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Water-saving agriculture can deliver deep water cuts for China

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ABSTRACT

China is working hard to reconcile growing demands for freshwater with already oversubscribed renewable water resources. However, the knowledge essential for setting and achieving the intended water consumption cuts remains limited. Here we show that on-farm water management interventions such as improved irrigation and soil management practices for maize cultivation can lead to substantial water consumption reductions, by a simulated total of 28–46 % (7–14 billion m³/year) nationally, with or without the impacts of climate change. The water consumption cut is equivalent to 16–31 % of the ultimate capacity of the South-North Water Transfer Project. Much of the reduction is achievable at the populous and water-stressed North China Plain and Northeast China. Meanwhile, the interventions can increase maize production by an estimated 7–15 %, meeting 22–28 % of demand increase projected for 2050. The water management and food production improvements obtained are crucial for achieving multiple Sustainable Development Goals (SDGs) related to water, land, and food in China and far beyond.

1. Introduction

For over a decade, the lack of abundant freshwater resources has been a major constraint to China's socioeconomic development and a threat to its environmental sustainability (Liu et al., 2013; Liu and Diamond, 2005). Annual freshwater availability per capita in China is a mere one third of the global average (World Bank, 2017). The impact of such water shortage is worsened by an uneven spatiotemporal distribution of freshwater resources as well as vast yet inefficient water-intensive crop production, especially in North and Northeast China. The prolonged water overexploitation has already contributed to the disappearance of half of the rivers with significant catchment areas since the 1950s (Yan, 2013), groundwater-related land subsidence of > 10 cm per year in eastern Beijing (Chen et al., 2016), and habitat and biodiversity losses that are more difficult to quantify (Strayer and Dudgeon, 2010). Those impacts are predicted to worsen in the near future as a result of climate change (Elliott et al., 2014) and a countrywide diet shift fueled by urbanization and rising living standards (He et al., 2018). Given the already tight links between China – the world's

most populous and second-largest economy – and the rest of the world, the consequences of China's water shortages have already become a global concern (Liu and Diamond, 2005). For instance, water shortages in China's major agricultural regions can cause a substantial disruption to global food security (Rulli et al., 2013). It is, therefore, crucial to provide systematic and detailed knowledge to facilitate prompt and substantial reductions in water consumption in China.

The current nature of China's irrigation practices entails substantial untapped potential for water consumption reduction. Irrigated agriculture accounts for 62 % of the country's total gross water abstractions, and 84 % of net water abstraction (i.e., the gross water abstractions minus return flows to surface water bodies or aquifers) (Gao et al., 2014a; Hoekstra and Mekonnen, 2012) as other water use sectors generate higher shares of return flows (Shaffer and Runkle, 2007). Despite increasing investment in and implementation of water-saving irrigation measures since the 1950s, over 90 % of the irrigation area in China or nearly 20 % of the world's total irrigated area is still using traditional surface irrigation techniques (e.g. furrow irrigation) (Zhu et al., 2013), which typically consumes 10–30 % more water than

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modern drip irrigation (Grafton et al., 2018). At the same time, irrigation plays a crucial role in crop production in China, avoiding 31 % of drought-related yield loss (Yu et al., 2018). In the annual “No.1 Document” issued in 2011 (commonly known as “the three redlines”), which reflects the central government’s top priorities, ambitious targets on curbing water consumption and lifting irrigation efficiency were outlined (Liu et al., 2013; Wang et al., 2019).

Maize accounts for the most crop production (measured in weight) in China and covers 40 % of the country’s cropland for cereal crops, especially in North and Northeast China (Meng et al., 2006). Groundwater is often the major source for irrigation in these regions (Yu et al., 2018). It is anticipated that the domestic production and water demand for maize will grow rapidly in the near future because maize is a critical feedstock to China’s growing meat consumption and ethanol production while being a strategic commodity in the country’s food security agenda (He et al., 2018; Liu et al., 2018a). Therefore, saving irrigation water in maize without reducing or even with increasing crop production can mitigate the water-food-energy nexus pressure in many places in China (Sušnik, 2018).

Field evidence across China shows that various on-farm water management interventions can reduce irrigation water consumption (IWC) to varying extents, depending on crop and soil types, weather, and other factors. Replacing surface irrigation by drip irrigation is found to reduce IWC by 6–13 % (Rajak et al., 2006; Araujo et al., 1995). Employing low-tech soil moisture conservation (SMC) practices can reduce IWC and improve crop yields at the same time. A recent meta-analysis of 266 field trials in China shows that, on average, plastic mulching reduces IWC by > 3 % (see Supporting Information A2) while increasing crop yield by 24 % (Gao et al., 2019). Moreover, farmers can adjust irrigation frequency and duration, known as irrigation scheduling, to achieve optimal plant growth per unit irrigation water consumed. With minimal yield losses, well-designed irrigation scheduling can reduce IWC of maize by 9–21 % across China (Kang et al., 1998; Wang et al., 2018).

However, existing knowledge of plausible irrigation water-saving potentials are confined to field studies. A simple extrapolation of the field-level measurements is challenging for China, because the heterogeneous biophysical conditions and agronomic practices throughout the country affect the water saving implications of single or combined on-farm interventions. Moreover, existing studies rarely combine different on-farm irrigation and soil water management interventions in an integrated form. Gridded global assessments show integrated on-farm water management interventions could reduce irrigation water consumption (IWC) by 23–37 % globally (Jägermeyr et al., 2015, 2016). Yet, there have been few studies on feasible water cuts for a country and robust sub-national analyses are lacking. To our knowledge, a systematic and comprehensive study that builds upon the best available data and targeted design of a country, such as China, is not available. Such analysis is key for establishing sound water management targets at local to national levels, and directing future investments on water conservation projects, so that existing environmental and socio-economic consequences of water shortages can be effectively and timely alleviated in some extent.

