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RESEARCH ARTICLE

The effect of different agricultural management practices on irrigation efficiency, water use efficiency and green and blue water footprint

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Abstract This paper explores the effect of varying agricultural management practices on different water efficiency indicators: irrigation efficiency (IE), crop water use efficiency (WUE), and green and blue water footprint (WF). We take winter wheat in an experimental field in Northern China as a case study and consider a dry, average and wet year. We conducted 24 modeling experiments with the AquaCrop model, for all possible combinations of four irrigation techniques, two irrigation strategies and three mulching methods. Results show that deficit irrigation most effectively improved blue water use, by increasing IE (by 5%) and reducing blue WF (by 38%), however with an average 9% yield reduction. Organic or synthetic mulching practices improved WUE (by 4% and 10%, respectively) and reduced blue WF (by 8% and 17%, respectively), with the same yield level. Drip and subsurface drip irrigation improved IE and WUE, but drip irrigation had a relatively large blue WF. Improvements in one water efficiency indicator may cause a decline in another. In particular, WUE can be improved by more irrigation at the cost of the blue WF. Furthermore, increasing IE, for instance by installing drip irrigation, does not necessarily reduce the blue WF.

Keywords field management, irrigation efficiency, water footprint, water productivity, water use efficiency

1 Introduction

Irrigation water, supplied to crop fields by diverting river water or pumping groundwater, helps to increase crop yields when limited precipitation would otherwise hamper crop growth. About 18% of global arable land is irrigated, 70% of global gross blue water abstractions and 92% of net blue water abstractions relate to irrigation and 40% of global crop production comes from irrigated lands[1,2]. Given population growth and socioeconomic developments, global food demand is increasing while irrigated agriculture in many places, especially in arid and semi-arid areas, faces limited availability of water and intensified competition with other water-demanding sectors[3]. Farmers and water managers as well as researchers have been pursuing the goal of achieving more "crop per drop." There have been two main directions toward this goal: increasing crop yield, and reducing non-beneficial water consumption (i.e., soil evaporation). The most widely implemented approach has been to boost crop yields by adding fertilizers and pesticides and expanding irrigated agriculture, which has led to widespread water pollution and pressure on limited freshwater resources. The focus has been on water supply rather than water demand management[4].

There are multiple water efficiency indicators, the most common ones being irrigation efficiency (IE), water use efficiency (WUE), which is alternatively called water productivity (WP), and water footprint (WF). IE measures the percentage of irrigation water used that will finally benefit the crop[5]. WUE measures the amount of crop produced per volume of water consumed over the cropping period (in $t \cdot m^{-3}$). WF measures water use per unit of time and is often expressed per unit of production (thus being expressed in $m^3 \cdot t^{-1}$). Whereas IE focuses on measuring the efficient use of blue water (the irrigation water abstracted from fresh surface water or groundwater sources), WUE and WF consider the efficient use of green water as well (rainwater stored in the soil). WUE considers the ratio of crop production to the sum of green and blue water lost to the atmosphere, while WF shows the inverse: blue and green water lost to the atmosphere per unit of crop production[6]. WUE takes green and blue water consumption

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together and is thus one number, while WF can be shown per water type: the green WF shows the green water consumption per unit of crop and the blue WF shows the blue water consumption per unit of crop. The sum of the two is referred to as the consumptive WF. There is a third component in a WF, which refers to water pollution per unit of crop, called the gray WF, but this component will be left out of further consideration in this paper since we will focus on water use, not pollution. The indicators differ in what they consider a loss. The IE indicator is based on the engineering perspective, whereby any irrigation water supplied but not taken up by the plant is considered a loss (because it is not used beneficially). The WUE and WF indicators consider all evapotranspiration (ET) as a loss, whether it is beneficial (transpiration, T) or non-beneficial (soil evaporation, E) and whether it is irrigation water that evaporated or transpired (blue ET) or rainwater (green ET), because this is water lost from the catchment, no longer available for another use[7]. Drainage is not considered as a water loss from the catchment point of view and therefore not counted as water use in the WUE and WF metrics, while it is regarded as a loss in the IE metric. The blue WF and IE both focus on efficiency of blue water use, but the difference is that the blue WF measures ET while IE measures T and that blue WF considers water use (ET) in relation to crop production, while IE measures water use (T) in relation to blue water supply.

