ABSTRACT

Title of Dissertation: TOPICS IN MODELLING ADAPTATION DYNAMICS OF CHINESE AGRICULTURE TO OBSERVED CLIMATE CHANGE

Honglin Zhong, Doctor of Philosophy, 2018

Dissertation directed by: Dr. Laixiang Sun, Professor, Department of Geographical Sciences

Chinese farmers have adopted multiple adaptation measures to mitigate the negative impact of, and to capture the opportunities brought by, the observed climate change in the last several decades. Such adaptations will continue in the coming decades given the foreseeing climate change. Scientifically assessing such dynamism of suitable agricultural adaptation requires unprecedented efforts of the research community to simulate and predict the interactions among crop growth dynamics, the environment and crop management, and cropping systems at and across various scales. This calls for efforts aiming to quantify the interactions of agro-ecological processes across different scales. This dissertation intends to make scientific contributions in this direction.

The leading goal of this dissertation is to develop a cross-scale modeling framework that is capable of incorporating the field agricultural advances into the

design and evaluation of regional cropping system adaptation strategies. It then applies this framework to identify feasible cropping system adaptation strategies under observed warmer climate and quantify their potential benefits to the grain production and water sustainability in the major cropping regions in north China. Three objectives of this study are:

(1) Develop a cross-scale model-coupling framework between the site level DSSAT model and the regional level AEZ model to improve the AEZ performance in capturing the northern expansion of japonica rice under a warmer climate in the Northeast China Plain.

(2) Construct a new wheat-maize cropping systems adaptation strategy to meet the double challenge of maintaining the regional grain production level and recovering local groundwater table in the semi-arid North China Plain, where the persistent overexploitation of groundwater has caused severe environmental damages.

(3) Establish a dynamic adaptation strategy to identify the desired water sustainable cropping systems across different localities and to meet the challenge of recovery local groundwater table and minimize the output losses of wheat and then total grain production in the Hebei Plain, where the irrigation water shortage has threatened wheat production and thus potentially compromising China's food security.

This dissertation will improve our understanding of the interactions and interlinkage across multi-scale agro-ecosystems in mitigating the environmental risks associated with the irrigation-intensive farming and in adapting to climate change. The cropping systems adaptation strategies proposed by this dissertation provide scientific basis for future agricultural adaptation policy design compatible with local agro-climatic, land and soil conditions across China.

TOPICS IN MODELLING ADAPTATION DYNAMICS OF CHINESE
AGRICULTURE TO OBSERVED CLIMATE CHANGE

by

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Dedication

To my parents Guohua Zhong, Liangying Lai,

my parents-in-law Minghua Chen, Dongmei Wang

Thank you for your support!

To my wife Jing Chen, my son Qiyuan Zhong and my upcoming baby

I love you!

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List of Abbreviations

AEZ	Agro-Ecological Zone
APSIM	Agricultural Production System sIMulator
AR	Irrigated area
Att	Attainable yield
CERES-rice	Crop-Environment Resource Synthesis rice module
D	Drainage from the soil profile
DAP	Days after Planting
DR	Crop irrigation requirement defined as evapotranspiration minus effective rainfall during the crop growth period
DSSAT	Decision Support System for Agro-technology Transfer
E-M	Early Maize
EM-F	Early maize - fallow cropping system
ET	Evapotranspiration
ET_{adapt}	Total Evapotranspiration under the adapted cropping system
ET_0	Reference crop evapotranspiration
ET_a	Actual evapotranspiration
ETM/ETM+	Enhanced Thematic Mapper/Enhanced Thematic Mapper Plus
ET_{pan}	Local observation from a 20 cm diameter evaporation pan
FAO	Food and Agriculture Organization of the United Nations
G1 (rice)	Spikelet number coefficient of rice
G1 (wheat)	Kernel number coefficient of wheat
G2 (maize)	Kernel number coefficient of maize
G2 (rice)	Kernel weight coefficient of rice
G2 (wheat)	Kernel weight coefficient of wheat
G3 (maize)	Kernel weight coefficient of maize
G3 (rice)	Tillering coefficient of rice
G3 (wheat)	Spike number coefficient of wheat
G4 (rice)	Temperature tolerance coefficient of rice
GC	Genotype Coefficient
GDD	Growing Degree Days
GLUE	Generalized Likelihood Uncertainty Estimation
GY	Grain Yield
HI	Harvest Index
HWSD	Harmonized World Soil Database
I	Irrigation
IBSNAT	International Benchmark Sites Network for Argo-technology Transfer project
IGSNRR	Institute of Geographic Sciences and Natural Resources Research
IIASA	International Institute for Applied Systems Analysis
IWR	Irrigation Water Requirement
K_c	Crop coefficients of water in different growth stages