Here we address the knowledge gap in three essential aspects. First, we estimate the water-saving potentials in terms of plausible reductions of irrigation water consumption (IWC) without compromising crop production in maize. Previously, analyses have mainly focused on reducing irrigation water abstraction (IWA) (Grafton et al., 2018). Since irrigation return flows remain in the hydrological system and are often important for downstream users, targeting IWC reductions is more appropriate and it allows water availability for the environment and other water users to be considered. Second, by choosing the county as the basic spatial unit for this study, we utilize the best available countywide empirical data (county-level irrigated and rainfed areas and crop yields) in China and our results can better inform decision-making from county to country level. The biophysical and agronomic heterogeneities

represented by the 2403 counties in China provide similar resolutions as grid-scale estimates. Third, we model the on-farm water management interventions (improved irrigation and soil management practices) that have been well-supported in experimental studies in China. We validate the main findings by a combination of tests (data-oriented reality checks, scenario ensembles of on-farm water interventions and climate change, and multi-model assessments).

2. Materials and methods

2.1. Computing irrigation water consumption and yield of maize

We computed water consumption (evapotranspiration) and crop yield using AquaCrop, a water-driven crop growth model that dynamically simulates daily soil water balance and crop growth (Steduto et al., 2009; Raes et al., 2009). Maintaining a good balance of simplicity, robustness, and accuracy, AquaCrop has been applied in simulating crop growth and water use of various crops in diverse regions (Jin et al., 2014; Greaves and Wang, 2016). AquaCrop keeps track of the soil water storage (S) over time by simulating daily (t) water fluxes (Eq. (1)), including the inflows of precipitation (PR) and irrigation (IRR) and the outflows of crop transpiration (T), soil evaporation (E), deep percolation (DP), and runoff (RO). Nearly all water uptake by the roots of the plants is lost by T and only a little fraction is used for plant biomass growth (Allen et al., 1998a). E and T are the two components of evapotranspiration (ET). The amount of water inflows, soil infiltration capacity and saturation level determine water infiltration in the surface soil layer. Once the soil water content in one layer reaches above the field capacity, water percolates into the layer beneath, depending on the layer’s soil water content and hydraulic conductivity. Water surplus that cannot infiltrate in soil becomes runoff (RO).

$$S_t = S_{t-1} + PR_t + IRR_t - T_t - E_t - RO_t - DP_t \quad (1)$$

Irrigation water consumption (IWC) is then calculated on a daily basis by partitioning ET following Chukalla et al. (2015) In essence, based on daily tracking of the fractions in soil moisture stemming from irrigation and precipitation, respectively, ET is partitioned into IWC (i.e. blue water consumption) that originates from IRR and green water consumption originating from PR . In this study, the maximum rooting depth of maize in China is 1 m below ground, which agrees with other studies (Ding et al., 2013; Jiang et al., 2016; Ran et al., 2017). So we assume no capillary rise from groundwater because groundwater tables in China are generally over 1 m below the ground surface and thus have little impact on maize growth (Zhuo et al., 2016).

Crop growth is simulated in AquaCrop based on a conservative relationship of above-ground dry biomass per unit transpiration (Eq. (2)) (Raes et al., 2009). The above-ground dry biomass (B) is calculated by first converting crop transpiration (T) using a water productivity parameter (WP) and then normalizing for atmospheric evaporative demand, i.e. the reference evapotranspiration (ET_0) (Andarzian et al., 2011). Crop yield (Y) is then obtained by multiplying B with a dynamic harvest index (HI) based on accumulated daily stresses from water and temperature (K_s). AquaCrop accounts for the impacts of water stress for crop growth, which is determined by soil water content in the crop root zone and crop growth stage, and assumes no other constraints, such as nutrient limitations or pests and diseases. This is likely a reasonable assumption because fertilizers and pesticides are generally over-applied in agricultural practices in China (Cui et al., 2018).

$$Y = HI \times K_s \times WP \times \sum \frac{T}{ET_0} \quad (2)$$

2.2. Modeling on-farm water management interventions

In AquaCrop, we modelled on-farm water management interventions whose performances on water use reduction have been observed

Table 1
Parameters for characterizing on-farm water management interventions in AquaCrop.

(I) Irrigation technology	Water application efficiency (%) (Brouwer et al., 1989)	Water conveyance efficiency (%) (Jägermeyr et al., 2015)	Surface soil wetting area (%) (Raes et al., 2009)
Furrow	60	By soil texture: Sand: 70 Loam: 75 Clay: 80	80
Sprinkler	75	95	100
Drip	90	95	30
(II) Soil management	Material factor (f_m) (Chukalla et al., 2015)	Mulching cover area (%) (Chukalla et al., 2015)	
Organic mulching	0.5	100	
Plastic mulching	1	80	
(III) Irrigation scheduling	Early seeding stage	Other stages (Raes et al., 2009)	
Full irrigation	86% of TAW ^a (Raes et al., 2009)	86% of TAW	
Regular deficit irrigation (RDI)	40% of TAW (Kang and Cai, 2002; Du et al., 2015)	86% of TAW	

^a TAW: Total available water in soil crop root zone.

