Mission Impossible? Maintaining regional grain production level and recovering local groundwater table by cropping system adaptation across the North China Plain

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Abstract

Insufficient precipitation and continuous over-exploitation of groundwater for agricultural irrigation led to rapid drop of groundwater table in a large part of the North China Plain (NCP), the bread basket of China. It has become widely acknowledged that current practice of winter wheat-summer maize sequential cropping system (WM-S) in the NCP will have to come to an end as soon as possible. Great research efforts have been made at the local level via both field experiments and model simulations to construct groundwater neutral cropping systems but virtually all such constructs show a substantial penalty on total output per unit of land per year. In this research, we propose a strategy to meet the double challenge of maintaining regional grain production level and recovering local groundwater table: 1) Widely adopt winter fallow and early-sowing summer maize monocropping (E-M) in water scarce part of the region to enable groundwater recovery; 2) replace WM-S by wheat-maize relay intercropping system (WM-R) in the water richer part of the NCP to increase grain production so as to compensate yield losses in the water scarce part of the region. Our simulations using DSSAT 4.6 at the site level show that both yield and water productivity of E-M are 33.7% and 41.8% higher than those of existing summer maize, with less than 20% of increase in water requirement. In comparison with spring maize, E-M requires 62.4% less irrigation water, with a yield penalty of only 4.52%. At the regional scale, the simulations targeting at maximizing groundwater saving in water scarce area subject to maintaining the current level of regional total output indicate that about 20.45% of the wheat planting area can be put on fallow in winter, most of which is located in the driest regions of the NCP. This can result in a large amount of groundwater saving at 5.62×10^9 m^3 and a substitution of wheat by maize at 24.3% of the total wheat output. These findings provide new rooms for the relevant policy makers and stakeholders to address the urgent groundwater recovering issues in the northern NCP without compromising the level of food grain production of the region.

Keywords: Agricultural water saving; cropping system adaptation; relay intercropping; the North China Plain

1. Introduction

The North China Plain (NCP) is the bread basket of China. It produces about one-fourth of total food grains and two-thirds of total wheat output of the country. Such achievement has heavily depended on continuous overexploitation of groundwater for irrigation to meet the big water gaps between heavy water requirement of the prevailing wheat-maize cropping system and insufficient precipitation in large parts of the NCP (Fang et al., 2010a, 2010b; van Oort et al., 2016). Crop irrigation consumes about 70% of the total water use in the region. Continuous groundwater overexploitation has led to alarming drop of groundwater table during the last three decades, with many piedmont areas even suffering a drop rate of more than 1 meter per year for 40 years (Jia and Liu, 2002; Li et al., 2005; van Oort et al., 2016). The rapid drop of groundwater table also caused other environmental problems such as dried up rivers and lakes, seawater intrusion, land subsidence and ground fissures (Xue et al., 2000; Zhang et al., 2009). Health problems may increase as well when pumping reaches deep layers with water containing toxic levels of fluoride and arsenic (Currell et al., 2012). As forcefully pointed out in van Oort et al. (2016), the current practice of groundwater overexploitation in the region will have to come to an end in the foreseeable future so that groundwater extraction can be drastically reduced to conserve the aquifers.

Great research efforts have been made at the local level to reduce irrigation water consumption and thus groundwater overexploitation. These efforts include both the applications of water conservation technologies and the adoptions of alternative cropping strategies, with a focus on winter wheat because of its heavy irrigation requirement (Li et al., 2005). A number of water saving measurements, such as optimizing irrigation scheduling (Yao et al., 2000; Zhang and Deng, 2002), introducing limited and deficit irrigation (Wang et al., 2001; Kang et al., 2002; Li et al., 2005; Mei et al., 2013), and plastic mulching (Xu et al., 2015), are carefully evaluated based on both field experiments and crop model simulations, with the objective of maximizing irrigation water savings subject to minimum yield loss. Nevertheless, because precipitation can only meet 25-40% of the water requirement for achieving average wheat production in a large part of the region (Li et al., 2005), to support the prevailing winter wheat-summer maize sequential cropping system (WM-S) system, great amounts of groundwater are still needed for irrigation use even with such water saving technologies.

The adoptions of alternative cropping strategies has been characterized by replacing current WM-S with groundwater neutral cropping systems (Yang and Zehnder, 2001; Zhang et al., 2004; Yang et al., 2015; van Oot et al. 2016).[1] Many field studies suggest spring maize monoculture as an alternative cropping system because it is much less irrigation demanding and has higher yield potential than the prevailing summer maize (Pei et al., 2015). Other major alternative cropping systems suggested include three harvests in two years (1st year: WM-S; 2nd year: spring maize) (Meng et al., 2012) and winter wheat-spring maize strip intercropping (Gao et al., 2009). However, the literature shows that the adoptions of groundwater neutral cropping systems in the water deficit parts of the NCP face the substantial penalty of total grain output per unit of land per year (total grain yield, hereafter). Limiting wheat irrigation with groundwater will cause a great reduction of wheat yield potential from 9.7 t/ha to 3 t/ha (Wu et al., 2006). Compared with WM-S under optimal irrigation strategy, total grain yield of the three harvests in two years as suggested in Meng et al. (2012) and spring maize monoculture as suggested in Pei et al. (2015) will decrease by 19.9% and 33.8% respectively.

van Oort et al. (2016) evaluated the performance of 11 groundwater neutral combinations of alternative cropping systems and water saving technologies based on simulations with APSIM cropping systems model and the SOILWAT water balance module. The calibration and validation of the APSIM model was based on experiments at the university farm of the Agricultural University of Hebei in Xinji County (37.54°N, 115.12°E), which is located in the alluvial plain of the Taihang Mountain in the northwest of the Hebei plain, an area with the most serious water shortage in the NCP. The evaluation concludes that the total grain yield of the WM-S under groundwater neutral constraint will drop by 44% in comparison with that of the WM-S under the current practice; and water conservation by plastic film could limit this reduction to 21-33% but possible environmental impacts of plastic film need additional attention.

The literature suggests that the two policy goals of maintaining grain production level and recovering local groundwater table seem irreconcilable in the NCP. However, the existing studies focus on reconciling the two goals either at the site level or a locality. In this research, we promote a macro-perspective and argue that we can better utilize richer agro-climatic resources

[1] Groundwater neutral cropping systems refer to cropping systems with sustainable pumping rates. The evapotranspiration (ET) differs between each cropping system, therefore each ground-water neutral cropping system has its own and different sustainable pumping rate (van Oort et al., 2016).

(temperature and precipitation) available in the southern NCP to reconcile the two policy goals at the regional level. In more detail, we propose a cropping system adaptation strategy across the North China Plain and evaluate the performance of this regional strategy with reference to the prevailing WM-S system. The strategy consists of (1) widely adopting winter wheat fallow and early-sowing summer maize mono-cropping (E-M) in water scarce part of the region to enable groundwater recovery, and (2) replacing WM-S by wheat-maize relay intercropping system (WM-R) in the water richer part of the NCP to increase grain production and compensate yield losses in the water scarce part of the region. We employ DSSAT 4.6 to evaluate the relative performances of the prevailing WM-S system and the alternative E-M, WM-R and spring maize in terms of yield and irrigation water demand at the three sites and across all grid-cells of cropland in the NCP. Based on these results, we develop a procedure to allocate the above four cropping regimes to each grid-cell with the objective of maximizing groundwater saving in water scarce area under the constraint to maintain the current level of regional total output. A successful implementation of this procedure would demonstrate that it is feasible to reconcile the two policy goals of maintaining grain production level and recovering local groundwater table at the regional level of the NCP, thus providing a scientific basis for regional cropping system adaptation design.