Most analyses employ one specific efficiency indicator without considering the implications of the choice made. Improving IE has been the most common approach by engineers to save water, but a higher IE can lead farmers to purchase more irrigation water, resulting in an increase in consumptive water use[7]. Since the beginning of this century, there is increasing focus on achieving “more crop per drop,” which means increasing water productivity or water use efficiency. Irrigation is a common way to increase WUE, while this obviously results in a significant blue WF of a crop and, if done at a significant scale, a large overall blue WF in a region[8]. A focus on improving one of the efficiency indicators can easily result in a negative impact on one of the other indicators. A relevant question is whether a certain agricultural management practice that is relatively efficient based on one indicator is also efficient when considering other indicators. The current study explores the effect of various agricultural management practices on different efficiency indicators: IE, crop WUE, and green and blue WF. We analyzed in particular the effect of different irrigation techniques, different irrigation strategies (regarding how much irrigation water is applied) and different mulching methods. We took irrigated winter wheat grown in an experimental field in Northern China as a case study and conducted modeling experiments with AquaCrop, a soil water balance and crop growth model developed and maintained by the Food and Agriculture Organization[9–11]. AquaCrop simulates the water balance of the root zone over the cropping period and biomass growth based on water limitations. The model has been developed so as to obtain a reasonable balance between model complexity and number of parameters on the one hand and model accuracy and robustness on the other hand[10]. The model has been widely used and calibrated to simulate crop water use and yield for a number of crops under diverse environments and types of water management[12–18].

2 Methods and data

2.1 Modeling the soil water balance and crop growth

We chose irrigated winter wheat planted in the location of Xiaotangshan experimental site (44.17° N, 116.433° E) in Beijing, Northern China for the study case. The AquaCrop model was used to simulate the soil water balance and crop growth and to calculate irrigation efficiency, water use efficiency and green and blue water footprints at field level under different management practices in a number of modeling experiments. The experiments were conducted for three planting years with different levels of precipitation over the cropping period: 2004 (a dry year), 2006 (an average year) and 2007 (a wet year). The crop parameters (Table 1) and soil characteristics (Table 2) for the case study have been calibrated and validated by Jin et al.[13] for the AquaCrop model based on local measurements. With the calibrated input parameters, AquaCrop simulates yield rather well, with an R^2 value of 0.93 and root mean square error of less than 10% of measured yield[13].

Table 1 Crop parameters of winter wheat at Xiaotangshan experimental site[13]

Description	Value
Crop planting date	7th October
Crop growing period	270 d
Time from sowing to emergence	7 d
Time from sowing to flowering	232 d
Time from sowing to start senescence	236 d
Maximum effective root depth	1.2 m
Minimum effective root depth	0.3 m
Reference harvest index (HI_0)	46%
Crop coefficient	1.1

2.2 Modeling water efficiency indicators

Irrigation efficiency has been defined in several ways. Generally, a distinction is made between conveyance and distribution efficiency (the ratio of the water volume reaching the field to the water volume abstracted from its source) and field application efficiency (the ratio of the irrigation water volume benefiting the crop and the water

Table 2 Soil characteristics at Xiaotangshan experimental site[13]

Depth/m	Soil water content/%			K_{sat}/(mm·d^{-1})
	Field capacity	Saturation	Wilting point	
0.0–0.1	27.3	51.1	8.8	240
0.1–0.2	27.3	51.3	8.7	240
0.2–0.3	34.8	54.7	13.2	224

volume applied to the field)[19,20]. In this study, we focus on the field application efficiency. At field level, irrigation efficiency (IE, %) is equal to the ratio of blue water transpiration (T_b, mm) to the applied irrigation water (IRR, mm) over the cropping period[5,121]:

