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Water resources and water use efficiency in the North China Plain: Current status and agronomic management options

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ABSTRACT

Serious water deficits and deteriorating environmental quality are threatening agricultural sustainability in the North China Plain (NCP). This paper addresses spatial and temporal availability of water resources in the NCP, identifies the effects of soil management, irrigation timing and amounts, and crop genetic improvement on water use efficiency (WUE), and then discusses knowledge gaps and research priorities to further improve WUE. Enhanced irrigation and soil nutrient (mainly nitrogen) management are the focal issues in the NCP for enhancing WUE, which are shown to increase WUE by 10–25% in a wheat–maize double cropping system. Crop breeding has also contributed to increased of WUE and is expected to play an important role in the future as genetic and environmental interactions are understood better. Agricultural system models and remote sensing have been used to evaluate and improve current agronomic management practices for increasing WUE at field and regional scales. The low WUE in farmer's fields compared with well-managed experimental sites indicates that more efforts are needed to transfer water-saving technologies to the farmers. We also identified several knowledge gaps for further increasing WUE in the NCP by: (1) increasing scientific understanding of the effects of agronomic management on WUE across various soil and climate conditions; (2) quantifying the interaction between soil water and nitrogen in water-limited agriculture for improving both water and nitrogen-use efficiency; (3) improving irrigation practices (timing and amounts) based on real-time monitoring of water status in soil-crop systems; and (4) maximizing regional WUE by managing water resources and allocation at regional scales.

1. Introduction

The North China Plain (NCP) is also known as Yellow-Huai-Hai Plain named after the three major rivers (Yellow River, Huai River and Hai River) that traverse it (Fig. 1), and is the most important wheat and maize production area in China. It produces about 29.6% of the nation's food, including about half of the wheat production and a third of the maize production (NBSC, 1998). The main cropping system is wheat and maize double cropping (two crops per year) with average water consumptions of about 450 mm for wheat and 360 mm for maize (Liu et al., 2001). Due to a summer monsoon climate with about 70–80% of the mean annual rainfall (550 mm) concentrated in the summer (July to September), the rainfall during wheat growth period can only meet 25–40% of the crop water requirement, which leaves a 200–300 mm water deficit in the northern part of the NCP (Liu et al., 2001; Zhang et al., 2006b). Irrigation is critical for maintaining high wheat yield, especially in the northern part of the NCP, and about 75% of the agricultural land is irrigated and consumes 70–80% of the total water resource allocation in the NCP (Lin et al., 2000). In the recent years, however, increased water deficits associated with overuse of surface water, declining groundwater levels, water pollution, and soil salinization are threatening the sustainability of agricultural production in the region (Hu et al., 2005; Liu et al., 2001; Wang et al., 2007a). The water supply for agricultural production will unavoidably decrease with the increasing demands from domestic and industrial water users. At the same time, the agricultural water use efficiency is still very low due to the poor irrigation management practices (Deng et al., 2006; Wang et al., 2002) and lack of investment in infrastructure (Lohmar et al., 2003; Xu, 2001). Furthermore, recent studies showed that climate change could greatly influence the water cycle and aggravate the water crisis situation in the NCP (Tao et al., 2003, 2005; Xiong et al., 2009).

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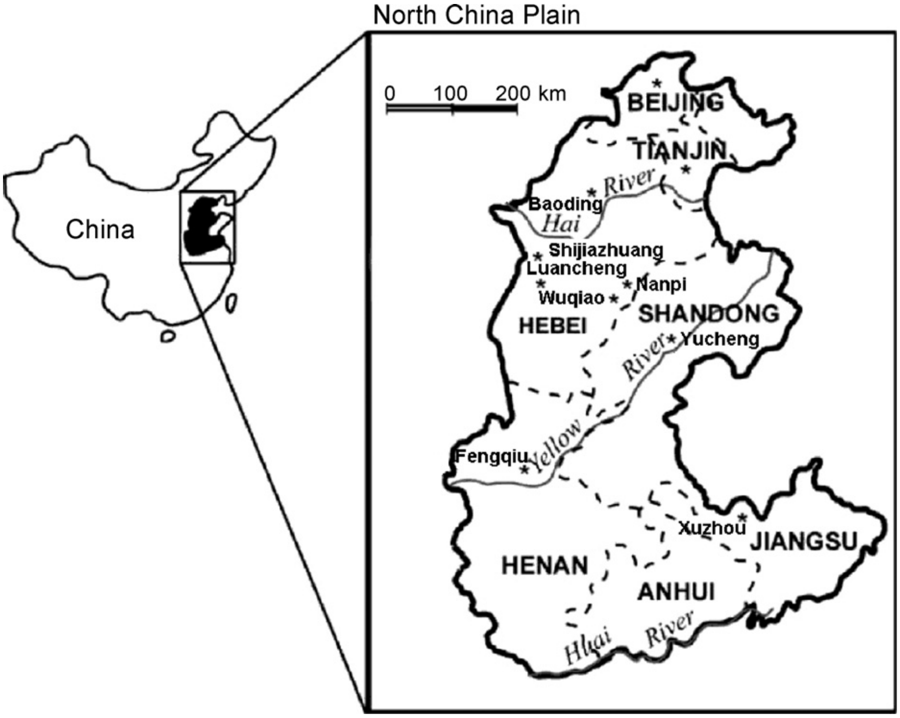

Fig. 1. The North China Plain (NCP), provinces, rivers and the experimental sites (*) for studying water use efficiency in the region.

System-wide water saving can be obtained by reducing unnecessary evapotranspiration (ET) and increasing crop water use efficiency (WUE). Although seepage during water transmission and deep drainage are of concern during peak demand, these irrigation losses recharge the shallow aquifer and do not leave the NCP system permanently (Kendy et al., 2004), even though energy is required to pump it up. WUE can be calculated at the single leaf level (leaf photosynthesis rate/leaf transpiration rate), canopy level (crop biomass/ET), field level (crop yield/ET) or regional level (crop yield/water available) (McVicar et al., 2002; Sinclair et al., 1984; Wang, 1993). Precision irrigation practices and soil and crop management can be used to improve WUE at these different levels, and the interactions among these management practices are also very important for regional water resource management in the NCP (Table 1). Wang et al. (2002) and Deng et al. (2006) reviewed water-saving agriculture in China by focusing on agronomic options, and Kang et al. (2004a,b) discussed the technology and theory of agricultural and ecological water-saving engineering. Other recent reviews on improving WUE in a comprehensive way under water limited conditions are the molecular plant breeding and agronomic management for high WUE (Passioura, 2006), generic principles for improving WUE at different scales (Bouman, 2007), improvement of irrigation methods to reduce water demand and negative environmental impacts at farm level (Pereira et al., 2002), and sustainable management of available water resources at global, regional, and site-specific levels (Qadir et al., 2003). Steduto et al. (2007) demonstrated the conservative behavior of biomass water productivity defined as biomass/transpiration, and methods for scaling water productivity from leaf to regional scales. Water productivity defined by Kassam and Smith (2001) can be quantified in terms of yield, nutritional value or economic return. The WUE used here was defined as the ratio of grain yield to ET at a field scale unless otherwise specified, which has the same meaning as water productivity in terms of grain yield per unit ET. In this paper, we first analyze the current water resources (surface and ground water resources) situation in the NCP and associated agricultural water use, and then assess the current status of scientific research on agronomic management practices for improving WUE in the NCP. Finally, the knowledge gaps in agronomic management and future research needs for enhancing WUE are discussed.

