Supplementary Information for "Water-Saving Agriculture Can Deliver Deep Water Cuts for China"

This Supplementary Materials contains three sections, with additional treatment of the following topics:

Data and methods

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A. Data and methods

A.1 Irrigation water consumption (IWC) calculation

Irrigation water consumption (IWC, i.e. blue *ET*) is quantified by tracing evapotranspiration (*ET*) back to either rainfall (green *ET*) or irrigation (blue ET). For such partitioning, we use the dynamic irrigation-to-precipitation ratio method employed in Chukalla et al[1] and Zhuo et al[2]. For daily soil water balance (*S*), precipitation, irrigation and capillary rise are water inflows, while soil evaporation, crop transpiration, surface runoff, deep percolation the water outflows. Changes of precipitation, irrigation, and capillary rise are described in Eqs 1-3, respectively:

$$\frac{dS_g}{dt} = R - (Dp + Es + Tr) \times \left(\frac{S_g}{S}\right) - RO \times \left(\frac{P}{I+P}\right) \qquad [1]$$

$$\frac{dS_{b-irr}}{dt} = I\ - (Dp + Es + Tr) \times \left(\frac{S_{bcr}}{S}\right) - RO \times \left(\frac{I}{I+P}\right) \qquad [2]$$

$$\frac{dS_{b-cr}}{dt} = CR - (Dp + Es + Tr) \times \left(\frac{S_{bcr}}{S}\right) \qquad [3]$$

Where dS_g, dS_{b-irr} and dS_{b-cr} are changes of green water (i.e. precipitation), blue water from irrigation, and blue water from capillary rise in one time step of the calculation (dt, 1 day in model simulation). *P* is precipitation (mm), *I* is irrigation (mm), *Dp* is deep percolation (mm), *Es* is soil evaporation (mm); *Tr* is crop transpiration (mm); *RO* is surface runoff (mm). Capillary rise in the soil crop root zone is ignored in this study. In the calculation, we assumed that initial soil water moisture at the start of the simulation is fully contributed by green water. Model runs from 1990-1994 and 2006-2014 are used as warming-up period for stabilizing water balance in the soil for our historical simulations and future simulations.

A.2 IWC reduction: literature review

Gao et al[3] recently collected 266 field studies across China, covering irrigated and rainfed farms, full and various deficit irrigation strategies, and a variety of irrigation technologies. They estimated mulching's effects on crop water use and yield based on water use efficiency (WUE, Eq. 4) and yield indictors. Based on the result of changes in WUE (ΔWUE) and yield (ΔY) of mulching vs. no-mulching (Eqs. 5-6), we calculate the changes of ET (ΔET, Eq. 7). Our results show that the average effect of plastic mulching on *ET* among 266 fields is 3%, which comprises of changes in both precipitation (green *ET*) and irrigation (blue *ET*). Mulching intervention can effectively enable the full use of limited rainfall and better utilization of soil moisture[4], resulting in a higher (lower) fraction of green (blue) ET. Thus, the reduced irrigation water consumption (i.e. blue *ET*) is higher than 3%.

$$WUE = \frac{Y}{ET} \qquad [4]$$

$$\Delta WUE = \frac{WUE_1 - WUE_2}{WUE_2} = \frac{WUE_1}{WUE_2} - 1 = \frac{Y_1 \times ET_2}{Y_2 \times ET_1} - 1 \qquad [5]$$

$$\Delta Y = \frac{Y_1 - Y_2}{Y_2} = \frac{Y_1}{Y_2} - 1 \qquad [6]$$

$$\Delta ET = \frac{ET_1 - ET_2}{ET_2} = \frac{ET_1}{ET_2} - 1 = \frac{\Delta Y + 1}{\Delta WUE + 1} - 1 \qquad [7]$$

A.3 Water scarcity map

We obtain gridded monthly water scarcity estimates from Hoekstra et al[5] and spatially matched them to each of the 2403 counties in China. Here, water scarcity index (WSI) of 2 is regarded as a high water scarcity threshold, beyond which irrigation expansions are considered as inapplicable.

