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# Optimizing regional cropping systems with a dynamic adaptation strategy for water sustainable agriculture in the Hebei Plain

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## Abstract

Unsustainable overexploitation of groundwater for agricultural irrigation has led to rapid groundwater depletion and severe environmental damage in the semi-arid Hebei Plain of China. Field experiments have recommended annual winter fallowing (i.e., forgoing winter wheat production) as the most effective way to replenish groundwater. However, adopting the recommendation across the Hebei Plain would lead to a significant reduction in total wheat production. This research aims to find the most favorable water-sustainable cropping systems for different localities in the Hebei Plain, which at the regional aggregation level maintains the uppermost overall levels of wheat and grain production respectively. Our simulations indicate that in the Hebei Plain, an optimal allocation of a *wheat-early maize relay intercropping system* and an *early maize-winter fallow cropping system* across the Hebei Plain could lead to significant water savings while minimizing grain production losses to around 11%. Compared to the prevailing *wheat and summer maize cropping system*, to prevent a drop in the water table, 39% of the current wheat cropping land would need to be fallowed in winter, reducing irrigation water use by 2,639×$10^6$ $m^3$. Replacing the prevailing *wheat and summer maize cropping system* with our optimized allocation system could lead to a 36% increase in total maize production and 39% decrease in total wheat production, resulting in total agricultural irrigation water savings of 2,322 ×$10^6$ $m^3$ and a total grain production reduction by 11%. The findings indicate the potential benefits of our cropping system adaptation method to meet the challenge of recovering local groundwater level with the least possible reduction of wheat and total grain production in the Hebei Plain.

**Keywords**: relay intercropping system; groundwater overexploitation; cropping system adaptation; water sustainable agriculture; the Hebei Plain; China

## 1. Introduction

Heavy dependence on groundwater irrigation has been the key feature of wheat production in the water scarce Hebei Plain (Yuan and Shen, 2013; Hu et al., 2016), where much of China's wheat is produced. Current intensive multi-cropping systems constitute about 70% of the total water use in the Hebei Plain, of which 70% is consumed by wheat irrigation (Lv et al., 2013). About 400 mm of groundwater is required to irrigate wheat under local farmers' conventional practice (Sun et al., 2011). The large amount of water demand for agricultural irrigation exceeds the renewable water availability, and has led to subsequent unsustainable groundwater over-exploitation. As a result, the water table has dropped rapidly from 10 meters below the land surface in the 1970s to 40 meters in the early 2010s (Shen et al., 2002; Zhang et al., 2011), which has caused serious environmental degradation and considerable economic losses (Zhang et al., 2009). The scarcity of groundwater in the Plain is alarming; and the soaring water use from industries and municipalities has put additional pressure on the rapidly dropping groundwater table (Wang et al., 2009). The agricultural sector in the Plain faces a two-fold challenge. On the one hand, the groundwater shortage has already threatened wheat production in the Plain (Li et al., 2015), potentially compromising China's food security in the near future. On the other hand, the current practice of overexploiting groundwater would need to stop as soon as possible to conserve the aquifers (van Oort et al., 2016).

The two-fold challenge of the agricultural sector has stimulated a large body of research on water saving irrigation technologies, less water-intensive cropping systems, and cost-benefit analyses of fallow cropland (Kang et al., 2002; Li et al., 2005; Sun et al., 2011; Yang et al., 2015; van Oort et al., 2016). Under the current cropping system, even reducing the irrigation frequency to one time per crop growth cycle (i.e., deficit irrigation) cannot prevent the water table from dropping (Sun et al., 2015). Thus, many researchers have tried to construct alternative water-sustainable cropping systems. Because of dry winter and spring, wheat growth requires much more irrigation than other cereal crops in the Plain (Yang et al., 2015), alternative water-sustainable cropping systems that partially or completely forgo winter wheat are suggested to replace the prevailing *winter wheat-summer maize sequential cropping* (WM-S). These alternative cropping systems include single cropping of spring maize (Pei et al., 2015), double cropping per year of early maize and late maize (Meng et al., 2017), and triple harvests in two years of WM-S followed by spring maize (Meng et al., 2012), and strip relay-intercropping of wheat followed by spring maize (Gao et al., 2009).

The recent field experiments reported in Pei et al. (2015) revealed that early maize, which moves the traditional maize sowing date earlier by 10-20 days, has a much higher water productivity compared with summer maize and spring maize. Based on the productivity advantage of early maize, Zhong et al. (2017) recommended a regional-scale cropping system adaptation strategy for the North China Plain, which includes the Hebei Plain, under the constraints of local water supply. Their recommendation would supersede the current WM-S with the *early maize-winter fallow* (EM-F) and the *winter wheat-early maize relay intercropping* (WM-R). Their recommended strategy reconciles the two-fold challenge of maintaining regional grain production while recovering groundwater in the North China Plain. However, this reconciliation is a result of a large-scale substitution of wheat for maize and would lead to a considerable reduction in wheat production. Reduced wheat production would undermine the food security of Northern China, where wheat is the number one staple food for locals. Xiao et al. (2017) presented a farm-level water sustainable cropping system of triple cropping in two years, with winter wheat-summer maize sequential cropping in the first 12 months followed by winter fallow and early maize in the second 12 months (WM-FE), at Luancheng Agro-Ecological Experimental Station (114.41°E, 37.53°N) in the Hebei Plain. Their simulations using the APSIM model (Keating et al., 2003) showed promising potential of the WM-FE regime to achieve neutral groundwater depletion with a moderate reduction in total grain yield of 13%, but a significant wheat yield reduction of 50% compared with the existing WM-S regime. However, the equilibrium of the water table depth under WM-FE could not be established without two groundwater recharge sources: (1) A groundwater recharge of 113 mm/year from the mountain-front recharge system, which is only available in the piedmont part of the Hebei Plain (Chen et al., 2003; Hu et al., 2010; Sun and Ren, 2013). (2) An additional surface water recharge of 41 mm/year from the South-North Water Transfer Project. An application of this site-based result to other locations would lead to a water table drop by about 200 mm/year and a reduction of regional total wheat production by 50% in the Hebei Plain (Luo et al., 2018).

Although the adaptation strategies suggested by Zhong et al. (2017) and Xiao et al. (2017) were unable to avoid significant reduction in wheat production, a combination of the complementary advantages of WM-R in higher yield and EM-F in water savings may allow us to develop an optimal allocation method; one that achieves local groundwater equilibrium and minimizes the reduction of total wheat production in the Hebei Plain. Our method also considers other various existing multi-cropping systems along with the water usage of various crops, vegetables, and fruit trees. To facilitate the design and assess the performance of our method, we employ DSSAT 4.6 to simulate the crop growth processes and the associated evapotranspiration levels of the WM-S, WM-R and EM-F regimes under the optimal irrigation schedules presented in Sun et al. (2011). Owing to the lack of field observation data and the limitations in scope of the DSSAT model, we employ AEZ v3.0 to simulate the evapotranspiration levels in each growing stage of other crops, vegetables and fruit trees.

Our results demonstrate that it is possible to meet the two-fold challenge in the Hebei Plain of maintaining regional grain production while stopping overexploitation of groundwater. The spatially explicit winter-wheat sacrificing strategy demonstrated in this research provides support to future agricultural policy designs aiming to recover groundwater in the Plain.

## 2. Study Region

The Hebei Plain (113.5°E–117.8°E, 36.0°N–39.5°N) is located in the northern part of the North China Plain, bounded by the Taihang Mountains on the West and Bohai Sea on the East (Figure 1). It includes 84 counties, covers a total area of 61,636 $km^2$, and has a semi-arid monsoon climate with average annual temperatures of 12-13°C and 450-600 mm of annual precipitation. Seasonal precipitation is highly variable, with about 80% of the annual precipitation occurring in the summer (June to September), and less than 20% occurring in winter and spring. The local thermal resource is sufficient for sequential cropping systems of two harvests in one year or three harvests in two years. In the Hebei Plain, WM-S is the prevailing cropping system. Farmers cultivate summer maize from mid-June to late September, while sow winter wheat in early October and harvest it in early June in the following year.