2. Water resources status in the NCP

Water resources in the NCP are scarce with uneven distributions both spatially and temporally, which makes it difficult to achieve efficient water utilization (Liu and Wei, 1989). The surface water resources in the NCP are mainly from surface runoff locally in the NCP and from the adjacent mountainous regions. The Yellow river is an important surface water resource in the area. On average across the region, the annual runoff in the NCP is about 126 mm (17.9%) for an annual rainfall of 704 mm and the rest is lost as evportranspration (ET) (Liu and Wei, 1989). The average annual discharge fraction (ratio of runoff to rainfall) varies from 11% in the northern part (north Yellow river) to 22% in the southern part (south Yellow river). The coefficient of variation in runoff across years is high, increasing from 0.20 in north to 0.35 in south. The average annual surface runoff in the three river basins is 3.82×10^{10} m^3 with a decrease from south (Huai River basin) to north (Hai River and Yellow River basins) (Fig. 2), which is only 1.5% of national surface water resource (Liu and Wei, 1989). Discharge from the mountain regions comprises 48% of surface water within the three river basins. The highest runoff from mountain areas occurred in the Hai River basin (Fig. 2). Water abstraction from the Yellow River is about 47%, which is higher than other rivers in China. The annual water flow in the downstream reaches of the Yellow River is 4.56×10^{10} m^3 (within the NCP), of which about 20% is used for agricultural and industrial production in the river basin (Liu and Wei, 1989). Because the Yellow River basin is the second-largest river basin in China and contributes greatly to agricultural and socioeconomic development, many studies have been carried out to analyze and evaluate water resources in this river basin (Cai and Rosegrant, 2004; Liu and Xia, 2004). Some studies showed that water scarcity and longer period of ‘no flow’ days have become more severe (Barnett et al., 2006; Liu and Xia, 2004; Zhang et al., 2009). Also, an increase in air temperature has been observed, with decreased precipitation/runoff in the river basin in the last 50 years (Fu et al., 2004; Yang et al., 2004; Zhang et al., 2009). Due to the high sediment deposition under low water flows in the river, the rising river bed has increased the threat of flooding in the lower reaches (Wang et al., 2005a; Yu, 2002). The associated environmental problems also showed high sensitivity to climatic change and human activities (Zhang et al., 2009). Maintaining a reasonable flow in the Yellow river is becoming one of the highest priorities for ecological water requirement as argued by Barnett et al. (2006) and Webber et al. (2008).

Estimates of groundwater resources differ depending on the definition of the aquifer boundary and estimation methods (Fei, 1988; Liu and Wei, 1989). Fresh groundwater resources generally increase from south to north and from piedmont areas to coastal areas. Among the three river basins (Yellow River, Huai River and Hai River), fresh shallow ground water resources are abundant in the Huai River basin (more than 60% of water resources in the three river basins) but are limited in the Yellow River basin (about 4%) (Fig. 2). The groundwater dynamics have been studied in recent years from both socioeconomic and scientific points of view (Kendy et al., 2004; Liu et al., 2001; Wang et al., 2005b). The main conclusion from these studies is that the groundwater table has declined continuously, particularly in the northern part of the region, due to intensive abstraction. The overdraft of groundwater has caused land subsidence and seawater intrusion into fresh water that has resulted in poor water quality in some areas. About 40,000 km^2 of the southern Hai River basin had subsided more than 200 mm as of 1995 (Liu et al., 2001; Wang et al., 2007a).

Fig. 3 is an example of groundwater table dynamics from 1974 to 2008 at Shijiazhuang city about 20 km south of Luancheng Station (Fig. 1), where a high rate of decline (−0.8 m/yr) occurred from 1978 to 2008. In the northern part of the NCP, groundwater tables decreased at a rate from −0.32 m/yr between 1964 and 1984 and to −0.65 m/yr between 1984 and 1993 (Fig. 4). This result was mainly due to the increase in groundwater withdrawals for irrigation as surface water resources declined since the 1970s. The groundwater accounted for from 40% to 58% of irrigation from the 1970s to 1990s, and almost 70% of irrigation water in 2004 (Wang et al., 2006a, 2007a). The south part of the NCP showed lower rates of decline than the northern part, where the ratio of groundwater abstraction to recharge was above 1.5 as reported by Liu et al. (2001). During 2004–2006, the groundwater table was still decreasing in the piedmont plain, including Beijing, ShijiaZhang and Baoding locations, while in the central and littoral plain, groundwater levels were relative stable with no or very little decline (Wang et al., 2009c). Across Hebei province within the NCP, there was an average decline in groundwater table from 13.5 m in 1995 to 15.6 m in 2000 with a rate of −0.42 m/yr (Xu and Cai, 2005). Wang et al. (2009a) also reported that about half of the sampled communities from seven provinces in northern China showed little or no decline in groundwater tables from 1995 to 2004, with only 11% of the sampled communities having groundwater table decreases greater than 1.5 m per year. This result indicted that the groundwater resources crisis may not be serious across all parts of the NCP (Wang et al., 2009a).

In light of these recent declines in groundwater levels, however, there is a water deficit of more than 4.00 × 10^{10} m^3 between water supply and demand in the region (Brown, 2001). In another study, annual water deficit in the NCP was estimated as 2.28 × 10^{10} m^3 (349 mm) based on the irrigated area (Lin et al., 2000). Due to the variation in annual rainfall, water deficit ranges from 1.85 × 10^{10} m^3 in a normal year (P = 50%) to about 3.25 × 10^{10} m^3 in a dry year (P = 75%), and the uneven distributions of annual rainfall also

Table 1
Studies on water use efficiency (WUE) at different scales in the North China Plain.

Method	Sites	Agricultural management	Detail information	Other factors	Scale of WUE				Reference
					Leaf level	Canopy level	Yield level	Regional level	
Field experiment	Luancheng; Wuqiao; Beijing	Soil tillage	Zero tillage; Conventional tillage Conservational tillage	Specific soil and climate			√		Zhang et al. (1999), Chen et al. (2006a,b)
Field experiment	Luancheng; Beijing; Yucheng	Crop residual or straw cover	Wheat or maize straw	Specific soil and climate	√		√		Zhao et al. (1996), Zhang et al. (2003), Chen et al. (2007a)
Field experiment	Fengqiu; Luancheng; Wuqiao; Yucheng	Soil nutrient	Nitrogen and Phosphorus	Specific soil and climate	√		√		Fang et al. (2006), Wang et al. (2007c, e), Yi et al. (2008)
Field experiment	Fengqiu; Luancheng; Wuqiao;Yu cheng; Nanpi	Irrigation	Deficit/limited/regulated irrigation	Specific soil and climate	√	√	√		Zhang et al. (1999, 2004), Fang et al. (2007)
Field experiment	Luancheng; Yucheng	Crop cultivars	High yield, High WUE High drought torrorence	Specific soil and climate	√		√		Zhang et al. (2005b, 2006b)
Field experiment	Luancheng; Wuqiao	Cropping system	Specific soil and climate	Specific soil and climate			√		Liu et al. (2008a, b), Wu et al. (2008a)
System modeling	Luancheng; Yucheng	Irrigation and nitrogen	Climate variations	Climate variations			√	√	Fang et al. (2008), Hu et al. (2006)
Model coupled with RS and GIS[a]	Luancheng; Yucheng;	Traditional managements	Soil and climate variations	Soil and climate variations			√	√	McVicar et al. (2002), Mo et al. (2005)

[a] RS is remote sensing; GIS is geographic information systems.

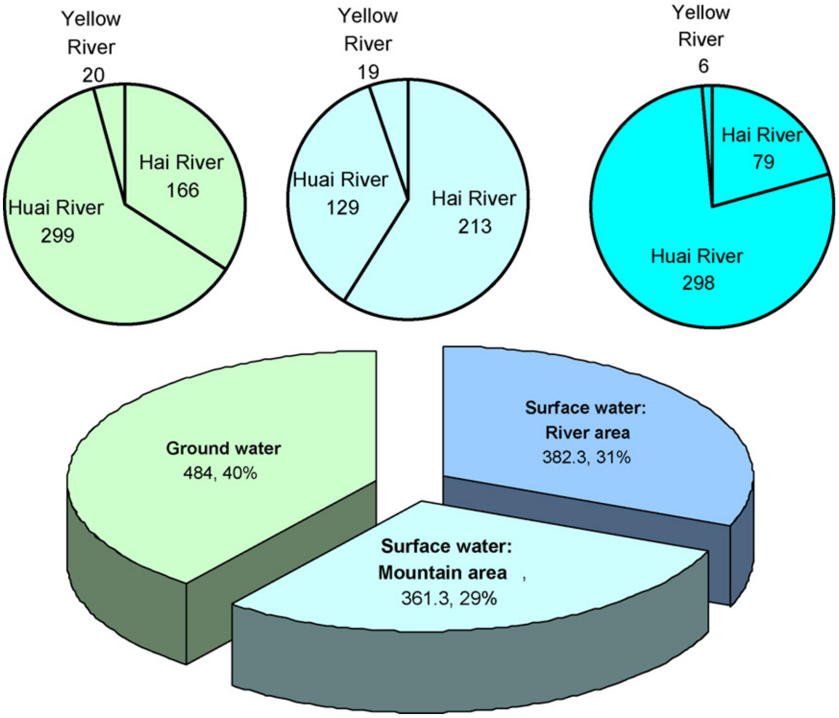

Fig. 2. Distribution of water resources (volumes in 10^8 m^3) averaged from 1956 to 1979 across the three river basins (Huai, Huang (Yellow), and Hai rivers from south to north) in the North China Plain (adapted from Liu and Wei, 1989) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.).