Table 2
Scenarios of on-farm water management interventions examined in this study (* indicates those analyzed in the main manuscript).

		S1	S2	S3*	S4*	S5	S6*	S7	S8*	S9*	S10
Irrigation technology	Furrow	√					√				
	Sprinkler		√					√			
	Drip			√	√	√			√	√	√
Soil mulching	Straw				√					√	
	Plastic					√					√
Irrigation scheduling	Full	√	√	√	√	√					
	RDI						√	√	√	√	√

in field studies across China (Table 1).

2.2.1. Irrigation technologies

We modelled and examined three irrigation technologies that are most popular in China: furrow, sprinkler and drip irrigation. These can be characterized by three parameters: water application efficiency, water conveyance efficiency, and wet surface area (Jägermeyr et al., 2015; Raes et al., 2009; Brouwer et al., 1989). Among these technologies, furrow has the lowest water application efficiency and water conveyance efficiency (Table 1); while drip irrigation has the highest water application efficiency and the lowest surface soil wetting area due to its ability to limit water releases to the direct vicinity of crop roots (Van der Kooij et al., 2013). Due to high water loss through evaporation from soil and wind dispersal, sprinkler irrigation can lead to higher water consumption than furrow irrigation (Chukalla et al., 2015).

2.2.2. Mulching

Soil mulching contributes to water saving by reducing soil evaporation, preventing erosion, and mitigating weed infestation. The performance depends on coverage area and mulching materials, which are commonly distinguished as organic mulching (e.g. straw) and plastic mulching. In our model, with a material-dependent factor, the area coverage is assumed to be 100 % and the evaporation reduction factor 50 % for organic mulching; for plastic mulching coverage is assumed to be 80 % with 100 % reduction (Chukalla et al., 2015).

2.2.3. Irrigation scheduling

Full irrigation and deficit irrigation represent two irrigation scheduling practices. Full irrigation satisfies *ET* requirements over the entire crop growth period (Galindo et al., 2018). In AquaCrop, water supply of full irrigation is triggered once soil moisture in the crop root zone is below 86 % of total available water (TAW) to avoid any physiological stress due to water shortage during maize growth. Regulated deficit irrigation (RDI), as the most common deficit irrigation practice,

improves water use efficiency through precise control of the timing and quantity of irrigation water supply at different crop growth stages while minimizing the negative water stress impacts on crop yield (Raes et al., 2009). Previous studies show mild water deficit at early seeding stage of maize (May or June across China) is beneficial for improving yield and water use efficiency of maize cultivation in China (Kang and Cai, 2002; Du et al., 2015). Thus we assumed here that irrigation supply was triggered when depletion ≥ 40 % of TAW at the early seeding stage; at other crop stages, RDI was set as the same as full irrigation. This represents a conservative modeling of RDI but ensures no significant yield loss in a necessary consideration, given the demand for maize (as food, feed, and energy crops) in China is expected to grow rapidly in the near future.

2.2.4. Scenarios of integrated on-farm water management interventions

We investigated a total of ten scenarios of integrated on-farm water management interventions (S1-S10, Table 2). Five of these are discussed in the main text; the results of other scenarios are discussed in the Supporting Information C1.

We adopted a baseline case ("Business as Usual", BAU) representing China's existing irrigation system, i.e. 97 % of irrigated area are under furrow irrigation and 3 % under sprinkler irrigation (Jägermeyr et al., 2015). We assumed that irrigation water demand in each county is fully met under BAU and performed several tests on this critical assumption (see the Discussion section and SI C1-C3). Because spatially-specific information of mulching practices in China is unavailable and the country-level estimate remains low (< 4 % of agricultural land) (Liu et al., 2014), we assumed none (i.e. 0 %) under the baseline case. It is worth noting that the above scenarios are designed for maize. For instance, it is difficult to apply mulching and drip irrigation in high-density crop, such as wheat. In such cases, sprinkler irrigation combined with deficit irrigation is an option.

2.3. Data and model simulation protocol

2.3.1. Simulation based on historical climate data

In AquaCrop, we simulated maize growth and assessed irrigation water consumption at the county scale on a daily time step, using temperature and precipitation from 1995–2014. For each county i , we simulated maize yield (Y_i , in ton/hectare or t/ha), distinguishing yield of irrigated land ($Y_{irrig,i}$) and of rainfed land ($Y_{rainfed,i}$), under the baseline case and each intervention scenario, respectively. Based on county-level yield statistics ($Y_{stat,i}$, t/ha), we corrected the simulated yield using a scaling factor (f_i , Eq. (3)). $Area_{irrig,i}$ and $Area_{rainfed,i}$ are irrigated and rainfed maize cropping area (ha) in county i , respectively.

$$f_i = \frac{Y_{stat,i} \times (Area_{irrig,i} + Area_{rainfed,i})}{Y_{irrig,i} \times Area_{irrig,i} + Y_{rainfed,i} \times Area_{rainfed,i}} \quad (3)$$

The scaling factor accounts for uncontrollable factors such as improper field management, fertilizer or pesticide effect. In our study, f_i vary from 0.3 to 0.8 across the counties. At regional level, f ranges from 0.5 to 0.7, which is similar to prior regional estimates of 0.5–0.8 (Liu et al., 2017). We then calculated the maize production in each county (P_i) using the corrected yield estimates, $f_i \cdot Y_{irrig,i}$ or $f_i \cdot Y_{rainfed,i}$.