The Hebei Plain is divided into three zones: the piedmont, central, and coastal plain. The piedmont plain has relatively more plentiful groundwater resources than its central and coastal counterparts because of the mountain-front recharge, waterbody leakage (reservoir), and groundwater lateral flow. The once abundant groundwater resources of the shallow aquifer and better soil conditions made the piedmont plain the most suitable zone for irrigation expansion, and has the highest cropland irrigation ratio among the three zones. However, persistent groundwater over-pumping has led to a precipitous drop in the water table at an annual rate of 0.3-1.3 meters. The fastest drop has been in the Shijiazhuang-Baoding irrigation district of the piedmont plain. In contrast, groundwater resources for most of the central and coastal plains are limited and stored deep within the aquifer. The brackish groundwater in the shallow aquifer of the coastal plain is typically not suitable for crop irrigation because of the high soil salinization risk. Groundwater recharge from rivers, lakes, and wetlands has reduced significantly because surface water flow to the central and coastal plains is often cutoff by reservoirs built upstream, especially during the dry seasons. Limited groundwater availability constrains cropland irrigation expansion in these regions. On the other hand, continuous over-pumping of the limited freshwater resources has caused the deep groundwater level to rapidly drop. Groundwater depletion has triggered considerable seawater intrusion in the coastal region. The deepest groundwater level is 100 meters below the mean seawater level (Foster and Perry, 2010), The Cangzhou irrigation district of the coastal plain has been especially affected.

*(Figures 1 and 2 are about here)*

# 3. Data and Methodology

## 3.1 Data

Input data to run the DSSAT model and AEZ model includes daily weather, soil profiles, land use map, wheat and maize cropping management information, and irrigated versus rainfed land for all crops and fruit trees that grow in the Hebei Plain.

A historical daily weather dataset (2000-2010) of the Hebei Plain was taken from the observation-based WATCH Forcing Data methodology to ERA-Interim data (WFDEI) product (Weedon et al., 2014), with a spatial resolution of 0.5 degrees. Meteorological variables of daily minimum and maximum temperature, Downward Shortwave Radiation flux, rainfall and snowfall rates were used to generate the weather dataset required by the DSSAT model. In addition, wind speed and relative humidity data were used to meet the requirements of the AEZ model.

The cropland map of the Hebei Plain in 2000 was extracted from the National Land Cover database provided by the Institute of Geographical Sciences & Natural Resources Research (IGSNRR) of the Chinese Academy of Sciences, with a spatial resolution of 100 meters. Cropland was further divided into four sub-types: plain cropland, hilly cropland, mountain cropland, and cropland with slope greater than 25 degrees. Only plain cropland was considered suitable for the WM-R in this study, and WM-S on other cropland sub-types would be partially or completely replaced by EM-F to reach water balance. The soil profile dataset, employed as a DSSAT model input and required by the AEZ model, was obtained from the Harmonized World Soil Database (HWSD) (Fischer et al., 2008), with a spatial resolution of 1 km. Additional soil properties not covered by the HWSD, but required by the DSSAT model, were retrieved using the methods described in Tian et al. (2014).

Crop-specific, irrigated and rainfed harvest areas of wheat, maize, and all other crops in the Hebei Plain grown in 2000 were obtained from the MICRA2000 database (Portmann et al., 2010). It provided monthly irrigated and rainfed area measurements for 26 crops grown in 2000, with a spatial resolution of 5 arc minutes (about 9.2 km in the Hebei Plain). The harvest area database is capable of representing multi-cropping systems and maintains consistency by construction with the census-based agricultural statistics from the National Bureau of Statistics of China. This dataset has been successfully applied to estimate water consumption change caused by changing the area sown to winter wheat in the North China Plain (Wang et al., 2015). Figure 2 shows that the area ratios of irrigated wheat, irrigated maize and rainfed maize to the county's total cropland were much higher for wheat and moderately higher for maize in the piedmont than in the central and coastal plains. The observed pattern was a result of lateral flow recharge from the Taihang Mountains on the west of Hebei Plain in combination with better soil condition and richer shallow-groundwater resources there (Mo et al., 2006).

All DSSAT inputs were resampled into grid cells with a spatial resolution of 1 km.

### 3.2 DSSAT model

The DSSAT model was developed by the International Benchmark Sites Network for Argo-technology Transfer project (IBSNAT). It simulates the growth and development of crops within a uniform plot of cropland under precise or assumed field management conditions on a daily basis. It also simulates changes in water, carbon, and nitrogen levels in the soil associated with crop growth and development (Jones et al., 2003). The performance of the DSSAT model in simulating soil water balance, crop growth and yield had been validated with field observations at Luancheng site in Hebei Plain (Yang et al., 2006) and Yingke site in Northwest China (Jiang et al., 2016). The DSSAT model was employed to quantify the amount of irrigation water savings required to stop groundwater drawdown under the prevailing WM-S regime in the Shijiazhuang Irrigation District of Hebei Plain (Hu et al., 2010).

The soil-water balance module in the DSSAT model simulates the soil-water processes and the soil-water content in all soil profiles (Ritchie, 1985). Daily soil-water balance is calculated using precipitation, infiltration, runoff, soil transpiration, plant evaporation, and drainage during the crop growth period (Jones et al., 2003), presented in Eq. 1.

$$\Delta S = P + I - ET - R - D \quad (1)$$

In Eq. 1, *ΔS* is the net change in soil water content. *P*, *I*, *ET*, *R*, and *D* denote precipitation (water resources), effective irrigation, evapotranspiration, surface runoff, and drainage from the soil profile, respectively. All inputs and results are in mm. The local water resource change, which is the difference between water recharge (i.e., drainage: *D*) and water extraction (i.e., effective irrigation: *I*), is expressed as:

$$D - I = P - ET - R - \Delta S \quad (2)$$

To estimate local groundwater resource change across grid-cells in a large region using the DSSAT model, previous studies have employed several critical assumptions: (1) Surface runoff can be neglected ($R = 0$) for the regional scale assessment due to the dried off of the surface, high soil infiltration, flat topography, and small cropland parcels in the North China Plain (Yang et al., 2015). (2) Soil moisture storage can be considered stable and soil moisture change is negligible ($\Delta S = 0$) in this Plain (Moiwo et al., 2009, 2010), because large-scale intensive irrigation and the lack of long-term drying trends in the root-zone. (3) Due to the lack of reliable observational data on groundwater lateral flow, surface water flow and distribution of wells in the piedmont plain, the mountain-front recharge from the Taihang Mountains in the piedmont plain and vertical infiltration from waterbodies are not considered in the regional simulation (Chen et al., 2010). Nevertheless, we believe mountain-front recharge and vertical infiltration may still benefit groundwater recovery. Therefore, the local water resource change is expressed as:

$$D - I = P - ET \quad (3)$$

In Eq. 3, *P* and *ET* refer to the local water resource and the crop water consumption (evapotranspiration). Local water balance is achieved if $D - I = P - ET = 0$. Because the DSSAT model can simulate water consumption (*ET*) of different cropping systems and precipitation (*P*) is available from the regional climate dataset, we use $P - ET$ to calculate the local water resource change (or Irrigation Water Requirement, $IWR = P - ET$) under different cropping systems during the study period.

The total Irrigation Water Requirement ($IWR_{total}$) from the annual harvested area of winter wheat, summer maize, and early maize under irrigated condition was calculated using the equation from Yang et al. (2010):

$$IWR_{total} = \sum_{i=1}^{n} IWR_i \times AR_i \quad (4)$$

Where $IWR_i$ refers to the Irrigation Water Requirement of crop $i$ during the crop growth period, which includes winter wheat, summer maize, and early maize. And $AR_i$ is the irrigated area of wheat and maize in each grid cell. Irrigation water requirement of each cropping system (WM-S, WM-R, EM-F) was simulated at a daily step under a given crop calendar and irrigation condition.

The DSSAT wheat and maize models have been widely applied in the Plain (Figure 1). Yang et al. (2006) calibrated and validated the performance of the DSSAT wheat and maize models at the Luancheng experimental station (114.68°E, 37.88°N). They obtained the genetic coefficients of local winter wheat and summer maize varieties via DSSAT calibration and then employed these coefficients to simulate the total crop irrigation water use and soil water balance. Zhong et al. (2017) calibrated the DSSAT-maize model and obtained the genetic coefficients of early maize based on the field observations of intercropped early maize in the Tangyin agro-meteorological observation station (114.24°E, 36.03°N) and the shading algorithm developed by Knorzer et al (2011) for the wheat-maize co-growing period. Among 10 agro-meteorological observation stations in the North China Plain that have valid records of wheat-maize multiple cropping, Tangyin station is the only one with valid records for the WM-R system. Table 1 presents the cultivar coefficients of local wheat, summer maize and early maize varieties. For other crops, vegetables, and fruit trees planted in the Hebei Plain, we employed the simple soil-water balance module of the AEZ model to simulate their water use. This is because the DSSAT model could not cover all crops in the Plain, and the model calibration requires detailed field observations, which were difficult to obtain for other crops and vegetables.

