661.5	32.43	31.53	4.00	3.30	Zhang et al. (2012)
	10	Turpan Hami Basin, Xinjiang, 2012	–	675.0	810.0	34.88	32.09	5.17[a]	3.96[a]	He et al. (2013)
	11	Xinjiang, 2009	–	590.0	629.7	12.44	11.88	2.11[a]	1.89[a]	Liu et al. (2010a)
	12	Zhangye, Gansu, 2013	–	329.8	353.8	31.56	32.57	6.99	6.92	Zhang et al. (2014)

[a] Means that WUE is irrigation water productivity.

Increase in population had led to an ever-increasing demand for food and over expansion of cultivated land in the region. The water demand greatly surpassed the carry capacity of water resource that could support sustainable development of the region. With the increase of population and rapid expansion of irrigated area in the middle reach, original allocation of water resources was altered, and water usage in the middle reach increased from the 1950s to 2000. As a result, water allocated to the up and low reaches of the Shiyang River Basin has been greatly cut back. The ratio of water usage in the middle reaches to the lower reaches was 1:0.57 in the 1950s, and in 2000, it has become 1:0.07. Hongyashan reservoir dried up and land salinization and desertification emerged in Minqin oasis of the lower reach in the early 2000s.

The issue of the Shiyang River Basin is not only a local problem, but a whole scale challenge to national ecological sustainability. Therefore, an integrated program to solve the water problem was designed and partly implemented in the last 18 years in the Shiyang River Basin (Fig. 7). Water Saving Research Network was established in the Shiyang River Basin, and more than 30 experiments have been conducted, which covered board areas related to increasing water use efficiency in the region. Specifically, studies carried out included interactions between surface water, soil water and ground water, water transport in soil-plant-atmosphere continuum, crop water requirement and irrigation scheduling for maize, wheat, potato, cotton, alfalfa, grapevine, pear, apple, tomato, green house crops, and desert plants usually for wind sheltering and sand

Table 3
Comparison of yield and water use efficiency (WUE) for regulated deficit irrigation (RDI) and full irrigation (FI) on different vegetables in China.

Crop	Study No.	Location and time	Rainfall in growing season (mm)	Irrigation volume (mm)		Yield ($t\,ha^{-1}$)		WUE($kg\,m^{-3}$)		Reference
				RDI	FI	RDI	FI	RDI	FI	
Tomato	1	Yangling, Shaanxi, 2007	–	79.5^{a}	106.9^{a}	42.10	44.42	52.96	41.55	Guo et al. (2007)
	2	Wuwei, Gansu, 2008	–	224.0	252.0	174.44	172.32	68.47	59.24	Wang et al. (2008)
	3	Wuwei, Gansu, 2010	–	280.5	420.8	182.15	194.04	58.04	41.86	Yin et al. (2011)
	4	Shijiazhuang, Hebei, 2011	–	180.0	225.0	101.81	101.95	56.56	45.31	Liang et al. (2011)
	5	Nanjing, Jiangsu, 2011	–	195.5	312.8	126.43	142.86	64.66	45.68	Shao et al. (2013)
Eggplant	6	Xinxiang, Henan, 2011	–	186.2	206.1	62.6	56.52	33.11	27.42	Wang et al. (2012)
	7	Yangling, Shanxi, 2009	–	286.4^{a}	294.7^{a}	70.75	73.65	24.7	24.99	Yang et al.(2010b)
Hot pepper	8^{b}	Minqin, Gansu, 2009	63	337.0	388.2	63.23	66.3	13.29	12.89	Huang et al. (2012)
	9	Nanjing, Jiangsu, 2006	–	176.0	288.0	18.72	19.57	10.47	6.78	Shao et al. (2008a)
Cucumber	10	Nanpi, Hebei, 2001	–	330.0	696.0	161.88	194	46.28	28.40	Mao et al. (2003)
	11	Yangling, Shaanxi, 2013	–	785.0	1180.0	269.8	250.9	34.37	21.27	Qiao et al. (2014)

[a] Means that the value is ET because irrigation volume was not collected in the reference.
[b] Means No 8 study was conducted under field condition, the others were conducted in greenhouse.

Table 4
Comparison of yield and water use efficiency (WUE) for alternate partial root-zone irrigation (APRI) and full irrigation (FI) on different field crops in China.