aggravate the water deficit situation (Liu and Xia, 2004). As water supply from surface water and groundwater will decline, regional water resources are expected to be more vulnerable to over-use and pollution under global warming trends (Liu and Xia, 2004). On the other hand, the irrigation utilization efficiency is only 25–40% due to the high losses to drainage and evaporation in water delivery systems (Xu, 2001), along with environmental problems, such as a salinization (Nickum, 1988). Improving irrigation delivery system and water availability are essential to enhancing WUE and minimizing environmental problems in the NCP, but need more effort and help from both farmers and local government as discussed by Wang et al. (2005c, 2009a).Other approaches have also been presented and discussed for mitigating the increasing water deficits and environmental problems, such as using polluted or saline water, transferring water from the Yangtze River to the NCP (Liu et al., 2001; Barnett et al., 2006), and more efficient water utilization. Other studies attempted to investigate the water problems from a socioeconomic view (Huang et al., 2009; Wang et al., 2006b; Yang et al., 2003). As reported by Webber et al. (2008), however, there is no simple solution to water resource problems in the Yellow River basin and some solutions lie outside the basin requiring integrated social and economic management, and local farmers and governments collaborations (Barnett et al., 2006).

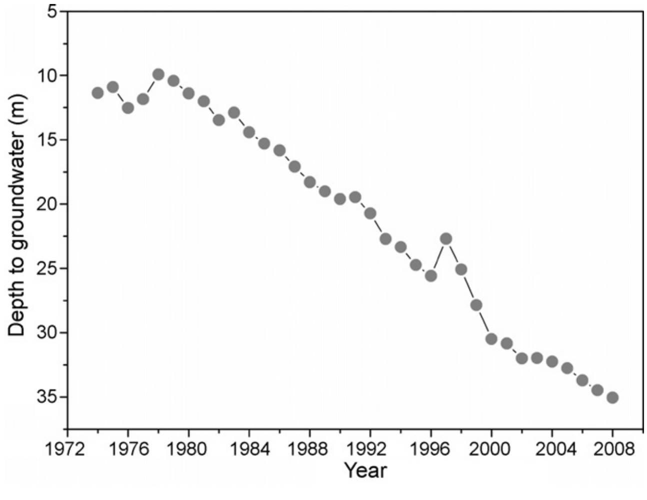

Fig. 3. Groundwater table dynamics from 1974 to 2008 at Shijiazhuang city in the North China Plain (Dr. Xiying Zhang provided these data).

In the NCP, the area of agricultural land is about 8.85 × 10^7 ha with an irrigated area of 6.53 × 10^7 ha, which consumes about 70% total water used (Lin et al., 2000). An analysis of water deficits in the NCP using a water balance method is presented in Fig. 5. The average water deficit across the region is 222 mm with an aridity index (rainfall/potential ET) of 0.76, and decreases from the Hai and Yellow River basins (345 mm) to the Huai River basin (92 mm). The three river basins have different water resource situations as indicated in Figs. 2 and 5. Based on the data from 1995, 1996 and 1997, the Yellow River basin only accounts for 3–4% of the total water resources in the NCP, and Huai River and Hai River basins account for 60–75% and 25–40% of the water resources, respectively, which is similar to the averaged values from multiple years (Fig. 2). The Hai River and Yellow River basins have similar water deficits but different water supplies. River water is the main water resource in the Yellow River basin, whereas surface water from the mountainous areas and groundwater are abundant in the Hai River basin. Huai River basin has the lowest water deficit level with adequade surface water and groundwater. In this context, different agricultural water management strategies can be applied according to the different levels of water supplies and deficits in each river basin.

3. Current WUE in the NCP

The WUE values for the main crops of wheat and maize in the NCP are still low and vary spatially. Yet there has been an increase in WUE from 0.23 to 0.90 kg/m^3 for cereal crops in Fengqiu area

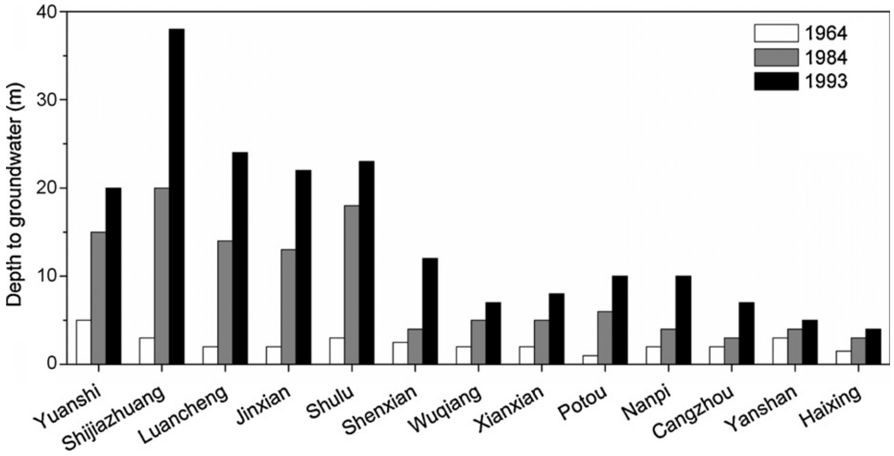

Fig. 4. Changes in groundwater table depths during the thirty years from 1964 to 1993 at different locations in the North China Plain (adapted from Hu et al., 2005).

(Henan province) during the past 50 years mainly due to increasing irrigation and fertilizer inputs (Xu and Zhao, 2001). In another study based on data from 4422 sites across 22 provinces in China, the averaged WUE values were estimated as 1.1 kg/m^3 for the cereal crops under well irrigated conditions (Duan and Zhang, 2000). The WUE for wheat and maize ranged from 1.0 to 1.9 kg/m^3 under well managed experimental sites in the NCP (Deng et al., 2006; Wang et al., 2002), which is comparable to the reported WUE values based on a global survey (Zwart and Bastiaanssen, 2004).Above results show that WUE in farmer's fields is generally lower than on the experimental sites due to the irregularity and deficit of irrigation amounts and limitations of soil nutrients, pest and weeds (Duan and Zhang, 2000). Since the traditional management generally irrigated in excess of crop requirements, with totally 300–500 mm (4–6 times per season) for wheat and 100–300 mm (1–3 times per season) for maize (Zhang et al., 2006b). It is possible to reduce water consumption with no or little reduction in grain yield (Wang et al., 2002; Hu et al., 2006), thereby increasing WUE.

4. Agronomic management for high WUE

Stanhill (1986) proposed three ways of coping with water deficits: (1) reducing water delivery losses in irrigation systems; (2) improving soil water availability to crop roots; and (3) increasing crop water use efficiency. Other studies have pointed to socio-economic factors, such as the irrigation institutional reforms, privatization of wells, government policy and the response of farmers to water crisis and incentives in the NCP (Blanke et al., 2007; Lohmar et al., 2003; Wang et al., 2009a). They found that with increased private ownership of wells and better water delivery, such as low-pressure water underground pipeline conveyance systems, the water delivery efficiency was improved in recent years but needs to be further extended widely in the NCP. Economic incentives were also effective in getting farmers to save water. However, the traditional irrigation technologies practiced by farmers, such as flood, border and furrow irrigation methods, are still used widely in the region and constrain the efficiency of agricultural water utilization. The household-based water-saving technologies, including plastic sheeting, retaining crop stubble on the surface, and drought resistant varieties have been adopted in recent years (Blanke et al., 2007; Wang et al., 2009a), but the innovative water-saving irrigation management, such as regulated deficit irrigation strategies have not been adopted widely by the farmers for economic reasons.