2.3.2. Simulation based on future climate projections

For each of the ten on-farm water management scenarios, we simulated future water consumption and yield of maize using projected daily climate data for 2020–2050. The climate data we used are produced by the Geophysical Fluid Dynamics Laboratory model (GFDLESM2G), which has been validated for simulating future climate conditions in China (Bao et al., 2015; Song et al., 2013; Huang et al., 2013). We used the climate data modeled after three representative concentration pathways (RCPs: 2.6, 4.5, 8.5) to capture a range of possible climate futures. For the three RCPs, long term precipitation trends projected by GFDLESM2G lie within the 25th–75th percentiles of those projected by a multi-model ensemble adopted by the Intergovernmental Panel on Climate Change (Van Oldenborgh et al., 2013) (Fig. S2). We calculated daily reference evapotranspiration (ET_0) using the FAO Penman-Monteith equation (Allen et al., 1998b). To explicitly quantify the water and production effect of changing CO₂ concentrations, commonly known as the CO₂ fertilization effects, we run each simulation with constant (year 2014) and transient CO₂ concentration, respectively.

2.3.3. Irrigation expansion

We explored the potential of increasing maize production if the water saved in each county were to be applied in the rainfed maize growing area in the same county. It is reasonable to assume that irrigation expansion should be constrained by local water scarcity conditions. Therefore, water savings achieved in areas with high water scarcity are reserved for relieving local water use and environmental pressures, instead of irrigation expansion. As such, we modelled irrigation expansion only when local water scarcity level was below a long-term monthly threshold. The monthly water scarcity levels and threshold (water scarcity > 2.0) are obtained from Hoekstra et al. (2012).

2.3.4. Data sources

County boundaries for 2403 counties in China are obtained from Yu et al. (2018) Biophysical characteristics for crops within each county were quite homogenous. The county-scale data on land use and crop calendar represents the best data available in China. Prior usage of gridded data are commonly downscaled from crude country-level statistics (Jägermeyr et al., 2015). Rainfed and irrigated areas in each county were represented by their averages of 2007–2011, while the total harvested maize area was 31.3 million hectares (ha) in China during this period. The spatial distribution of maize cropland was

obtained from the MIRCA2000 dataset (Portmann et al., 2010). Soil properties including soil texture and hydraulic parameters were obtained from Dai et al. (2013). Sowing data were county-specific but fixed during the simulation period. Historical climate data, including temperature and precipitation from 1995 to 2014, were obtained from Liang et al. (1994), Zhang et al. (2014) GFDLESM2G future climate data (precipitation, temperature, and CO₂ concentrations) are obtained from Dunne et al. (2012), 2013.

3. Results

3.1. Substantial national IWC cuts achievable based on historical climate conditions

Under the ‘business-as-usual’ baseline case (existing irrigation technologies, no mulching and full irrigation), an average of $35 \times 10^9 \text{ m}^3$ of irrigation water was consumed each year in China for cultivating maize between 1995 and 2014. Our modelling indicated that, with improved on-farm management practices, up to 39 % ($14 \times 10^9 \text{ m}^3$) of the irrigation water consumption (IWC) can be reduced each year. The IWC cut is more than 30 % of the ultimate annual capacity of the South-North Water Transfer Project. National water saving estimates for five on-farm water management intervention scenarios are shown in Fig. 1.

The maximum IWC reduction was achieved in the ‘D-R-M’ scenario. ‘D-R-M’ represents a complete upgrade from the baseline case by drip irrigation (‘D’), regulated deficit irrigation (RDI, ‘R’), and straw mulching (‘M’). The combined interventions would most effectively reduce unproductive evaporation of water from the soil, increase the ratio of crop transpiration to soil evaporation, and prevent additional transpiration when it is marginally efficient to increase crop yield. Implementing one or two of the on-farm interventions resulted in lower but still considerable IWC cuts. By directly applying irrigation water to the root zone and thus minimizing soil evaporation, drip irrigation alone can reduce IWC by 9 %. If combined with straw mulching, which further obstructs soil evaporation, the IWC cuts rise to 31 %. By limiting irrigation frequency during the early seeding stage, RDI alone reduces IWC by 16 %.

All management interventions above would have negligible negative effects on crop productivity; while in some cases productivity may be improved. The 16 % water saving by RDI costs less than 1 % of maize production. Our modeled results are consistent with findings of field experiments indicate that, in comparison to full irrigation, deficit irrigation applied in maize farms reduces IWC by 9–21% with 1–3% yield reduction across China (Kang et al., 1998; Wang et al., 2018). Unlike drip irrigation and RDI, which only apply in irrigated farming systems, straw mulching also improves water use efficiency in rainfed systems, leading to a simulated 17 % increase in rainfed maize production at

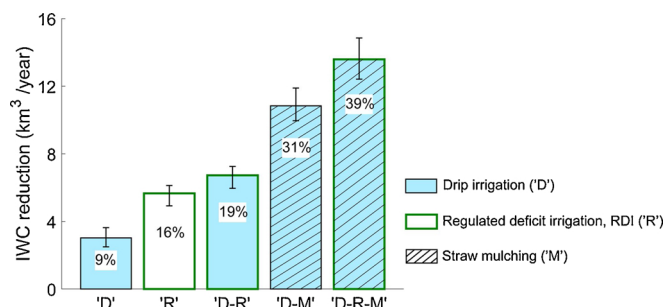


Fig. 1. Annual average reduction of irrigation water consumption (IWC) in maize cultivation in China under five scenarios of improved on-farm water management. Bars refer to the absolute annual average IWC reduction (km³/year) for maize, with the relative change (%) compared with BAU, indicated by the number inside each bar. Whiskers indicate the extent of inter-annual variations of simulated IWC reduction during 1995–2014.