Fig. S1 presents the spatially matched WSI by county in May, a major maize growth period throughout China.

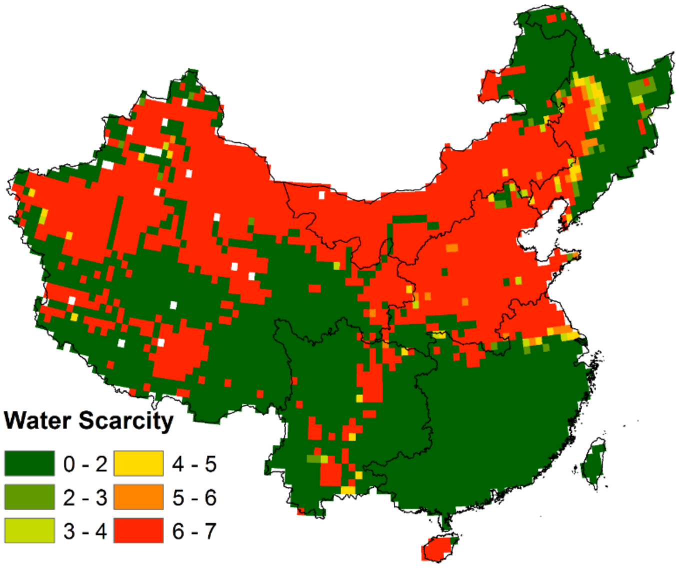
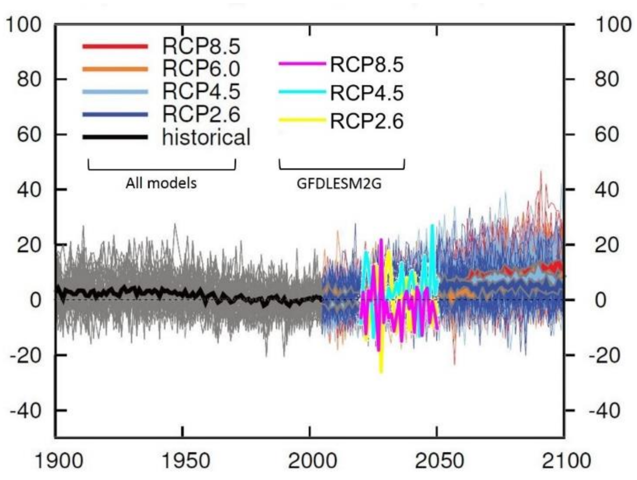


Fig S1. Water scarcity index by county in May, China.

A.5 GFDLESM2G climate data

There are a wide range of climate models whose predictions on future climates can differ a lot from each other. We thus compare the future precipitation changes in East Asia (covering most of China) produced by GFDLESM2G with those produced by a range climate models included in the IPCC AR5 report[6]. As shown in Fig. S2, the GFDLESM2G data exhibits a good coverage of the climate change uncertainty during 2020-2050. As shown in the table (Fig. S2 right), the GFDLESM2G data are within the 25th-75th percentile of all of the IPCC climate models during 2080-2100.



		RCP 2.6	RCP 4.5	RCP 8.5
All IPCC models	5th	-2.15	1.07	2.91
	25th	1.84	3.68	6.74
	50th	4.44	6.74	9.50
	75th	7.20	11.19	15.02
	95th	17.47	17.47	21.46
GFDLESM2G		5.49	7.45	6.77

Fig. S2. Left: Time series of precipitation change relative to 1986–2005 averaged over grid points in Eastern Asia (20°N to 50°N, 100°E to 145°E) in April to September. April to September also overlaps the maize crop growth period. We highlighted the GFDLESM2G results under RCPs 2.6, 4.5 and 8.5 in the figure. **Right: 20-year (2080-2100) mean precipitation changes**