$$\mathrm{IE} = \frac{\mathrm{T_b}}{\mathrm{IRR}} \tag{1}$$

The blue water transpiration of a crop needs to be distinguished from the overall transpiration of a crop. The water taken up and transpired by an irrigated crop partly originates from rainwater (green water) and partly from irrigation water (blue water). The blue component of total crop transpiration has been estimated before by taking the crop water requirement minus the effective precipitation[19]. This works under full irrigation, when the crop water requirement is fully met, and under the assumption that the water not available through rainwater (the effective precipitation) must have been met by irrigation water. The approach does not work under deficit irrigation and faces the problem of how to define effective precipitation. Here, we make a more accurate estimate of blue water transpiration by keeping track, from day to day, of the green to blue water ratio in the soil moisture, so that for all outflows from the soil we know the green to blue water ratio as well.

Following Zhuo et al.[22] and Chukalla et al.[23], the green and blue components of (non-beneficial) evaporation (E) and (beneficial) transpiration (T) are estimated by drawing daily green and blue soil water balances at the boundaries of the root zone as simulated by AquaCrop:

$$\begin{aligned}\mathrm{S}_{\mathrm{g}[t]} = {} & \mathrm{S}_{\mathrm{g}[t-1]} + (\mathrm{PR}_{[t]} + \mathrm{IRR}_{[t]} - \mathrm{RO}_{[t]}) \\ & \times \frac{\mathrm{PR}_{[t]}}{\mathrm{PR}_{[t]} + \mathrm{IRR}_{[t]}} - (\mathrm{DP}_{[t]} + \mathrm{E}_{[t]} + \mathrm{T}_{[t]}) \\ & \times \frac{\mathrm{S}_{\mathrm{g}[t-1]}}{\mathrm{S}_{[t-1]}}\end{aligned} \tag{2}$$

$$\begin{aligned}\mathrm{S}_{\mathrm{b}[t]} = {} & \mathrm{S}_{\mathrm{b}[t-1]} + (\mathrm{PR}_{[t]} + \mathrm{IRR}_{[t]} - \mathrm{RO}_{[t]}) \\ & \times \frac{\mathrm{PR}_{[t]}}{\mathrm{PR}_{[t]} + \mathrm{IRR}_{[t]}} - (\mathrm{DP}_{[t]} + E_{[t]} + T_{[t]}) \\ & \times \frac{\mathrm{S}_{\mathrm{b}[t-1]}}{\mathrm{S}_{[t-1]}}\end{aligned} \tag{3}$$

where $S_{g[t]}$ and $S_{b[t]}$ (mm) refer to the green and blue soil water content at the end of day *t*, respectively, and where $PR_{[t]}$ (mm) is the precipitation on day *t*, $IRR_{[t]}$ (mm) the irrigation water applied, $CR_{[t]}$ (mm) the capillary rise from groundwater, $E_{[t]}$ (mm) the evapotranspiration from the field (excluding crop transpiration), $T_{[t]}$ (mm) the crop transpiration (mm), $RO_{[t]}$ (mm) the daily surface runoff and $DP_{[t]}$ (mm) the deep percolation. The initial soil water moisture at the start of the growing period is assumed to be green water. The contribution of precipitation (green water) and irrigation (blue water) to surface runoff is calculated based on the respective magnitudes of precipitation and irrigation to the total green plus blue water inflow. The green and blue components in DP, E and T are calculated per day based on the fractions of green and blue water in the total soil water content at the end of the previous day.

Water use efficiency (WUE, t·m^{-3}) is calculated as crop yield (Y, t·hm^{-2}) divided by total evapotranspiration (ET, m^3·hm^{-2}) over the cropping period:

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{ET}} \tag{4}$$

The consumptive WF per unit of a crop (in m^3·t^{-1}) is equal to the reciprocal of the WUE. The green WF (WF_g) or blue WF (WF_b) per unit of a crop (m^3·t^{-1}) is calculated by dividing the green or blue ET over the growing period by the crop yield (Y, t·hm^{-2})[6]:

$$\mathrm{WF_g} = \frac{\mathrm{ET_g}}{\mathrm{Y}} \tag{5}$$

$$\mathrm{WF_b} = \frac{\mathrm{ET_b}}{\mathrm{Y}} \tag{6}$$

Total ET follows from the water balance in the AquaCrop model; the partitioning into green and blue ET is done based on green to blue water ratio in the soil moisture as described above.