2. Study Area

The North China Plain (112.18°E–120.25°E, 32.19°N–40.18°N), also called Huang-Huai-Hai Plain, is a large alluvial plain built up along the shore of the Yellow Sea by deposits of the Huang He (Yellow River) and the Huai, Hai, and a few other minor rivers of northern China. The plain is bordered on the north by the Yanshan Mountains, on the west by the Taihang Mountains and the Henan highlands, and on the southwest by the Tongbai and Dabie Mountains. To the south it merges into the Yangtze Plain in northern Jiangsu and Anhui provinces. From northeast to southeast it fronts the Bo Hai (Gulf of Chihli), the hills of Shandong Peninsula, and the Yellow Sea (www.britannica.com/place/North-China-Plain). It covers a total area of 4.4×10^5 km^2 (Fig. 1), with a temperate semi-arid monsoon climate. About 60% of the precipitation occurs in summer (June to September), while less than 20% happens in winter and spring. Precipitation decreases from south to north and east to west.

Local climate resources can support the cropping systems of double harvests per year or triple harvests in two sequential years. The WM-S is currently the dominant cropping system in the NCP.

Winter wheat is usually sown in early or middle October and harvested in early or middle June in the following year, while summer maize is sown right after the harvest of winter wheat and harvested in late-September. Under the WM-R, summer maize is sown in a single straight line between every two rows of wheat during mid to late May, about 7-15 days before the harvest of winter wheat. Spring maize is usually planted in late April. Please note that the Yimeng Mountain of the Shandong Province takes a large part of the central-east NCP, where the shares of both planting and irrigation areas for wheat and maize in its limited hilly and mountainous cropland are very small although annual precipitation is higher compared to the northern NCP. The far southern part of the NCP is in the transit zone between wheat-maize cropping system and wheat-rice or double rice rotations because of richer thermal and water resources. There is a tendency of increased rice planting in this part of the NCP, especially in the northern Jiangsu Province (Liu et al., 2013). Nevertheless, rainfed wheat is still the major winter crop in this part of the region, which is also confirmed by the high-resolution dataset of MIRCA 2000 on the wheat and maize harvest area (Portmann et al., 2010) (Fig. 2). In this study, we focus on maintaining the aggregate production level of wheat and maize in the NCP, discounting the contribution of rice production in the southern part of the NCP.[2]

We select three sites – Beijing (116.35°E, 40.04°N), Jining (116.51°E, 35.34°N) and Tangyin (114.24°E, 36.03°N), to represent different water and thermal resource conditions and alternative cropping systems in the region. Another important reason for selecting these three sites is because the genetic coefficients (GCs) of the DSSAT model for winter wheat, summer maize and spring maize have been well-calibrated by the existing researches (Yu et al., 2006; Binder et al., 2008; Fang et al., 2010b; Liu and Tao, 2013). Jining site experienced a cropping system shift from WM-R to WM-S in 1996. Tangyin site has long records of WM-R observations. Both WM-S and spring maize monocropping are recorded in Beijing site. Average annual precipitation (1980-2010) in Jining (684 mm) is higher than Tangyin (550 mm) and Beijing (531 mm).

(Figure 1 is about here)

[2] Please note that adding the contribution of rice production in the southern part of the NCP would strengthen rather than weaken the major argument of this research.

3. Materials and Methods

3.1 Data

The data used in this research include: climate/weather data, land and soil information, crop growth and yield observations, and irrigated and rainfed area of wheat and maize (actual harvest area) in the NCP. The performance comparison across the four cropping systems of the WM-S, WM-R, E-M, and spring maize will focus on the period of 2001 to 2010, mainly because crop cultivars information are obtained using observations between 2001 and 2010, and the maps of cropland and irrigated cropland are for year 2000.

Although the GCs of the DSSAT model for winter wheat, summer maize and spring maize have been calibrated, there is no GCs available for intercropped maize in the region. We use the observations of intercropped maize at Tangyin site, including crop growth, crop management, yield and yield components, to calibrate GCs and validate DSSAT for intercropped maize. Crop management records include sowing and harvest date, application of irrigation and fertilizer. Observed crop phenology stages are sowing, emergence, shooting, flowering and maturity. Yield components include dry weight per kernel, tiller number per plant, and kernel number per tiller.

Weather data for three sites include daily records over 1980-2010 from Data Center of China Meteorological Administration. This dataset reveals the observed climate change during these 31 years at the site level. Historical climate/weather data for regional simulations are based on the interpolations of the observations from over 700 meteorological stations nationwide over the period of 2001-2010. These meteorological stations are much more intensively located in the areas with high population density such as the NCP. The daily solar radiation, maximum and minimum temperature, precipitation are used as weather inputs for the DSSAT model. Because solar radiation is not available in the site observations, we converted it from the recorded daily sunshine hours using the empirical global radiation model, we understand that radiation in the temperate latitude regions might be underestimated due to a seasonal dependence of the accuracy of the empirical model (Pohlert, 2004).

Land-use map of year 2000 is obtained from National Land Cover database (100m×100m) provided by the Institute of Geographical Sciences & Natural Resources Research (IGSNRR) of the Chinese Academy of Sciences. Cropland is further divided, according to the slope, into four categories of plain, hilly and mountain cropland, and cropland with slope greater than 25 degrees. Soil profile attributes of the NCP are from the Harmonized World Soil Database (Nachtergaele and Batjes, 2012) with a spatial resolution of 1 km. Because the DSSAT model requires more detailed soil properties inputs compared with the existing information in the Harmonized World Soil Database, the missing properties are calculated using method described in Tian (2014).

Harvest area of winter wheat and summer maize under irrigated and rainfed conditions are obtained from the global data set of monthly irrigated and rainfed crop areas in the year 2000 (MIRCA 2000) (Portmann et al., 2010) (Fig. 2). They are used to calculate the yield and water requirement of irrigated/rainfed wheat and maize under different cropping systems.

For DSSAT upscaling runs at the grid-cell level, all DSSAT input data will be resampled or aggregated into 1 km resolution grid data, and the simulation results of total grain production and irrigated water consumption under the WM-S, WM-R and E-M cropping system will be aggregated to the county level for presentation convenience.

(Figure 2 is about here)

3.2 Sequential cropping and relay intercropping

The WM-S is the dominant cropping system in the NCP, under which farmers grow wheat in early to middle October and plant maize after the harvest of wheat in June. By contrast, maize is planted into wheat field before the harvest of wheat under the WM-R. The total grain production has increased significantly under the WM-S in the NCP in the last decades due to the improvement of crop management (irrigation, fertilization and pesticide), adaptation of new early-mature high-yield crop cultivars and agricultural machinery, and expansion of irrigation (Wang et al., 2010; Zhang, 2011; Chen et al., 2012; Wang et al., 2012; Yu et al., 2012; Shi et al., 2013; Tao et al., 2014). It is worth highlighting that the development of compact-type early maturity summer maize enables WM-S to greatly increase maize yield under the constraint of limited thermal resources (Feike et al., 2012).