B. Additional results

B.1 National estimation for all scenario managements

National irrigation water consumption and irrigation water abstraction associated with each of the ten management scenarios described in Table 2 of the main manuscript are presented in Fig. S3. For irrigation water consumption (IWC), crop transpiration needs to be fed for crop growth and so the potential IWC savings mainly come from evaporation. All but one management scenario (sprinkler irrigation, S2) result in lower IWC than the baseline case. In comparison to furrow irrigation, the dominant irrigation technology under BAU, sprinkler irrigation lead to more unproductive evaporation and thus more IWC[1]. Switching from sprinkler irrigation to drip irrigation, i.e. from one with the highest evaporation rate to one with the lowest evaporation rate among the three irrigation technologies, IWC can be reduced by 13%. When sprinkler irrigation is combined with regulated deficit irrigation (RDI), i.e. S7, 15% IWC cut from BAU can be achieved on the national level. Mulching can prevent soil water evaporation, improving both green and blue water use efficiency, and reduce IWC.

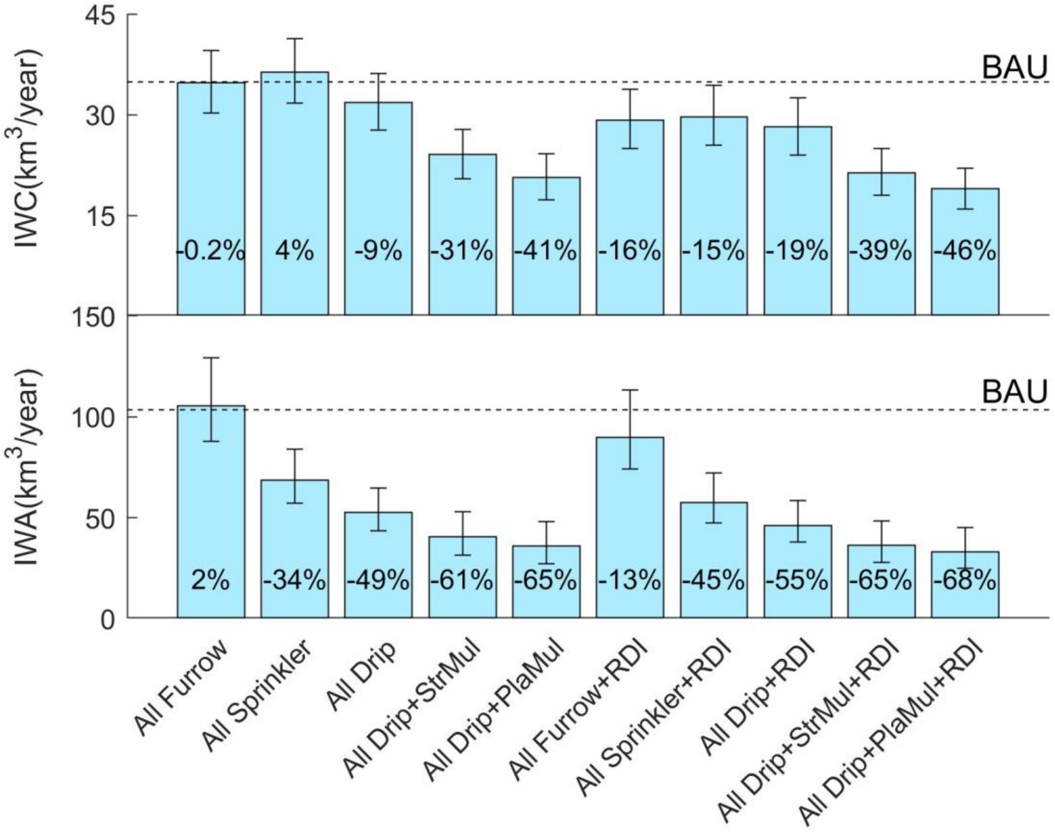


Fig S3. National estimates of all scenarios in (a) irrigation water consumption (IWC) and (b) irrigation water abstraction (IWA). All Furrow: furrow irrigation; All Sprinkler: sprinkler irrigation; All Drip: drip irrigation; StrMul: straw mulching; PlaMul: plastic mulching; RDI: regulated deficit irrigation. Error bars represent inter-annual variations over 1995-2014. Within the bars, annual average water savings in percentage are shown by numbers. The dash lines indicate baseline estimates under the BAU ('business-as-usual') case, which is 97% of furrow and 3% of sprinkler irrigation, no mulching, and full irrigation[7].