Crop	Study No	Location and time	Rainfall in growing season (mm)	Irrigation volume (mm)		Yield ($t\,ha^{-1}$)		WUE ($kg\,m^{-3}$)		Reference
				APRI	FI	APRI	FI	APRI	FI	
Maize	1	Minqin, Gansu, 1997–1998, 1999–2000	72.0	165.0	315.0	9.60	10.68	3.99	2.70	Kang et al. (2006), Du et al. (2010)
	2	Xinxiang, Henan, 2001, 2009–2010	248.1	233.3	344.3	7.50	7.90	2.17	1.84	Sun (2002), Li et al. (2014)
Wheat	3	Wuwei, Gansu, 2007–2009	131.1	315.0	315.0	3.67	3.84	2.35	2.08	Yang et al. (2010a)
Sorghum	4	Xiuwen, Shanxi, 2011	276.8	75.0	135.0	10.94	10.98	14.58^{b}	8.13^{b}	Cao et al. (2011)
Potato	5	Xinxiang, Henan, 2008–2009	158.5	125.6	167.6	20.03	21.45	12.83	10.78	Huang et al. (2010), Hu et al. (2011a)
	6	Huhehot, Inner Mongolia	149.0	104.2	416.9	24.85	32.91	23.84^{b}	7.89^{b}	Xie et al. (2012)
	7	Qinwangchuan, Gansu	68.0	111.1	444.4	11.75	15.67	10.58^{b}	3.53^{b}	Xie et al. (2012)
	8	Yulin, Shanxi, 2014	–	266.7	457.1	44.18	36.55	16.56^{b}	7.99^{b}	Wang and Zhang (2015)
Broad bean	9	Qinwangchuan, Gansu, 2006	284.8	473	531	6.60	6.05	1.40	1.14	Ding et al. (2007)
Soybean	10	Shenyang, Liaoning, 2010	–	264	308	4.58	3.99	1.73	1.30	Xu et al. (2011)
	11	Changchun, Jilin, 2009–2010	–	443^{a}	375.5^{a}	2.96	2.44	0.70	0.64	Zhang et al., (2011)
Peanut	12	Shenyang, Liaoning, 2011	–	80.7	114.8	4.44	4.76	1.01	0.72	Xia et al. (2014)
Cotton	13	Fukang, Xinjiang, 2003, 2005–2007	–	420	600	4.45^{c}	4.62^{c}	0.78	0.61	Tang et al. (2005, 2010)
	14	Minqin, Gansu, 2004–2005	87.3	105	225	2.48^{c}	2.05^{c}	0.71	0.58	Du et al. (2006)
	15	Xuebai, Gansu, 2004–2005	87.3	132	132	2.65^{c}	2.37^{c}	0.69	0.60	Du et al. (2008a)

[a] Means that the value is ET because irrigation volume was not collected in the reference.
[b] Means that the value is irrigation water productivity.
[c] Means seed yield.

Table 5
Comparison of yield and water use efficiency (WUE) for alternate partial root-zone irrigation (APRI) and full irrigation (FI) on different fruit trees in China.

Crop	Study No.	Location and time	Rainfall in growing season (mm)	Irrigation volume (mm)		Yield ($t\,ha^{-1}$)		WUE($kg\,m^{-3}$)		Reference
				APRI	FI	APRI	FI	APRI	FI	
Pear	1	Yongnian, Hebei, 2004–2007	438	120	200	54	57	45.14^{a}	28.54^{a}	Zhao et al. (2007, 2008)
Peach	2	Haidian, Beijing, 2004–2005	–	1090	1889	72	79	6.6^{a}	4.2^{a}	Song et al. (2008)
	3	Yangling, Shanxi, 2001	–	205	300	22	23	10.5^{a}	7.9^{a}	Gong et al. (2004)
Grape	4	Wuwei, Gansu, 2005–2006	124	87	125	16	15	6.8	5.5	Du et al. (2008b, 2013)
Apple	5	Shexian, Hebei, 2004, 2006	492	90	180	28	29	3.31^{a}	2.31^{a}	Cheng et al. (2008)
	6	Yantai, Shandong, 2006–2007	457	592	1188	69	78	11.7^{a}	6.6^{a}	Liu et al. (2010b)

[a] Means that the value is irrigation water productivity.

fixation, RDI and APRI on different crops, optimizing application of water and fertilizer, and saline water irrigation. Field experimental data on hydrology, soil and crop physiology, irrigation have been collected for more than 18 years.

