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Assessing potential water savings in agriculture on the Hai Basin plain, China

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ABSTRACT

The Hai Basin in China exemplifies problems that are observed in many arid environments: excessive water consumption, depletion of aquifers, and damage to eco-systems. Progressively since the 1970s water resources in Hai Basin have been over-exploited, primarily for irrigation, while the water requirements of other sectors have increased. Water tables are falling and outflows to the sea are sporadic and heavily polluted. Current consumption of water in the basin is estimated to exceed the renewable supply from rainfall by $6.25 \times 10^9\ m^3\ yr^{-1}$. Traditional approaches—improving irrigation efficiency through structural works and on-farm technologies such as drip and sprinkler—have failed to restore a balance. Researchers have investigated various on-farm techniques to reduce consumption, including mulching, zero tillage, deficit irrigation, revised cropping patterns, and improved cultivars. We project the results of such experiments for winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and cotton (*Gossypium* spp.) to basin scale to assess their potential in restoring sustainable water consumption. Widespread adoption of mulching, which is the most promising option for farmers, would reduce the over-consumption by 25% ($1.6 \times 10^9\ m^3\ yr^{-1}$). If water quotas are introduced, forcing a reduction in consumption, current production could be maintained while saving $4.1 \times 10^9\ m^3\ yr^{-1}$. Ending the remaining over-consumption of $2.15 \times 10^9\ m^3\ yr^{-1}$ would require reducing grain production by 4–7.8 Mt yr^{-1}.

1. Introduction

Irrigation, especially in countries with limited rainfall, dominates water use, often accounting for 70–80% of total water use. Population growth, improved and diversified diets, industrialisation, and economic development increase the pressure on limited water resources (Peng, 2000). Surface water, being most accessible, is often exploited first, but since the 1970s, when deep tube-wells using submersible pumps became affordable, groundwater has been a major additional source of irrigation. Wada et al. (2012) report that the most significant examples of this unsustainable consumption are in India ($68 \times 10^9\ m^3\ yr^{-1}$ of non-renewable groundwater depletion) followed by Pakistan ($35 \times 10^9\ m^3\ yr^{-1}$), the United States ($30 \times 10^9\ m^3\ yr^{-1}$), Iran ($20 \times 10^9\ m^3\ yr^{-1}$), and China ($20 \times 10^9\ m^3\ yr^{-1}$). These volumes range from 15 to 30% of total irrigation water delivered.

Irrigated agriculture is likely to experience substantial future reductions in water availability. Total consumption by all sectors must be reduced to restore, or at least stabilise, depleted aquifers and damaged ecosystems, and agriculture is often a low priority user of water, such that its share in the aggregate is likely to decline. Nevertheless, irrigation will continue to be a substantial component of water demand (Xu and Kang, 2002), and as such, reducing consumption in this sector will remain a high priority.

The North China Plain is an example of this pattern of development. Traditionally a rainfed, agrarian economy, the area has contributed substantially to national food security. Since the 1970s groundwater tables have fallen substantially as the area under tube well irrigation expanded. Industrialisation and urbanisation have progressed rapidly, and outflows from the river system are now limited and heavily polluted. The area continues to contribute substantially to food security in China. Maintaining production while re-establishing a sustainable, ecologically and environmentally acceptable water regime is a high priority for the government. Achieving this goal will be challenging, and will require careful consideration of the costs and benefits of water use and water saving in the region.

To date, the response to excessive agricultural water use on the Hai Basin plain, which constitutes about 40% of the total area of the North China Plain, has focused on improved infrastructure

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(Gong et al., 2003; Blanke et al., 2007). Since 1980, canal lining and pipeline distribution technology have been introduced on more than 2.7 Mha (37.2% of the irrigated area) in the Hai Basin (Zhu et al., 2008). Drip and sprinkler irrigation have been introduced on 492,000 ha (7% of the irrigated area), largely for orchards and greenhouses (Zhu et al., 2008).

Such investments have been widely promoted as "water saving", because less water needs to be withdrawn from the source to meet the water requirements of the crop.

However, several authors stress the need to evaluate the impacts of changes in irrigation management and technology in the full hydrologic context (Willardson et al., 1994; Seckler, 1996; Jensen, 2007; Perry, 2007; Perry et al., 2009; Crase and O'Keefe, 2009). The common issue they raise is the extent to which "losses" return to useable aquifers or streams. Specifically for the Hai Basin, Kendy et al. (2003, 2004) conclude that improved irrigation technology cannot restore the water balance because the vast majority of "losses" are in fact recovered and reused.

Humphreys et al. (2010) evaluate an array of potential interventions in northwest India—where groundwater is also a major source of irrigation water. The authors conclude that:

> "Reducing deep drainage will not "save water" nor reduce the rate of decline of the water table. In these regions, it is critical that technologies that decrease evapotranspiration (ET) and increase the amount of crop produced per amount of water lost as ET (i.e., crop water productivity) are implemented" (p 157).