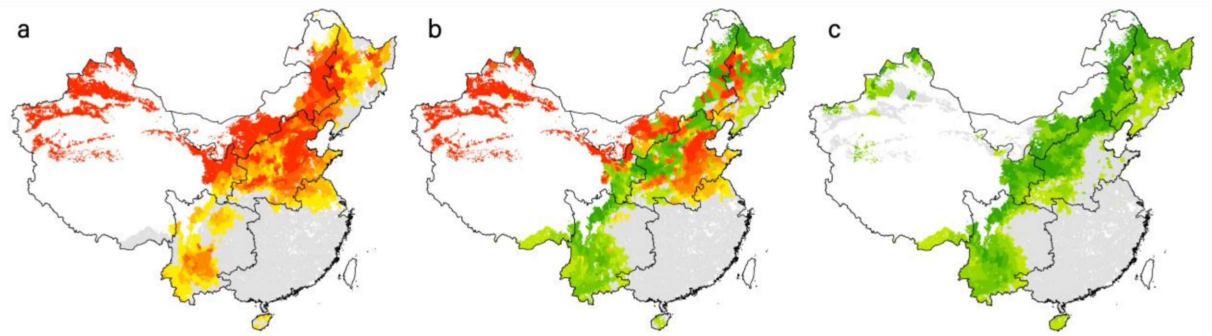
Irrigation savings based on irrigation water abstraction (IWA) are more significant than those based on IWC. Compared to traditional irrigation method (i.e. furrow irrigation, the dominant irrigation technology in the baseline case), sprinkler and drip irrigation technologies have higher water conveyance efficiency and make more water applied in soil zone, rather than producing more return water (see Table 2).

B.2 Water and production effects: management scenario vs. climate change

To obtain the water and production effects of the 'D-R-M' management scenario in the future, we run the future simulations twice, one with the 'D-R-M' scenario and one without, for year 2030 and year 2050, respectively. To quantify the water and production effects of climate change (CC) for 2030 and 2050 respectively, we simulate the model with the 'D-R-M' management scenario twice, one using the climate conditions in 2014 and the other using the future climate conditions described by GFDLESM2G. Those results are then compared against the simulated results under the climate conditions in 2014, with no management interventions. As shown in Table S2, we found the irrigation water savings of 'D-R-M' appear robust under future climate conditions. D-R-M scenario contributes 35-38% of IWC cuts in 2030 and 35-38% in 2050. Climate change has much less impact on IWC in 2030 than in 2050. In 2050, climate change affects IWC by -6-8% and production by 4-10%.

Table S2. Contribution (percentage value, %) of the D-R-M scenario (drip irrigation, straw mulching, and deficit irrigation) and climate change (CC) on savings of irrigation water consumption (IWC) and production (Prod) improvement in 2030 and 2050, compared with 2014.

	2030				2050			
	IWC		Production		IWC		Production	
	D-R-M	CC	D-R-M	CC	D-R M	CC	D-R-M	CC
Mean	36	-0.2	8	2	37	2	7	7
RCP2.6	35	-5	10	-2	38	4	8	4
RCP4.5	38	4	7	3	38	8	5	10
RCP8.5	35	1	7	3	35	-6	7	5