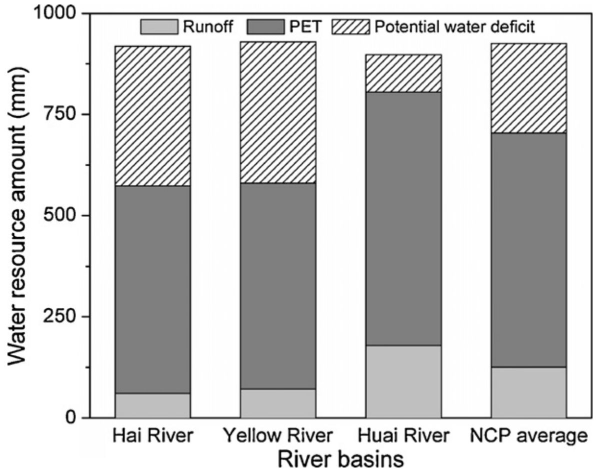

Fig. 5. Water resource balance (Runoff + Potential Evapotranspiration (PET) – Water resource supply = Water deficit) in the three river basins in the North China Plain (adapted from Liu and Wei, 1989).

4.1. Increasing soil water availability by soil surface management

Soil evaporation is an important component of ET, and is mainly controlled by soil surface energy balance and soil hydraulic properties. Soil evaporation can be altered by soil surface management, such as tillage, crop residue cover and mulching, and thus affect field-level WUE. Tillage is one of the traditional soil management practices for weed control and seed bed preparation to increase crop yield in irrigated agriculture in the NCP, but has influence on soil properties and soil water storage in dryland agriculture without mulching as commonly practiced by farmers in the NCP (Li et al., 2007b; Shangguan et al., 2001; Wang et al., 2007c). Wang et al. (2002) reported that about 90% rainfall in the summer can be stored by soil with deep tillage. Jin et al. (2006) found that deep tillage with crop residue mulching reduced runoff by 50% and soil erosion by 90% compared with conventional tillage (15–20 cm depth without mulching). However, tillage effects may be short-lived and the effects of tillage on long-term infiltrability have been mixed due in part to spatial and temporal variability of field soils (Strudley et al., 2008) and the differences in management and weather conditions. Furthermore, the effects of tillage on WUE, and crop yield are complex and related to other management practices, such as crop residue management (Hatfield et al., 2001). Table 2 is a summary of recent studies on the effects of tillage on ET and WUE under irrigated agriculture in the NCP. Although there is great variability in WUE among these studies across different soil and climate conditions, conventional tillage (CT) showed higher

Table 2
Evapotranspiration (ET) and water use efficiency (WUE) responses to tillage practices in the North China Plain.

Reference	Location	Crop type	Tillage practice[a]	ET (mm)	WUE (kg/m^3)
Su et al. (1999)	Xinxiang, Henan	Maize	CT	438	1.85
			No tillage	397	2.20
Zhang et al. (2000a)	Jingxian, Hebei	Maize	CT	478	1.79
			Reduced tillage	483	1.73
			No tillage	425	2.05
Zhang et al. (2002a)	Yucheng, Shandong	Maize	CT	362	–
			Reduced tillage	377	–
			No tillage	359	–
Zhang et al. (2006a)	Gaocheng, Hebei	Wheat	Deep tillage	548	1.41
			No tillage	576	1.38
Chen et al. (2006b)	Luancheng, Hebei	Wheat	Conventional tillage (CT)	234	1.51
			No tillage	430	1.11
Li et al. (2007c)	Luancheng, Hebei	Wheat	CT	373	2.06
			CT + Residues	409	1.83
			Rotary tillage with residues	425	1.45
			Zero tillage	369	1.39

[a] CT is the conventional tillage, 15–20 cm depth by plough.

WUE than zero tillage by about 29% for wheat due to poor seeding caused by previous maize residues under zero tillage conditions (Li et al., 2007c). Here, CT is defined as tillage to 15–25 cm depth without mulching commonly practiced by farmers in the NCP. For maize, the opposite results were obtained with a 17% higher WUE under zero tillage with residue cover due to increased grain yield and similar ET. In these studies, the differences in WUE among tillage practices were attributed to either differences in ET, or grain yield or both depending on the crop. Reasonable tillage practices, such as reduced tillage with crop straw mulching can increase WUE by about 13% (0–48%) for wheat and by about 17% (5–23%) for maize depending on soil types, climate (rainfall) and other management practices. Other studies on conservation tillage, including reduced or no tillage with crop residue mulching in the dryland agriculture in northwest China found that it could effectively conserve soil water, reduce soil erosions, and improve crop yield and WUE (Gao et al., 2003; Jin et al., 2007; Wang et al., 2007c). However, conservation tillage should be carefully applied in irrigated agriculture, due to its negative influence on early crop growth and yield (Chen et al., 2007a).

Hatfield et al. (2001) concluded that WUE can be increased by 25–40% through soil surface managements based on experiments conducted in many countries. The effects of crop straw and residue mulching on WUE varied among crops, seasons and other management practices (Hatfield et al., 2001). Deng et al. (2006) found that WUE was improved by 10–20% using crop residue management in northern China. Table 3 summarizes the recent studies on WUE in response to crop straw or residue management in the NCP. Residue mulching can improve WUE by about 13–27% for wheat or spring by increasing soil water storage with reducing soil evaporation by 17–68 mm during the early crop stages and fallow periods (Zhao et al., 1996), but the total ET values were similar between mulching and no mulching treatments (Table 3). For wheat, very different results were reported. Zhang et al. (2003) found an increase in WUE under mulching conditions, but Chen et al. (2007a) reported a similar or a slight decline in WUE under mulching conditions mainly due to delayed wheat growth caused by the low soil temperature in early spring. However, most studies showed that mulching with crop residue can improve maize yield and WUE (Table 3). In dryland agriculture, residue mulching can significantly improve WUE of wheat because more soil water is available under mulching, which can offset the negative influence of the low temperature on crop growth (Xu et al., 2006).

Plastic film mulching is another water-saving technique developed recently, which can reduce soil evaporation substantially by about 50% compared with no mulching. Although this technique is generally used to increase soil temperature for better crop growth, it can also save water especially under non-irrigated conditions, such as rainfed maize in the north and northwestpart of China. (Deng et al., 2006; Yuan et al., 2006; Zhang et al., 2005a). However, due to the economic costs, plastic film is mainly applied to cash crops, such as vegetable and oil crops, under irrigated conditions. On the other hand, plastic film mulching has some disadvantages, such as premature senility and difficulty to removal and disposal.

4.2. Soil nutrient management

Improving soil nutrient status can have a positive influence on WUE (Hatfield et al., 2001; Wang et al., 2002). In China, previous studies mainly focused on the effects of soil nutrients on crop yield and WUE in dryland agriculture (Xu et al., 2007; Yu et al., 2005). For irrigated agriculture, most studies were focused on how soil nutrient management affected crop yield and grain quality (Yu et al., 2002; Xu et al., 2003). Recently, researchers have paid more attention to fertilizer effects on WUE and environmental impacts (Fang et al., 2006; Liu et al., 2003; Yi et al., 2008). There is a great variation of WUE reported in the literature across different years or locations as influenced by soil nutrient management in the NCP (Table 4). Generally, nitrogen (N) application increased WUE with maximum WUE obtained at N rates ranging from 150 to 250 kg N/ha per crop season depending on crop types, soil and climate conditions. Current N inputs are generally excessive with N application rates of 250–300 kg N/ha per crop or higher for cash crops, which results in low N use efficiency and high N losses (about 70 kg N/ha per crop) (Fang et al., 2006; Liu et al., 2003). Because soil N availability is influenced by multiple factors, such as climate, soil type, tillage, and crop residue and rotation management (Hatfield et al., 2001), responses of crop yield and WUE to N management vary greatly. Some studies showed a slight increase (about 10–20%) in WUE with N application rate (Wang et al., 2007b,e; Zhong et al., 2000), whereas others showed a large increase (more than 50%) in WUE with N application rate (Dang et al., 2006; Wu and Yang, 2004; Zhao et al., 1999). This discrepancy was probably due to the difference in N supply from soils with different mineralization across the region. In general, WUE increased more for maize than for wheat (Table 4), indicating a higher response to water and N by maize than by wheat. Fertilizer (mainly N fertilizer) applications increased WUE by about 20% on

Table 3
Evapotranspiration (ET) and water use efficiency (WUE) responses to mulching with crop straw or residue in the North China Plain.