The experimental results showed that the regional total water consumption in agriculture was increased about 0.5-0.6 billion m^3 in the last 50 years of the 20th century, but the water use per unit area decreased during the same period. Apparently, total plant-

Table 6
Comparison of yield and water use efficiency (WUE) for alternate partial root-zone irrigation (APRI) and full irrigation (FI) on different greenhouse crops in China.

Crop	Study No.	Location and time	Rainfall(mm)	Irrigation volume (mm)		Yield ($t\,ha^{-1}$)		WUE($kg\,m^{-3}$)		Reference
				APRI	FI	APRI	FI	APRI	FI	
Tomato	1	Yangling, Shaanxi, 2011	–	–	–	837.59 g/plant	819.15 g/plant	38.87[a]	31.76[a]	Liu et al. (2013a)
	2	Yangling, Shaanxi, 2002	–	277.1	518.2	607.84 g/plant	651.09 g/plant	14.66	9.08	Hu et al. (2005)
Hot pepper	3	Nanjing, China, 2006	–	144.0	288.0	14.88	19.57	9.20	6.78	Shao et al. (2008b)
Cantaloup	4	Yangling, Shaanxi, 2012	–	238.3	198.6	40.43	38.68	17.0[a]	19.5[a]	Zhao et al. (2013)
Strawberry	5	Taian, Shandong, 2007–2008	–	12.2 L/plant	17.8 L/plant	745.2 g/plant	752.3 g/plant	61.1[a]	42.3[a]	Wang et al. (2009)
Nectarine	6	Taian, Shandong, 2002–2003	–	640	1280	7.8 kg/plant	8.2 kg/plant	16.16	8.52	Bi et al. (2005)
Cucumber	7	Shunyi, Beijing, 2008–2009	–	225	413	88.58	91.51	61.51	42.42	Cao et al. (2010)

[a] Means that the value is irrigation water productivity.

ing acreage and irrigated land expansions were the main reason of increased agricultural water use in the basin. Therefore, replacing cereal crops with cash crops might decrease the water use per unit area. Based on a simulation study of a multi-objective decision-making model, the optimum water allocated to ecological systems would be 105 million m^3, and 1.53 billion m^3 for social economic sectors with a total of 1.66 billion m^3 of available water resources. The results also showed that ground water table in Minqin would recover with recharge rate of 30 million m^3 per year and the inflow at Caiqi station and Jinchuanxia reservoir could be increased to 312 and 173 million m^3, respectively. To achieve sustainable development, the total irrigated area should be around 218.3×10^3 hm^2, 91.6×10^3 hm^2 less than the current level, and the ratio of cereal, cash and fodder crops should be 54:31:15 with the cereal grain production about 420 kg per capita.

Based on the research, an integrative approach had been proposed in recent years to appropriately allocate water resources to different sectors and improve water productivity in the Shiyang River Basin. The approach could be described as "'Close wells + Reduce planting and irrigation areas + Adjust planting system' + Develop comprehensive water-saving technologies and their integrated models + Water right management + Demonstration and farmer training" for reducing regional evapotranspiration, improving water productivity and insuring farmer's income, as well as for sustainable development of agriculture and environmental protection in the Shiyang River Basin.

During the period of 2007–2011, 3318 wells have been closed, and 42.6×10^3 ha of cultivated land was has been returned to fallow. Meanwhile, cropping pattern has been adjusted with spring wheat and maize replaced by grapevine and cotton, which led to less water consumption by large portion of cultivated lands of the region because wheat and maize have larger ET (450 and 500 mm, respectively) than grapevine and cotton under mulch (350 and 320 mm respectively) in the region. Also incentives to build solar greenhouse with high-value vegetables and fruits has been provided by the local governments, given that greenhouse crops usually consume less water and achieve better return. These combined measures have reduced planting areas and overall agricultural water use while maintaining or increasing farmers' income in the region.

Meanwhile, a number of means in terms of improving irrigation water use efficiency of irrigation systems, such as adopting deficit irrigation, drip irrigation under mulch, field leveling or other approaches for improving conventional surface irrigation, infrastructure upgrading, have also been implemented in the basin. Optimal regulated deficit irrigation schedules based on experimental research for wheat, maize, cotton and melon were widely used. In terms of water policy reform, the region initiated a strict irrigation quota and step-price system, and consequently about 13644 wells were equipped pumps and controlled by IC cards.