LGC or L or LGP	Length of Growth Cycle/Period
LUT	Land Utilization Type
MaxLAI	Maximum Leaf Area Index
MIRCA2000	global Monthly Irrigated and Rainfed Crop Areas around the year 2000
MRE	Mean Relative Error
NCP	North China Plain
Obs	Observation
P	Precipitation
P1 (maize)	Juvenile phase Growing Degree Days coefficient of maize
P1 (rice)	Juvenile phase Growing Degree Days coefficient of rice
P1D (wheat)	Photoperiod sensitivity coefficient of wheat
P1V (wheat)	Vernalization coefficient of wheat
P2 (maize)	Photoperiod sensitivity coefficient of maize
P2O (rice)	critical photoperiod coefficient of rice
P2R (rice)	photoperiodism coefficient of rice
P5 (maize)	Grain filling duration coefficient of maize
P5 (rice)	Grain filling duration coefficient of rice
P5 (wheat)	Grain filling duration coefficient of wheat
PHINT (maize)	Phyllochron interval coefficient of maize
PHINT (rice)	Phyllochron interval coefficient of rice
PHINT (wheat)	Phyllochron interval coefficient of wheat
R	Surface Runoff
RMSE	Root Mean Square Error
Sim	Simulation
SNWT	the South-North Water Transfer project
WATCH	the Water and Global Change program
Wb	current Water balance
WFDEI	the Water and Global Change program Forcing Data European Reanalysis Interim
WISE	World Inventory of Soil Emission Potentials
WM-FE	Winter wheat – summer Maize – winter Fallow – Early maize sequential cropping system
WM-R	Winter wheat - summer Maize Relay intercropping system
WM-S	Winter wheat - summer Maize Sequential cropping system
Wr	Threshold of readily available soil water
WR_{remain}	Remaining total Water Resource
WUE	Water Use Efficiency
ΔS	Net change in soil water content
λ	Actual evapotranspiration and the pan-evaporation coefficient for the crop or fruit tree
ρ	Soil-water coefficient in the Agro-Ecological Zone model

Chapter 1: Introduction

1.1 Background

Food security is the most important issue for the development of China. China needs to feed its large population with only about 7% of the world arable land. The projected food demand in China will increase by 30-50% in the following two decades (Zhang et al., 2011a), driven by the fast social and economic development, the pursuing of better economic living standard and the increasing urban population (Gould and Villarreal, 2006; Burggraf et al., 2015; Jiang et al., 2015). This leads to a great concern and debate about whether China can produce enough food to meet the growing demand (Prosterman et al., 1996; Heilig et al., 2000; Gong, 2011).

While China has made great efforts in agricultural development and achieved great success in increasing food production and guaranteeing its food security (FAO, 2012), there are still many great challenges that China has to face in the future, such as the decreasing cropland areas in the major cropping zones (Cai et al., 2013), water deficit in the north China (Piao et al., 2010), farming labor shortage due to the rapid urbanization (Xie et al., 2014), and most of all, the great variability of the climate and agro-climatic resources under climate change (Thomas, 2008; Wang et al., 2009a). Most studies predict negative potential impacts to China's crop yield under the projected climate change. China may suffer from a yield-reduction of 4~14% for rice, 2~20% for wheat, and 0~23% for maize by the 2050s (Xiong et al., 2009b). The aggregated potential crop productivity may decrease by 2.5~12% in the eastern China in the absence of CO_2-fertilization effect (Chavas et al., 2009). The rice yield in China may decrease by 3.3~10.1%, 2.5~16.1%, and 0.18~19.3% for global mean temperature changes of 1, 2, and 3 censorious degrees, respectively, even taking into account the CO_2-fertilization effect (Tao et al., 2008). This is because higher temperature will accelerate the crop growth and shorten the crop growth cycle, change the phenology of the existing crop cultivars, increase the evapotranspiration and pose greater water stress on crops, and reduce the crop yield (Tao et al., 2003; Tao et al., 2006; Li et al., 2011).

Agricultural adaptation can largely reduce the potential negative impacts of climate change and climate variability on crop yields (Howden et al., 2007; Tilman et al., 2011). Statistics show that China achieved a great success in increasing the crop productivity and food production under the observed climate change in the past decades (NBSC, 2008) and under the obvious climate warming in the last 50 years (Piao et al., 2010). This success is mainly attributed to China's long term adaptation efforts in enhancing the crop productivity and intensifying multi-cropping systems across China. These achievements also show the great potentials to mitigate the climate change impacts on crop yields and new opportunities to further increase crop production if similar or better adaptation measures are taken in the future (Bu et al., 2015; Zhang et al., 2015; Zhao et al., 2015). For scientific research and simulations, the above discussion indicates that we should incorporate field agricultural adaptations into our modeling process and furthermore, into the design of regional cropping system adaptation strategies, so that we can more reliably evaluate the climate change impacts on crop yields with the presence of alternative adaptation measures.