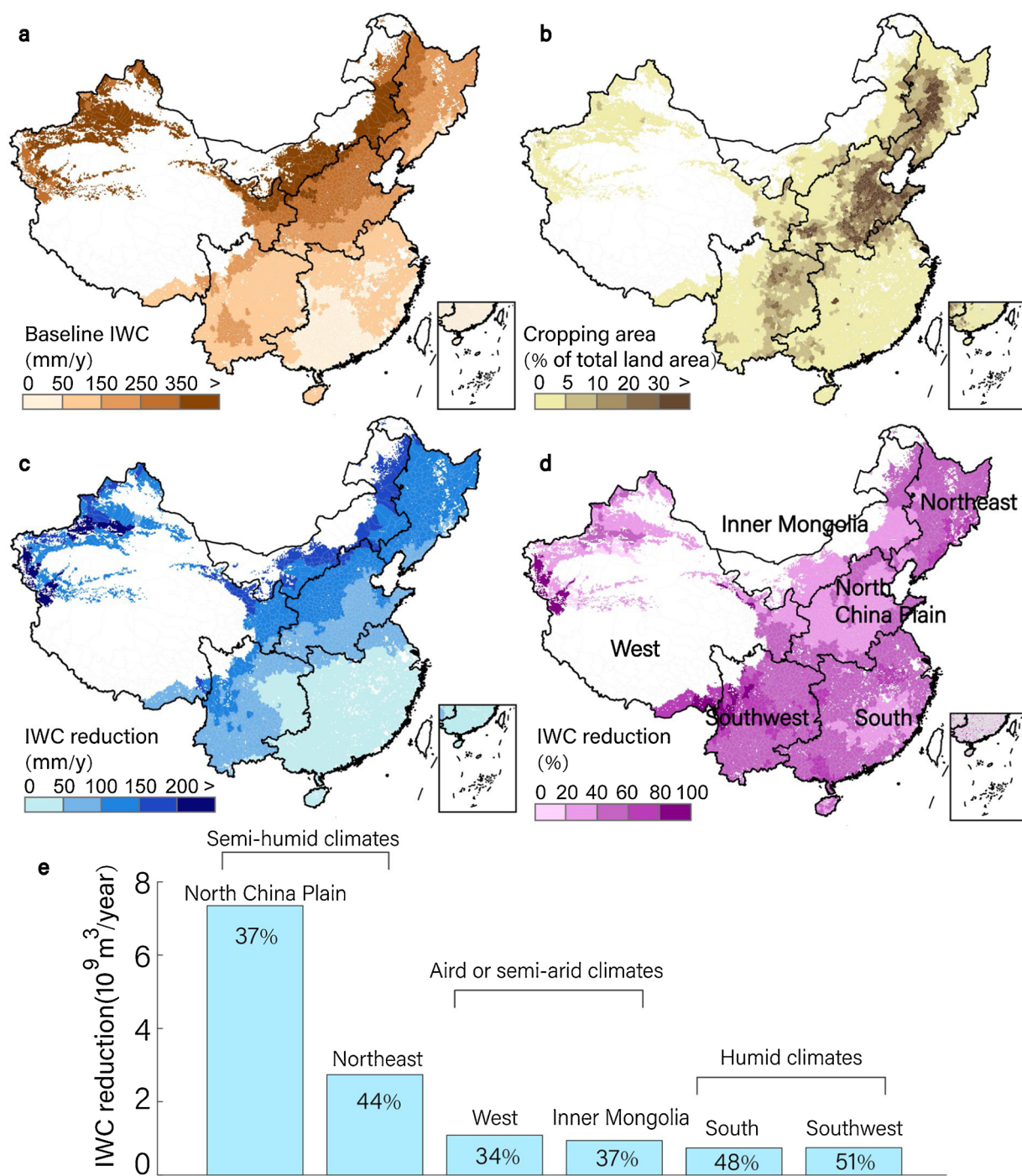


Fig. 2. Spatial pattern in changes of irrigation water consumption (IWC) for maize cultivation in the 'D-R-M' scenario in China. The maps show current county-level irrigation water consumption (IWC) (a), current total (rainfed and irrigated) maize cropping area (b), absolute (c), and relative (d) potential IWC reductions (mm/year). Both IWC reductions are based on the 'D-R-M' scenario. Regional IWC reductions, in absolute values (bars) and relative changes in percentages (numbers within bars) compared with BAU, are shown for the five main agronomic regions in China (e).

national level. As such, the 'D-R-M' scenario enables substantial IWC cuts along with a considerable increase in maize production. Our results are robust to inter-annual climate variations for the period 1995–2014, with the maximum IWC cuts (under the 'D-R-M' scenario) ranging between 36 % (wet year, 2002) and 41 % (dry year, 2014).