On the other hand, a series of efforts have been made to introduce the newly technologies to local farmers, aiming to promote wide application of those technologies. For example, training courses on newly developed water-saving technologies were offered to local farmers, and workshops about water resources management and water-saving in agriculture were held in Wuwei every year. Researchers, managers, and technicians from Wuwei together took part in the workshops. Also the hand books entitled "User Manual for Constructing Water-saving Community in the Shiyang River Basin" and "Question & Answers on the Construction of Water-saving Community in the Shiyang River Basin" were published and disseminated. More than 200,000 farmers and technicians had participated in the training courses about water saving technologies organized by the local government, local agro-tech extension center and China Agricultural University.

As a result of the integrative approach for improving water productivity in the Shiyang River Basin, the regional irrigation water productivity has been improved from 1.21 to 1.42 $kg\,m^{-3}$, and irrigation water efficiency was also improved from 49.7% to 54.5% during the last 15 yrs. The yield of cereals and cash crops were improved from 97×10^4 ton to 133×10^4 ton and 115×10^4 to 166×10^4 ton respectively. Discharge into the low reaches of the river has been steadily increasing from less than 1×10^8 m^3 to more than 3×10^8 m^3 in recent 10 years because water-saving technologies were widely used in the middle reaches, and the groundwater level has been recovering in the downstream from 2012 (Fig. 8).

Experience in the Shiyang river basin could serve as an example for adopting integrative measures to improve overall water productivity in arid inland regions. Water shortage is the main problem in the driest inland regions of China where agriculture relies heavily on irrigation, but unrestrained irrigated agriculture development would aggravate groundwater table drop and environmental deterioration, threatening the sustainability of agricultural development in those regions. Therefore, excessive irrigated agriculture expansion should be avoided in arid ecologically fragile areas of Northwest China, and sufficient amount of water resources should be allocated to local ecological systems. Optimized and integrated technologies are available, but adopting those measures requires cooperation from many aspects of scientists, technicians, local agencies, financial incentives, and farmers.

5. Critical issues for improving irrigation water productivity to ensure food security under changing environment

Scientists worldwide have made great progresses in agricultural water research and contributed considerably to higher yield and saving water in crop production (Aragüés et al., 2014; Biswas, 2008; Blackman and Davies, 1985; Blum, 2009; Boland et al., 1993; Chalmers et al., 1981; Davies et al., 2002; Dodd, 2009; García, 2008; Hsiao et al., 2007; Kang et al., 1997, 2002, 2009; Kang and Zhang, 2004; Zhang et al., 2005, 2013). However, current research in the related fields seems insufficient to meet the increasing challenges the world may face ahead. Biology-based research on high-efficient