Improvements in breeding new high yield crop cultivar and in crop management have increased the crop productivity greatly in China (Li et al., 2011; Lv et al., 2015). Agricultural scientists are trying to breed new crop cultivars by enhancing some biophysical features, such as higher harvest index, higher vegetation index and greater tolerance of heat/cold and drought, to improve the biomass accumulation and yield (Tian et al., 2011; Li et al., 2012). Cultivar renewals account for about 52% of the wheat yield increase in the North China Plain (Zhang et al., 2013). The new salt-tolerance rice, wheat and maize varieties can be irrigated using blackish groundwater and planted in the saline soil of the coastal regions in the North China Plain where used to be considered unsuitable for rice cultivation (Ma et al., 2008; Liu et al., 2016; Feng et al., 2017; He et al., 2017). Farmers also greatly improved their crop management technologies, and new adaptation measurements are developed to fully utilize the increasing thermal resources under warming climate. For example, in order to mitigate the impact of higher temperature on the early days of wheat growth, the "double delay" (delaying both the harvest date of summer maize and the sowing date of winter wheat) is applied in the North China Plain, and the later maturity summer maize is planted to fully utilize the extra heat resource to improve yield. As a result, the regional overall crop production had in fact increased by 4-6% (Wang et al., 2012). To an opposite direction, a set of experiments showed that by moving the summer maize sowing dates 21 days ahead of the traditional practice, which further increases the crop growing length, maize yield can be increased by up to 47% (Pei et al., 2015). Another interesting adaptation example is that in order to avoid frost damage during the rice seedling period and to fully utilize the warmer climate, rice is cultivated in the greenhouse during the seedling stage, and transplanted to the field when the temperature is higher and stable. This management measure has greatly expanded the rice planting area, increased the rice growth cycle and the regional rice output (Tian et al., 2014).

Cropping system and cropping zone boundaries have changed significantly to reap the benefits of the prolonged crop growing season under the warming climate (Yang et al., 2015a). Potential multi-cropping index increased by 13% and 7% under irrigated and rainfed conditions from 1960s to 2000s (Liu et al., 2013a), and local multi-cropping pattern has been adjusted in different parts of China. For example, double cropping was replaced by triple cropping in some subtropical regions in the eastern China (Zhao, 1995), single cropping was replaced by double cropping in the central China (Yang et al., 2011) and the Tibetan Plateau (Zhang et al., 2013). Previous single cropping was replaced by three crops in two years in part of the North China (Dong et al., 2009). Warmer climate is also the major driving factor for the expansion/northward shift of the crop zone boundaries in the North China (Shi et al., 2014). For example, the boundary of the double rice cropping zone has been extended northward by 80km from 1970 to 2006 (Chen et al., 2012), and the boundary of the triple-cropping zone is expected to extend northwards by as much as 200 to 300 km in 2050 (Ju et al., 2013b). In addition to increasing multi-cropping index, such farm level adaptation measurements as the crop cultivar selection, cultivation timing (both sowing and harvest date) will enhance the gains associated with multi-cropping system adaptation and bring extra benefits to food production.

However, water has been a critical constraints to the adaptation efforts aiming at agricultural intensification under the observed warmer climate for high cropland productivity. For example, the continuous unsustainable over pumping of groundwater for meeting the irrigation demand of winter wheat-summer maize sequential cropping (WM-S) in the breadbasket of the semi-arid North China Plain (Fang et al., 2010) has led to very severe water crisis and other environmental damages. Immediate actions have been called by scientists, policy makers, and other stakeholders for reducing the irrigation water use so as to stop the current overexploitation of groundwater before it becomes too late (van Oort et al., 2016). Nevertheless, such water-saving efforts have been constrained by food security issue because the North China Plain produces about one-fourth of total food grains and two-thirds of total wheat output of the country.