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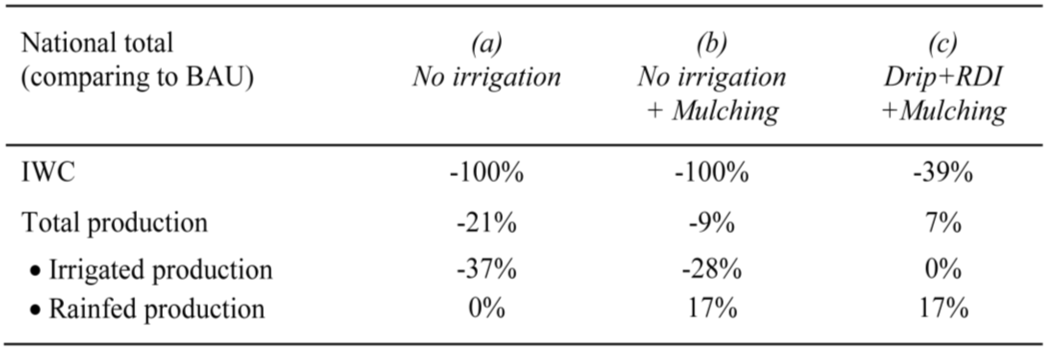

National total (comparing to BAU)	*(a)* *No irrigation*	*(b)* *No irrigation* *+ Mulching*	*(c)* *Drip+RDI* *+Mulching*
IWC	-100%	-100%	-39%
Total production	-21%	-9%	7%
• Irrigated production	-37%	-28%	0%
• Rainfed production	0%	17%	17%

Fig. S4. Spatial pattern of changes in maize production and irrigation water consumption (IWC) under different water management scenario. The maps show maize production changes based on three water management assumptions: all irrigated systems are operated under rainfed conditions (**a**), in addition, straw mulching is applied on all areas (**b**), drip systems are implemented on all currently irrigated areas, irrigation scheduling is applied, and straw mulching is added on all areas ('D-R-M' scenario, **c**). The table lists respective IWC and production changes aggregated to the country level (**d**). All data are shown for the time period 1995 to 2014 and irrigated areas are not expanded**.**

C. Model evaluation

C.1 Irrigation deficiency assessed from yield gaps and loss indicators

Liu et al.[8] obtained a total of 4037 sets of actual maize yield data from farm surveys and used a Hybrid-Maize model to estimate the optimal maize yield in irrigation and rainfed cropland across China. Based on Liu' data, we calculate indicators for yield loss and some implied reduction factors (Eqs. 8-11):

$$\text{Potential yield loss} = 1 - \frac{\text{rainfed yield}}{\text{irrigated yield}} \qquad [8]$$

$$\text{Rainfed management reduction} = 1 - \frac{\text{actual rainfed yield}}{\text{potential rainfed yield}} \qquad [9]$$

$$\text{Irrigated management reduction} = 1 - \frac{\text{actual irrigated yield}}{\text{potential irrigated yield}} \qquad [10]$$

$$\text{Unavoided water stress reduction} = \frac{\text{Rainfed management reduction}}{\text{Irrigated management reduction}} \qquad [11]$$

The results we calculated are presented by region in Table S3. In Liu et al. (2017), the actual yield loss (from irrigated to rainfed) varies from 5% to 15% across China. In comparison, the yield loss calculated from our simulated results ranges from 22% to 65%, which is similar to the potential yield loss from Liu et al.[8] (17%-49%) due to the no water stress assumption in model simulation. Fertilizer application on agricultural cropland has been regarded as overused in China (Cui et al., 2018). So the difference between actual and modeled yield loss may come from improper field management or water deficit in irrigated area. The improper field management in China's maize belt (i.e., Northeast and North China plain) makes 31-35% of the potential yield reduction, while water deficit can drive an additional 6-8%. In West China, irrigated management results in a huge gap (50%) between actual and potential yield. The irrigation supply there might be at strong deficit. Meanwhile, extreme climate condition in West China restricts the rainfed yield improvement from field management. In total, 82% of yield reduction in China is from improper field management while only the rest (18%) is due to the irrigation water deficit. Thus the assumption of no water stress in irrigated area and our model estimation, using a factor to scale from potential to actual yield across China, are applicable, with West China being the only exception. West China takes 10% of harvested area for maize and the IWC reduction estimation is 1.1 km^3 (8% of total IWC reduction). Even though our water saving may be mildly overestimated, the result is solid and not considerably affected.