Reference	Location	Soil type	Crop	Year	ET (mm)		WUE (kg/m^3)	
					Mulching	No mulching	Mulching	No mulching
Zhao et al. (1996)	Beijing	–	Wheat	1989–1990	376	399	0.94	0.74
				1990–1991	315	320	0.93	0.82
				1991–1992	297	301	1.08	0.89
				1992–1993	262	261	1.05	0.89
			Maize	1989	402	396	1.76	1.45
				1990	396	407	1.51	1.22
				1991	404	407	1.08	0.93
				1992	320	291	1.16	1.01
Zhu et al. (2000)	Zhengzhou Henan	Sandy loam	Wheat	1998				
				Low water	215	201	1.39	1.34
				Medium water	385	393	1.53	1.31
				High water	391	396	1.50	1.36
Zhang et al. (2002b)	Luancheng Hebei	Loam	Maize	1999				
				Low water	338	–	2.26	–
				Medium water	367	–	2.22	–
				High water	430	–	2.00	–
			Maize	2001				
				Low water	243	–	2.45	–
				Medium water	352	368	2.09	1.82
				High water	412	–	1.93	–
Chen et al. (2002)	Luancheng Hebei	Loam	Maize	2001	331	334	2.78	2.47
Zhang et al. (2003)	Luancheng Hebei	Loam	Wheat	1998–1999	367	390	1.94	1.72
			Maize	1999	386	431	1.84	1.55
Zhang et al. (2004)	Luancheng	Loam	Maize	1999	475	478	2.05	1.73
Chen et al. (2007a)	Luancheng Hebei	Loam	Wheat	2000–2001	418	395	1.55	1.51
				2001–2002	–	–	1.21	1.25
				2002–2003	–	–	1.01	1.05
				2003–2004	–	–	1.50	1.49
				2004–2005	–	–	1.31	1.35
Li et al. (2007c)	Luancheng Hebei	Loam		2004–2005	409	373	1.83	2.06
					425	–	1.45	–
					369	–	1.39	–
					431	–	1.31	–
Wang et al. (2007d)	Zhengzhou Henan	Sandy loam	Maize	2005				
				Sole planting	408	417	1.08	0.92
				Bed planting	426	422	1.22	1.16

Table 4
Water use efficiency (WUE) response to nitrogen (N) rates in the North China Plain.

Reference	Location	Soil type	Year	N rates (kg/ha)	Crop	WUE (kg/m^3)		
						No[a]	Medium	High
Zhao et al. (1999)	Zhengzhou Henan	Sandy loam	1995–1996	0–300	Wheat	0.96	1.52	1.37
Zhong et al. (2000)	Mengjing Henan	Loam	1992–1993	0–300	Wheat	0.64	–	0.83
Li et al. (2000)	Wuqiao Hebei	Clay loam	1997–1998	0–375	Wheat	0.71	1.18	1.10
Wu and Yang (2004)	Jingxian Hebei	–	1996–1998	0–450	Wheat	0.54	1.67	1.46
Dang et al. (2006)	Changwu Shanxi	loam	1998–1999	0–180	Wheat	0.76	1.02	1.05
			1999–2000			0.88	1.39	1.41
			2000–2001			0.25	0.83	0.98
			2001	0–180	Maize	1.18	1.64	1.75
Wang et al. (2007c)	Wuqiao Hebei	Clay	2004–2006	0–295	Wheat	1.81	2.04	2.02
Wang et al. (2007e)	Huantai Shandong	Sandy loam	2003–2004	0–300	Wheat	1.16	1.27	1.34
Wu et al. (2008b)	Wuqiao Hebei	Clay loam	2003–2004	157–295	Wheat	–	1.86	1.78
Yi et al. (2008)	Wuqiao Hebei	Clay	2004	0–180	Maize Zhengdan958	1.85	1.98	2.00
			2005			2.11	3.23	3.36
			2004	0–180	Maize Nongda108	2.16	2.22	2.32
			2005			2.69	3.37	4.03

[a] No, Medium, and High denote zero, medium and highest N application rates for specific experimental N treatments.

average (9–66%) for wheat and by 26% (2–53%) for maize (Table 4). This result was similar to the report from Hatfield et al. (2001) who reported that soil nutrient management increased WUE by15–25% across a range of climates and crops. The high variability of measured WUE indicated strong interactions between these management practices across the different soil and climate conditions.

Interactions between soil water and N greatly affect soil water and N balance and WUE, and N application rate in the NCP should be reduced under water limited condition for more efficient use of water and N (Fang et al., 2006, 2008; Liu et al., 2003). Other studies found that increase in WUE by N application was mainly due to a deep root system with more soil water available for crops (Du et al., 1999; Li et al., 1994, 2001; Song and Li, 2004). Shen et al. (2001) reported that the optimal N rates for high wheat yield were about 300 kg N/ha under adequate irrigation conditions and 200 kg N/ha under limited irrigation conditions. Wu et al. (2008b) and Wang et al. (2007d) found N application rates of 150–200 kg N/ha were suitable for wheat under limited irrigation conditions. Li et al. (2003) found an N application rate of 144 kg N/ha with highest N recovery and lowest N loss under limited irrigation conditions during wheat seasons. These results suggested N application rates should vary according to irrigation levels (Wang et al., 2008).

Only limited studies have documented the effects of phosphorus fertilizer on crop WUE. Liang (1996) found that phosphorus nutrition can improve root water potential, root growth and dry weight, and grain WUE under water stress conditions. Other studies reported that phosphorus fertilizer can increase WUE especially under moderate water stress conditions, and the effects of phosphorus fertilizer on WUE had a close relationship with the N and irrigation management (Zhang et al., 2000b; Zhang and Li, 2005). Some other studies reported that potassium can increase crop drought resistance and WUE by increasing crop growth and reducing water consumption (Li et al., 2001, 2005b).

4.3. Irrigation management

Under field experimental conditions in the NCP (Table 5), the highest WUE was generally obtained at the moderate supplemental irrigation levels from 150 to 250 mm for wheat depending on experimental site conditions. The high variation in WUE across seasons or locations suggested that management other than irrigation, such as tillage and soil nutrients, influence WUE greatly. In the NCP, irrigation management can improve WUE of wheat by about 25% (7–88%). For maize, very few studies were carried out to investigate the effects of supplemental irrigation on WUE mainly due to the high rainfall during the maize season. Zhang et al. (2004) found no significant relation between maize yield with irrigation at Luancheng Ecological station, NCP (Hebei province), whereas Fang et al. (2007) found a severe water stress occurred at the early stage (jointing stage) of maize, which can substantially reduce maize yield even with irrigation later in the season.

Several water-saving irrigation strategies have been developed for high WUE, including limited irrigation (Shan et al., 2006), regulated deficit irrigation (Kang et al., 2000; Zhang et al., 1998a; Cui et al., 2008) and controlled alternative partial root-zone irrigation (Kang et al., 1998; Kang and Zhang, 2004; Li et al., 2007a). These irrigation techniques can save 15–35% of irrigation water with an increase in WUE of 10–30% as reported by studies in China (Kang et al., 1998). Zhang et al. (1998a) reported that one irrigation application at booting stage produced comparable grain yield with 24–30% higher WUE compared to the four irrigation treatments in the NCP, and the increased WUE was attributed to a deep root system associated with early water stress and improved harvest index. In another study, Kang et al. (2002) concluded that regulating soil water depletion moderately in the early vegetative growth period and more during maturity resulted in high grain yield and WUE in a semiarid area. Kang and Zhang (2004) also reviewed alternative controlled partial root zone irrigation studies

Table 5
Water use efficiency (WUE) response to irrigation managements in the North China Plain.