Shifting maize sowing/harvest date has also been proven as an effective way to extend maize growth period and further boost yield and water productivity of maize under the WM-S, because warmer temperature favors the growth of maize (Wang et al., 2012). Spring maize is usually sown in late April in the NCP, when precipitation is still low and water deficits occur frequently during the germination and vegetative stages. A delay of spring maize sowing by 30-days may lead to a yield increase by 13% (Binder et al., 2008) because of the reduced drought risk in the sowing season. Advancing the sowing date of summer maize to mid-late May can raise maize yield up to

14 t/ha, on a par with the average total grain yield of the prevailing WM-S system (Pei et al., 2015). The advanced sowing dates of summer maize in Pei et al. (2015) are close to the field records of the WM-R system observed in Tangyin site. This discussion indicates that the potential benefit of earlier sowing summer maize (E-M) in raising yield and lowering irrigation demand can be materialized under the WM-R system in the NCP.

3.3 Irrigation water requirement

Irrigation Water Requirement (*IWR*) and total grain production of E-M, WM-S, WM-R, and spring maize in a given grid-cell are two key indicators for allocating the above four cropping regimes to each grid-cell with the target to maximize groundwater saving in water scarce area under the constraint of maintaining current regional total output level. The *IWR* is calculated from the annual harvest area of wheat and maize under irrigated condition in the grid-cell using Eq. 1 (Yang et al., 2010).

$$IWR = \sum_{i=1}^{2} DR_i \times AR_i \, , \tag{1}$$

where *IWR* is the irrigation water requirement for the grid cell, *i* is the specific crop, including wheat and maize, *DR* is defined as the evapotranspiration minus effective rainfall during the crop growth period, and *AR* is the current irrigated areas of wheat and maize in the grid cell. *IWRs* of all four cropping systems are simulated at daily step under the given crop calendar and irrigation condition.

3.4 Cropping system adaptation strategy

Our NCP-level cropping system adaptation strategy for maximizing groundwater saving in water scarce areas subject to maintaining the current level of regional total output of the NCP is established by a procedure which allocates one of the E-M, WM-S, WM-R and spring maize cropping systems to each individual grid-cell across wheat and maize area of the region. Figure 3 depicts the major steps, which can be summarized as follows. (1) Estimate total grain productions and total irrigation water requirements in each grid cell of wheat and maize growing areas for all four cropping systems. (2) Sort all grids in descending order by *IWR* under the prevailing WM-S cropping system. (3) Start from the grid with highest *IWR* downwards and assign the E-M regime to these irrigation-intensive grids, start from the grid with the lowest *IWR* upward and assign the WM-R regime to these water-rich grids, the rest grids keep the WM-S or spring maize regime, and then calculate the total output loss from fallowing the original wheat areas and the total output gain from adopting the WM-R, in comparison with the WM-S, respectively. (4) Continue to assign the E-M regime to the irrigation-intensive grids as specified in (3) until no irrigation water saving can be made, and continue to assign WM-R to water-rich grids until the total output loss caused by adopting the E-M can be fully compensated by the WM-R. In theory, such a procedure may not have a balanced ending position. Fortunately, our simulations across the NCP do produce such an ending position.

In the above procedure, we do take consideration the potential higher irrigation demand of the WM-R system and therefore, in those rainfed grid-cells, we adopt the WM-R if the plain area ratio is greater than 25% of total cropland in the grid cell. In addition, in the hilly areas of the region, if rainfed summer maize is dominant, we assign higher yield E-M to increase maize yield.

(Figure 3 is about here)

3.5 Crop water management

At the site level, the following optimized irrigation schedule for winter wheat developed by Sun et al. (2011) is employed in our simulations. Irrigation is applied when the moisture of 0-100 cm soil is less than 65% of the filed capacity and the irrigation reaches 80% of soil water capacity except for the grain filling stage. For summer maize, irrigation is applied at the stem elongation stage according to Fang et al., (2010b) and 50 mm water is applied in line with Binder et al. (2008). In order to quantitatively assess the water productivity of crops under different cropping systems at the site level, the indicator of water use efficiency (*WUE*) as specified in Eq. 2 is employed (Ali et al., 2007).

$$WUE = \frac{GY}{ET}, \qquad (2)$$

where *ET* stands for the total evapotranspiration and *GY* for total grain output.

At the regional level, it is impossible to specify detailed water management schedule across all grid-cells owing to the lack of data, we take the simple schedule that crop on irrigated farmland is irrigated to 80% of soil water capacity when the capacity becomes less than 65%, implying that no irrigation take place on existing rainfed cropland, unless explicitly mentioned.

3.6 Intercropping shading algorithm

Because summer maize is sown before the harvest of winter wheat under the WM-R, the two crops compete for solar radiation and micro-climate during the co-growth period. We adopt the shading algorithm regards to the height of the neighboring crop as specified in Knorzer et al. (2011) and incorporate it into the DSSAT 4.6 to modify the solar radiation inputs during the co-growth period. However, we have to ignore the effects of micro-climate change to the growth and water requirements of these two co-growing crops owing to the lack of detailed micro-climate observations at the surface level.

In general, summer maize is sown 7-15 days ahead of winter wheat harvest under the WM-R, in order to maximize yield by extending growth period of summer maize. In our regional level simulations, the co-growth period is set at 15 days in the WM-R system.

3.7 DSSAT model calibration and validation

The DSSAT model is developed by the International Benchmark Sites Network for Argo-technology Transfer project (IBSNAT), it simulates the growth and development of crops within a homogeneous plot in a daily time step. Soil water balance is simulated using precipitation, infiltration, runoff, transpiration, evaporation and drainage during the crop growth period (Jones et al., 2003). It has been used to estimate the total crop irrigation requirement (Yang et al., 2010) and the impact of agriculture water requirement on groundwater table (Yang et al., 2006) in the NCP, and the irrigation management of maize in arid northwestern China (Jiang et al., 2016) and wheat in the Texas High Plains of the USA (Attia et al., 2016).

The DSSAT model uses genotype coefficients (GCs) to describe the genotype-by-environment interactions and simulate performance of diverse cultivars under different conditions (Penning de Vries et al., 1992). Each cultivar of a crop has specific parameters to describe the genotypic information of the cultivar within the parameter ranges of the crop. Because there are obvious gaps of crop management between farmers practice and field experiment, the attainable yield under ideal crop management conditions (no water, nitrogen and pest stress) is adopted to calibrate and validate the GCs of the E-M system at Tangyin site in this research. The maximum attainable yield is calculated from optimum yield components, including the maximum grain number per tiller and the correspondent grain weight, maximum tiller number per plant and the optimum plant density. Other important field observations for the calibration and validation include critical phenological information such as sowing, flowering, maturity and harvest dates.

The procedure of DSSAT model calibration and validation using attainable crop yield was described in Tian et al. (2014). The procedure is based on the Generalized Likelihood Uncertainty Estimation (GLUE) Module (He et al., 2010) as built in DSSAT 4.6. In addition to the probability calculations of GLUE, conventional statistics of the root mean square error (RMSE) as specified in Eq. 3 and mean relative error (MRE) in Eq. (4) are employed to evaluate the departure between the observed (O) and the simulated (S) values.

$$RMSE = \left[\frac{\sum_{j=1}^{n}(S_j - O_j)^2}{n}\right]^{1/2}, \tag{3}$$

$$MRE = \frac{1}{n}\sum_{j=1}^{n}\frac{S_j - O_j}{O_j}, \tag{4}$$

in which *j* refers to the *j*-th run of the calibration or validation.