Most recently, reflecting the importance of these insights, interventions funded by the World Bank and the Global Environmental Facility[1] focus directly on reducing consumptive use ("evapotranspiration management") rather than pursuing the traditional engineering concept of efficiency.

Complementing this approach, we review research results, in terms of reduced ET at field level and associated changes in crop production, and we identify the most promising interventions. We then project reported water savings and production impacts from research scale to basin scale for the Hai Basin for the main crops grown in the area (wheat, maize and cotton). We also discuss the constraints that will limit the water savings potential of adopting the water management measures described in research findings.

Our analysis is relevant to recent policy statements in China. In Document No. 1 of 2011,[2] the State Council decided to accelerate water reform and development through the "strictest water resources management" and enforcement of the "Three Red Lines" which will reduce water use, restore aquifers and rivers, and increase production per unit of water used.

2. Materials and methods

2.1. The study area

The Hai Basin plain is located between the longitudes and latitudes of 113.2–119.8 ° E and 35.0–40.4 ° N. The area is about 131,000 km^2, accounting for about 40% of the total land area of the Hai Basin. The study area belongs to the temperate zone continental monsoon climate. About 80% of the annual precipitation occurs between June and September. Rainfall since 1990 has averaged 557 mm yr^{-1}. The total arable land of our study area is about 81,200 km^2.

We divide the plain of the Hai Basin into eight river-plain districts: Beisi, Luan, Daqing west, Daqing east, Ziya, Heilonggangyundong, Zhangwei and Tuhaimajia. There are several agricultural research stations in the study area (Fig. 1). Among them, Baoding, Luancheng, Wuqiao and Yucheng are major stations. Tunliu, Fengqiu, Luoyang and Shangqiu, are outside Hai Basin plain, but they are located near the border of the Hai Basin plain and have similar agro-climatic conditions.

Research reports usually only state the county name but not the specific location. Therefore we use the county borders to identify the general "experimental regions" where the reported studies took place, as shown in Fig. 1. Winter wheat and maize are grown at all stations. Beijing Xijiao is the only experimental site where cotton was grown.

2.2. Cropping patterns and water use

The crop rotation over the North China Plain in 2010 was derived from the research of Wu et al. (2013). The charge-coupled device on the HJ-1A/B satellite at a resolution of 30 m was used to obtain the training data for classification. A decision tree algorithm was applied to the time series of vegetation indices (NDVI and EVI) to identify areas with different crop rotations. We extracted the crop rotation data for the study area and calculated the crop areas. Major crops were winter wheat (3.67 Mha), spring maize (2.49 Mha), summer maize (2.73 Mha, of which 1.92 Mha follows wheat), and cotton (0.73 Mha).

Winter wheat rotated with maize is the predominant cropping system in the Daqing west, Ziya, Zhangwei and Tuhaimajia river plains, which are the main grain producing regions, accounting for about 46% of the study area, and more than 50% of the basin's total production (53.2 Mt yr^{-1}). Single crop rotations (cotton or maize) are most common in the Beisi, Luan, Daqing east and Heilonggangyundong river plains.

Wu et al. (2014) estimated the incremental consumption of water in the Hai basin due to human intervention at 36×10^9 m^3, of which 6.25×10^9 m^3 is the excess over the sustainable consumption rate that would stabilise aquifers and restore adequate river flows.

Monthly ET data for the study area from 2002 to 2009 were produced by using the remote sensing model-ETWatch, which was validated using the observation data (Wu et al., 2012). The deviation for individual fields on a seasonal basis is 12% and decreases to 6% for an annual cycle, and the deviation is 3% for catchments for an annual cycle. Average crop ET derived from the remote sensing analysis was 333 mm for wheat, 319 mm for maize, and 585 mm for cotton. Wang (2013) used the same remote sensing data to derive the average "natural" ET from the uncultivated landscape for the periods corresponding to the major crops. During the winter wheat season, natural ET was 145 mm, and for the maize season it was 259 mm.

2.3. Reported impact of water-saving techniques

The government of China has supported research on water-saving techniques since the 1980s, involving many specialists and institutions. More than 3000 experimental results have been reported over the last 30 years. Techniques include improved irrigation technology (lining of channels, drip and sprinkler systems), mulching, conservation tillage, deficit irrigation, improved crop varieties, and improved weed control (Zuo, 1997; Blanke et al., 2007; Fang et al., 2010a).

Our empirical analysis is based on existing research on interventions designed to reduce ET and improve crop water productivity (defined as kg m^{-3}) in the conditions of the Hai Basin. The

[1] http://www.worldbank.org/en/results/2013/04/09/china-improving-water-resource-management-pollution-control-in-hai-basin, viewed June 7, 2014.

[2] http://www.china.org.cn/china/2012-02/17/content_24664350.htm, viewed 9 June, 2014.