3.2. Highest IWC cuts in the northern maize belt

Due to the distinct spatial climatic pattern and different maize cropping intensities throughout China, irrigation water consumption

and water saving potentials vary across the country (Fig. 2). The arid and semiarid areas in China include four different regions: the North China Plain, Northeast China, West China, and Inner Mongolia. They are characterized by the highest irrigation water requirements of maize cultivation in China (> 150 mm/year, Fig. 2a), yet account for 80 % of the total cropping area (Fig. 2b). Under the baseline condition, 75 % of the country's total maize IWC can be traced to the North China Plain ($20 \times 10^9 \text{ m}^3/\text{year}$) and Northeast China ($6 \times 10^9 \text{ m}^3/\text{year}$). Our results suggest the irrigation water saving potential is also the highest in these two regions (Fig. 2c,e). Under the 'D-R-M' scenario, 7×10^9 and

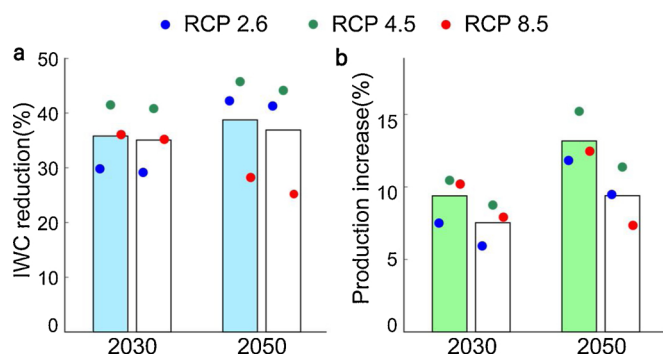


Fig. 3. Irrigation water consumption (IWC) reductions and production increases in maize production in China under different future climatic conditions. The percentage changes are relative to the levels of irrigation water consumption and maize production simulated under the baseline case in 2014. Bars indicate results with (colored bars) and without (white bars) the CO₂ fertilization effects. Dots represent simulations under different RCPs and bars their average response (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

3×10^9 m³/year of IWC could be ‘freed up’ in the North China Plain and Northeast China, respectively, accounting for more than 70 % of national irrigation water savings for maize. Although water savings in the southern regions account for a small fraction of the national total, owing to the low irrigation water requirement and low maize cropping intensity there, the southern regions appear more responsive to the water interventions (Fig. 2d). As shown in Fig. 2e, the ‘D-R-M’ scenario roughly halves the baseline IWC in the two southern regions.

3.3. The substantial irrigation water savings are robust to future climate change

Considering climate change predicted by the GFDLES2G model and assuming maize cropping areas are unchanged in the near future, the irrigation water saving potentials remain substantial. Compared with ‘business-as-usual’ irrigation water consumption in 2014, the irrigation water consumption (IWC) cuts achievable in the ‘D-R-M’ scenario range between 30–42% in 2030 and 28–46% in 2050 under Representative Concentration Pathways (RCPs) 2.6, 4.5, and 8.5 (Fig. 3). We find that the increased CO₂ concentrations in the climate change scenarios have little effect on the expected water savings.

Our results show that maize production in China will be enhanced by the implementation of ‘D-R-M’ under future climate change. Under the ‘D-R-M’ scenario, maize production is expected to increase by 8–11% (14–19 million tons) in 2030 and 12–15% (22–28 million tons) in 2050. China’s maize demand is expected to grow to 318 million tons by 2050, a 44 % increase from the 2014 level (Gao et al., 2014b). The modelled production improvement owing to ‘D-R-M’ and climate change meets 22–28 % of the demand increase. Higher CO₂ concentrations have a fertilizing effect on crop growth, as crop transpiration efficiency and thus the capacity to withstand water stress increases. As Fig. 3b shows, CO₂ fertilization alone may contribute to 1–2 % and 2–5 % in production increases in 2030 and 2050, respectively. Production improvements attributed to ‘D-R-M’ and climate change (changing temperature, precipitation, and CO₂ concentrations), respectively are presented in Supporting Information.

3.4. Sustainable irrigation expansion based on irrigation water savings

Without additional irrigation expansion, our results indicate that a simulated total of 7–11 billion m³ IWC (range of RCPs) can be freed up in China’s 2165 maize growing counties by 2050 under the ‘D-R-M’ scenario. In each county, the IWC reductions range from 33 % to 64 %. About 12–14 % of the total water savings are achieved in 1416 counties

Table 3

IWC reductions and production increases for China’s maize production under different irrigation expansion and RCP scenarios. Changes are shown as relative and absolute differences between the 2014 baseline case and the D-R-M scenario in 2050.

Scenarios	IWC reduction		Crop production increase		
	%	10 ⁹ m ³ /year	%	10 ⁶ ton/year	
RCP 2.6	‘D-R-M’	42	11	12	22
	‘D-R-M’ + expansion	34	9	14	25
RCP 4.5	‘D-R-M’	46	11	15	28
	‘D-R-M’ + expansion	40	10	16	29
RCP 8.5	‘D-R-M’	28	7	13	23
	‘D-R-M’ + expansion	22	5	14	26

where existing water scarcity is relatively low. If, in those counties, the IWC cuts are allocated for the irrigation of rainfed maize, national maize production could increase by another 1–2% by 2050 (Table 3), with 5–6 million hectares of rainfed farms being converted to irrigated ones. As shown in Fig. 4a, the most prominent county-level production increases (up to 0.23 million tons/year) are mainly achievable in counties located in Northeast China and Inner Mongolia, predominantly in rainfed systems. Less than 10 % of the expansion-induced production increases are in the North China Plain, owing to the low fraction of rainfed area and high levels of water scarcity in this region. In the southern regions, precipitation provides sufficient water supply for maize cultivation hence irrigation expansion would have little effect on production.