*(Table 1 is about here)*

## 3.3 AEZ model

The AEZ 3.0 model was employed to estimate the evapotranspiration of non-wheat and non-maize crops. The AEZ model was jointly developed by the International Institute for Applied Systems Analysis (IIASA) and the Food and Agriculture Organization (FAO) of the UN (IIASA/FAO, 2012). It uses the prevailing climate resources, soil profile and topography conditions, and detailed agronomic-based knowledge to simulate crop productivity and soil water balance with standardized soil-plant-atmosphere interaction algorithms. Such standardized methodologies make the AEZ well suited for crop productivity assessment at the regional level where detailed and spatially explicit input data are relatively limited (Tubiello and Fischer, 2007; Gohari et al., 2013). The AEZ model has been successfully applied to estimate the actual evapotranspiration ($ET_a$) of wheat and maize in the Hebei Plain (Wang et al., 2015). The equation to estimate the $ET_a$ is as follows:

$$ET_a = \begin{cases} ET_0 \times K_c & \rho = 1 \\ P + \rho \times ET_0 \times K_c & \rho < 1 \end{cases} \qquad (5)$$

Where $ET_0$ refers to the reference crop evapotranspiration, which is calculated using the widely applied Penman-Monteith equation (Allen et al., 1998). $K_c$ refers to the crop coefficients, which varies in different crop growth stages. The $K_c$ coefficients for all other crops are obtained from FAO (Allen et al., 1998). $P$ is the daily precipitation. ρ refers to the soil-water coefficient in the AEZ model. If the current water balance is greater than or equal to the threshold of readily available soil water, then $\rho = 1$. If the permanent wilting capacity is less than the current water balance, and the current water balance is less than the readily available soil water, then $0 < \rho < 1$. If the current water balance is less than the permanent wilting capacity, then $\rho = 0$ (IIASA/FAO, 2012; Wang et al. 2015).

Because not all of the crops in the MICRA2000 dataset were planted in the Hebei Plain, and there was a mismatch of the crop types between the AEZ model and the MICRA2000 dataset, we grouped crops planted in the Hebei Plain into 14 groups (rice, barley, rye, millet, sorghum, soybean, sunflower, potato, sugar cane, sugar beet, groundnut, citrus/fruit tree, cotton, cabbage/vegetables). The evapotranspiration of fruit trees (other than citrus) were calculated with the Pan-ET method using the Pan-evaporation coefficient from Yang et al. (2010). The Pan-ET method derives evapotranspiration by,

$$ET_i = \lambda_i \times ET_{pan} \quad (6)$$

where $ET_i$ is the actual evapotranspiration, and $\lambda_i$ is the pan-evaporation coefficient for fruit tree $i$. $ET_{pan}$ is the local observations of evapotranspiration from a 200 mm diameter evaporation pan in the meteorological stations in the Hebei Plain.

It is worth noting that the estimation of evapotranspiration played a central role in this research. We ensured that evapotranspiration estimates were compatible across the DSSAT model, the AEZ model, and the Pan-ET method, as all of them used the same Penman-Monteith equation (Allen et al., 1998) for the estimates.

## 3.4 Cropping system adaptation strategy

Using a loop method (Figure 3), we established our cropping system adaptation strategy to keep total local agricultural water consumption within the limits of the local water resource. It replaces the current WM-S with WM-R or EM-F across the grid-cells within each county of the Hebei Plain. For other crops, vegetables, and fruit trees, we assumed that their areas and planting locations remained the same, as did their evapotranspiration. The WM-R and EM-F cropping area were dynamically allocated within the WM-S occupied grid-cells. Our aim was to achieve local water balance under the constraint of minimizing the reduction in wheat production and subsequently total grain production in each county. The reason for doing the initial balance loop at the county level is as follows. Our simulated balance loop experiments for the whole of the Hebei Plain led to significantly higher reductions of wheat production in comparison with the simulated balance loop experiments within each county. In more detail, for the whole of the Hebei Plain, completely forgoing winter wheat results in excessive water saving in the northern Hebei Plain to compensate for water over-consumption in the southern Hebei Plain; whereas at the county level, partially forgoing winter wheat to lower groundwater exploitation-discharge balances out within each county. The intuition is that while there were no significant lateral water flows across the three sub-plains, at the intermediate scale of a county, it becomes more likely for groundwater to be balanced via lateral underground water flow from the areas with a higher water table (groundwater recovery) to the areas with a lower water table (groundwater overdraft), as shown in Figure 11 of

Kendy et al. (2003). Therefore, we applied the cropping system allocation method across grid-cells within each county.

Major steps of the allocation method (Figure 3) are: (1) At the grid-cell level, we estimated the evapotranspiration of the WM-R, WM-S, EM-F regimes under an optimal irrigation schedule using the DSSAT model; and estimated the evapotranspiration of other crops, vegetables, and fruit trees using the AEZ model and the Pan-ET method. (2) We identified the areas of existing planting systems —*wheat and summer maize cropping system* (WM-S), *wheat-other crops multi-cropping system*, and *other cropping systems*—based on the existing wheat and maize cropping areas within each grid cell. We assumed that land occupied by other crops, vegetables, and fruit trees would remain unchanged, and that fallowing might replace wheat in the areas occupied by the *wheat-other crops multi-cropping system* to save water. (3) At the grid-cell level for a given county, we calculated the *remaining total water resource* from the total water supply from precipitation less the total evapotranspiration of the *winter fallow-other crops multi-cropping system*s and all other cropping systems not including the *wheat-maize multi-cropping* system. We then sorted all grid cells in ascending order according to their *remaining total water resource*. (4) Using the algorithm developed by Zhong et al., (2017), we estimated the baseline of WM-R and EM-F allocations under the constraint of no loss in total grain production within each county. We then compared the total evapotranspiration of the adaptive cropping systems (WM-R and EM-F) to the ascending list of *remaining total water resources*. (5) If the evapotranspiration from the adaptive cropping systems is less than the *remaining total water resource*, then using more water would increase wheat production. We then replaced EM-F with WM-R starting from the grid-cell with highest *remaining total water resource*. If the evapotranspiration from the adaptive cropping systems is greater than the *remaining total water resource*, then fallowing wheat fields would increase water savings. We then replaced WM-R with EM-F starting from the grid-cell with lowest *remaining total water resource*. We perform this final adjustment to balance the agricultural water use and groundwater recharge within a county. We repeated steps 3-5 for each county in the Hebei Plain. (6) Finally, we compared the adaptive cropping systems to the existing wheat and maize cropping systems in the Hebei Plain, to measure the impact on grain production, fallowed area extent, and groundwater flows.

*(Figure 3 is about here)*

### 3.5 Crop management and DSSAT model upscaling

Regional crop production and evapotranspiration across the Hebei Plain were simulated using the DSSAT model up-scaling method (Tian et al., 2012) with local wheat, maize and early maize cultivars (Yang et al., 2006; Zhong et al., 2017). The local summer maize sowing dates in the Hebei Plain under the WM-S were obtained from Figure 2 in Binder et al. (2008), which were based on observations from 14 agro-meteorological stations in the North China Plain. Summer maize was sown right after the harvest of wheat, and wheat was sown 10 days after the harvest of maize for land preparation. In contrast, under the WM-R and EM-F, early maize was sown 15 days before the existing wheat harvest date (Zhong et al., 2017).

Optimal wheat and maize irrigation schedules, as developed by Sun (2011), were applied to reduce the irrigation water amount, and automatic irrigation was selected in the DSSAT model to maintain the soil moisture between 45% and 80% of soil water capacity during the critical wheat growing stages. Maize was irrigated during germination and the jointing stage in the case of dry weather condition (Pei et al., 2015; Sun et al., 2011). The optimal crop management was applied with the absence of weeds, no pests and diseases, and no nutrient constraint. 100 kg of nitrogen fertilizer was applied at sowing and stem elongation to ensure no nitrogen limitation during the crop growth period (Wang et al., 2012). Therefore, the wheat and maize yield were the attainable yields under optimal crop irrigation and management conditions.