4. Results

4.1 Observed precipitation change at the site level

Precipitation is the most important water resource for agricultural production. Annual trend and seasonal distribution of precipitation over 1980-2010 at Jining, Tangyin and Beijing sites are shown in Figs. 4 and 5. The average annual precipitation of 684 mm at Jining site was much higher than 531 mm at Beijing and 550 mm at Tangyin over the period of 1980-2010. In terms of trend, while Beijing became significantly drier and Tangyin became moderately drier, Jining became significantly wetter. The gap of annual mean precipitation between Jining and Beijing extended to 320 mm during 2001-2010, 167 mm larger than the average gap over 1980-2010. The corresponding figure between Tangyin and Beijing was 86 mm, 68 mm larger than the average gap of 1980-2010. Declining precipitation in Beijing means even more groundwater being required for supplemental irrigation for the same level of grain production, whereas more precipitation in Jining relaxes groundwater stress for the same level of grain production. The distribution of average monthly rainfall across calendar months is illustrated in Fig. 5. Most of the precipitation occurred during the summer maize growing season (June to September), which accounts for

73.1%, 78.6% and 73.0% of annual precipitation in Jining, Beijing and Tangyin sites, respectively. The average precipitation during the wheat and maize growing seasons in Jining were 70.8 mm and 82.7 mm higher than that in Beijing. Tangyin had 34.7 mm more rainfall during the wheat growing season but 15.8 mm less rainfall during the maize growing season than Beijing. Rainfall during the E-M sowing month (May) was 26.7 mm, 24.4 mm and 12.1 mm higher than that in spring maize sowing month (April) at Jining, Tangyin and Beijing sites, respectively.

(Figure 4 and 5 and Tables 1-3 are about here)

4.2 Crop cultivar coefficients and model performance

Tables 1 and 2 present genetic coefficients (GCs) of crop cultivars under the WM-S, WM-R, E-M, and spring wheat cropping systems. The GCs of relay-intercropped summer maize are calibrated and validated using field observations at Tangyin site (Section 3.7). The MRE and RMSE measures reported in Table 3 show that the performances of both calibration and validation are very well. All other GCs are obtained from Binder et al. (2007, 2008), Fang et al. (2010), and Liu and Tao (2013).

4.3 Comparing the performances of maize in different cropping systems at the site level

We compare the performance of the E-M system with that of local summer maize in the WM-S system at Jining and Beijing sites over the period of 2001-2010. Table 4 shows the results. At Jining site, the average yield of the E-M system is 33.7% higher than that of local summer maize in the WM-S system, with a relatively moderate increase of total evapotranspiration by 19.5%. This makes water productivity of the E-M 12.6% higher than local summer maize. More striking improvements happen at Beijing site where maize yield and total evapotranspiration of the E-M increase by 41.8% and 17.5%, respectively, implying a rise of water productivity by 21.2%.

Many studies have suggested spring maize monoculture as an alternative cropping system to reduce agricultural irrigation water consumption in the water deficit regions of the NCP. We also compare the performance of the E-M system with the results of spring maize field experiment conducted in 2005 and 2006 at Dong Bei Wang experimental site (116.3°E, 40.0°N), which is nearby our Beijing site, as reported in Sun et al. (2011). The last column in Table 4 shows the comparative results. It can be seen that spring maize and the E-M produce a similar level of yield but the water productivity of the E-M is 21.6% higher. It is because spring maize typically requires more water in its early growing period. Another set of experiments presented in Pei et al. (2015, Table S1) at a nearby site (Luancheng) shows that yield of the E-M system can reach up to 12.4 t/ha with two irrigations at 60 mm each, indicating even greater potential of the E-M in keeping high level of yield with less irrigation water requirement. These findings indicate that the E-M system is more suitable than spring maize to be an alternative cropping system for reducing irrigation water demand while keeping the high level of grain production in the region.

(Tables 4 and 5 and Figure 6 are about here)

4.4 Performance of the regional cropping system adaptation strategy

We run the procedure as specified in Section 3.4 to establish our NCP-level cropping system adaptation strategy with the objective to maximize groundwater saving in water scarce areas under the constraint of maintaining the current level of regional total output. The procedure is implemented using DSSAT up-scaling method as detailed in Tian et al. (2012). The sowing dates of local summer maize in the WM-S system are obtained from Figure 2 in Binder et al. (2008), which are based on observations from 14 agro-meteorological stations in the region.

Table 5 reports changes in wheat areas, total grain production, and irrigation water consumption once the balanced allocation of alternative cropping system being reached under our procedure. Figure 6 depicts the spatial pattern of the location at the county level. It can be seen from Table 5 that about 2.5 million hectares (20.45%) of the existing wheat area will become fallowed under the adaptation strategy. The left map in Figure 6 shows that most of the fallowed areas are located in Hebei, Tianjin, and Beijing, the driest areas of the region heavily depending on underground water irrigation for wheat production. Such extent of fallow leads to a total loss of wheat production by 15.4 million tons, accounting for about 24.3% of total wheat production under the current WM-S system. On the other hand, because of the adoption of E-M following the winter fallow, total maize production will increase significantly and its share in total grain production will increase from 35.1% to 50.9%.

It is worth highlighting that the resultant reduction in total irrigation water requirement will be 5.62 billion m^3 and Hebei Province alone will take 78.6% (4.37 billion m^3) of this saving. Yang et al. (2010) estimated the irrigation water requirement of the prevailing WM-S system in Hebei Plain over the period of 1986–2006 and their research is based on agronomic, hydrologic and climate data collected from 43 well-distributed stations across the plain. The average irrigation water requirement over 1986-2006 in their estimation was 6.16 billion m^3 (4.82 billion m^3 for wheat and 1.34 billion m^3 for maize). This comparison indicates that about 71% of irrigation water requirement can be saved in Hebei with the cropping system adaptation strategy we suggested and the saving comes from fallowing the winter wheat field. This means that our strategy would be able to zero groundwater withdrawal for growing winter wheat in vast majority areas of Hebei Province, thus forcefully promoting the recovery of local groundwater table.

On the contrary to the widespread winter fallow in Hebei, Tianjin and Beijing, there is no need for fallowing winter wheat areas in southern Henan, southern and eastern Shandong, and Jiangsu and Anhui provinces, where precipitation during the winter wheat growing season is much higher. The popular adoption of the WM-R system in the southern and eastern NCP will lead to significant increase in maize production with ignorable amount of increase in irrigation water demand. The increase in maize production can fully compensate the lost quantity of grain output caused by winter fallow in the northern NCP.

5. Discussion and Conclusion

It is well-acknowledged that groundwater overexploitation in the NCP has caused devastate ecological consequences and would result in vast scale hazard to the NCP ecosystem if without immediate actions. For example, groundwater depression cone recently covers about 5×10^4 km^2 of land in the piedmont of Hebei Plain, and severe land subsidence happened in many regions with a maximum of 3.1 m in some locations in Tianjin (Zhang et al., 2009). Groundwater recharge has shifted from surface runoff to irrigation returns owing to the constructions of numerous reservoirs upstream. Groundwater contamination from rapid increase of nitrate concentrations and mineralization has expanded from shallow to deep groundwater and such expansion will pose greater challengers to the freshwater supply in the NCP (Currell et al., 2012). Dried out rivers and lakes not only damage the surface ecosystem but also reduced the freshwater recharge in the downstream plain of the NCP. Overexploitation of limited freshwater resources in the deep aquifers has caused seawater intrusion and soil salinization in the coastal plain, where salinized cropland has harmed crop growth and led to reduced crop production.