Reference	Location	Soil type	Year	Crop	Irrigation (mm)	WUE (kg/m^3)		
						No[a]	Medium	High
Zhang et al. (1998a)	Beijing		1991–1995	Wheat	0–300	0.98	1.47	1.13
Zhang et al. (1999)	Luancheng Hebei	Sandy loam	1986–1995	Wheat	0–249	1.22	1.39	1.10
	Gaocheng Hebei	Loam	1982–1985	Wheat	0–369	1.07	1.36	1.17
	Linxi Hebei	Loam	1982–1986	Wheat	0–435	1.06	1.35	0.91
	Nanpi Hebei	Loam	1986–1992	Wheat	0–251	0.98	1.18	1.13
Wang et al. (2001)	Luancheng Hebei	Loam	1986–1995	Wheat	0–400	1.15	1.29	1.11
Zhang et al. (2003)	Luancheng Hebei	Loam	1997–2000	Wheat	0–280	1.73	1.76	1.38
				Maize			1.55	
Zhang et al. (2004)	Luancheng Hebei	Loam	1998–1999	Wheat	250–400	1.22	1.42	1.24
			1999–2000	Wheat	250–400	1.61	1.49	1.16
			2000–2001	Wheat	250–400	1.20	1.29	1.20
			1998	Maize	0–180	1.41	–	1.01
			2001	Maize	0–180	1.39	–	1.72
Li et al. (2005a)	Wuqiao Hebei	Sandy clay loam	1994–1995	Wheat	0–300	1.48	1.62	1.23
			1995–1996	Wheat	0–300	1.73	1.73	1.58
			1996–1997	Wheat	0–300	1.56	1.75	1.74
Sun et al. (2006)	Luancheng Hebei	Loam	1999–2002	Wheat	80–400	1.52	1.52	1.08
Fang et al. (2007)	Yucheng Shandong	Sandy loam	2001–2002	Wheat	0–180	1.41	1.91	1.67
			2002–2003	Wheat	0–180	1.58	1.58	1.36
			2002	Maize	150	1.55	1.92	2.00
Qiu et al. (2008)	Luancheng Hebei	Loam	2002–2003	Wheat	0–300	2.13	–	1.13
			2003–2004	Wheat	0–300	1.48	–	1.29

[a] No, Medium, and High denote zero, medium and highest irrigation levels for specific experimental N treatments.

in China, and found that this irrigation technique can reduce water consumption by 35% with only about 6–11% reduction in biomass. Hu et al. (2009) found alternative controlled partial root zone irrigation could improve both N and water use efficiency for maize with less (70%) irrigation water. These irrigation strategies are being applied for many cash crops, such as vegetables under various conditions, but are rarely applied to cereal crops under field conditions.

All these irrigation techniques require a better understanding of the sensitivities of crops to water stress and its ecological and physiological basis, which generally varies among different crop growth stages (Shan and Zhang, 1999; Zhang et al., 1999). For example, the sensitive stages of wheat to water stress are from jointing stage to grain filling stage depending on climate conditions (Table 5). Some studies (Chaves and Oliveira, 2004; Jones, 2004) have also shown that (1) the responses of different physiological processes, such as cell growth, photosynthesis, transpiration and photosynthate transfer between organs, to water stresses were also different; (2) the relationship between crop yield or WUE and ET showed WUE generally reached its highest value before maximum crop yield; and (3) the interactions between crop canopy and roots, such as abscisic acid (ABA), generally resulted in more efficient water use by crop. These results provide a theoretical basis to improve WUE by regulating irrigation according to plant water demand as discussed above. Another method is to schedule irrigation based on crop water stress as detected by canopy surface temperature measured with infrared thermometers (Alderfasi and Nielsen, 2001; Nielsen, 1990; Nielsen and Gardner, 1987). Correctly determining crop water stress index (CWSI) is a prerequisite of this irrigation management. Many studies were carried out to compare and improve CWSI calculation methods across different crop and climate conditions (Idso et al., 1981; Jackson et al., 1988; Jones, 1999). In the NCP, Yuan et al. (2004) found that the Jackson CWSI method was better for detecting crop water stress of winter wheat compared with the Idso definition (Idso et al., 1981) or the Alves definition (Alves and Pereira, 2000). Li et al. (2010) concluded that CWSI calculated by the Jackson method based on the canopy-air temperature difference may be used for irrigation scheduling and agricultural water management of maize in the NCP. Other methods to monitor plant water stress for irrigation scheduling are soil water measurement, plant water potential, tissue water status measurement and stomatal conductance (Jones, 2004, 2008). Remote sensing provides another promising tool to monitor soil and crop water stress status for irrigation management at large areas (Jones, 1999).

4.4. Crop improvement and breeding

Drought resistant crop cultivars have been shown to improve crop WUE, but crops with high drought resistance are usually associated with low grain yield, which limits the application of these cultivars in the NCP (Wang et al., 2002; Zhang et al., 2006c). High WUE has become a very important indicator for crop breeding because it combines drought resistance and high potential yield (Zhang et al., 2006c). Based on the drought resistance and WUE for wheat, for example, there are four cultivar types: (1) low WUE with low ET and low grain yield; (2) high WUE with both moderate ET and grain yield; (3) highest WUE with highest grain yield and moderate ET; and (4) lowest WUE with high ET and low grain yield. Among the four cultivar types, types 2 and 3 are the favorite crop breeding traits.

Many studies have found that large variations in WUE among different crop types were due to the different responses of these crops to water stress (Shan and Zhang, 1999; Zhang et al., 2006c), and even for the same crop, such as wheat, different crop cultivars also had different WUE under water stress conditions (Yi et al., 2008; Zhang et al., 2000c). As much as 50% difference in WUE was found among wheat cultivars in semiarid areas (Shan et al., 2006). Zhang and Shan (1998b) demonstrated a progression in WUE from diploid to hexaploid wheat cultivar in the semiarid area. Zhang et al. (2005b) reported that wheat cultivars showed a large difference of 40% in WUE at leaf level (photosynthesis rate/transpiration rate). For different crop cultivars, WUE generally has weak relationship to physiological processes, such as leaf photosynthesis and transpiration rates, but is closely related to grain yields (Zhang et al., 2006b). These results showed great opportunities to select drought resistant crop cultivars with high WUE. In the NCP, WUE for wheat and maize showed an obvious increase with time as reported by Zhang et al. (2005b). An increase in WUE of about 40% for maize and about 20% for wheat from 1982 to 2002 was found in the NCP, which was due to both improved crop cultivars and management practices.

4.5. Cropping systems

The main double cropping system of wheat and maize with high water consumption may not be sustainable considering the increasing water deficit in agriculture and serious environmental problems in the NCP. Other alternative cropping patterns or farming systems with less water requirement may be helpful to mitigate the water crisis (Liao and Huang, 2004). However, limited studies have been conducted on how cropping systems, such as wheat–maize two crops one year, winter wheat–summer maize–spring maize three crops two years, faba bean–maize, spring soybean two crops one year, influenced WUE and water consumption in the NCP (Liu et al., 2008a,b; Ma et al., 2008; Wu et al., 2008a; Ye et al., 2008). The main conclusion thus far is that wheat and maize double cropping systems can use water more efficiently with higher production but consume more water compared to other cropping systems, such as peanut–wheat–maize, and bean–maize in the area. However, some alternative cropping systems, such as crop–fruit tree systems, may have higher economic returns than the main cropping system. These lower water-consumption cropping systems can be alternatives to the main cropping system, especially in areas with serious water deficit. Rainfed cropping systems in the NCP should be investigated for possible transitions from irrigated agriculture to rainfed agriculture in the area to cope with the decline in water supply and mitigate the water crisis in the future.

The partitioning of water between wheat and maize in the double cropping system also has a great influence on WUE mainly due to the uneven distributions of the annual rainfall between crop seasons. Supplemental irrigation in the wheat season can contribute to a high initial profile water storage for the subsequent maize (Fang et al., 2007), and mulching with crop residues during wheat season can maintain more water for the subsequent maize as reported by Chen et al. (2007a). High seasonal rainfall during the maize season contributes significantly to a high soil water level before wheat planting in the NCP (Fang et al., 2010). In this context, irrigation strategies should consider the whole cropping system and the interactions between crops to improve WUE of all crops across different climate conditions.