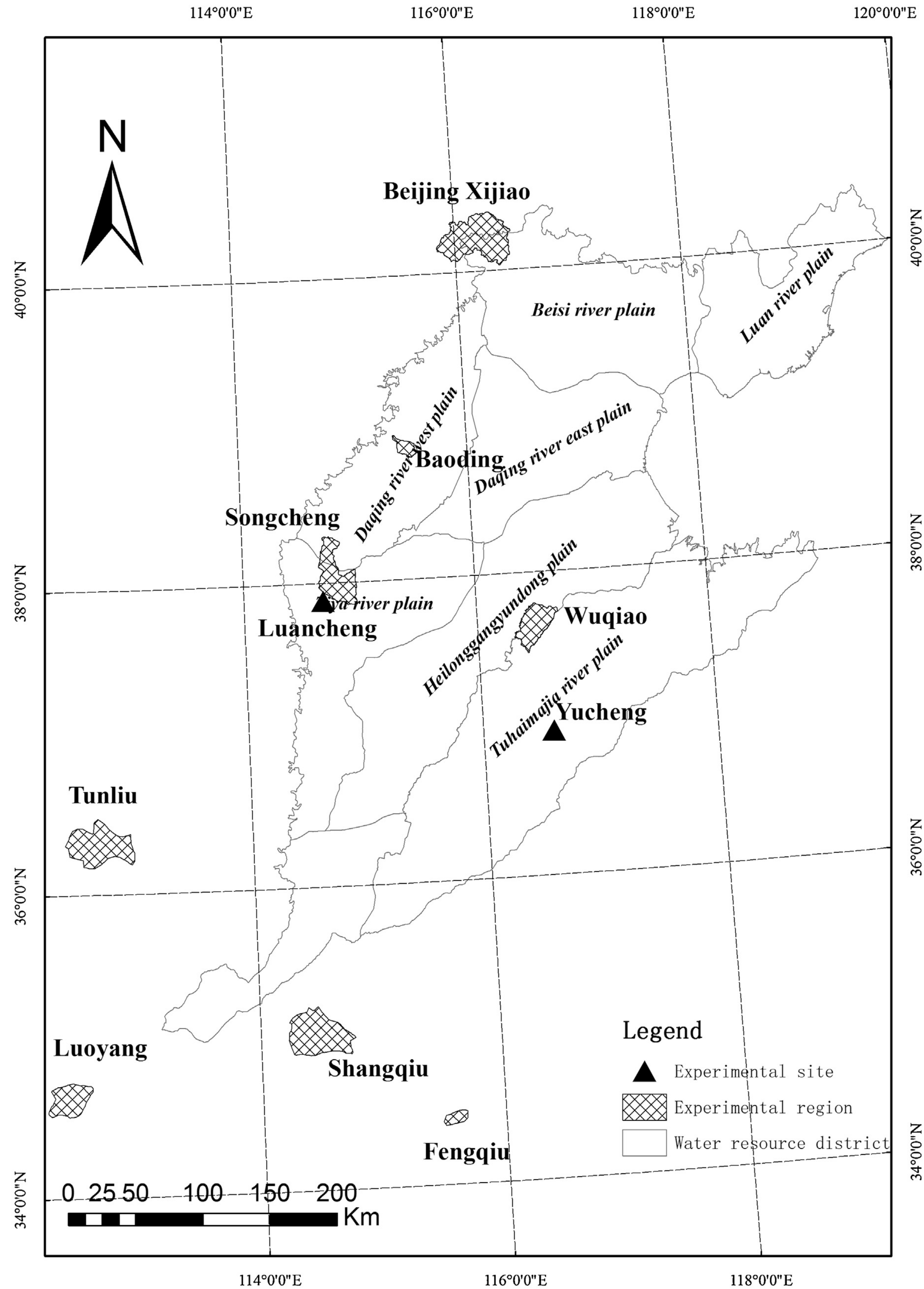

Fig. 1. Location of the study area (the plain of the Hai Basin), water resources districts and experimental sites.

Table 1
Water savings and production impacts of mulching.

Crop, reference	Location	Period	Change in water consumption		Change in production	
			mm	%	kg ha^{-1}	%
Winter wheat, straw mulch						
Zhou et al. (1996)	Fengqiu	1992–1995	−15	−4	728	18
Zhao et al. (1996)	Tunliu	1988–1989	−8	−2	689	17
Hu (1992)	Shangqiu	No report	−13	−3	764	20
Wang and Xu (1991)	Hebei	1987–1990	−14	−4	813	17
Maize, straw mulch						
Wang et al. (2001)	Luancheng	1992–1997	−14	−4	268	5
Cotton, plastic mulch						
Fan and Wang (2010)	Baoding	2006	−51	−13	148	11
Zhu and Wang (1996)	Beijing Xijiao	1999	−38	−8	286	35

interventions evaluated include mulching, tillage practices, deficit irrigation, revised cropping patterns, and improved cultivars.