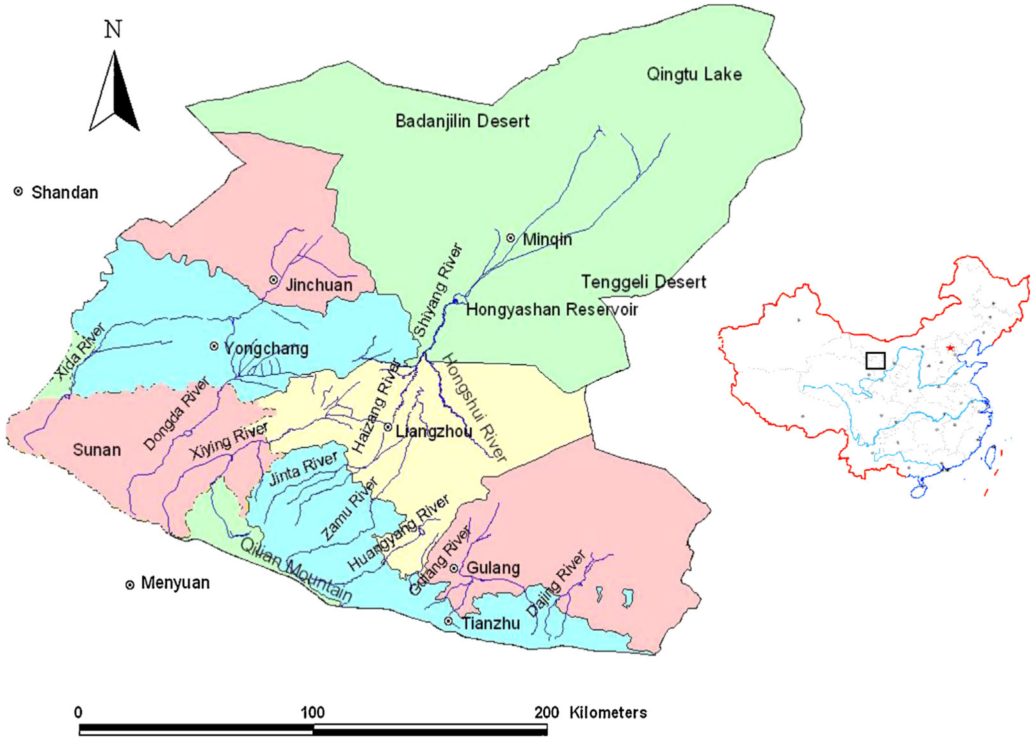

Fig. 6. Layout of Shiyang River Basin and its location in China. Different Colors indicate different administrative counties in Gansu Province of Northwest China.

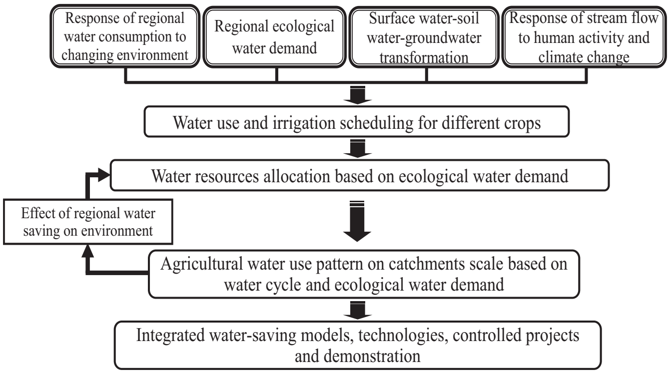

Fig. 7. The research framework of the integrative approaches proposed to solve the water problem in Shiyang river basin of Northwest China.

water use tends to focus more on the physiological mechanisms at molecule level and looking at isolated processes, while applying those findings at larger scales, such as population, field, and regional scales with an integrative approach concerning multiple processes and multiple elements remains difficult (Fig. 9). Great breakthroughs in theories and technologies on balancing crop high-yield and high-efficient water use are still lacking, and to achieve such balance, great progresses have to be made in the following areas:

(1) Responses of crop water demand to changing environment and associated spatio-temporal optimization of water allocation. One important work ought to be in what ways crop water demand responding to climate change, such as the elevated atmospheric CO_2 concentration and temperature and why, especially the effects of combined effects of the climatic factors on stomatal conductance from crop physiological perspective. The potential impacts of human activities, especially newly developed water-saving management practices (e.g. mulching, alternate partial root zone irrigation, etc.), on crop water demand need to be quantified. Accompanying with the development in above-mentioned theoretical areas, efforts should also be made to develop crop water demand estimation model that can be adapted for different environments (e.g. different climates, landscape, cropping patterns, etc.), and to expand point-based model to a distributed crop water demand model at regional scale which is required for decision making on agricultural policies and management practices. Meanwhile, crop (fruit) quality is directly linked to its marketable price and farmer's income, thus in addition to crop water demand responses to changing environment based solely on crop yield, the relationship between crop quality and water use also should be taken into account when developing water management practices, despite that crop quality does not affect crop water use efficiency (or water productivity).

(2) Response of hydrologic cycle to changing climate and environment, especially in agricultural systems under strong influences of human activities. Quantifying the impacts of natural and human-induced changes in climate and environment on hydrologic cycles remains a great challenge to agri-hydrologists and engineers, since most conventional agri-hydrological models were developed based on natural hydrological processes and historical observations which are not sufficient for future predictions (Wagener et al., 2010). Specifically in farmland systems, future research should focus on the change behaviors of farmland soil-plant-atmosphere continuum (SPAC) system, crop growth, water dynamics in canals, and groundwater flow under temporal evolutions of crops, soils, canal networks, topography, management practices, and other things to quantify and predict regional irrigation water transformation and efficiency.