4.6. Agricultural systems modeling at field scales

Variations in WUE can be attributed to agricultural management (e.g., soil management practices, irrigation, crop cultivars) and environmental factors (e.g., soil and climate conditions) (Zwart and Bastiaanssen, 2004). Climate and soil variations are the biggest obstacles to extending advanced management strategies from experimental results to other field conditions, and to improve regional WUE. System modeling and analyses are useful tools to evaluate various water management scenarios across various climate conditions and soil types (Ma et al., 2007). In the NCP, only in recent years, agricultural system models have been used to investigate soil water balance and WUE across various soil, climate and management conditions (Yu and Wang, 2001). Wang et al. (2001) used a process-based model (WAVES) to simulate the effect of irrigation management on crop growth and soil evaporation, and found that mulching can reduce soil evaporation up to 50% in the NCP. Yang et al. (2006) found that 100 mm irrigation water can be saved with an improvement of WUE from 1.27 to 1.45 kg/m^3 for wheat (ET was reduced by 76 mm) based on a 12-year simulation period using CERES-wheat model in the NCP. Chen et al. (2007b) used a crop growth model coupled with water and N management modules to optimize water and N use efficiency for wheat, and found that a 13% increase in WUE along with a 25% reduction in irrigation was obtained for the optimized management scenario compared with the control. Several studies using the Root Zone Water Quality Model (RZWQM) investigated interactions between soil water and N and its impact on crop yield and environmental quality in the NCP (Yu et al., 2006; Hu et al., 2006; Fang et al., 2008), which showed that there was a great potential to reduce current N inputs according to the irrigation levels with little or no influence on crop yield.

As examples of managing N in a wheat–maize system in the NCP, Yu et al. (2006) showed that a reduction of 25% of current water and N applications reduced N leaching by 24–77% with crop yield reduction of 1–9% only based on RZWQM sensitivity analysis results. Hu et al. (2006) also found that typical applications of water and N can be reduced by about 50% with only little reduction in crop yield (less than 10%) but with about 50% reduction in N leaching. Fang et al. (2008) also used RZWQM to evaluate the effects of different combinations between soil water levels and N application rates, and concluded that, auto-irrigation triggered at 50% of the field capacity and recharged to 60% field capacity in the 0–50 cm soil profile with 200 kg N/ha per crop application rate were adequate for obtaining acceptable yield in a wheat and maize double cropping system. They also showed potential savings of more than 30% of the current N application rates per crop from 300 to 200 kg N/ha, which could reduce about 60% of the N leaching without compromising crop yields. Another example for evaluation of different irrigation scheduling using RZWQM in the NCP was reported by Fang et al. (2010). The results showed that the most sensitive stage of wheat to water stress was the stem extension (jointing) stage, and irrigation applied during this stage achieved higher WUE. Two irrigations applied at jointing and booting stages resulted in the highest yield and WUE. Irrigation before planting wheat commonly practiced by local farmers should be postponed to the most sensitive stage for higher WUE. In another study, Chen et al. (2010) used the Agricultural Production Systems Simulator (APSIM) to investigate the effects of climate variations and irrigation on crop WUE based on long-term weather conditions, and recommended one (70 mm), two (150 mm) and three (200 mm) irrigations for wheat, and zero, one (60 mm), and two (110 mm) irrigations for maize in the wet, medium and dry seasons, respectively. These modeling studies provided useful guidance to managing limited water resources, and results can be transferred more efficiently across different climate conditions.

However, the effect of soil characteristics on soil water balance and WUE have not been quantified fully under different agricultural management conditions. As discussed above and in other studies (McVicar et al., 2002), very large deviations in WUE can occur among different soil types (Ma et al., 2002), because soil type controls soil water and nutrient dynamics (Wang et al., 2009b; Ma et al., 2007). Several studies were conducted to evaluate irrigation and N managements across different soil types and climate conditions in the NCP by linking geographic information systems (GIS) and crop growth model (Huang et al., 2001; Gao et al., 2006a,b), and found close relationship among WUE and rainfall, irrigation and soil hydraulic conductivity across the different soil types, and provided useful information on regional agricultural management.

5. Regional WUE assessment and improvement

Crop WUE at regional scales is a very important indictor for regional water resource assessment and management. Quantifying regional WUE is essential to understanding variations in WUE as influenced by multiple factors, such as water resources, soil, climate and agronomic management. Many studies have focused on the assessment of water resources and its potential influence on agricultural production in the NCP (Liu and Xia, 2004). McVicar et al. (2002) defined regional agricultural WUE as grain yield per water available (mm) for crop growth, and monitored regional WUE in the NCP, where WUE from 75 to 80% of observed areas was 0.5–1.5 kg/m^3 in the Hebei province from 1984 to 1996. Large spatial and temporal variations in WUE can occur due to rainfall distributions, water quantity and other management factors. Mo et al. (2005) using the SWAT model with remotely sensed data simulated regional WUE of 1.23–1.58 kg/m^3 for irrigated wheat and 1.10–1.93 kg/m^3 for irrigated maize across the NCP, and concluded that improving irrigation efficiency can significantly enhance crop yield and WUE in the area. In another study, Liu et al. (2007), using the GIS-based EPIC model, reported that the simulated regional WUE averaged over different areas in the NCP was 1.20 kg/m^3 (0.75–1.42 kg/m^3) for irrigated wheat. All these studies showed a 30–50% higher WUE for irrigated agriculture than rainfed agriculture, confirming that irrigation in the NCP is the most important method to maintain high yield and WUE. Based on the simulated WUE levels for irrigated areas in the NCP (Liu et al., 2007), about 360 mm of irrigation water is needed for both wheat and maize, which obviously exceeded water supply of about 160 mm (considering water transfer efficiency) in the region (Lin et al., 2000), and will likely result in a quicker decline in groundwater levels in the area (Chen et al., 2010).

Climate change also has a likely influence on WUE but with high uncertainties due to the magnitude and pattern of climate change and the response of ecosystem. In theory, increased atmospheric CO_2 concentration can increase WUE (Grant et al., 1999; Gregory and Ingram, 2000; Triggs et al., 2004). Other factors, such as air temperature increase and changes in rainfall patterns change may decrease crop yield and WUE, especially in water-limited semiarid areas (Ju et al., 2005; Lin et al., 2005). Xiong et al. (2007) used the CERES-Maize model to simulate rainfed and irrigated maize yields under two climate change scenarios, and found a decrease in maize yield without considering CO_2 fertilization effect. Maize yield can also increase under rainfed conditions but decrease for irrigated maize when CO_2 fertilization effect was taken into account. In another study, based on survey data from households, Wang et al. (2009b) found that global warming may affect rainfed farmers negatively but benefit irrigated farmers, and that agricultural irrigation supply will play a more important role in maintaining high yield under future climate change conditions. The changes in water resource availability and agricultural water requirements as influenced by climate change may have substantial influences on soil water balance, crop water use and WUE in the future (Chen et al., 2005a, 2006a; Wang et al., 2007e). The uncertainty from the interactions between climate change, crop response, land use pattern and water resources availability should be investigated as a complex system for its impacts on crop yield and WUE (Betts, 2005; Xiong et al., 2009).