Many of the reports are in Chinese. We include only research carried out in or adjacent to the Hai Basin, and only research that reports quantitative results in terms of both ET and production. For each category of intervention, we first summarise all available data, then indicate the intervention selected for basin-wide evaluation in the analysis.

2.3.1. Mulching

Straw mulching involves the use of wheat straw and corn stalks to cover fields and reduce non-productive evaporation (E) from the soil. It can be particularly effective for winter wheat during the long pre-emergence period. Although E is small during this time, the conservation of moisture improves conditions for seed germination, which in turn leads to vigorous early growth, further reducing evaporation as foliage shades the soil around the crop.

The reported results for straw mulching of wheat are quite consistent, reducing water consumption by about 3% while increasing yield by about 18% (Table 1). For maize, the corresponding figures are 4% reduction in water consumption and 5% increase in yield. These figures are used in the basin-wide analysis.

Plastic mulching involves the use of polyethylene plastic film, fully covering the soil during the early crop season. Due to high cost, plastic mulching technology is mostly applied to cash crops such as cotton. The technology increases the water use efficiency, but the mulch residue can be a problem for farmers (Xiao and Zhao, 2005). The reported impact of this technology (reducing water consumption by 8–13% while increasing yield by 11–35%) is substantially greater than the impact of mulch (Table 1). For the basin-wide analysis, we use the averages of these values (11% reduction in water consumption; 23% increase in yield).

2.3.2. Tillage

Soil tillage measures are designed to increase soil water retention and water storage capacity while reducing evaporation, thus saving water by changing the structure of the soil-air interface (Chen et al., 2006). Conservation tillage has been promoted in several countries since the 1980s to improve soil structure and control erosion. Impacts on yield, total ET and water productivity are complex. In particular the impact of tillage combined with other measures needs further study. The only study to report quantified impacts on ET and yield (Chen, 2005) found that tillage practices reduced yield by 20% while only reducing ET by 9%, such that water use efficiency was reduced. Soil tillage is not evaluated further at basin scale as a single intervention, though it is a component of combined interventions, reported below.

2.3.3. Regulated deficit irrigation

Regulated deficit irrigation imposes deliberate water stress during the crop season. Sometimes deficit periods are chosen according to a crop's genetic and physiological characteristics to limit vegetative growth with minimum impact of harvestable yield. In other cases a uniform restriction is applied throughout the season or a single irrigation is given in pre-season.

Since the yield of most field crops is reduced by water stress (Perry, 2011), the objective is to reduce water consumption by more than the reduction in yield, so that crop water productivity (kg m^{-3}) is increased. Table 2 summarises reported results for selected deficit irrigation experiments on wheat and maize.

With deficit irrigation, significant reductions in ET generally are accompanied by reductions in yield at approximately proportionate levels for many field crops (Fig. 2) (e.g., Howell, 1990; Steduto et al., 2007). Small reductions in ET, if carefully managed, can be achieved with no reduction in yield, or even with small increases if periods of stress are precisely timed. In our scenario analysis, we use the average values of the high deficit for wheat and maize (181 mm reduction in water consumption; 4.1 t ha^{-1} reduction in yield) and the medium deficit for wheat and maize (47 mm reduction in water consumption; 2.3 t ha^{-1} reduction in yield).

2.3.4. Cropping pattern adjustment

Wang (2006) reports that the cropping pattern changed substantially between 2001 and 2003 in the Heihe irrigation district. Cash crops with relatively low water consumption and high economic value increased, replacing relatively low-value maize which has higher water consumption. The reduction in water consumption as a result of such cropping pattern adjustment reached 95 Mm^3 (5%). However, the reason for these changes seems likely to have been an interest in increasing income, rather than saving water.

Other researchers have analysed the potential to reduce water consumption by replacing the main wheat–maize rotation (Table 3).

In the cases reported by Liu et al. (2008), the fall in production is proportionally about twice as much as the reduction in water consumption. Liu (2007) reports that the one-year crop system (wheat) reduced water consumption 53% for a 43% reduction in yield—a marginal increase in water use efficiency. We only used the values of the interventions (Table 3) for scenario analysis below when the implementation of other interventions that not resulting in the loss of production cannot make up the gap of overdraft water resources.

2.3.5. Combined interventions

Some interventions can be used in combination—for example, deficit irrigation plus mulching, so that the negative impacts of one intervention are offset, or at least reduced, by the other (Table 4).

Table 2
Water savings and production impacts of regulated deficit irrigation on wheat and maize.