## 4. Results

### 4.1 Evapotranspiration under existing cropping systems

The evapotranspiration of wheat, summer maize, and early maize under optimal irrigation schedule, and the evapotranspiration of other crops and fruit trees under the existing regional cropping systems are estimated using the DSSAT model, the AEZ model, and the Pan-ET method. Table 2 reports the aggregate evapotranspiration of wheat, maize, and the combination of other crops, vegetables, and fruit trees across the three plains. And Figure 4 depicts the spatial distribution of their evapotranspiration shares. As shown in Table 2, wheat and maize account for 28% and 23% of the total evapotranspiration in the Hebei Plain. In the piedmont plain where the area share of wheat and maize is the highest among the three plains, wheat and maize together account for 56% of the total evapotranspiration. In contrast, the evapotranspiration shares of wheat and maize in the central and coastal plains are smaller than the evapotranspiration share of other crops, vegetables, and fruit trees combined.

*(Table 2 and Figure 4 are about here)*

### 4.2 Areas for wheat fallow and *wheat-early maize relay intercropping system* (WM-R)

In Table 3 we present the aggregate results for winter wheat fallow areas and the potential of WM-R. And Figure 5 shows the spatial distribution of winter wheat fallow areas compared with existing wheat cropping areas, and WM-R compared to the existing WM-S cropping area, at the county-level. Table 3 shows that compared with the central and coastal plains, the piedmont plain has the highest ratio of wheat fallow land to the existing wheat land (45%). The disparity is because of the higher area-share of wheat in the county's total cropland and the greater Irrigation Water Requirement of wheat in the piedmont plain. Some counties in the piedmont plain would even need to fallow about 70% of their wheat cropped land to achieve water balance. In contrast, about 36% and 33% of the wheat cropped land would need to be fallowed in the central and coastal plains, especially in the southern part of the Hebei Plain. The central plain becomes the preferred location to fallow because wheat cropped land in the central plain is much larger than the piedmont and coastal plains.

Our results in Figure 5 and Table 3 also indicate that WM-R would be the dominant cropping system under our adaptation strategy. Thus, 72%, 76%, and 68% of the existing WM-S area in the three sub-plains will be replaced by WM-R in order to minimize the reduction of both the total wheat production and the total grain production. Figure 5 shows that counties in the southern Hebei Plain would have a larger portion of their existing WM-S cropping area replaced by WM-R due to the smaller ratio of fallowed land to the existing wheat land. Whereas, counties with a high ratio of fallowed land would be located in the middle of the piedmont plain and central plain. The relatively smaller portion of their existing WM-S cropping land would need to adopt WM-R.

*(Table 3 and Figure 5 are about here)*

### 4.3 Regional grain production and Irrigation Water Requirement (IWR) change

Table 4 shows the changes in the potential production of wheat, maize, and the regional total grain production between our adaptive cropping systems and the existing cropping systems in the Hebei Plain. It shows that the total wheat production in the piedmont, central and coastal plain would be 45%, 36% and 33% less than that under the existing cropping system, respectively. This implies that our wheat fallow strategy may lead to a total reduction in wheat production of 39% in the Hebei Plain, which is smaller than about 50% under WM-FE (at Luancheng site in Xiao et al. 2017 and at the regional level of the Hebei Plain in Luo et al 2018, without considering water-balance of the whole cropping sector) and 100% under EM-F. On the other hand, adopting early maize may increase total maize production by about 35%, 37% and 36% in the piedmont, central and coastal plains, respectively, and this means that the reduction in total production of wheat and maize in the three plains would be decreased to the level of 16%, 9% and 3% respectively. For the Hebei Plain as a whole, total early maize production would increase by 36%, and the total grain production would suffer a moderate 11% reduction

The spatial distribution of the wheat production reduction (see Figure 6) is highly depended on the area ratio of fallowed wheat (see Figure 5), because most of the wheat is irrigated in the Hebei Plain. To various extents, all counties may suffer a reduction in wheat production as a result. Generally speaking, there would be a greater increase in maize production in the south than in the north; which is mainly due to higher precipitation, better thermal resources, and earlier sowing dates of maize during the summer in the south. Although the irrigated maize area in the south Hebei Plain is smaller than in the north, our results indicate that adopting early maize may lead to more maize production in the south. For some counties located in the north piedmont plain, east central plain, and coastal plain, maize production gains would be smaller than in the rest of the Hebei Plain, due to maize growth more often under rainfed conditions during the summer.

The IWR changes in each county across the Hebei Plain (Figure 6) and the total IWR changes across the three plains (Table 5) are also estimated. The total IWR change of wheat and maize is determined by total wheat fallow area and irrigated early maize cropping area in each county. The IWR reduction from wheat fallow is the highest in the north piedmont plain and the central plain, where the area ratio of fallowed land is the highest. Similarly, the IWR increase from replacing summer maize with early maize is also the highest in the north piedmont plain and the central plain because of the share of existing irrigated maize cropping area is the highest there (Figure 2). Aggregated results shown in Table 5 indicate that forgoing winter wheat may reduce the total wheat IWR by 63%, 61% and 42% in the piedmont, central and coastal plain, respectively, a saving in total IWR of $2{,}638.88\times10^6$ $m^3$ for the Hebei Plain as a whole. On the other hand, replacing summer maize with early maize would lead to an IWR increase by 30%, 41% and 23% in the three plains respectively, an increase in total IWR of $316.95\times10^6$ $m^3$. Taking together the above IWR saving and increase, the total IWR in the Hebei Plain would decrease by 44% ($2321.93\times10^6$ $m^3$), which would contribute significantly to the groundwater recovery in the Plain.

*(Tables 4-5 and Figures 6-7 are about here)*

## 5. Conclusions and Discussions

The ongoing water crisis in the semi-arid Hebei Plain, driven by rapid urbanization and irrigation-intensive agricultural systems, has raised public concerns in recent years. Agricultural irrigation, which relies heavily on groundwater and consumes more than 70% of the total regional water use, has received special attention in the Hebei Plain (Lv et al., 2013). A number of groundwater sustainable cropping systems and water saving irrigation technologies have been tested in field experiments, with the aim to optimize field irrigation water management and recover the groundwater table. However, the field experiments all exhibit significant costs in wheat production loss. The significant loss of wheat production would threaten the wheat supply of the northern Chinese population, for whom wheat has been the most important staple food. To overcome the limitations of the existing adaptation proposals, we propose a dynamic adaptation strategy in this research to identify water sustainable cropping systems, with the minimum production loss of wheat and regional grain production overall. Our strategy takes advantage of two alternative cropping systems: *early maize-winter fallow cropping system* to save water, and *wheat-early maize relay intercropping system* to increase grain production. And our strategy is subject to the local constraints at the county level of water balance, climate, soil, water resources, and existing cropping systems for other crops, vegetables, and fruit trees. Results of our simulations using the DSSAT and AEZ models demonstrate that our cropping system adaptation strategy may potentially reduce irrigation water consumption by up to $2{,}321.93\times10^6$ $m^3$, and minimize the penalty of wheat production loss to 39% and total grain production loss to 11%. This level of reduction in wheat and total grain production is much less than comparable figures reported in the alternative cropping system adaptation proposals (see Xiao et al., 2017; Luo et al, 2018). In this way, our simulated scenarios may help prevent ecological disasters from the alarming groundwater crisis, and help to ensure food security for the Chinese population.

To make the newly proposed dynamic cropping system adaptation strategy more practical for local farmers, income compensation policies for fallow cropland, enforceable regulations and pricing for irrigation water use, skill training of water saving irrigation technologies, and mechanization of relay intercropping are necessary (Webber et al., 2008; Feike et al., 2012). Currently, farmers in the Hebei Plain have limited incentive to save irrigation water largely because the pumping of groundwater is constrained only by pumping costs. Great effort should be made to draw the attention of the local farmers to groundwater conservation, and more fundamentally to encourage them to participate in fallowing winter wheat (Wu and Xie, 2017). Income compensation policies with subsidies transferred from the urban sectors to local farmers would greatly promote the willingness of local farmers to abandon winter wheat planting. To encourage the adoption of the *wheat-early maize relay intercropping system,* specialized machines for early maize sowing in row between wheat are needed. In this regard, the “interseeder” machine designed for row relay intercropping of wheat-soybean (Feike et al., 2012) could be adapted for row intercropping of the *wheat-early maize relay intercropping system*.