After irrigation expansion, our results indicate that 5–10 billion m³/year of water savings remain. Nearly 90 % of these are in 749 counties where irrigation expansion is deemed unfeasible in one or multiple months during the maize growing period when water stress is high (Fig. S1). Application of the water saved can potentially relieve existing water stress levels to various extents, especially in major maize cropping counties experiencing severe aquifer depletion. For instance, in Luancheng county (Hebei province, the North China Plain), maize cropping occupies 65 % of the total land area and irrigation has led to groundwater level declining at nearly 1 m per year since the 1970s (Yang et al., 2015). Our model suggests 28 % (17×10^6 m³/year) of IWC for maize cultivation there could be freed up under the ‘D-R-M’ scenario.

The IWC savings can also contribute to the sustaining of environmental flow requirements, an additional competitor for water use expected to gain weight under unabated climate (Jägermeyr et al., 2017). An aggressive irrigation expansion scenario – reallocating the IWC cuts without the constraints of local water stress level or county boundary – leads to further production increase, by another 6–10% on country level. But such extreme water re-allocations would further intensify a variety of human and ecological damages already threatening many of the water-scarce counties (Liu et al., 2018b).

4. Discussion

Irrigated agriculture produces 75 % of China’s food supply on half of its arable land (Zhu et al., 2013). As water scarcity and competition among different water users continue to increase, reconciling future irrigated farming with environmental sustainability targets becomes an evident challenge. In an extreme case, complete elimination of maize irrigation would potentially free 30–40 billion m³ of water consumption each year, but reduce national maize production by 21 % and up to 40–50 % in the northern regions (Fig. S4a, d). By applying straw mulching, national production losses may be dampened to 9 % (Fig. S4b), although production losses of 20–30 % remain in parts of the northern regions. Meanwhile, straw mulching might effectively raise rain-fed maize production by 17 % on the national level with no

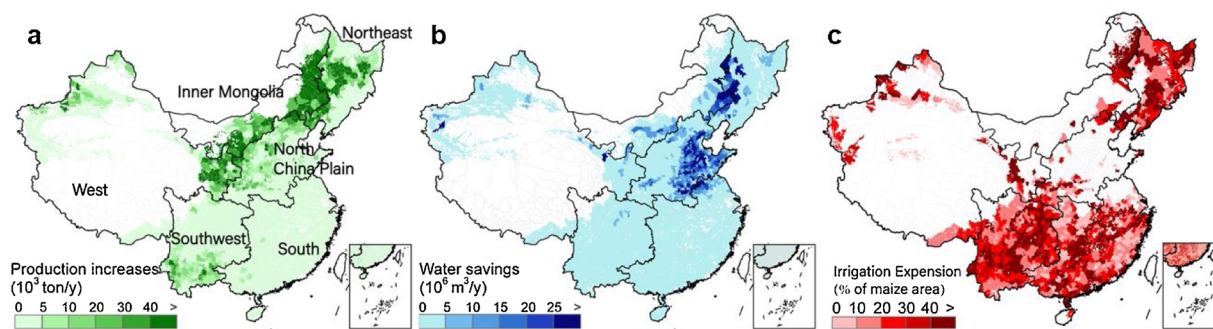


Fig. 4. Effects of sustainable irrigation expansion throughout China. (a) production increases (10^3 tons/year), (b) remaining water savings (10^6 m³/year) after irrigation expansion, and (c) irrigation land expansion pattern (percentage of maize cropping area within a county). The results showed here are simulated under RCP 8.5 in 2050, which leads to more conservative estimate of IWC reduction and production increase than RCP 2.6/4.5 (Table 3).

additional water costs. This production increase is even higher, estimated at 20–60 %, in the four northern regions. As discussed below, mulching in these regions is not common, indicating potential room for gains.

Straw mulching has been used as a soil moisture conservation (SMC) practice in China since the mid-1980s, but has been rapidly replaced by plastic mulching since the 2000s (Lal, 2018). In comparison to straw mulching, plastic mulching has the advantages of easier access, lower economic costs, and better performance in water saving and yield improvement (Qin et al., 2015). The application of plastic mulching in China increased nearly fourfold in the past 30 years, especially in extreme water-scarce regions within Xinjiang Province (West China) and Inner Mongolia (Liu et al., 2014). However, plastic mulching has low recyclability (10 % by volume) and limited disposal options (mainly landfill), already causing soil contamination and land use concerns in China, commonly known as the “white pollution” (Liu et al., 2014). A possible future substitute is biodegradable plastic mulching, which could be tilled into the soil after use and degraded by soil organisms, saving labor and disposal costs and provoking less environmental concern (Brodhagen et al., 2015). Provided that biodegradable plastic mulching is ready and safe for large-scale application and can replace straw mulching in the ‘D-R-M’ scenario, AquaCrop model simulates a 35–52 % (9–13 billion m³/year) cut in irrigation water consumption with 16–17 % maize production increase in 2050, in comparison to the baseline case in 2014.