Crop, reference	Location	Period	Change in water consumption		Change in production		Notes
			mm	%	kg ha^{-1}	%	
Winter wheat							
Sun et al. (2010)	Luancheng						Normal practice: irrigate to field capacity whenever soil moisture <65% of field capacity. High deficit: one irrigation prior to dormancy. Medium deficit: no irrigation during grain filling; otherwise Normal
a) High deficit		2003–2005	−121	−28	−735	−16	
b) Medium deficit			−1	0	0	0	
c) High deficit		1997–1999; 2001–2003;	−160	−37	−1561	−30	
d) Medium deficit		2005–2006	−20	−5	208	4	
e) High deficit		1999–2001	−189	−39	−2095	−42	
f) Medium deficit			−41	−10	−28	1	
Iqbal et al. (2014)	Luancheng						Normal practice: irrigate to field capacity when soil moisture <65% of field capacity. A: no irrigation during spring green-up stage, otherwise Normal B: no irrigation during stem-extension stage, otherwise Normal C: no irrigation applied during grain-filling stage, otherwise Normal D: only irrigated before the winter dormancy.
a) A		1999	−78	−17	−600	−2	
b) B			−62	−14	−600	−2	
c) C			−63	−14	−500	9	
d) D			−244	−54	−3300	−52	
e) A		2000	−39	−9	200	4	
f) B			−33	−8	0	0	
g) D			−198	−47	−1900	−35	
h) A		2001	−49	−11	−300	−6	
i) B			−47	−10	−400	−7	
j) C			−49	−11	−500	−9	
k) D			−175	−39	−2200	−40	
Fang et al. (2010b)	Yucheng						Normal practice: four irrigations during the growing season. High deficit: only irrigated at the planting; Medium deficit: no irrigation applied during grain-filling stage.
a) High deficit		2001–2003	−147	−39	−2355	−44	
b) Medium deficit			−41	−11	−495	−9	
Zhang et al. (2004)	Luancheng						
a)High deficit		1998–2001	−212	−47	−2250	−42	
b)Medium deficit			−55	−12	93	2	
Fang et al. (2010b)	Yucheng	2002–2003	−76	−22	−863	−16	Compares irrigation only at planting with irrigation at stem extension and flowering
Maize							
Sun et al. (2010)	Luancheng	1997–2005					Compares single irrigation after sowing to regular irrigation to field capacity.
a) Wet year		2004	−98	−20	−2399	−31	
b) Normal year		1999, 2002–2003, 2005	−84	−17	−1389	−17	
c) Dry year		1997–1998 2000–2001	−89	−20	−3124	−44	
Zhang et al. (2004)	Luancheng	1999–2001	−106	−28	−1295	−26	Compares no irrigation to three irrigations during season (three year average)

Table 3
Water savings and production impacts of replacing winter wheat–maize rotation.

Reference	Location	Period	Change in water consumption		Change in production		Replacement rotation
			mm	%	kg ha^{-1}	%	
Liu et al. (2008)	Wuqiao	2004–2006	−79	−12	−3327	−23	Winter wheat + summer maize + spring maize
			−179	−27	−6503	−45	Spring wheat only
Liu (2007)	Luoyang	1992–1999	−324	−53	−3176	−43	Winter wheat only

Table 4
Water savings and production impacts of combined interventions.

Reference	Location	Period	Change in water consumption		Change in production		Treatment, crop
			mm	%	kg ha^{-1}	%	
Chen et al. (2004)	Luancheng	1997–2001	−28	−9	380	19	Deficit irrigation + straw mulch (winter wheat)
Zhu and Wang (1996)	Beijing Xijiao	1986–1990	−25	−6	818	13	No-tillage + straw mulch (maize)
Liu et al. (2011)	Luancheng	2007–2009	−50	−10	81	1	Deficit irrigation + straw mulch + other[a] (winter wheat)
			−52	−15	−432	−7	Deficit irrigation + straw mulch + other[a] (maize)

[a] Other measures include reduced line spacing in wheat, more uniform plant spacing in maize, and adjusting the crop sowing or harvest period.