2.3 Design of modeling experiments

For each year, we conducted 24 simulations by combining four different irrigation techniques (furrow, sprinkler, drip and subsurface drip irrigation) with two irrigation strategies (full and deficit irrigation) and three mulching methods (no mulching, organic mulching and synthetic mulching) (Table 3), following a similar approach to that of

Chukalla et al.[23].

Irrigation techniques differ in the way irrigation water is applied to the field, in terms of wetted areas, and in the total amount of irrigation water to be applied to achieve optimal water conditions in the soil[23,24]. We used default AquaCrop settings for irrigation techniques: furrow irrigation with 80% surface wetting, sprinkler irrigation with 100% wetting, drip irrigation with 30% wetting, and subsurface drip irrigation with 0% surface wetting.

With full irrigation, fully satisfying ET requirements over the growing period, AquaCrop can automatically generate the irrigation schedule. As a criterion for irrigation we assume that 80% of the readily available soil water is to be depleted before irrigation is applied[25]. According to Chukalla et al.[23], deficit irrigation strategies can be divided into two categories: (1) regulated deficit irrigation with non-uniform water deficit levels during the different phenological stages, and (2) sustained deficit irrigation with uniform water deficit over the cropping period. In our deficit irrigation simulations, we applied sustained deficit irrigation that uniformly applies 50% of the full irrigation levels. In the deficit irrigation strategy, we keep the same irrigation intervals as in the full irrigation strategy, but take the irrigation volume in every irrigation event at 50% of full irrigation volume.

Mulching of fields is a widely-used measure aimed at reducing soil evaporation. In AquaCrop, the fraction of the soil surface covered and the reduction in soil evaporation need to be specified for different types of mulching. Organic mulches may consist of unincorporated plant residues that cannot totally cover the soil surface, while synthetic (plastic) mulches substantially reduce the soil surface evaporation with a high degree of coverage[26]. We used the settings for mulches as applied by Chukalla et al.[23]: organic mulching with 80% of the soil covered and 50% soil evaporation reduction, and synthetic mulching with 100% of the soil covered and 80% soil evaporation reduction.

2.4 Data sources

Climate data inputs on monthly precipitation, ET_0 and temperature for the years considered at Xiaotangshan experimental site were obtained from CRU-TS-3.10.01[27]. Monthly values for precipitation, ET_0 and temperature are downscaled to daily values in AquaCrop through the interpolation procedure presented by Gommes[28] based on weight of ET_0 rates and temperature in the previous month[26]. The values of crop parameters and data on soil type and hydraulic characteristics were taken as reported by Jin et al.[13].

3 Results

3.1 Y, T and ET under different management practices

Table 4 lists the simulated crop yield (Y) of winter wheat under different agricultural management practices at Xiaotangshan experimental site. Y was more sensitive to different irrigation strategies than to different irrigation techniques or mulching methods. Under full irrigation, thus without water stress, yields were 4.8, 4.6 and 5.1 $t \cdot hm^{-2}$ for the years 2004, 2006 and 2007, respectively, irrespective of the mulching practice. The relatively high yield in the wet year 2007 was due to a slightly higher biomass water productivity (the factor WP* in the AquaCrop model) in that year and a slightly higher ratio of T to ET_0. The yield in the dry year 2004 was a bit higher than in the average year 2006 as a result of the higher ratio of T to ET_0 mainly in the “canopy development stage” of the cropping period. With deficit irrigation, yields were lower by 11%, 10% and 6% respectively for the three years, and 9% lower as an average for the three years. Yields hardly vary across different irrigation techniques (simulated Y being 1% higher on average for subsurface drip compared to furrow irrigation) or across different mulching methods (simulated Y being 1% higher on average for synthetic compared to no mulching).