The on-farm water management interventions examined in this study can lead to greater reductions in irrigation water abstractions (IWA) than those in irrigation water consumption (IWC). The difference between the two is the reduction of return flows: IWA reductions also account for cutting irrigation water that is not consumed but seeps into the ground or returns to surface water. Our model suggests that, under the ‘D-R-M’ scenario, IWA of maize cultivation in China can be reduced by about 65 % from the baseline BAU case (Fig. S3). Although the IWA reduction does not necessarily improve local water availability or reduce water stress, it relieves the impacts of human water extraction on surface and/or groundwater environments and lessens agricultural non-point source pollution, a major source of water quality impairment in China (Ongley et al., 2010). IWA reduction is directly associated with irrigation efficiency (IE) improvement, the target of one of the three ‘redlines’ in China’s water policy, i.e. achieving more than 60 % of irrigation efficiency by 2030. Our analysis shows that the ‘D-R-M’ scenario can lift the BAU irrigation efficiency of maize cultivation from 34 % to 53–58 % by 2030. It is crucial to note that IWC reduction leads to increase in IE, yet increases in IE do not guarantee IWC reduction and may even increase IWC, for instance, when replacing surface irrigation techniques with sprinkler irrigation (Fig. S3). Furthermore, the water saving effects (both IWC and IWA cuts) of IE improvement may be offset by a stimulus to irrigation land expansion in real-world practices, highlighting the importance of measuring and set regulatory targets on

water consumption (Grafton et al., 2018). Capping total water consumption to avoid the rebound effect of water efficiency improvement is especially critical in places where the economic and ecological systems are already threatened by high water scarcity levels, such as North China (Liu et al., 2018b). Thus, our exploration of irrigation expansion is restricted to areas where water scarcity has been minimal or low.

A critical assumption in our AquaCrop simulation is the full irrigation setup, that is, irrigation is unconstrained by surface- and groundwater availability. This is linked to the fact that AquaCrop – in line with many other crop models (Müller et al., 2017) does not come with a hydrological river routing module. In practice, however, lower volumes of irrigation water might be applied if the water potentially required is unavailable. In fact, crop models that account for surface water constraints show much lower IWC estimates (Jägermeyr et al., 2015). This shortcoming is circumvented here by focusing on relative changes.

To assess the extent of watering deficiency in irrigated maize farms in China, we compare the yield gaps of rainfed farms and irrigated farms (Table 4). The logic is that, if the yield gaps of irrigated maize farms are larger than those of the rainfed farms, it may indicate that irrigation deficiency, aside from the stressors common to rainfed and irrigated practices (e.g. lack of nutrients, pests and diseases), is further limiting yield in irrigated farmlands. The yield gap comparison indicates existing irrigation is likely insufficient in Northwest China while the deficiency is less evident in Northeast China, the North China Plain, or China as a whole. This yield gap analysis and other verifications of this assumption (see *Supporting Information C1*) suggests we have overestimated the IWC cuts for Northwest China but, by and large, they corroborate our simulated estimates of the IWC cuts in the country’s major maize cropping regions and on the national level. In addition, the AquaCrop simulations of key water and yield variables are in good agreement with field observations (*Supporting Information C2*).

To further improve the confidence in our main findings, we compared our results simulated using the AquaCrop model with those in Jägermeyr et al. (2015) (2016), which performed similar simulations using the LPJmL model. For the baseline case, AquaCrop simulates 6 % higher national average irrigation water consumption (213 mm/y by LPJmL and 225 mm/year by AquaCrop). The ‘D-R’ AquaCrop scenario is

Table 4

Observed rainfed and irrigated maize yield gaps in China. Regional yield gaps (%) are shown for irrigated and rainfed farms respectively as the fraction of potential yields that have not been achieved by current practices. Yield observed at 4037 farms across maize cropping regions in northern China in 2007–2008 and potential yields under optimal conditions are obtained from Liu et al. (2017).

	Northeast	Northwest	North China Plain	China
Irrigated farms	41%	50%	39%	42%
Rainfed farms	35%	15%	31%	35%

somewhat similar to the 'All Drip' LPJmL scenario presented in Jägermeyr et al. (2015), whereas AquaCrop simulates lower IWC changes (-19 %) compared to LPJmL (-34 %, see more comparisons in *Supporting Information C3*). The difference can be explained by different deficit irrigation strategies. Regarding different deficit irrigation schemes, we model regulated deficit irrigation (RDI) in AquaCrop, that is, water supply is only constrained at early seeding stages as this seems most beneficial for balancing yield and water use efficiency (Kang and Cai, 2002; Du et al., 2015). That said, the comparison with LPJmL suggests that AquaCrop slightly overestimates absolute IWC values, but it does not seem to overestimate relative changes in IWC and maize production associated with the water management interventions analyzed in this study.

This study presents a comprehensive and systematic assessment of agricultural water savings potentials in China. Focusing on maize, which occupies 40 % of China's land for cereal crops and 5 % of the world's irrigated land globally, the study highlights that (1) improved on-farm water management can cut existing irrigation water consumption of maize cultivation by a simulated total of 28–46 (7–14 billion m³/year) nationally, with or without the impacts of climate change. The IWC cut is equivalent to 16–31% of the ultimate capacity of the South-North Water Transfer Project; (2) much of the reduction is achievable at the North China Plain (37 %) and in Northeast China (44 %), the country's two major maize cropping, densely-populated, and water scarce regions; and (3) the interventions (straw mulching in particular) can increase total maize production by an estimated 7–15% (12–28 million metric tons in the rainfed areas), meeting 30–39% of the projected demand increase by 2050. The production improvement is achievable without increasing pressure on land use elsewhere, while lessening water consumption in hundreds of water-stressed counties in China. The water and production improvements on 5 % of the world's irrigated land is crucial for achieving the Sustainable Development Goals (SDGs) related to water, land, and food in China as well as in the world.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.resconrec.2019.104578>.

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