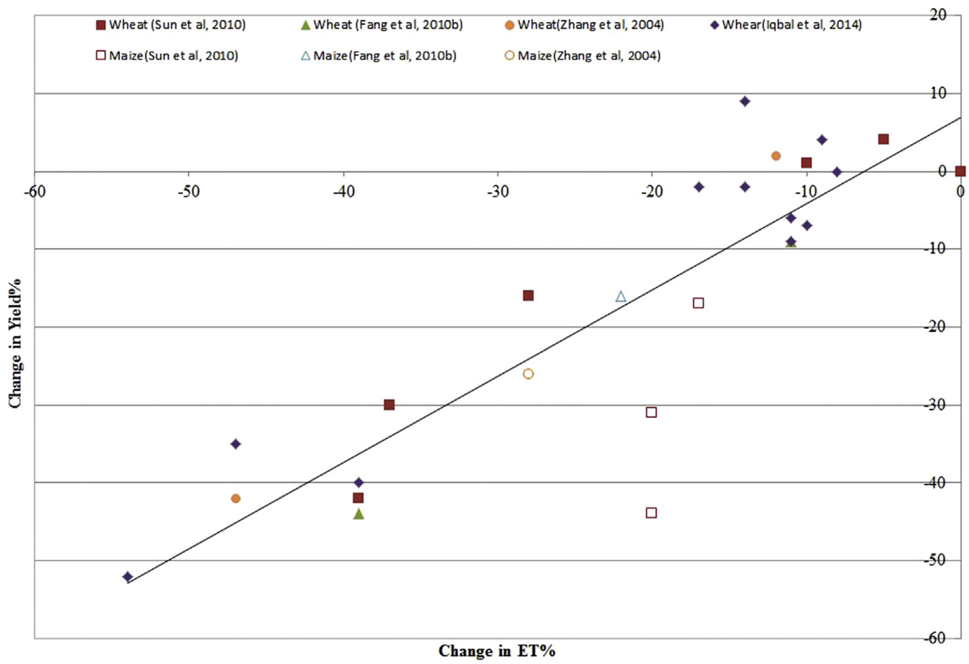

Fig. 2. Change in ET versus change in yield under deficit irrigation. Sun et al. (2010) analysed the effect of different regulated deficit irrigation (RDI) treatments on wheat and maize in Luancheng station for wet, normal, and dry years. Zhang et al. (2004) carried out the experiments on winter wheat during 1998–2001 and maize during 2000–2001 in Luancheng station, and reported that the ET and yield change for different RDI treatments. Fang et al. (2010b) reported the effect of different treatments on winter wheat and maize during 2001–2003 in Yucheng station. Iqbal et al. (2014) reported the ET and yield change for different RDI treatments in Luancheng station during 1999–2001.

For the basin-wide analysis of combined interventions, it is assumed that water savings are 9% while production increases by 19% in the case of wheat. The corresponding figures for maize are 6% and 13%.

2.3.6. *Improved varieties*

Improved varieties are often proposed as a way to increase production—either by increasing yield per hectare or yield per unit of ET. Shen et al. (2004) describe the yields of recently developed cultivars that have yet to be widely adopted, while Zhang et al. (2010) describe the potential yield of existing, widely adopted cultivars (Table 5). All reported results are based on research farm data.

Yan and Wu (2014) analysed crop water productivity for the Hai Basin, and found that the average was 1.1 kg m^{-3}, while the most productive farmers (top 5%) achieved 1.4 kg m^{-3}. As such, the reported experimental farm data are only marginally better than already achieved by the highest performing farmers and are not evaluated further at basin scale.

3. Analysis and results

To estimate potential savings at basin scale, the impacts reported in the most promising research studies are extrapolated to the relevant areas under wheat, maize and cotton (Table 6).

As background to each of the calculations, we repeat that current annual over-consumption of water in the Hai Basin is estimated at 6.25×10^9 m^3 while total water consumption (that is, from rainfall and irrigation) by wheat, maize and cotton is 12.2, 16.6, and 4.3×10^9 m^3 respectively (total 33.1×10^9 m^3). Average current annual production of these crops is 12.8, 28.6, and 1.4×10^6 t, respectively (Table 7).

Initially, two scenarios are evaluated: adoption of mulching, which results in significant gains in production with relatively small water savings, and the maximum water savings and production achievable by adoption of the combined interventions (Table 7).

The annual water savings from simple mulching would amount to 1.6×10^9 m^3 while substantially increasing production. Combined interventions perform considerably better, and including the saving on cotton (for which no combined interventions were identified) potential savings would offset 2.6×10^9 m^3 of the current 6.25×10^9 m^3 annual excessive consumption.

Two further scenarios are evaluated: (1) the extent to which ET can be reduced while maintaining current production levels of the major crops, and (2) the impact on production if average annual ET is reduced by the full 6.25×10^9 m^3 required to restore balance in the system.

A complication in both these calculations is the “natural” ET that will take place from the land that is fallowed when the irrigated area is reduced. The extent of the reduction in ET is computed as follows:

$$\Delta \mathrm{ET} = A_0 \times \mathrm{ET}_0 - \left[A_0 \times \frac{(100 - \Delta Y)}{100} \times \mathrm{ET}_0 \times \frac{(100 - \Delta \mathrm{ET})}{100} + A_0 \times \frac{\Delta Y}{100} \times \mathrm{ET}_{\mathrm{nat}} \right]$$

where ΔET is the change in ET as a result of the intervention; A_0 is the areas under the crop before the intervention; ET$_0$ is ET before the intervention; ΔY is the percentage increase in yield as a result of the intervention; and ET$_{\mathrm{nat}}$ is the ET from the fallowed area.