Many people have advocated that groundwater should be priced in line with its scarcity so as to induce an economic mechanism that would facilitate the sustainable use of groundwater for irrigation (Anderson and Leal, 2001; Nyberg and Rozelle, 1999; Wang et al., 2016; Zhang and Zhang, 1995). However, the literature review of Kendy et al. (2003) indicated that such a pricing policy change is not necessarily beneficial to the North China Plain, and may impose an undue financial burden on already cash-strapped farmers without solving the intended problem. They argued that higher prices could be justified only if water pricing encourages land-use change. Congruent with their argument, our research findings provide a useful recommendation for future water-pricing policy designs in the Hebei Plain. Namely, to promote the allocation of the *wheat-early maize relay intercropping system* and the *early maize-winter fallow cropping system*.

In addition to reducing irrigation water use for wheat and maize, our simulations of total water consumption in terms of evapotranspiration indicate that it is important to improve the water use efficiency of other crops, vegetables, and fruit trees, and to increase infrastructure investment for highly water-efficient vegetable production via rainwater harvesting and recycle use of water in green houses. Previous studies have focused on optimizing irrigation water management and water use efficiency of wheat and maize in the piedmont plain. As shown by our simulations and Yang et al. (2010), reducing the irrigation of other crops, vegetables, and fruit trees should be considered in future research because they consume nearly 50% of the total irrigation water in the Hebei Plain. More studies at both site-specific and regional scales should be constructed also to identify detailed water saving measurements and strategies for other crops, vegetables, and fruit trees.

Despite the usefulness of both the DSSAT and AEZ models in quantifying the amount of Irrigation Water Requirement and soil water balance based on crop growth, crop management, and climate conditions (Yang et al., 2006; Wang et al., 2015), several limitations of our simulations should be specified. First, our simulations are unable to incorporate additional groundwater recharge from ponds and rivers, drainage water from surface water runoff in the central plain, and underground lateral aquifer flow from the Taihang Mountains. Second, because both the DSSAT and the AEZ models simulate only the soil water balance in the root zone during the crop growing cycle, to further assess the impact of irrigation volume change on groundwater variability and to include additional groundwater recharge sources requires integration of crop-growth models and physical hydrological models (Nakayama et al., 2006; Hu et al., 2010; Shu et al., 2012) or machine learning models (Guzmán et al., 2017). Unfortunately, the integrated crop-hydrology models require very large data inputs for model calibration and up-scaling to the regional scale. Moreover, the existence of numerous dams and wells makes it cost prohibitive to collect detailed data across the region to meet the data requirements of the integrated modeling. Third, although the radiation interception effect on crop growth and yield during the co-growth period of wheat and early maize has been successfully integrated into the DSSAT model, crop transpiration and soil evaporation change during this co-growth period are still unclear due to the lack of field observations on soil temperature and wind speed change during the period (Knorzer et al., 2011). Total evapotranspiration may be slightly overestimated, although only for 15 days at the early stage of maize growth.

Our agricultural adaptation strategy may have beneficial implications for other major cropping regions, which face the same challenge of rapid groundwater depletion, in North America, South Asia, North Africa and Middle East (Konikow and Kendy, 2005; Aeschbach-Hertig and Gleeson, 2012). For example, the Indo-Gangetic Plains (IGP) in India, where severe groundwater depletion has occurred because of the water-intensive wheat-rice double cropping system and irrigated cropland expansion (Zaveri et al., 2016). Similar to the Hebei Plain in China, the summer dominant rainfall monsoon climate in the IGP leads to excessive groundwater irrigation requirements for wheat during the dry winter seasons (Biemans et al., 2016). Besides, proposed field measurements could not reconcile the conflicts between grain production and groundwater recovery in the IGP: site-focused conservation measurements could not stop the groundwater depletion, and agricultural de-intensification will lead to grain production reduction (Bhatt et al., 2016; Balwinder et al., 2015). The similarities between the IGP and Hebei Plain, suggests that our approach to search for a dynamic adaptation strategy could produce a more environmentally sustainable solution to achieve the balance between food security and groundwater recovery in the IGP in India too. On the other hand, it is worth noting that the accuracy of similar regional studies in either China or other regions of the world are highly depended on the data availability in hydrology, agriculture and climate observations and on multiple-model integration across crop model, hydrology model and climate model. More research work in the future is needed to address the accuracy issue.

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Table 1. Genetic coefficients of local wheat, summer maize and early maize

| Winter Wheat | | Summer Maize | | Early Maize | |
|---|---|---|---|---|---|
| Parameter | Value | Parameter | Value | Parameter | Value |
| P1V | 1.5 | P1 | 300 | P1 | 277 |
| P1D | 2.4 | P2 | 0.3 | P2 | 1.05 |
| P5 | -6.0 | P5 | 640 | P5 | 787 |
| G1 | 3.9 | G2 | 740 | G2 | 711 |
| G2 | 3.0 | G3 | 14 | G3 | 10.0 |
| G3 | 2.9 | PHINT | 60 | PHINT | 48 |
| PHINT | 90 | | | | |

Note: (1) Wheat: P1V: vernalization; P1D: photoperiod sensitivity; P5: grain filling duration; G1: kernel number; G2: kernel weight; G3: spike number; PHINT: phyllochron interval. (2) Maize: P1: duration of the juvenile phase; P2: photoperiod sensitivity; P5: duration of the reproductive phase; G2: kernel number; G3: kernel growth rate; PHINT: phyllochron interval. See Jones et al. (2003) for technical details.

Source: Yang et al., (2006) and Zhong et al., (2017).

Table 2. ET of wheat, maize and all other crops, vegetables and fruit trees combined in the three plains

| Plain | Wheat | | Maize | | Others | |
|---|---|---|---|---|---|---|
| | $10^6$ m$^3$ | % of existing total ET | $10^6$ m$^3$ | % of existing total ET | $10^6$ m$^3$ | % of existing total ET |
| Piedmont plain | 2808.61 | 31.74 | 2139.02 | 24.17 | 3900.59 | 44.08 |
| Central plain | 4242.48 | 27.00 | 3487.24 | 22.19 | 7985.42 | 50.81 |
| Coastal plain | 495.31 | 19.91 | 489.39 | 19.67 | 1502.69 | 60.41 |
| **Total** | **7546.40** | **27.90** | **6115.64** | **22.61** | **13388.70** | **49.49** |

Table 3. Areas for winter wheat fallow and potential WM-R cropping

| | Winter fallow area | | WM-R cropping area | |
|---|---|---|---|---|
| | $10^3$ ha | % of existing wheat area | $10^3$ ha | % of existing WM-S area |
| Piedmont plain | -319.92 | -44.78 | 394.54 | 71.50 |
| Central plain | -377.37 | -36.15 | 666.59 | 75.66 |
| Coastal plain | -39.15 | -32.76 | 80.35 | 68.05 |
| **Total** | **-736.44** | **-39.22** | **1141.47** | **73.26** |

Table 4. Changes in wheat and maize production under the adapted cropping systems

| | Wheat | | Maize | | Total | |
|---|---|---|---|---|---|---|
| | $10^3$ ton | % of existing total production | $10^3$ ton | % of existing total production | $10^3$ ton | % of existing total production |
| Piedmont plain | -2469.74 | -44.57 | 1083.53 | 35.27 | -1386.21 | -16.09 |
| Central plain | -2859.09 | -36.02 | 1688.41 | 36.61 | -1170.68 | -9.32 |
| Coastal plain | -282.13 | -32.95 | 233.18 | 32.63 | -48.95 | -3.24 |
| **Total** | **-5610.96** | **-39.14** | **3005.13** | **36.04** | **-2605.83** | **-11.49** |

Table 5. Changes in Irrigation Water Requirement of wheat, maize, and the whole cropping sector under the adapted cropping systems

| | Wheat | | Maize | | Total | |
|---|---|---|---|---|---|---|
| | $10^6$ $m^3$ | % of existing wheat IWR | $10^6$ $m^3$ | % of existing maize IWR | $10^6$ $m^3$ | % of existing total IWR |
| Piedmont plain | -931.05 | -63.47 | 102.18 | 29.89 | -828.86 | -45.82 |
| Central plain | -1588.87 | -60.92 | 201.17 | 40.71 | -1387.70 | -44.73 |
| Coastal plain | -118.97 | -42.09 | 13.60 | 23.14 | -105.36 | -30.86 |
| **Total** | **-2638.88** | **-60.56** | **316.95** | **35.42** | **-2321.93** | **-44.20** |