Table S3. Yield loss (from irrigated to rainfed practices) and yield reduction indicators assessed across China.

	Northeast	West	North China Plain	China
Yield loss				
Actual yield loss from farm survey	11%	14%	5%	15%
Potential yield loss from Liu et al	19%	49%	17%	25%
Potential yield loss from this study	22%	65%	29%	30%
Implied reduction factor analysis				
Rainfed management reduction	35%	15%	31%	35%
Irrigated management reduction	41%	50%	39%	42%
Unavoided water stress reduction*	86%	31%	78%	82%

* Unavoided water stress reduction: part of reduction factor for irrigated production that is not attributable to other field management.

C.2 AquaCrop simulated results vs. field-level measurements

The water-yield balance (i.e. ET, WUE, and yield) we simulate for maize farms under various management scenarios are compared against field-level measurements regarding one or more comparable interventions (Table S4). We collect the field-level data from literature and then extract the modeled results based on the geospatial locations of the field data. Such comparisons are presented in Fig. S5.

Table S4. Comparison of AquaCrop simulated results with field-level measurements

Study site	Indictor	Observed	Modeled result	Agricultural management
Luancheng, Hebei[9]	WUE	15	12	Organic mulching
	ET	-10.8	-10	Organic mulching
Tunliu, Shanxi[10]	Yield	19.8	20.2	Organic mulching
	WUE	19	24	Organic mulching
Chengcheng, Shaanxi[11]	Yield	12	16	Organic mulching
	Yield	52	22	Plastic mulching
Changwu, Shaanxi[12]	Yield	17	16	Organic mulching
	Yield	28	21	Plastic mulching
Qingyang, Gansu[13]	Yield	27.5	44	Plastic mulching
Changwu, Shaanxi[14]	Yield	20.2	21	Plastic mulching
	WUE	22	30	Plastic mulching
	ET	-6	-7	Plastic mulching
Shouyang, Shanxi[15]	ET	-13	-12	Plastic mulching
Fuxin, Liaoning[16]	Yield	30	27	Organic mulching
	WUE	37	33	Organic mulching
Pengyang, Ningxia[17]	Yield	45	37	Plastic mulching
	WUE	38	45	Plastic mulching
Changwu, Shaanxi[18]	Yield	-1	-1	Deficit irrigation
	ET	-13	-9	Deficit irrigation
	Yield	-1	-1	Deficit irrigation

Haerbin, Heilongjiang[19]	ET	-12	-21	Deficit irrigation
Xinxiang, Henan[20]	Yield	-7	-1	Deficit irrigation
	ET	-10	-8.3	Deficit irrigation
	WUE	3	5	Deficit irrigation
Changwu, Shaanxi[21]	WUE	2	6	Deficit irrigation
Wuwei, Gansu[22]	Yield	-1.5	-1	Deficit irrigation
	WUE	25	10	Deficit irrigation
Fuxin, Liaoning[23]	Yield	-2.4	-1	Deficit irrigation
Fuping, Shaanxi[24]	WUE	5	5	Drip irrigation
	WUE	12	19	Drip irrigation + Plastic mulching
Wuweu, Gansu[25]	WUE	26	12	Drip irrigation
	ET	-16	-12	Drip irrigation
Jianping, Liaoning[26]	WUE	36	29	Drip irrigation + Plastic mulching + Deficit irrigation
Taiyuan, Shanxi[27]	WUE	7.5	8.3	Drip irrigation
Tongzhou, Beijing[28]	WUE	13	9	Drip irrigation + deficit irrigation