The simulated crop transpiration (T) and overall evapotranspiration (ET) from the field over the cropping period of winter wheat under different management practices at Xiaotangshan site are shown in Table 5. Both T and ET responded most strongly when changing from full to deficit irrigation. With 50% less irrigation input under deficit as compared to full irrigation, T was on average 10.5% lower and ET 9.4% lower. The reduced T goes together with the reduction in Y. Different mulching practices hardly affected T, but from no mulching to organic mulching reduces ET by 4%, on average, and from none to synthetic mulching reduces ET by 8%. The reductions in ET were slightly larger under full irrigation than under deficit irrigation. Different irrigation techniques had little effect on T or ET, although subsurface drip

Table 3 Management practices considered in the modeling experiments

Irrigation technique	Irrigation strategy	Mulching practice
Furrow irrigation	Full irrigation	No mulching
Sprinkler irrigation	Sustained deficit irrigation at 50% of full irrigation levels	Organic mulching
Drip irrigation		Synthetic mulching
Subsurface drip irrigation		

Table 4 Simulated yield of winter wheat (t·hm^{-2}) under different management practices at Xiaotangshan experimental site

Irrigation strategy	Mulching practice	Year	Furrow irrigation	Sprinkler irrigation	Drip irrigation	Subsurface drip irrigation
Full irrigation	No mulching	Dry 2004	4.78	4.78	4.78	4.78
		Avg. 2006	4.60	4.60	4.60	4.60
		Wet 2007	5.09	5.09	5.10	5.10
	Organic mulching	Dry 2004	4.78	4.78	4.78	4.78
		Avg. 2006	4.60	4.60	4.60	4.60
		Wet 2007	5.10	5.10	5.10	5.10
	Synthetic mulching	Dry 2004	4.78	4.78	4.78	4.78
		Avg. 2006	4.61	4.61	4.60	4.60
		Wet 2007	5.10	5.10	5.10	5.10
Deficit irrigation	No mulching	Dry 2004	4.14	4.15	4.31	4.36
		Avg.2006	4.08	4.06	3.97	4.18
		Wet 2007	4.72	4.68	4.79	4.83
	Organic mulching	Dry 2004	4.15	4.15	4.32	4.32
		Avg. 2006	4.07	4.07	4.16	4.16
		Wet 2007	4.85	4.84	4.77	4.87
	Synthetic mulching	Dry 2004	4.03	4.23	4.33	4.35
		Avg. 2006	4.16	4.16	4.23	4.12
		Wet 2007	4.85	4.85	4.81	4.86

Note: Avg., average.

Table 5 Simulated ET (mm) and T (mm) of growing winter wheat under different management practices at Xiaotangshan experimental site. The T values are shown between brackets

Irrigation strategy	Mulching practice	Year	Furrow irrigation	Sprinkler irrigation	Drip irrigation	Subsurface drip irrigation
Full irrigation	No mulching	Dry 2004	500 (425)	501 (425)	485 (426)	478 (426)
		Avg. 2006	505 (415)	509 (415)	483 (416)	466 (416)
		Wet 2007	467 (391)	473 (391)	455 (392)	438 (392)
	Organic mulching	Dry 2004	481 (425)	481 (425)	474 (426)	451 (426)
		Avg. 2006	478 (415)	478 (415)	474 (416)	458 (416)
		Wet 2007	449 (391)	450 (391)	440 (392)	422 (392)
	Synthetic mulching	Dry 2004	451 (425)	451 (425)	453 (426)	437 (426)
		Avg. 2006	443 (415)	444 (415)	444 (416)	437 (416)
		Wet 2007	418 (391)	418 (391)	419 (392)	402 (392)
Deficit irrigation	No mulching	Dry 2004	434 (357)	437 (357)	437 (384)	425 (392)
		Avg. 2006	444 (353)	447 (352)	434 (365)	427 (380)
		Wet 2007	425 (345)	429 (346)	427 (369)	414 (373)
	Organic mulching	Dry 2004	415 (358)	415 (357)	427 (384)	415 (392)
		Avg. 2006	421 (358)	421 (352)	432 (365)	412 (371)
		Wet 2007	425 (345)	409 (346)	413 (369)	403 (373)
	Synthetic mulching	Dry 2004	415 (383)	392 (366)	411 (385)	399 (388)
		Avg. 2006	400 (372)	401 (372)	412 (386)	399 (378)
		Wet 2007	384 (358)	384 (358)	397 (371)	385 (375)