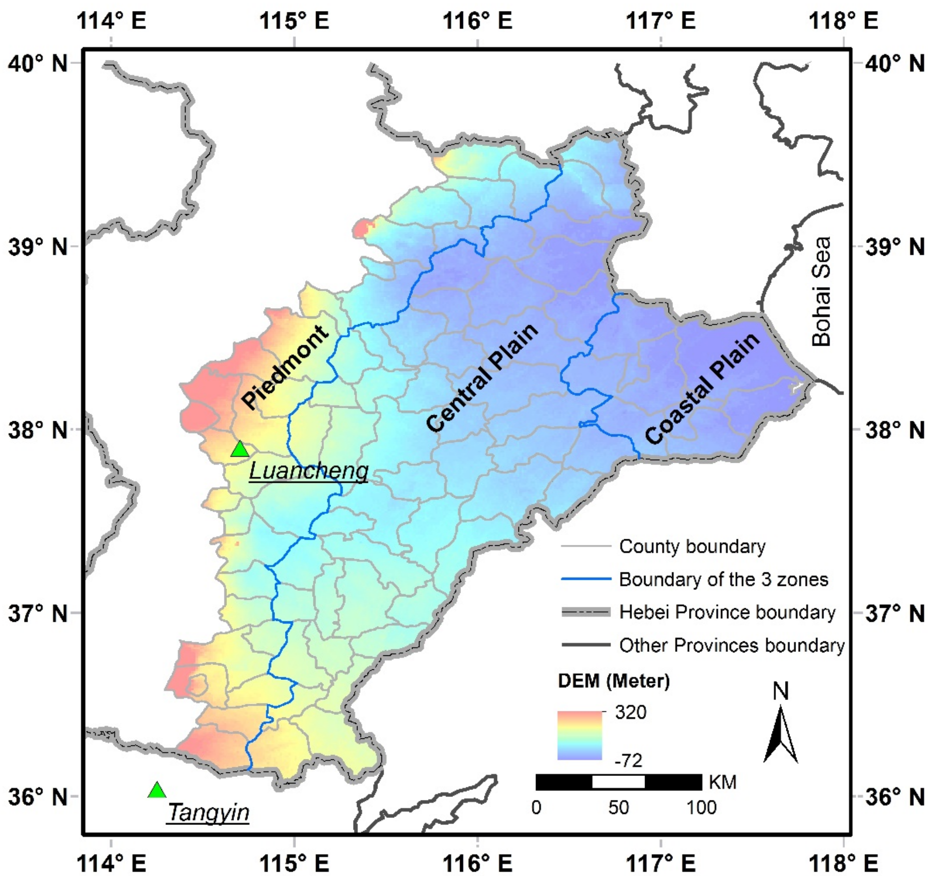


Figure 1. The Hebei Plain

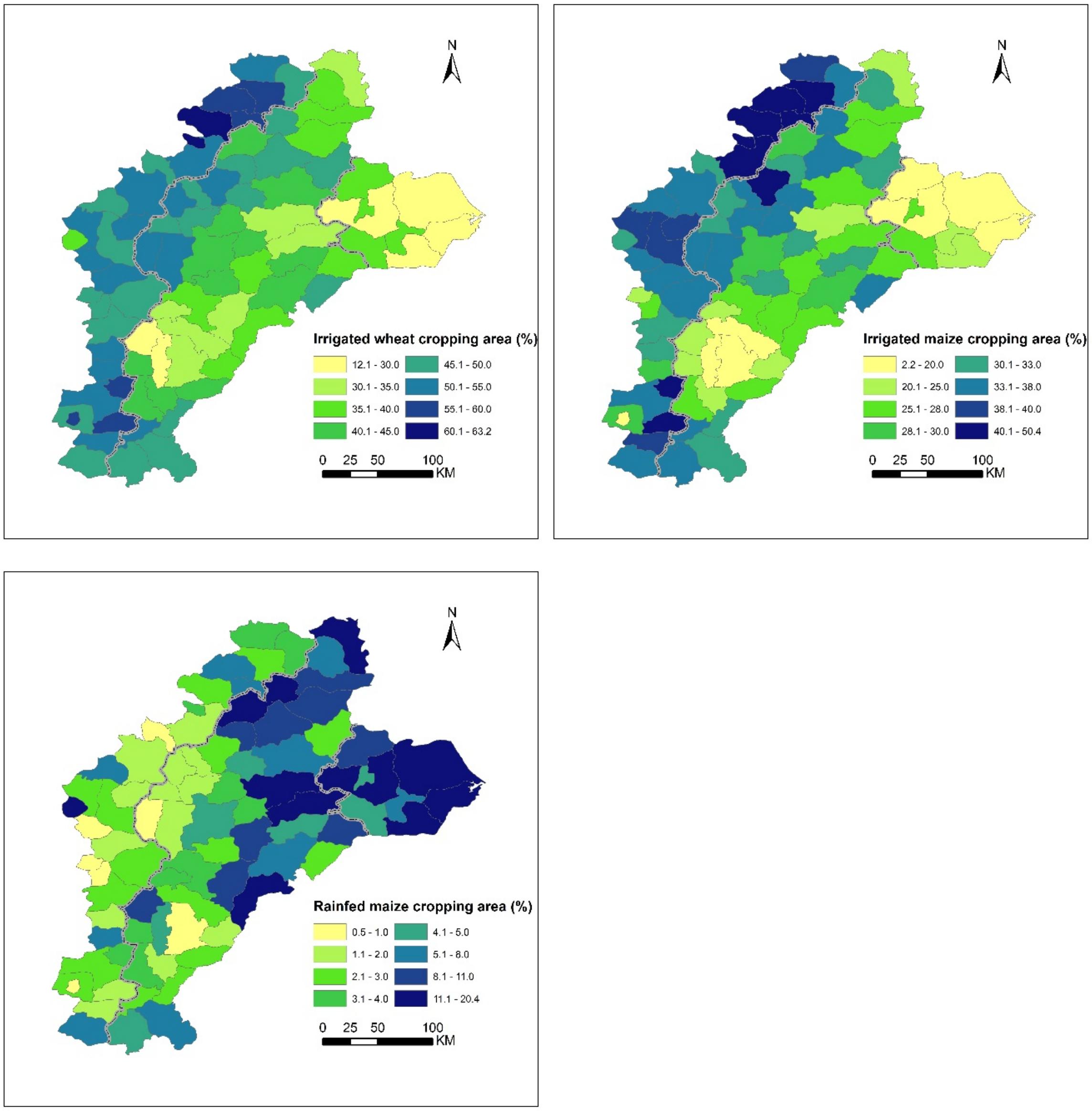


Figure 2. The shares of irrigated wheat, irrigated and rainfed maize cropping area in the county's total cropland across the Hebei Plain