To address the severe issue of groundwater overexploitation, cropping system adaptation has already happened. It is reported that farmers have taken wheat fallow in the driest parts of the NCP based on their own cost-benefit calculations. Policy initiatives aiming to encourage winter fallow have added momentum to farmers' own initiatives. In these initiatives, winter wheat was abandoned and "spring maize planting belt" was established to replace the wheat-maize double cropping (Feng et al., 2007; Meng et al., 2012; Wang et al., 2016). Although such initiatives would be able to result in significant groundwater saving if they were widely implemented, a great concern is about the losses in total grain production. Our research has designed a regional cropping system adaptation strategy and demonstrated that this adaptation strategy is capable of reconciling the two policy goals of maintaining current grain production level and recovering local groundwater table in the North China Plain (NCP).

Under our adaptation strategy, the winter fallow and early sowing summer maize (E-M) monoculture system is adopted to replace the existing winter wheat-summer maize sequential cropping (WM-S) system for saving irrigation water in the northern NCP, and the wheat-maize relay intercropping (WM-R) system is adopted to increase grain production in the southern and eastern NCP. We have employed DSSAT 4.6 model to evaluate the performances of the E-M, WM-R, WM-S, and spring maize, in terms of yield and water productivity, based on agro-meteorological observation data at Beijing, Jining and Tangyin sites. We have successfully run a procedure to allocate one of the E-M, WM-R, WM-S, and spring maize cropping systems to individual grid-cells across wheat and maize areas of the NCP, with the objective to maximize groundwater saving in water scarce areas under the constraint of maintaining the current level of total grain output of the region. The allocation procedure achieves a position in which the above two policy goals are reconciled. This reconcilability finding enriches the existing literature and reveals new rooms for policy makers and stakeholders to address the urgent groundwater recovering issues in the northern NCP.

Two obstacles must be overcome for our adaption strategy to be practical in the NCP. The first is mechanization of relay intercropping. Despite of obvious advantage of the WM-R system in boosting total grain output per unit of land, the lack of progress in mechanization has led to reduced adoption of the WM-R in last two decades in the NCP (Feike et al., 2012; Zhang et al., 2007; Spiertz, 2010). Fortunately, the "interseeder" machine has been successful developed and applied for the row relay intercropping of wheat-soybean (Feike et al., 2012), which can also be adapted for the wheat-miaze relay intercropping in the NCP. In addition, strip relay intercropping, which plant different crops in strip instead of row, has been recommended because of its high cropping efficiency with existing farming machines (Feike et al., 2012). The second obstacle is that giving up winter wheat production in water scarce areas will cause income loss of the local farmers involved. However, given the fact that the current practice of groundwater overexploitation in these areas has to come to an end as soon as possible to avoid irreversible environmental disaster, active policy efforts are needed to encourage outmigration of cropping labor force to the non-agricultural sectors, and to promote significant increase in farm scale so as to raise labor productivity. In the short-run, subside policies can be adopted to encourage farmers in the water scarce areas to abandon wheat cropping for groundwater recovery (Wang et al., 2016).

Another challenge is that although the existing level of total regional grain production can be maintained and great amount of water can be saved for groundwater recovery, the reduction of wheat area in the NCP as suggested by our adaptation strategy will lead to a significant reduction in total wheat production. To compensate this loss, more wheat needs to be produced in other parts of the NCP and this is possible as indicated by the observed north-south shift of the winter wheat growing area in the NCP (Wang et al., 2015). Figure 2 shows that in the southern NCP, irrigation ratio is much lower than in the northern counterpart. Given the higher rainfall condition and more available surface water for irrigation, to expand wheat irrigation area in the southern NCP will be able to increase wheat production without putting pressure to groundwater table. In addition, winter fallow area can be further reduced in areas with mild water deficit by adopting field water-saving technologies such as deficit irrigation, plastic mulching (Xu et al., 2015; van Oort et al.,2016) and no-tillage direct broadcasting (Liu et al., 2010). Of course, further study is needed to accurately quantify the potential benefits of the above-listed measures.

Two limitations of this research are worth mentioning. First, the simulation of relay intercropping system with crop process models has been severely constrained by data availability. In our case, due to the lack of field observations of soil temperature and surface wind speed change during the co-growth period of wheat and maize, the effects of such micro weather conditions on crop inspiration, soil evaporation, crop growth and yield of wheat and maize are not considered. For the regional simulations, it is impossible to fully meet the heavy input requirement of the DSSAT model without some simple assumptions in management practices and such simplification may limit the regional performance of up-scaled DSSAT model and introduce bias in to the estimations of regional irrigation water demand and crop production. Second, existing studies suggest that the soil water balance simulation method in the DSSAT model needs to be improved by employing more mechanistic approaches (Soldevilla-Martinez et al., 2014). While potential water-saving benefit can be estimated from cropping system adaptation using the DSSAT crop model as we have done in the research, the effects of such water-saving benefits to the groundwater recharge and local water resources need to be further studied by coupling the DSSAT with regional hydrological models, which in turn needs more detailed and spatially explicit information on irrigation sources from surface water and groundwater (Negm et al., 2014; McNider et al., 2015).

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Table 1. Cultivar coefficients of maize in Sequential double cropping and Relay intercropping

Parameters	Sequential double cropping		Relay intercropping
	Beijing (CF 024)	Jining (Nongda 108)	Tangyin (Zhengdan 958)
P1	180	230	277
P2	0.3	0.4	1.05
P5	685	830	787
G2	730	760	711
G3	8.0	6.0	10.0
PHINT	44	39	48

Note: 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: Binder et al. (2008), Fang et al. (2010) and our calibration.

Table 2. Cultivar coefficients of winter wheat

Parameters	Beijing (Jindong 8)	Jining (cv. 93-52)	Tangyin (Zhengzhou 761)
P1V	35	50	40
P1D	50	60	40
P5	500	440	450
G1	20	27	26
G2	36	25	40
G3	1.8	1.5	1.55
PHINT	95	80	85

Note: P1V: vernalization; P1D: photoperiod sensitivity; P5: grain filling duration; G1: kernel number; G2: kernel weight; G3: spike number; PHINT: phyllochron interval. See Jones et al. (2003) for technical details.

Source: Binder et al. (2007), Fang et al. (2010 b), Liu and Tao (2013)

Table 3. Calibration and validation of relay-intercropped maize at Tangyin site

	Anthesis day (DAP)			Maturity day (DAP)			Production (kg/ha)			
Year	Sim	Obs	MRE	Sim	Obs	MRE	Sim	Att	MRE	RMSE
Calibrations	65	68	4.41%	112.5	114	1.32%	9098.5	9190	-0.99%	464.6
Validations	68	68.5	0.73%	113	117	3.42%	9024.5	9190	-1.80%	282.14

Note: Calibrations are based on observations in 2002 and 2005. Validations are based on observations of 2006 and 2008. Sim is simulation, Obs is observation, Att is attainable yield, MRE is relative error, RMSE is root mean square error, DAP is days after planting.