Note: Avg., average.

irrigation slightly increased T while lowering overall ET. With subsurface drip irrigation, T was on average 3% higher than with furrow or sprinkler and 0.6% higher than with regular drip irrigation. Overall ET, on the other hand, was on average 4% lower than with furrow or sprinkler and 3% lower than with regular drip irrigation. Considered over all simulations, T accounted for between 79% and 98% of ET. The highest ratios were found for the combination of subsurface drip irrigation and synthetic mulching. The T/ET ratio reduced from subsurface drip irrigation (93% on average) to drip irrigation (90%) and sprinkler and furrow irrigation (87%). The T/ET ratio also reduced from synthetic mulching (94% on average) to organic mulching (88%) to no mulching (85%).

3.2 IE under different management practices

Table 6 provides simulation results for irrigation efficiency (IE) at field level for growing winter wheat under different agricultural management practices. IE under deficit irrigation was higher than under full irrigation, by 8% for furrow and sprinkler irrigation, by 18% for drip and subsurface drip irrigation, and by 13% on average. In most cases, IE with drip and subsurface drip irrigation was higher than with furrow and sprinkler irrigation, but the differences are small. On average, IE increased from 39% for sprinkler and furrow irrigation to 41% for drip irrigation and 42% for subsurface drip irrigation. The mulching practice did not influence IE in any specific direction. In the modeling experiments, the lowest IE was found for the combination of full irrigation using furrow or sprinkler irrigation without mulching. The highest IE was recorded for deficit irrigation using subsurface drip or drip irrigation; the mulching practice made little difference.

3.3 WUE under different management practices

The simulated WUE values for winter wheat under a variety of agricultural management practices are presented in Table 7. WUE, defined as Y/ET, changed little when moving from full to deficit irrigation, since Y and ET decreased with similar rates (Table 4; Table 5). In most cases, WUE was slightly higher with drip and subsurface drip irrigation than with furrow and sprinkler irrigation, but the differences were small: WUE for drip irrigation was on average 1% higher than for furrow or sprinkler irrigation, and WUE for subsurface drip irrigation was on average 5% higher than for furrow or sprinkler irrigation. On average, WUE with organic and synthetic mulching was 4% and 10% higher, respectively, than with no mulching. The lowest WUE (averaging 0.98 $\text{kg}\cdot\text{m}^{-3}$ over the three years) was recorded for full or deficit irrigation with sprinkler irrigation and no mulching, and only slightly higher (averaging 0.99 $\text{kg}\cdot\text{m}^{-3}$) for the case of furrow irrigation. The highest WUE (averaging 1.13 $\text{kg}\cdot\text{m}^{-3}$ over the three years) was found for the condition of full or deficit irrigation with subsurface drip irrigation and synthetic mulching.

Table 6 Simulated irrigation efficiency (IE) of growing winter wheat under different management practices at Xiaotangshan experimental site

Irrigation strategy	Mulching practice	Year	Furrow irrigation	Sprinkler irrigation	Drip irrigation	Subsurface drip irrigation
Full irrigation	No mulching	Dry 2004	36%	37%	40%	39%
		Avg. 2006	33%	33%	35%	37%
		Wet 2007	38%	38%	38%	39%
	Organic mulching	Dry 2004	35%	35%	39%	39%
		Avg. 2006	41%	41%	35%	36%
		Wet 2007	37%	37%	37%	39%
	Synthetic mulching	Dry 2004	44%	43%	41%	41%
		Avg. 2006	38%	38%	37%	36%
		Wet 2007	34%	34%	38%	38%
Deficit irrigation	No mulching	Dry 2004	39%	38%	46%	47%
		Avg. 2006	35%	35%	44%	42%
		Wet 2007	42%	43%	46%	48%
	Organic mulching	Dry 2004	37%	37%	45%	47%
		Avg. 2006	43%	41%	41%	41%
		Wet 2007	42%	41%	44%	47%
	Synthetic mulching	Dry 2004	47%	46%	47%	47%
		Avg. 2006	41%	41%	42%	43%
		Wet 2007	38%	38%	46%	45%

Note: Avg., average.