(3) Integrative approaches to improve agricultural water use efficiency at multiple scales. Future studies should involve theoretical and practical studies of different scales, such as mechanisms of leaf's regulation of stomatal opening, individ-

ual plant's allocation between reproductive and vegetative growths, population plants' ideal canopy shape, drought-tolerant varieties, water stress diagnosis methods, smart irrigation and fertilization (precision agriculture), and remedy measures for improving crop water use efficiency. Utilization of advanced sensing, measuring, photography, computation, modeling and engineering techniques into detecting and predicting crop growth status, and developing precision agricultural management practices (variate rate irrigation among other methods) should be a focus in future studies.

(4) Interactions and feedbacks between food production, water resources and ecological processes. Growing demand in agriculture water use and declining available water resources make it difficult to allocate sufficient water resources for healthy ecosystem and sustainable development. Specifically, future studies should address interactions and adaptability of grain production–water resources–ecosystem nexus, spatio-temporal interrelationships of water resources and grain production, response and adaption of ecosystem and environment to the changes of water resources in both quantity and quality, interactions between grain production and micro-climate of local ecosystem, as well as water resources management taking into consideration of both grain production and ecosystem services, water resources' carrying capability according to ecosystem footprint, and developing policies and management plans to achieve balance between grain production, water resources, and ecosystem.

6. Conclusions

Irrigation has played and is expected to continue to play a prominent role in maintaining stable grain crop production and ensuring food security of China. In China, more than 75% of total grain production and 90% of cash crop production are from irrigated agriculture, which is about 49% of total cultivated land. Owing to adoption of combined water-saving measures from drought-tolerant varieties to limited irrigation methods, irrigation water productivity in China has increased from 0.8 kg m^{-3} in the early 1990s to 1.1 kg m^{-3} in the late 1990s and reached 1.58 kg m^{-3} in 2013. Given that water shortage is the severest in the driest inland regions of China where agriculture relies heavily on irrigation, improving water productivity in the region is the key factor that is able to help strike balance between limited water resources and sustainable food production in China.

To improve irrigation water productivity is to reduce water loss in the agricultural production system while maintaining crop yield at certain level. In the recent decade, great progresses have been made in application of either a single technology or combination of various technologies. Regulated deficit irrigation (RDI) and alternate partial root-zone irrigation (APRI) are two irrigation methods that have been shown to achieve high water productivity without significant yield reduction for a variety of crops in China. Although there were successful examples of applying the two irrigation methods in China, concerted efforts are still needed to expand the application at large scale to have real meaningful impacts on improving irrigation water productivity.

Rapid expansion of irrigated area also brought out unfavorable environmental impacts, such as over-withdrawal of groundwater and ecosystem degradation. Therefore, irrigated agriculture in ecologically fragile regions like Northwest China should be limited so that sufficient water resources could be allocated to meet ecosystems need. The threshold of water demanded by ecosystems for sustainable development for a given region needs to be identified, and should be taken into consideration when making decisions on how to distribute regional water resources in different sectors.