Table 4. Comparison of the E-M with summer maize under the WM-S regime at Jining and Beijing sites (2001-2010)

	Jining			Beijing				
	E-M (a)	Summer Maize (b)	Change (%) (c = a/b – 1)	E-M (d)	Summer maize (e)	Change (f = d/e –1)	Spring maize (g)	Change (%) (h = d/g – 1)
Yield (kg/ha)	8409.5	6287.5	33.7%	8593.5	6058.6	41.8%	9000	–4.52%
ET (mm)	390.4	326.7	19.5%	364.4	311.3	17.5%	463.9	–21.5%
Irrigation (mm)	50	50	--	50	50	--	133	--
WUE (kg/mm)	20.54	18.24	12.6%	23.58	19.46	21.2%	19.4	21.6%

Source: Site experiment observations of spring maize are for 2005 and 2006, and reported in Sun et al. (2011).

Table 5. Changes in wheat areas, total grain output, and irrigation water consumption (IWC) under the regional cropping system adaptation strategy

	Winter fallow area		Change in total grain output		Change in IWC	
	10^3 ha	% of existing wheat area	10^3 ton	% of existing total output	10^6 m^3	% of existing IWC
Beijing	47.21	22.45	98.5	4.47	-114.04	-18.15
Tianjin	95.99	48.81	-238.3	-10.91	-251.07	-42.88
Hebei	1749.26	68.98	-6400.8	-19.80	-4373.02	-57.84
Jiangsu	0.00	0.00	581.9	13.41	11.59	2.09
Anhui	0.00	0.00	802.1	13.60	10.96	2.30
Shandong	336.81	9.30	3364.4	11.18	-572.55	-7.35
Henan	233.30	7.34	1792.1	8.78	-330.64	-6.11
NCP total	**2462.57**	**20.45**	**0.0**	**0.00**	**-5618.77**	**-24.42**

Note: The increased irrigation water consumption by the E-M in comparison with local summer maize leads to the departure between the percentage change of IWC and that of wheat fallow area.