3.4 Green and blue WF under different management practices

Consumptive WF is the inverse of WUE. Additional insight, however, is obtained when we look at how each of the two components of the consumptive WF, i.e., the green and blue WF, responds to varying agricultural management practices (Table 8; Table 9). When moving from full to deficit irrigation, we observed little changes in overall consumptive WF (no change on average), because ET and Y showed similar rates of reduction, but the blue WF decreased by 38% on average and the green WF increased by 19% on average. The ratio of blue to total (green plus blue) water supply strongly decreased because from full to deficit irrigation the volume of irrigation was halved. From furrow or sprinkler to drip irrigation, the overall consumptive WF decreased by 1% on average, and to subsurface drip irrigation it decreased by 5% on average. Drip irrigation had a relatively large blue WF compared to the other three irrigation techniques, 10% larger than furrow irrigation, due to the relatively large blue ET. This was caused by the higher irrigation frequency in the case of drip irrigation, so that the accumulative contribution of daily irrigation to form blue ET in total ET was relatively high. By lowering ET, organic and synthetic mulching reduced the green WF by 3% and 6%, respectively, compared to no mulching, and the blue WF by 8% and 17%, respectively. Considering all results, the largest blue WF values were found in combinations with full irrigation without mulching, and the smallest values in combinations with both deficit and synthetic mulching.

The ratio of blue to total consumptive WF increased from 21% on average for deficit irrigation (lowest values for synthetic or organic mulching) to 34% on average for full irrigation (with largest values for subsurface drip and drip irrigation). The blue WF fractions were the largest in the relatively dry year 2004.

4 Discussion and conclusions

The study showed for one specific crop and location for three different hydrological years how IE, WUE and green and blue WF responded differently to 24 different agricultural management practices, considering four irrigation techniques, two irrigation strategies and three mulching methods. When we altered the irrigation strategy from full to deficit irrigation, IE increased by 5% on average and the blue WF decreases by 38% on average, while WUE and overall consumptive WF remained more or less equal because ET and Y declined at similar rates. Mulching practices did not greatly affect IE, but WUE, and green and blue WF all improved moving from no mulching to organic mulching and further to synthetic mulching. IE, WUE and consumptive WF all improved from sprinkler and furrow to drip and subsurface drip irrigation, but drip irrigation had the largest blue WF. These findings for the response of the green and blue WF of winter wheat to

Table 7 Simulated water use efficiency (WUE, kg·m^{-3}) of growing winter wheat under different management practices at Xiaotangshan experimental site

Irrigation strategy	Mulching practice	Year	Furrow irrigation	Sprinkler irrigation	Drip irrigation	Subsurface drip irrigation
Full irrigation	No mulching	Dry 2004	0.955	0.953	0.986	1.000
		Avg. 2006	0.911	0.904	0.953	0.988
		Wet 2007	1.091	1.077	1.120	1.164
	Organic mulching	Dry 2004	0.993	0.993	1.008	1.060
		Avg. 2006	0.963	0.962	0.971	1.005
		Wet 2007	1.135	1.133	1.158	1.208
	Synthetic mulching	Dry 2004	1.059	1.060	1.055	1.094
		Avg. 2006	1.040	1.037	1.037	1.053
		Wet 2007	1.220	1.220	1.216	1.268
Deficit irrigation	No mulching	Dry 2004	0.954	0.950	0.987	1.026
		Avg. 2006	0.918	0.909	0.914	0.979
		Wet 2007	1.110	1.090	1.122	1.165
	Organic mulching	Dry 2004	1.000	0.999	1.011	1.040
		Avg. 2006	0.966	0.967	0.962	1.009
		Wet 2007	1.140	1.184	1.154	1.208
	Synthetic mulching	Dry 2004	0.971	1.080	1.053	1.089
		Avg. 2006	1.040	1.037	1.026	1.033
		Wet 2007	1.264	1.264	1.211	1.262

Note: Avg., average.