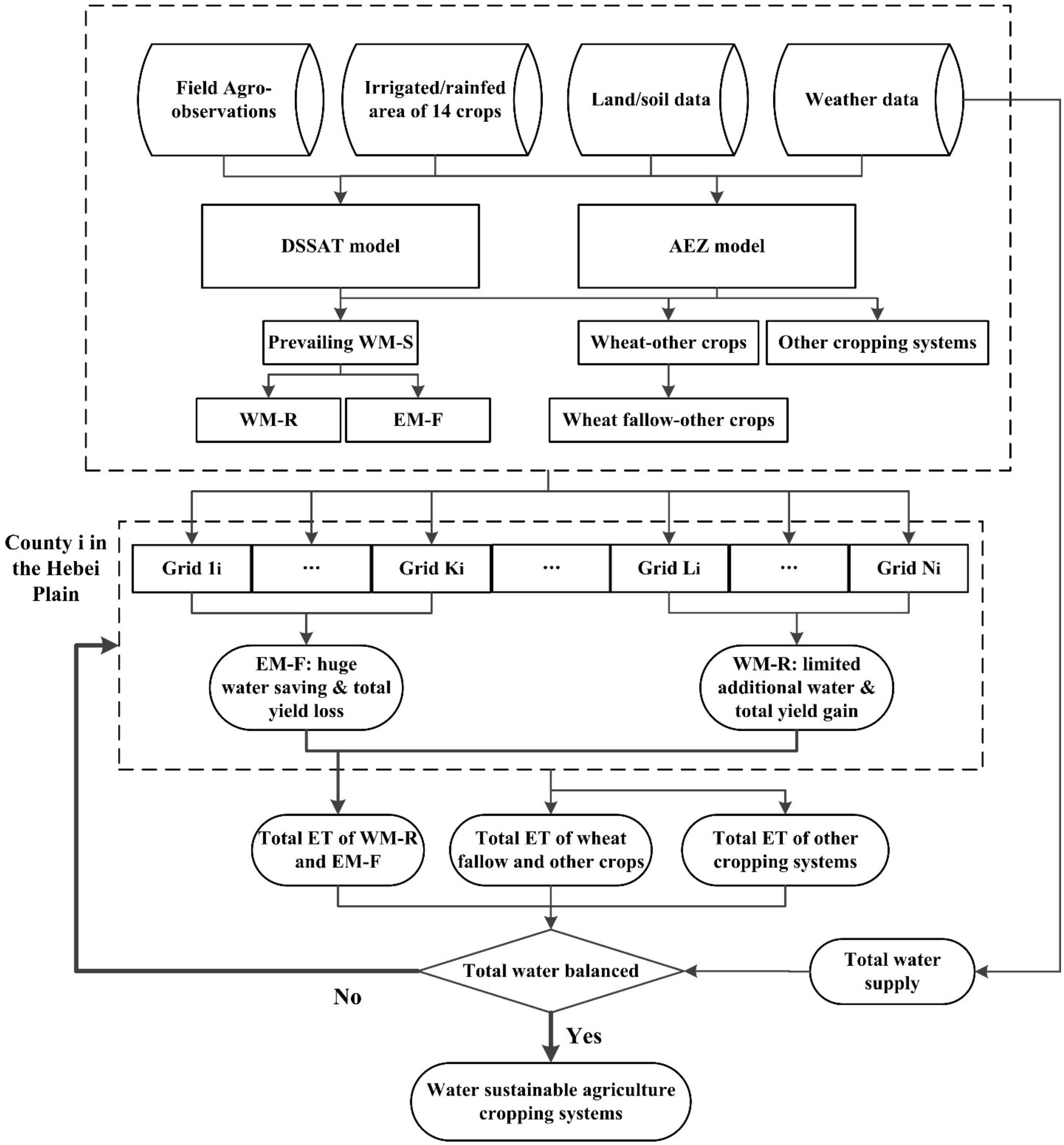


Figure 3. Regional cropping systems adaptation strategy: flow chart

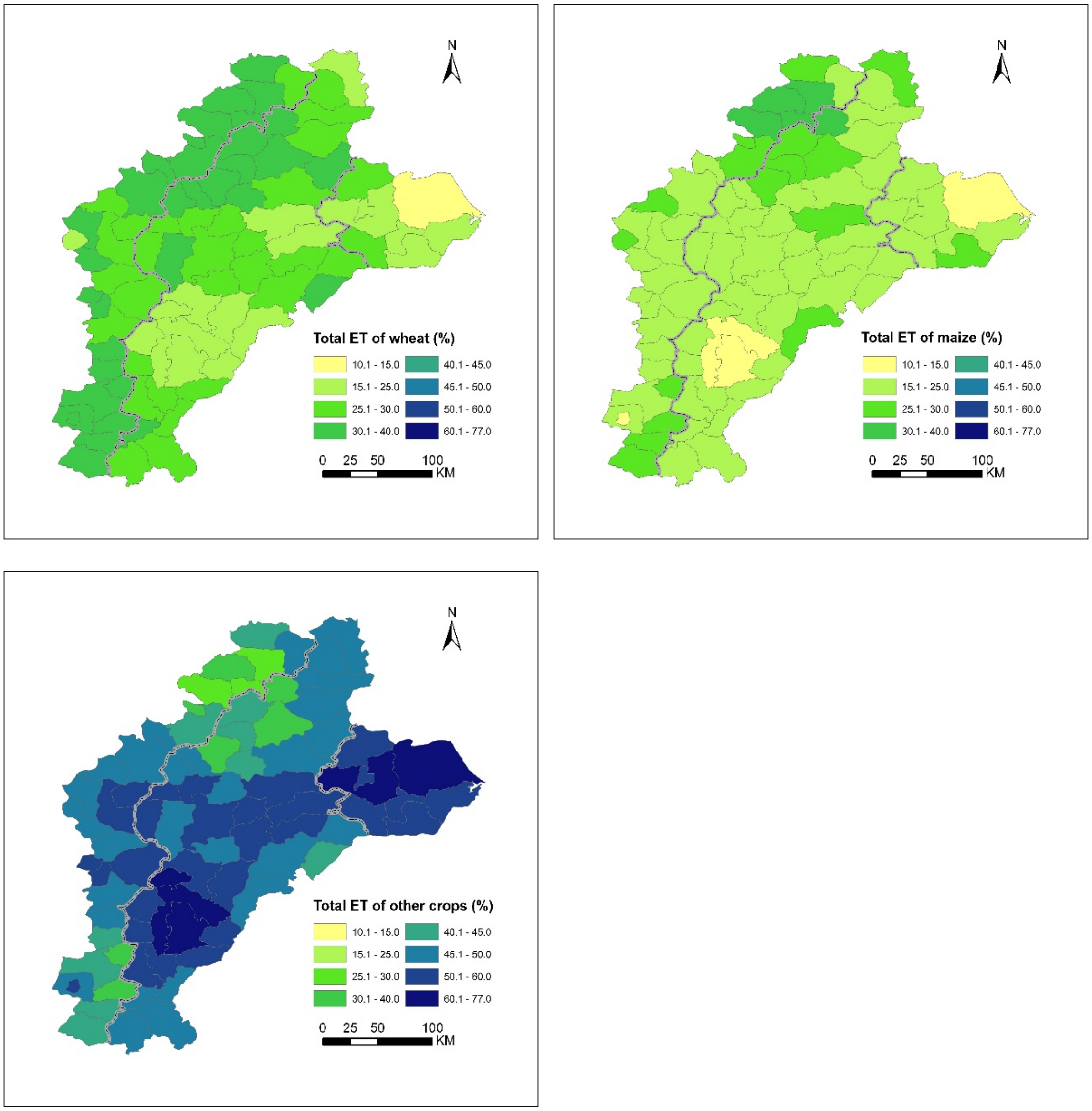


Figure 4. ET share of wheat, maize and the combination of all other crops, vegetables, and fruit trees in the total ET at the county level in the Hebei Plain

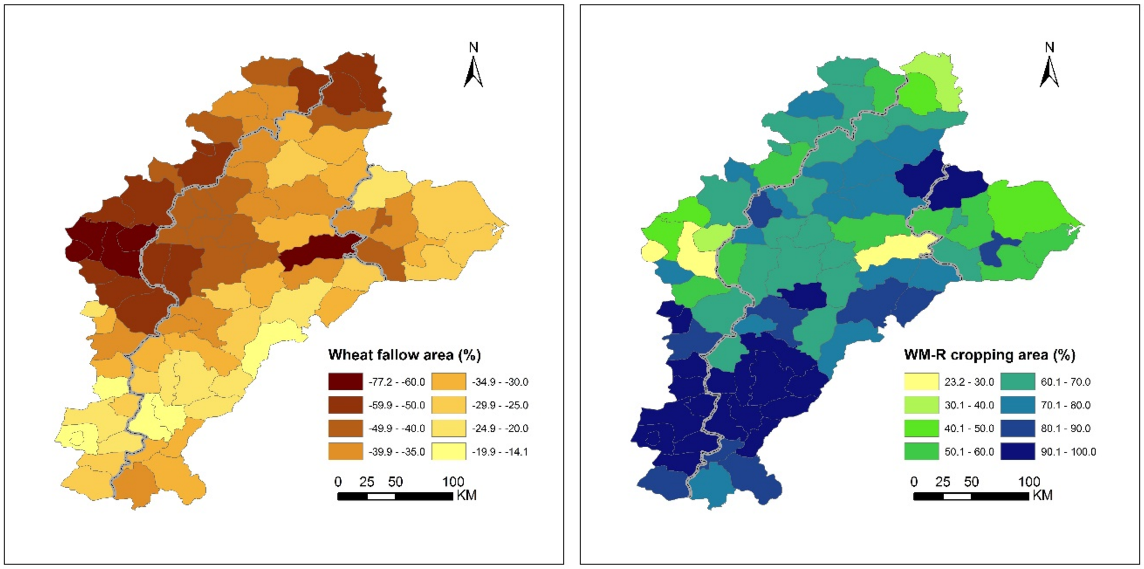


Figure 5. The share of wheat fallow area in the existing wheat area (left) and the share of potential WM-R cropping area in the existing WM-S area (right) at the county level in the Hebei Plain