New water management measures have been developed to increase crop irrigation efficiency and to reduce crop irrigation water demand in the semi-arid North China Plain, where agricultural water consumption accounts for about 70% of the total water use (Lv et al., 2013). Improved irrigation water saving technologies, especially with respect to wheat irrigation, have been constructed and validated via field experiments (Wang et al., 2014). For example, the scheme to optimize irrigation frequency and amount can reduce the total irrigation amount of the wheat-maize double cropping system from 373mm to 305mm (Sun et al., 2010), and even further reduce wheat irrigation amount to 150mm (Li et al, 2005) with a limited extent of yield loss. Mulching maize field by plastic film can reduce soil evaporation and irrigation requirement, resulting in a reduction of groundwater table drop from 1.6 to 1.3 m/year compared with traditional field practice (van Oort et al., 2016). Optimal irrigation scheduling as presented in Sun et al. (2014) could reduce groundwater overexploitation by about 16.3% during wheat growing period. Nevertheless, even reducing the irrigation frequency to one per crop growth cycle under current wheat maize double cropping system will lead to a groundwater table drop (Sun et al., 2015). On the other hand, reducing irrigation water use to the level of groundwater neutral (no groundwater table drop) under deficit irrigation schedule will lead to a loss of total grain production by 21% to 33% even with the help of plastic film mulching (van Oort et al., 2016).

Recognizing the limitations of the direct irrigation management measures in stopping groundwater table drop, many studies suggest to replace currently dominate WM-S regime with less intensive cropping systems such as complete/partial wheat fallow, spring maize single cropping (Sun et al., 2015), early maize-late maize double cropping (Meng et al., 2017), winter wheat-spring maize strip intercropping (Gao et al., 2009), and triple cropping of three harvests in two years (Meng et al., 2012). Because spring maize is less irrigation water demanding and has high yield potentials, alternative cropping systems based on spring maize are developed. For instance, irrigation water consumption can be reduced from 305 mm/year under WM-S to 249 mm/year under the regime of three harvests in two years (1st year: winter wheat summer maize sequential cropping, 2nd year: spring maize mono-cropping (WM-SP)), with a total yield loss of 22.8%. It is also found that the irrigation water use can be further reduced to 162 mm/year under spring maize mono-cropping (Sun et al., 2011). The work of Pei et al. (2015) highlighted the great potential of spring maize in increasing maize yield in the North China Plain compared with the US high land, which can even reach the current yield level of the wheat-maize combined in the WM-S regime if proper field management and high yield spring maize varieties are adopted. Recent experiments at the Luancheng site (Pei et al., 2015) showed the advantages of early maize, which moves the sowing date of traditional maize cultivars earlier by 10-20 days, in terms of higher water productivity and less irrigation water demand compared with spring maize. This advantage leads them to propose a cropping scheme of three harvests in two years of: winter wheat summer maize sequential cropping in the 1st year, and winter fallow and early maize in the 2nd year (we denote this regime as WM-FE). They show that the overdraft of groundwater can be reduced from 258 mm/year under WM-S to 140.7 mm/year under WM-FE, with a moderate reduction of total grain production per hectare by 13% (Xiao et al., 2017). More importantly, the WM-FE regime can potentially reach water balance if lateral recharge from the Taihang Mountains, additional surface water resources from the South-North Water Transfer Project and measurements of plastic film mulching are considered.

Previous studies prove that field advances in agriculture will provide more options of crop varieties, multi-cropping systems with higher productivity on the given unit of cropland, and more environmental friendly adaptation solutions under climate change. However, there is a shortage of effort to model the cross-scale interaction mechanism and to develop effective optimization procedures dealing with the difficult trade-offs between guaranteeing food security and addressing water crisis across diverse localities in a large region. In other words, without a good understanding of the interlinkage between the micro-scale agricultural advances and the macro-scale cropping system adaptation strategy, it would be very difficult to optimize the allocation of alternative adaptation measures across heterogeneous locations and to effectively address the severe environment issues. This dissertation intends to make scientific contributions in this niche.

1.2 DSSAT model and AEZ model

The DSSAT model and AEZ model are widely used in previous studies to assess the effects of various agricultural adaptation measures on agricultural production. The advantages and disadvantages of these two models are discussed below:

1) The Decision Support System for Agrotechnology Transfer (DSSAT) model is a process-based crop growth simulation model. It simulates the crop biophysical processes within a crop growth cycle at a daily step and the interaction of such processes with the surrounding environmental factors and farming practices, typically represented by soil and terrain features, weather variables (e.g. solar radiation, temperature, precipitation), and crop management measures (e.g. irrigation, fertilization, weed and pest control) (Jones et al., 2003). DSSAT can accurately simulate the response of crop growth and yield to various cropping adaptation measures and to different climate conditions. This advantage makes it the dominate tools in assessing the impacts of climate change on agriculture in the literature (Rosenzweig et al., 2001). For example, the DSSAT model is employed to predict

regional rice production under different climate change scenarios in the future (Xiong et al., 2009b; Basak, 2012).