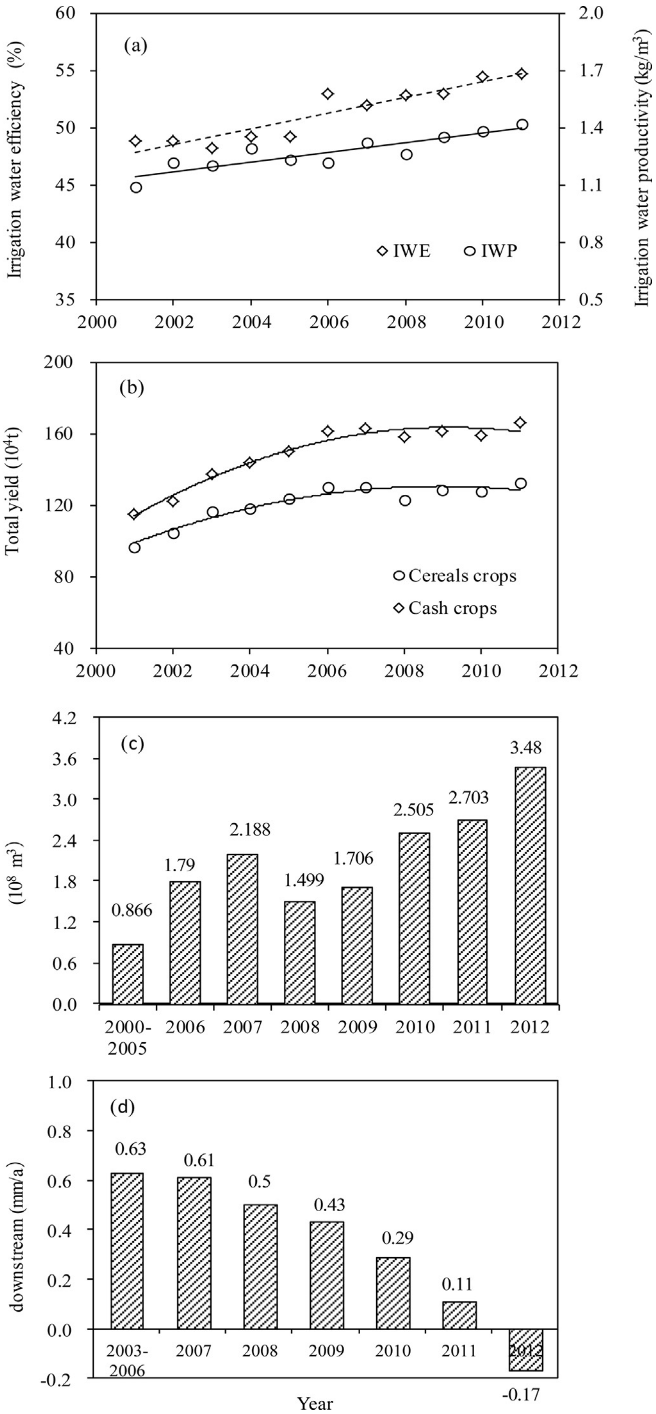

Fig. 8. The effects of the integrative approach on (a) irrigation water efficiency and water productivity; (b) total yield of cereals crops and cash crops; (c) surface water diverted into the downstream; and (d) groundwater table decline in the downstream in Shiyang River Basin during 2003–2012.

To achieve the balance between increasing food demand and dwindling water resource under the changing environment, future studies should focus on how crop water demand and hydrological processes in agricultural systems would respond to natural and human-induced changes in climate and environment, in what ways food production – water – ecosystem nexus interacts with each other, as well as how to develop policies and management plans to

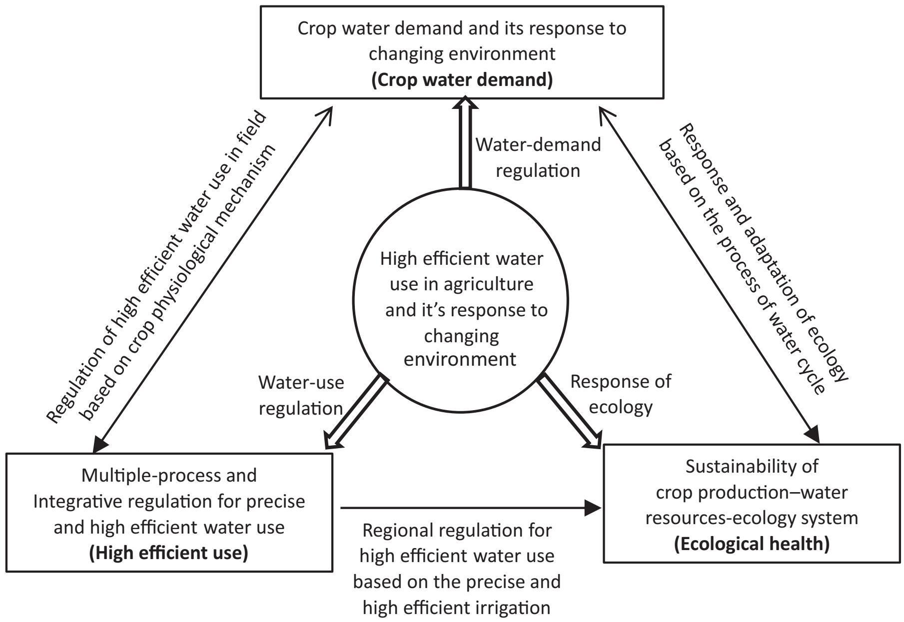

Fig. 9. Framework of the research areas that need further study for improving irrigation water productivity to ensure food security under changing environment.

improve water productivity at different scales with an integrative approach.

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