As an example, research results show that mulching increases wheat yield by 19%, allowing a proportionate reduction in cropped area while maintaining production at current levels. The new wheat area will thus be:

$$\frac{3,670,000 \times (100 - 19)}{100} = 2,972,700\ \mathrm{ha}$$

In addition, mulching reduces ET by 9% compared to the base case, so the new ET is:

$$\frac{2,972,700 \times 333 \times (100 - 9)}{100} \times 10^{-8} = 9.0 \times 10^9\ \mathrm{m}^3$$

Table 5
ET, yield and crop water productivity for winter wheat species.

Source	No.	Species name	Evapotranspiration (mm)	Yield ($kg\,ha^{-1}$)	Crop water productivity ($kg\,m^{-3}$)
Shen et al. (2004)	1	5135	512	7812	1.53
	2	5108	507	8209	1.62
	3	4158	475	8100	1.71
	4	Beijing 6	509	7221	1.42
	5	Short wheat	507	8156	1.61
	6	Lunkang6	496	7220	1.46
	7	Lunkang7	494	7070	1.43
		Average	**500**	**7684**	**1.54**
Zhang et al. (2010)	1	9905	374	6770	1.81
	2	Y361	383	6480	1.69
	3	KN208	391	5320	1.36
	4	KN213	355	5580	1.57
	5	DL2	370	5470	1.48
	6	5358	354	5660	1.60
	7	SX733	406	6650	1.64
	8	8901	390	5700	1.46
	9	6365	372	6250	1.68
	10	H6172	382	6040	1.58
	11	4185	372	6480	1.74
	12	L3279	358	5300	1.48
	13	6203	386	5130	1.33
	14	H3475	399	6540	1.64
	15	GY503	355	5860	1.65
	16	9204	417	5880	1.41
		Average	**379**	**5944**	**1.57**

Table 6
Interventions and impacts evaluated at basin scale.

Intervention	Crop	ET impact (%)	Yield impact (%)
Mulch	Wheat	−3	18
	Maize	−4	5
	Cotton	−11	23
Combination	Wheat	−9	19
	Maize	−6	13

The ET from the 19% of the land which is fallow is:

$$\frac{3{,}670{,}000 \times 19}{100} \times 145 \times 10^{-8} = 1.0 \times 10^9\,\mathrm{m}^3$$

The net saving in consumption compared to the current ET from wheat is thus:

$$12.2 - (9.0 + 1.0) \times 10^9\,\mathrm{m}^3 = 2.2 \times 10^9\,\mathrm{m}^3$$

Similar calculations for maize and cotton indicate savings of 1.3 and $0.7 \times 10^9\,\mathrm{m}^3$ respectively, so that the potential reduction in ET while maintaining current levels of production in these major crops is $4.1 \times 10^9\,\mathrm{m}^3$, or about two thirds of the average annual level of over-consumption ($6.25 \times 10^9\,\mathrm{m}^3$).

The residual gap of $2.15 \times 10^9\,\mathrm{m}^3$ can only be offset by additional fallowing of cropland or by deficit irrigation, either of which implies a reduction in grain production below current levels. Table 8 sets out the implications of these two approaches.

For example, if winter wheat is fallowed, the water saving is 188 mm ($1880\,\mathrm{m}^3\,\mathrm{ha}^{-1}$), calculated by the difference between the actual ET (333 mm) and nature ET (145 mm) for winter wheat. In order to reduce water consumption by $2.15 \times 10^9\,\mathrm{m}^3$ the reduction in area under wheat would be:

$$\frac{2.15 \times 10^9}{1880} = 1,143,617\,\mathrm{ha}$$

The associated reduction in production would be:

$$1{,}143{,}617 \times 3.5 \times 10^6 = 4.0\,\mathrm{Mt}$$

For some interventions, the area of implementation required exceeds the current cropped area, so that the intervention is not a feasible way to restore a sustainable water balance.

4. Discussion

We have reviewed published research reporting the impact on yield and water consumption of improved on-farm crop management practices for the major crops in the Hai Basin. Projecting the most promising research results to basin-scale, we estimate the potential of such interventions to contribute to closing the gap between current water consumption and the sustainable level of

Table 7
Impacts of straw mulching and combined interventions on production and ET at basin level.

Interventions	Crop	Area (ha)	Impact (%)		Current ET		Current yield ($t\,ha^{-1}$)	Current production (Mt)	Reduction in ET ($10^9\,m^3$)	Increase in Production (10^6 t)
			ET	Yield	mm	$10^9\,m^3$				
Straw mulch	Winter wheat	3,670,000	−3	18	333	12.2	3.5	12.8	0.4	2.3
	Maize	5,220,000	−4	5	319	16.6	5.5	28.6	0.7	1.4
	Cotton	730,000	−11	23	585	4.3	1.9	1.4	0.5	0.3
Total						**33.1**			**1.6**	
Combination	Winter wheat	3,670,000	−9	19	333	12.2	3.5	12.8	1.1	2.4
	Maize	5,220,000	−6	13	319	16.6	5.5	28.6	1.0	3.7
	Cotton	730,000	−11	23	585	4.3	1.9	1.4	0.5	0.3
Total						**33.1**			**2.6**	

Table 8
Scenario analysis for the water deficit and impacts on production.