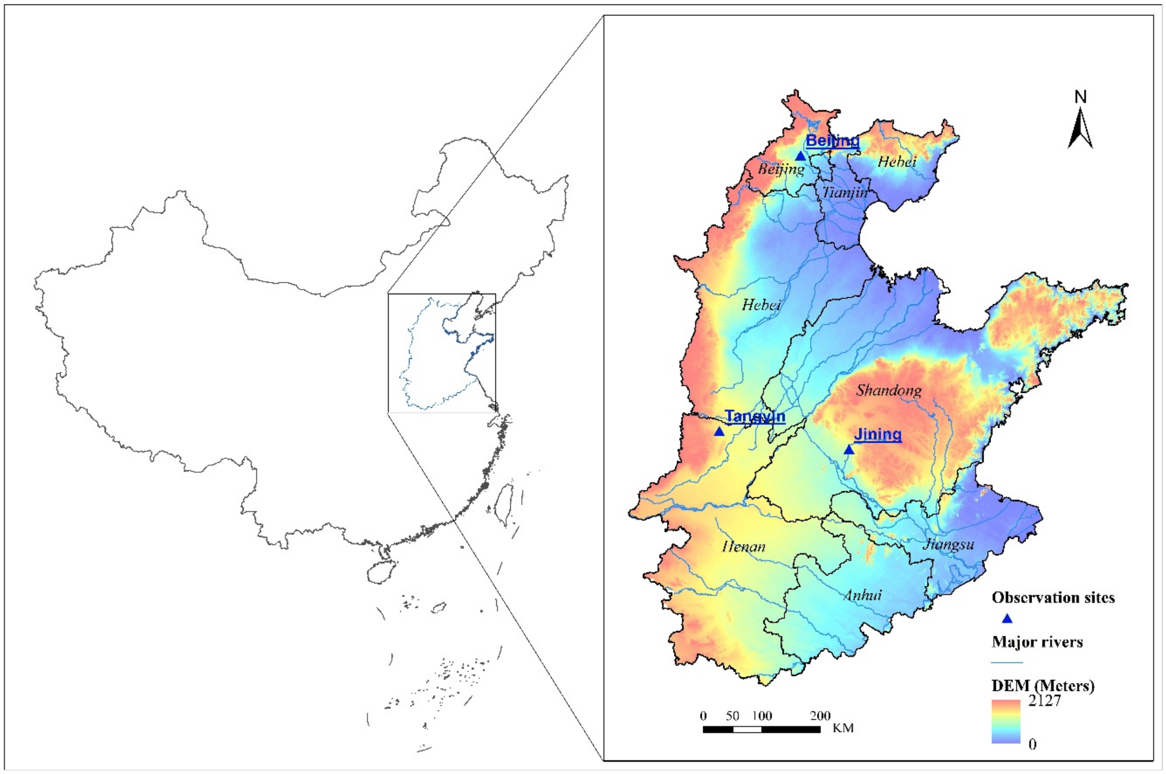

Figure 1. The North China Plain and observation sites

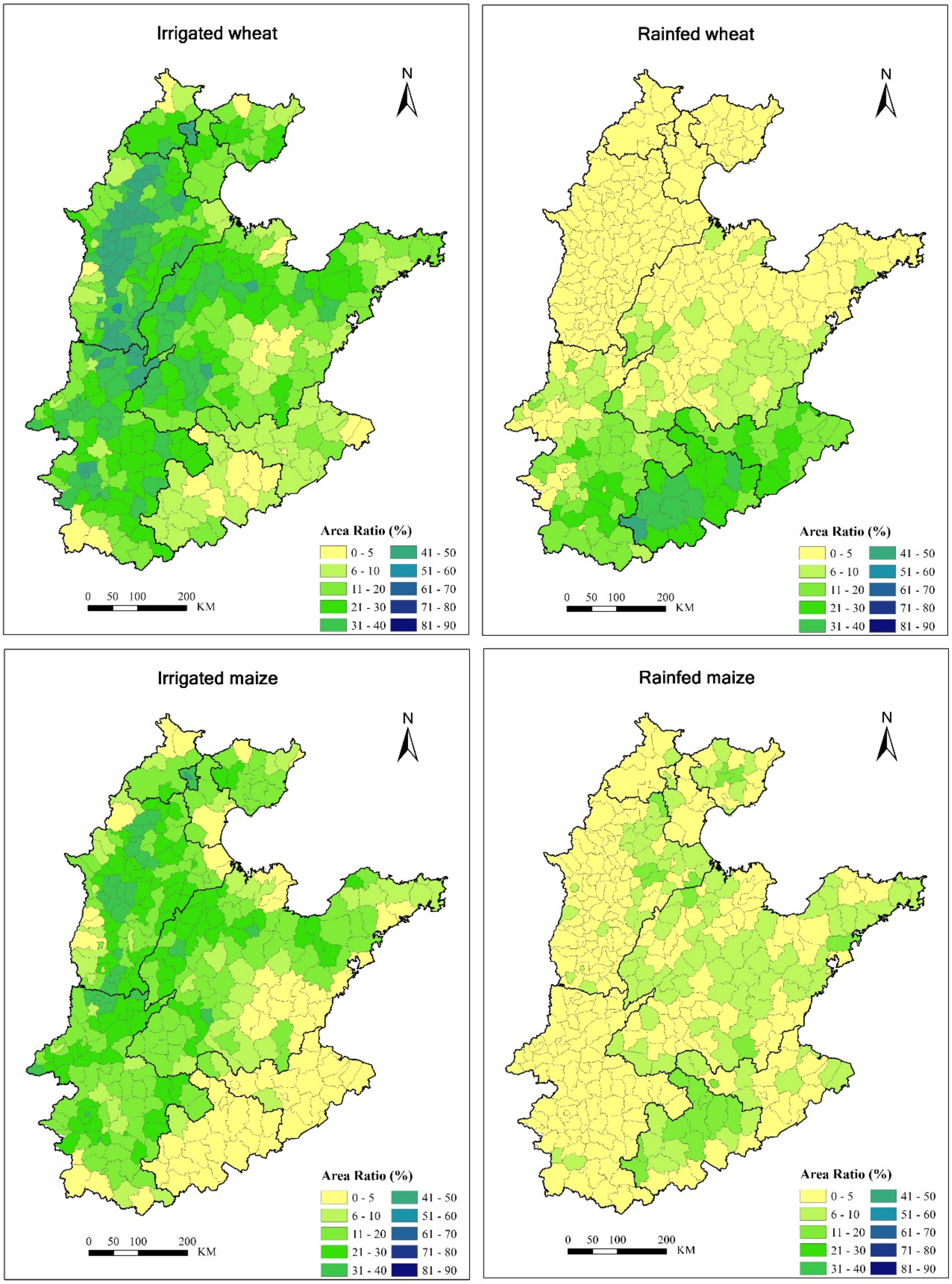

Figure 2. Area ratio of irrigated and rainfed wheat and maize to the total cropland at the county level in the NCP in year 2000

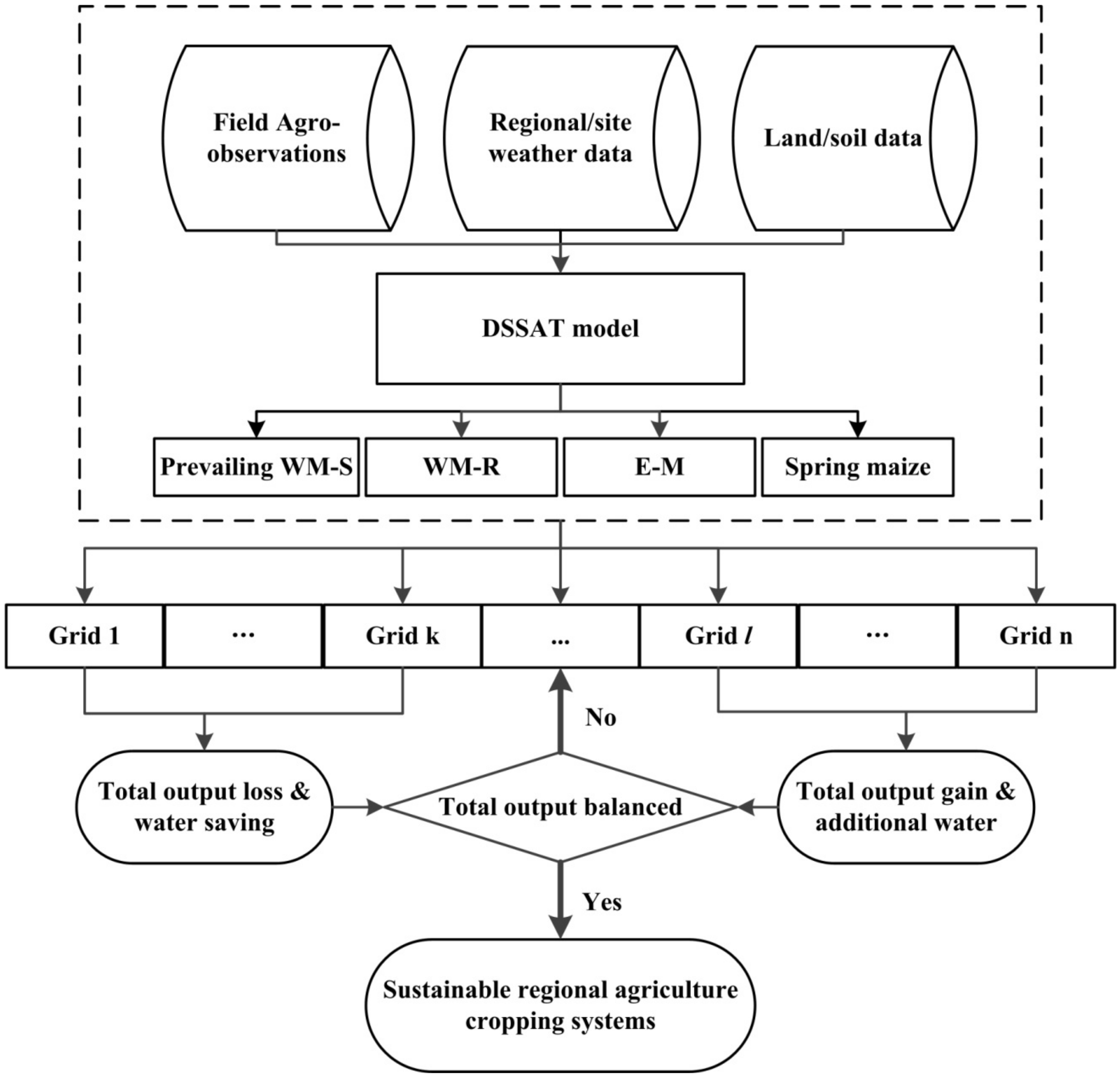

Figure 3. Flow chart for establishing the regional cropping systems adaptation strategy

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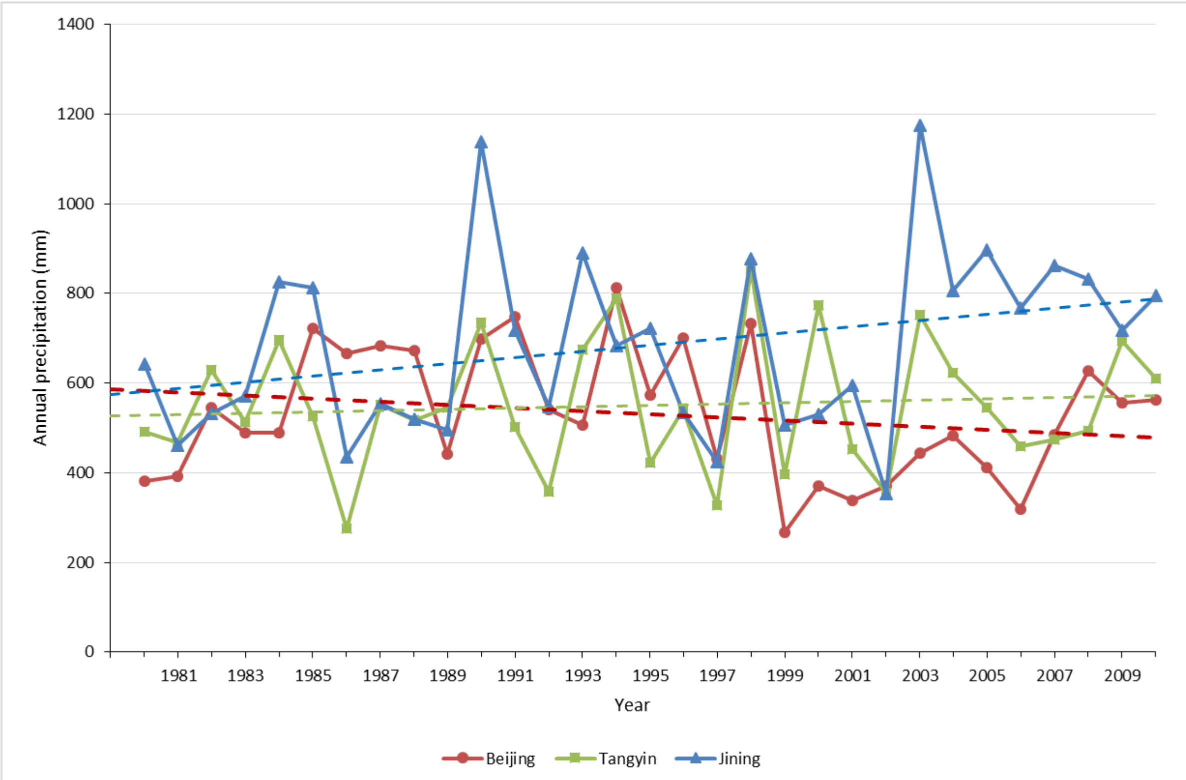