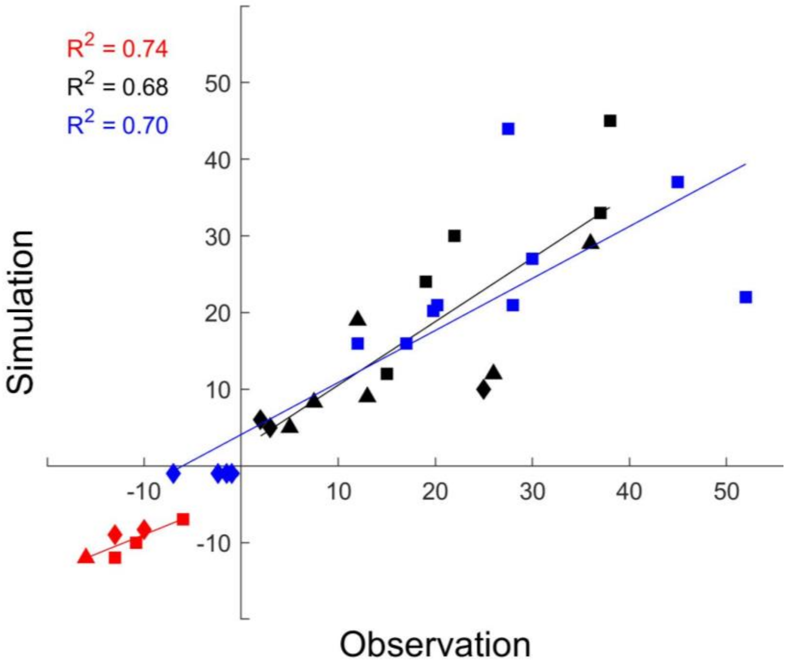

Fig. S5. Evaluation of the simulated key variables with field measurements. Percentage changes [%] in evapotranspiration, yield and water use efficiency (as *red*, *black*, and *blue* symbols, respectively) that are attributable to a management intervention: drip irrigation ('*triangle*'), regular deficit irrigation ('*diamond*'), and mulching ('*square*'), comparing with no intervention. The simulated results are averages of 1995-2014, extracted within or near the corresponding observation sites. Detailed field measurements are in Table S4.

C.3. Simulated results: AquaCrop vs. LPJmL

Table S5 shows relative changes [%] of national irrigation water consumption (IWC), irrigation water abstraction (IWA), and crop production (Prod) for three somewhat similar but not identical management scenarios between both models. AquaCrop scenarios: 'D-R' stands for drip systems with deficit irrigation, 'D-R-M' additionally assumes organic mulching, and 'D-R-PM' plastic mulching (as in Fig. 1, see Methods for details). LPJmL scenarios: 'All Drip' stands for drip systems with an implicit configuration of deficit irrigation, 'All Drip + RWH + Infil.' for additional rainwater harvesting (50% surface runoff collected for supplemental irrigation in rainfed cropland), increased soil infiltration capacity, 'All Drip + RWH + Infil. + 50% Mulching' and 'All Drip + RWH + Infil. + 85% Mulching' for the same but additional 50% alleviated soil evaporation (organic mulching) and 85% alleviated soil evaporation (plastic mulching), respectively. See Methods and Jägermeyr et al. 2015, 2016 for details.

Different results can be explained by different model setups: i) LPJmL simulates constrained surface water availability as opposed to unlimited water supply in AquaCrop, ii) both models are not harmonized in terms of parameterization of irrigation system (efficiencies, scheduling, deficit irrigation), and iii) they use different climate and landuse input data that can affect discharge and water availability.

Table S5. Comparison of the AquaCrop and LPJmL model in terms of water savings and yield potential.

AquaCrop				LPJmL			
Scenarios	IWC	IWA	Prod	Scenarios	IWC	IWA	Prod
D-R	-19	-55	-0.1	All Drip	-34	-57	0.3
				All Drip+RWH +Infil.	-34	-57	9
D-R-M	-39	-65	7	All Drip+ RWH +Infil. + 50% Mulching	-44	-64	13
D-R-PM	-46	-68	11	All Drip+ RWH +Infil. + 85% Mulching	-53	-70	15

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