Intervention	Change in ET (mm)	Area required (ha)	Current area (ha)	Feasible	Change in yield ($t\,ha^{-1}$)	Impact on production (Mt)	Note/source
High deficit for wheat and maize	−181	1,189,488	1,920,000	Yes	−4.1	−4.9	Average values for high deficit (Table 2)
Medium deficit for wheat and maize	−47	4,602,446	1,920,000	No	−2.3		Average values for medium deficit (Table 2)
Winter wheat fallow	−188	1,143,617	3,670,000	Yes	−3.5	−4.0	Wang (2013) and Table 7
Winter wheat and maize fallow	−248	867,796	1,920,000	Yes	−9.0	−7.8	Wang (2013) and Table 7
Winter wheat–maize rotation replaced by winter wheat–summer maize–spring maize	−79	2,721,519	1,920,000	No	−3.3		Table 3
Winter wheat–maize rotation replaced by spring wheat	−179	1,201,117	1,920,000	Yes	−6.5	−7.8	Table 3

consumption that would stabilise aquifers and contribute to healthier river systems.

The analysis is optimistic in assuming that research results can be replicated in the conditions on farmers' fields. The farmer is managing a variety of scarce inputs (labour, management time, finance, draft power, etc.) that are often given fixed amounts for kinds of experiments. Research results report only physical outcomes, and do not evaluate associated costs that will reduce the benefits of adopting the new techniques.

Furthermore, some research recommendations have already been adopted to some degree: mulching with retained stubble has risen from about 10% of the area in the 1980s to about 55% in 2004; use of plastic sheeting on cotton has expanded from about 5% in the 1980s to about 58% in 2004 (Blanke et al., 2007). No estimates exist of the precise nature, impact or distribution of these activities. Thus, they could not be evaluated. Existing levels of adoption reduce the potential incremental benefits estimated here.

Our analysis also does not capture dynamic responses to restrictions on water supply. Price changes are likely if production is significantly reduced by water shortages, thus increasing farm-level incentives to intensify crop husbandry. In addition, farmers are likely to innovate in unpredictable ways, as they strive to maintain income and production levels.

Despite these significant gaps, our analysis provides helpful insight regarding potential water savings.

First, it is unlikely that production of staple crops in the Hai Basin, and the North China Plain more generally, can be maintained while respecting the government's policy decision to protect and restore the environment. The available techniques to save water while maintaining production fall well short of the required water savings—at best closing the gap by about two thirds.

Second, as shown in Table 7, the water savings that can be anticipated on a purely "voluntary" basis amount to only about a quarter of the deficit: mulching alone significantly increases yield, but does not save much water because the effect of mulching is to reduce non-productive evaporation and increase productive transpiration. Only when combined with "other interventions" does mulching both increase production and save significant quantities of water. While access to water remains relatively open, the farmer will be much quicker to adopt production-enhancing measures than those that save water but require additional effort and costly inputs.

This logic points to the role of restricting water supplies, or setting quotas, to change the incentive structure. Faced with a progressively more limited water supply, the farmers' priorities will progressively move from techniques that enhance production with minor water savings, towards techniques that substantially reduce water consumption while maintaining production, and finally to a cropping pattern that achieves maximum production within the constraint of limited water supplies.

5. Conclusions

Water consumption in the Hai Basin has been estimated to exceed the sustainable average renewable supply by $6.25 \times 10^9\,m^3\,yr^{-1}$, or about 20% of current irrigation water consumption. Continued economic development in the basin, stabilisation of the aquifer, and restoration of environmental flows in the river, in accordance with government policy will have significant implications on water availability for irrigation.

The historic focus on engineering investments has not achieved anticipated water savings. Indeed the available evidence suggests that very little water is saved by canal lining, piped distribution systems, or implementing higher technology irrigation at the farm level.

In recent decades, more than 3000 research studies in China have addressed the topic of reducing water use and increasing yields of the major crops through on-farm management measures. Projections of the most promising research to basin scale for the major crops indicates that mulching—which significantly enhances yield, and thus is likely to be most attractive to farmers—would contribute only about 25% ($1.6 \times 10^9\,m^3\,yr^{-1}$) towards the annual savings required.

Further savings require additional measures, including the combination of deficit irrigation with mulching, closer plant spacing, and adjusting the crop sowing or harvest period. Adoption of these most effective practices would contribute about two thirds ($4.1 \times 10^9\,m^3\,yr^{-1}$) of the required savings while maintaining current levels of production. Further water savings to fully eliminate the over-consumption will require reducing grain production by as much as 4–7.8 $Mt\,yr^{-1}$.

Farm-level water quotas would encourage farmers to choose cropping practices that maximise production within sustainable levels of water consumption, consistent with the government's objective of increasing the quantity of water available to the environment.

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