677 Figure 4. Observed annual precipitation at Jining, Tangyin and Beijing sites in 1980-2010

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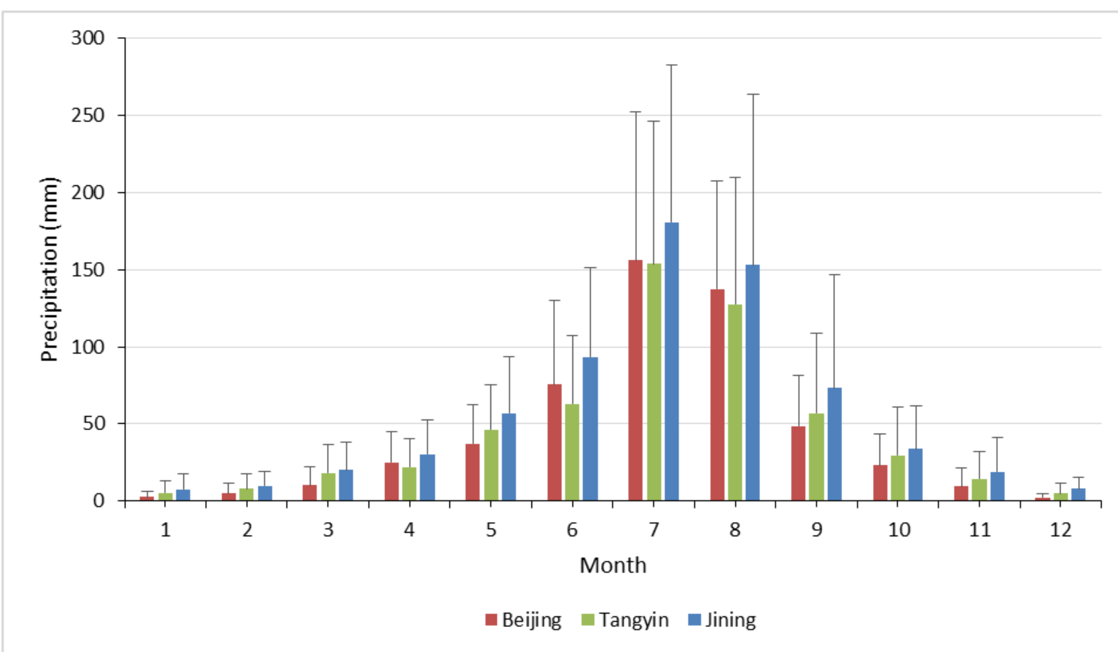

680 Figure 5. Average monthly precipitation at Beijing, Tangyin and Jining sites over 1980-2010

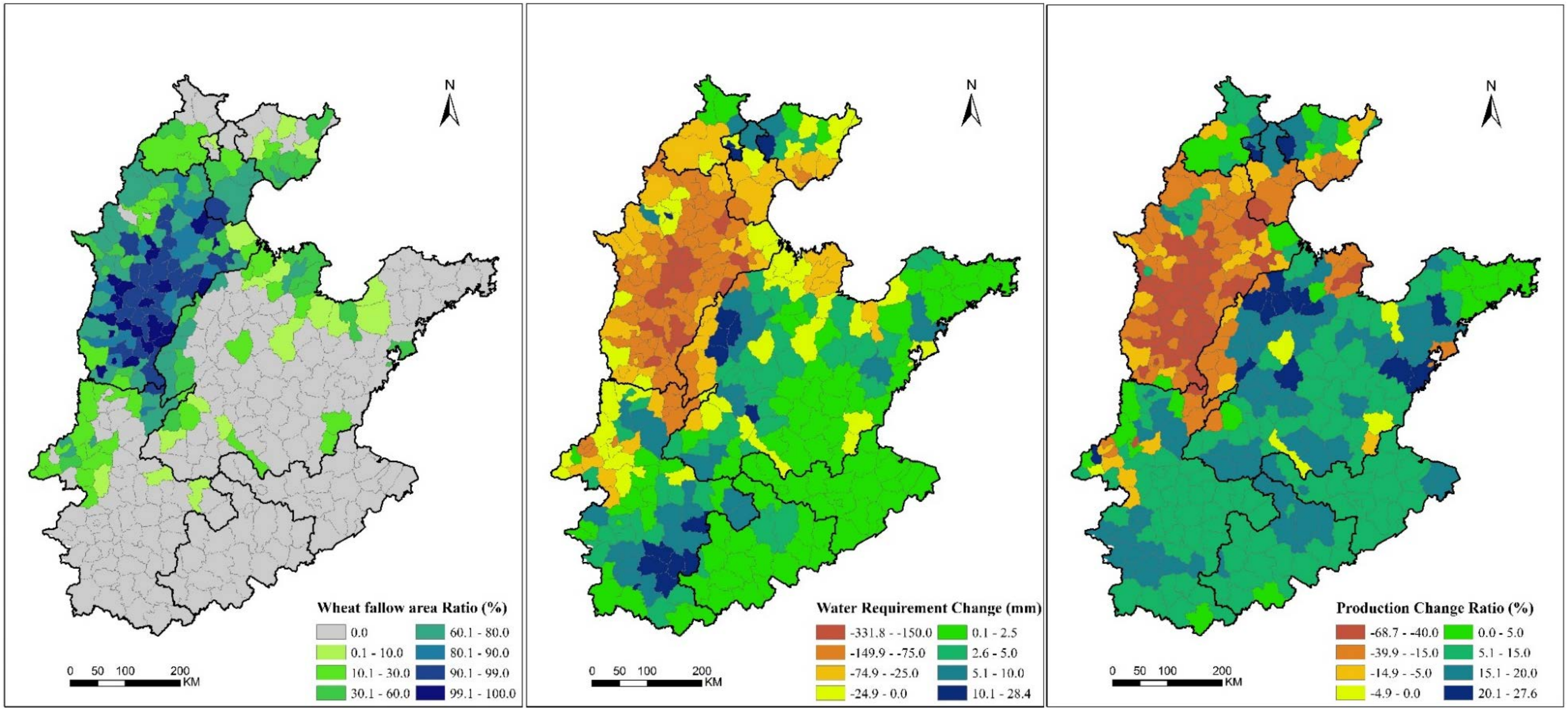

Figure 6. Area ratio of winter fallow (Left), change of water requirement (Central) and changes in total grain production (Right) at the county level (2001-2010)