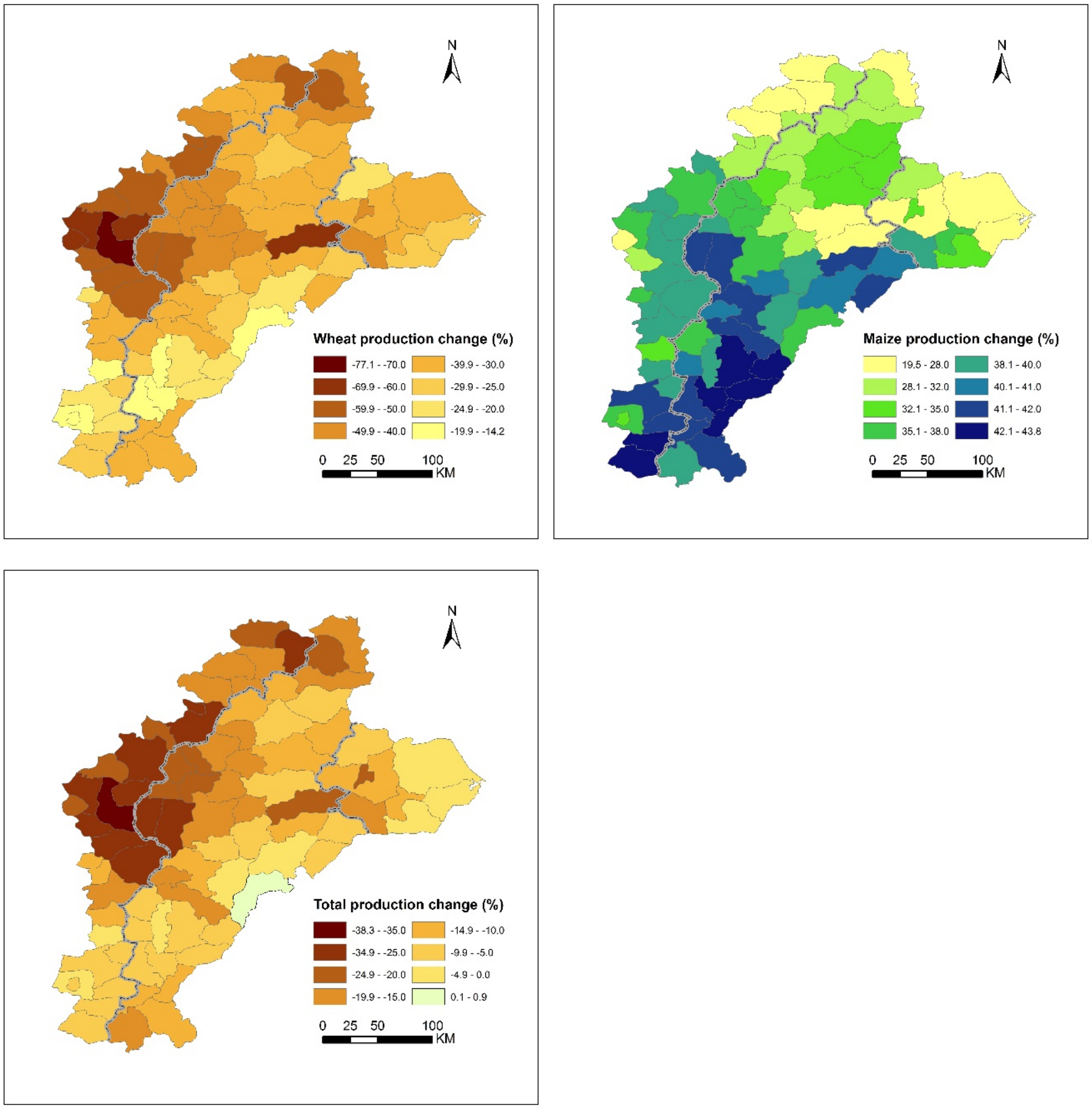


Figure 6. Changes in total production of wheat, maize and total grain at the county level in the Hebei Plain

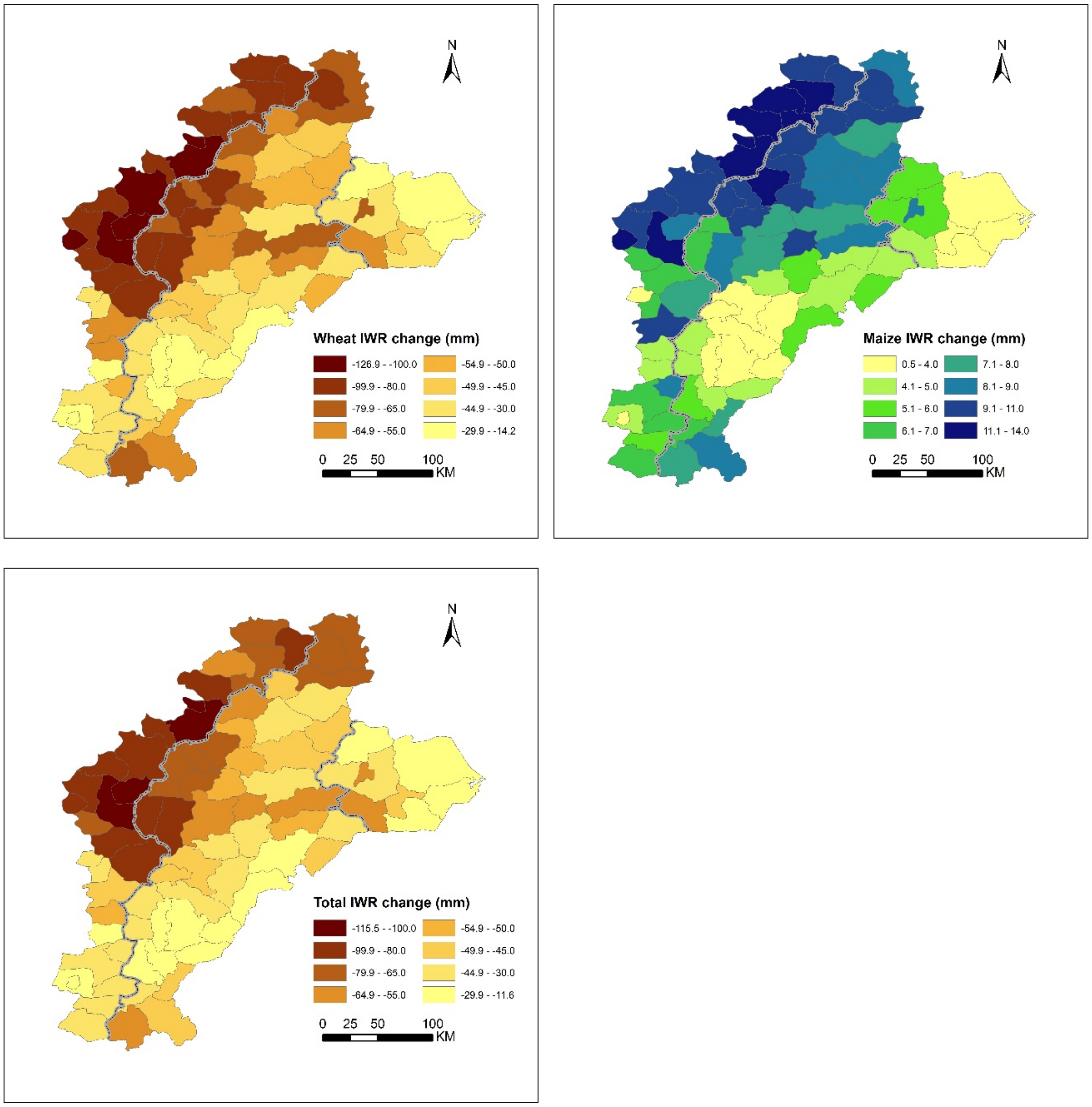


Figure 7. Changes in Irrigation Water Requirement (IWR) of wheat, maize, and the whole cropping sector at the county level in the Hebei Plain