Table 8 Simulated green WF ($m^3 \cdot t^{-1}$) of growing winter wheat under different management practices at Xiaotangshan experimental site

Irrigation strategy	Mulching practice	Year	Furrow irrigation	Sprinkler irrigation	Drip irrigation	Subsurface drip irrigation
Full irrigation	No mulching	Dry 2004	665	668	622	614
		Avg. 2006	729	731	673	662
		Wet 2007	623	626	577	569
	Organic mulching	Dry 2004	655	655	614	594
		Avg. 2006	709	710	667	656
		Wet 2007	604	604	564	554
	Synthetic mulching	Dry 2004	633	633	597	582
		Avg. 2006	680	680	643	634
		Wet 2007	578	578	545	536
Deficit irrigation	No mulching	Dry 2004	807	807	761	734
		Avg. 2006	859	866	851	800
		Wet 2007	718	728	690	675
	Organic mulching	Dry 2004	784	785	750	737
		Avg. 2006	834	833	809	798
		Wet 2007	699	678	676	653
	Synthetic mulching	Dry 2004	824	741	726	710
		Avg. 2006	789	789	773	779
		Wet 2007	645	645	650	633

Note: Avg., average.

Table 9 Simulated blue WF ($m^3 \cdot t^{-1}$) of growing winter wheat under different management practices at Xiaotangshan experimental site

Irrigation strategy	Mulching practice		Furrow irrigation	Sprinkler irrigation	Drip irrigation	Subsurface drip irrigation
Full irrigation	No mulching	Dry 2004	382	381	393	386
		Avg. 2006	369	376	376	350
		Wet 2007	294	303	315	290
	Organic mulching	Dry 2004	352	352	378	349
		Avg. 2006	329	330	362	339
		Wet 2007	277	279	300	274
	Synthetic mulching	Dry 2004	311	311	351	332
		Avg. 2006	282	284	322	315
		Wet 2007	242	242	277	253
Deficit irrigation	No mulching	Dry 2004	241	245	252	241
		Avg. 2006	230	234	243	222
		Wet 2007	183	190	202	183
	Organic mulching	Dry 2004	216	216	239	224
		Avg. 2006	201	201	231	192
		Wet 2007	178	166	190	175
	Synthetic mulching	Dry 2004	206	185	224	209
		Avg. 2006	173	175	201	189
		Wet 2007	146	146	175	159

Note: Avg., average.

changing agricultural management practices match well with those from Chukalla et al.[20] for maize, potato and tomato. The current study and the Chukalla study are both model-based, so the findings should be confirmed through agronomy experiments.

It is impossible to find a combination of management practices that optimizes IE, WUE, and green and blue WF simultaneously, but our results showed that: (1) deficit irrigation most effectively improved blue water use by increasing IE (by 5%) and reducing blue WF (by 38%), however with an average 9% yield reduction; (2) organic or synthetic mulching practices improved WUE (by 4% and 10%, respectively) and reduced blue WF (by 8% and 17%, respectively), with the same yield level; and (3) drip and subsurface drip irrigation improved IE and WUE, but drip irrigation had a relatively high blue WF. When we moved from the common combination of full sprinkler irrigation without mulching to deficit subsurface drip irrigation with organic mulching, we found that IE increases from 36% to 45%, WUE increased by 11% and blue WF decreased by 44%.

The study shows that it is useful to consider different water efficiency indicators, because improvements in one indicator may proceed at the cost of a decline in another indicator. The most common case is the one whereby WUE or overall consumptive WF can be improved by more irrigation at the cost of the blue WF. Furthermore, it has been shown that increasing IE, for instance by installing drip irrigation, doesn't necessarily reduce the blue WF.

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Compliance with ethics guidelines La Zhuo and Arjen Y. Hoekstra declare that they have no conflict of interest or financial conflicts to disclose.

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