Table 6

Water resources balance for Yellow River, Huai River, and Hai River basins in the NCP.[a]

Region	Crop	ET[b] (mm)	Rainfall (mm)	Water resources supply[c] ($\times 10^9\,m^3$)			Irrigation amount[d]		Potential water deficits[e] ($\times 10^8\,m^3$)	WUE[b] (kg/m^3)	Yield[f] ($\times 10^9\,kg$)	Groundwater table	Effective Irrigation area
				Surface water 1	Surface water 2	Groundwater	mm	$\times 10^8\,m^3$					
Yellow River	Wheat	550	174	25	100	20	376	418	−273	1.5	21	Decline	100%
		440	174	25	100	20	266	296	−151	1.8	20	Decline	
		330	174	25	100	20	156	173	−29	1.4	12	Decline	
		220	174	25	100	20	46	51	94	1.0	6		
	Maize	450	406				44	33		1.8	14		0%
	Wheat	550	174	25	100	20	376	209	−64	1.5	11	Decline	50%
		440	**174**	**25**	**100**	**20**	**266**	**148**	**−3**	**1.8**	**10**	Decline	
		330	174	25	100	20	156	87	58	1.4	6		
		220	174	25	100	20	46	26	119	1.0	3		
	Maize	450	406				44	16		1.8	7		0%
Huai River	Wheat	550	243	298	129	299	307	268	458	1.5	17		100%
		440	243	298	129	299	197	172	554	1.8	16		
		330	243	298	129	299	87	76	650	1.4	9		
		220	243	298	129	299	−23	−20	746	1.0	4		
	Maize	450	568				−118			1.8	11		0%
	Wheat	550	243	298	129	299	307	134	592	1.5	8		50%
		440	**243**	**298**	**129**	**299**	**197**	**86**	**640**	**1.8**	**8**		
		330	243	298	129	299	87	38	688	1.4	5		
		220	243	298	129	299	−23	−10	736	1.0	2		
	Maize	450	568				−118			1.8	5		0%
Hai River	Wheat	550	172	79	213	166	378	1390	−932	1.5	71	Decline	100%
		440	172	79	213	166	268	985	−528	1.8	68	Decline	
		330	172	79	213	166	158	581	−123	1.4	40	Decline	
		220	172	79	213	166	48	176	281	1.0	19		
	Maize	450	401				49	120		1.8	46		0%
	Wheat	550	172	79	213	166	378	695	−237	1.5	35	Decline	50%
		440	**172**	**79**	**213**	**166**	**268**	**493**	**−35**	**1.8**	**34**	Decline	
		330	172	79	213	166	158	290	167	1.4	20		
		220	172	79	213	166	48	88	369	1.0	9		
	Maize	450	401				49	60		1.8	23		0%

[a] Although irrigation can be applied due to the uneven rainfall distributions, seasonal rainfall is generally adequate in amount for maize, and we only calculated the water resources balance for wheat. Water resources balance was calculated based on the following equations: Evapotranspiration (ET) = Rainfall + water resources supply + Irrigation.

[b] Maximum ET is under no-water limited condition based on the references in the NCP (Zhang et al., 1998a, 2004, 2005b; Sun et al., 2006), and WUE values are determined by the relationship between WUE and ET, where maximum WUE are obtained at the 80% ET level and minimum WUE are obtained at 40% ET level (rainfed condition) according to above references (Table 5).

[c] Water resource supplies for the three river basins are the potential water available for irrigation in the regions based on Liu and Wei (1989), and sometimes they may be not available due to their uneven distributions. Surface water 1 occurs within the river basin and surface water 2 occurs from mountain areas.

[d] Irrigation and water deficits were calculated based on the effective irrigation area (100% and 50% two levels, and 50% is close to the real condition in the NCP) for wheat and the total crop yield were also calculated in a same way based on WUE at each water level.

[e] Water deficits are the difference between water resources supply and irrigation amount. The three scenarios selected with bold are the new scenario combination based on water allocation, where about $300 \times 10^9\,m^3$ water from Huai River is allocated to Yellow River ($50 \times 10^9\,m^3$) and Hai River ($250 \times 10^9\,m^3$) to reduce groundwater use and table decline.

[f] Crop yield are calculated only based on the irrigated area (effective irrigation area, 100% or 50%), and the effective irrigation area for wheat in the NCP is about 50% of crop area (Lin et al., 2000). Maize planting area is about 2/3 of wheat area in the NCP according to Yu and Ren (2001).

6. Regional water resources balance and crop production

Assessment of water resources balance on water supply and crop water demand is very important for applying reasonable water management strategies and realize potential water-saving and high WUE at regional scales. Table 6 presents various scenarios with different water balances and crop productions under different ET (40–100%) and WUE levels, where three different regions of the Yellow, Huai and Hai River basins with different water resources situations were analyzed (Fig. 2). In the Yellow River basin, water resources can only maintain up to 60% of the maximum ET for wheat without resulting in a decline in groundwater when 100% of crop areas are irrigated, and can maintain about 80% of the maximum ET for wheat when 50% of crop areas are irrigated. Similar results were found in the Hai River basin. In these two river basins, the rainfall for maize is usually adequate (about 80% of the maximum ET), but supplemental irrigation may be applied due to the uneven seasonal distributions. Poor irrigation efficiencies and spatial and temporal variations in water availability may increase water deficits, and the water deficits under different water supply levels shown in Table 6 (40–100% of maximum ET) are the best scenarios. In the Huai River basin, there are no obvious water deficits in the regions, the surplus water resources can potentially be transferred to the other two basins. Based on the current irrigation area (50% of crop land area) in the NCP, three scenarios for the three river basins were selected with higher crop yield (highest WUE) and reasonable water balances (e.g., no obvious decline in groundwater table) (Table 6). About $3.00 \times 10^{10}\,m^3$ from the Huai River may be allocated to the Yellow River ($0.50 \times 10^{10}\,m^3$) and Hai River ($2.50 \times 10^{10}\,m^3$) basins. Under such these scenarios, the total crop yield in the NCP is about 1.37×10^{11} kg (0.52×10^{11} kg for irrigated wheat, 0.14×10^{11} kg for rainfed wheat and 0.71×10^{11} kg for rainfed maize), which is close to the projected food demand ($1.51–1.55 \times 10^{11}$ kg) in 2010 in the NCP (Yu and Ren, 2001).

7. Discussions and perspectives

Water is the most important limiting factor to agricultural production in the NCP, and likely will be exacerbated by increasing food demand and deteriorating soil and water quality (Chen et al., 2005b; Zhang et al., 1996). Enhancing agricultural WUE at field and regional scales via innovative management is the key to coping with the above challenges in the NCP. Soil and irrigation management are the most important measures, which were the focus of many studies that showed potential to improve WUE significantly. Crop breeding has a high potential to save water and improve WUE in the future (Condon et al., 2004; Passioura, 2006).

Although some improvement in WUE has been achieved in the NCP during the past 20 years, the current results show that the WUE in farmer's fields are still lower than WUE at experimental sites. There are several research priorities to further improve WUE at field and regional levels. The interaction among agronomic management practices across various soil and climate conditions is one of the most important information studied for designing the best site-specific strategies. For example, interactions between irrigation and N management (Xu et al., 2007; Fang et al., 2008), irrigation method and scheduling (Pereira, 1999), and tillage and crop residue management (Hatfield et al., 2001), can potentially improve WUE. Combining multiple management practices should be more effective in improving WUE than any single management in the NCP. Understanding the variations in WUE associated with soil and climate conditions can also contribute to the transfer of irrigation technology to farmers and to optimizing regional agricultural water management.

Irrigation is a key to maintain high crop yields and improve WUE. Further evaluation and optimization from field to regional scales need to consider soil, climate and water resources variations. Similar to better N management strategies (Ladha et al., 2005), irrigation strategies can also be yield-targeting and variable for different soil conditions based on crop water demand and water supply. Newly developed precision irrigation has shown great promise to improve WUE (Jones, 2004, 2008), and can potentially improve WUE at field and regional scales.

Increasing regional WUE is an important objective for agricultural water management, but has not been resolved mainly due to the complex influences of multiple factors, such as soil variations, hydrological variability, and agronomic managements, on crop growth and WUE. As suggested by Wang (1993), there are several approaches to saving water and improving WUE at the regional level, such as minimizing soil evaporation by proper irrigation and crop residue cover, improving irrigation delivery system, optimal water allocation to different fields or crops, and optimizing irrigation time and amount based on rainfall and water resource availability. Combining crop water requirements with specific water resource availability is the key for water allocation and irrigation management, and for assessing potential water saving in the NCP. Water-saving irrigation strategies based on the above results should improve regional WUE significantly. Whole-system modeling, along with remote sensing and GIS should be used to address regional WUE issues. We also identified several knowledge gaps for further increasing WUE in the NCP by: (1) further understanding of the effects of agronomic management on WUE across various soil and climate conditions; (2) quantifying the effects of soil water and N interaction in water-limited agriculture on water and N-use efficiency; (3) improving irrigation practices (timing and amounts) based on real-time monitoring of water status in soil-crop systems; and (4) maximizing regional WUE by managing water resources and allocation between different regions.

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