However, such a site-specific modeling tool has some critical limitations when using it to simulate regional scale climate change impacts and adaptations effects. Upscaling methods of such models need to extrapolate information from limited experiment sites, this is because such a micro-scale model requires very heavy inputs and it is impossible to obtain detailed micro-scale information for its input variables across large areas. A typical compromise has been to assume that the important parameters characterizing the interaction between crop cultivars, farmland management practices and the environment are identical and thus fixed across grid-cells within a given region. As a consequence, the spatial heterogeneity of several critical adaptation measurements under different local conditions, such as shifting sowing/harvest date, locally adaptive crop species/cultivars, cannot be effectively considered, let alone the large scale agro-ecosystem adaptation measures, such as altering multi-cropping pattern and boundaries.

2) The AEZ model is jointly developed by the International Institute for Applied Systems Analysis (IIASA) and the Food and Agriculture Organization (FAO) of the UN (IIASA/FAO, 2012). The advantage of the AEZ model is that it provides standardized crop-modeling and environmental matching procedures to identify crop-specific limitations of prevailing climate, soil and terrain resources under assumed levels of inputs and management conditions. The concept of Land Utilization Types (LUTs), which include crop information such as crop eco-physiological parameters (harvest index, maximum leaf area index, maximum rate of

photosynthesis, etc.), cultivation practices and input requirements, and utilization of main produce, crop residues and by-products. The matching procedure is taken on each land unit under given agro-climatic resources and the different agricultural system with the different input level of water, fertilizer and management, and the LUT with the maximum potential crop yield is selected. Consequently, the agro-climatic resources, such as the improved heat resource, could be fully utilized in the simulation to maximize the land crop productivity. If well-designed, its simulation can select the most suitable crop cultivar from many, figure out the best planting date for each grid-cell across the give regional, and provide the optimized cropping system information for adapting to the changed climate projections. This advantage makes the AEZ model well suited for potential crop productivity assessment at regional, national and global scales (Fischer and Sun, 2001; Fischer et al., 2005; Tubiello and Fischer, 2007; Teixeira et al., 2013).

Because the crop growth, biomass accumulation and yield modelling procedures in the AEZ model are much simpler compared with the process based crop models, the response details of the single crop to the climate change could not be fully investigated. More importantly, the updating of the key eco-physiological parameters of crop cultivars in the LUT database is largely depend on literature review, and expert opinion and is exogenous to the AEZ modeling process. This limitation may make the simulations of the AEZ model lag behind the real adaption and technological progresses in farm fields, rendering the results biased and unrepresentative (Tian et al., 2014).

1.3 Research Objectives

The leading goal of this dissertation is to develop a cross-scale modeling framework that is capable of incorporating the field agricultural advances into the design and evaluation of regional cropping system adaptation strategies. It then applies this framework to identify feasible cropping system adaptation strategies under observed warmer climate and quantify their potential benefits to the grain production and water sustainability in the major cropping regions in north China...

The specific research objectives are:

(1) Develop a cross-scale model coupling framework between the site level DSSAT model and the regional level AEZ model to improve the AEZ performance in capturing the northern expansion of suitable area for growing japonica rice under the warmer climate in the Northeast China Plain (Chapter 2).

(2) Construct a new wheat-maize cropping systems adaptation strategy based on the latest progresses in field experiments and modeling development to reconcile the double challenge of recovering local groundwater table and maintaining regional total grain production level in the semi-arid North China Plain, where the persistent overexploitation of groundwater has caused severe environmental damages (Chapter 3).

(3) Identify desired water sustainable cropping systems across different counties, aiming to meet the twin challenge of recovery local groundwater table and minimize the output losses of wheat and then total grain production in the Hebei Plain, where the irrigation water shortage has threatened wheat production and thus potentially compromising China’s food security (Chapter 4).

1.4 Outline of Dissertation

This dissertation consists of five chapters. Chapter 1 presents a brief overview of the literature on agricultural management improvements and adaptation efforts aiming at increasing grain production and reducing irrigation water amount for groundwater recovery under climate change. An important research niche is identified from this review. The chapter then proposed a conceptual framework for designing and evaluating multi-scale compatible cropping system adaptation strategy to capturing the opportunities brought in by and to mitigate the negative impact of, climate change.

Chapter 2 focuses on the cross-scale modelling effort in simulating the observed northern-ward expansion of rice cropping boundary in the Northeast China Plain as a result of local farmers' adaptation to the better thermal condition under warmer climate and the observed yield gains resulting from the new management method in the rice seedling stage. An integration framework by coupling the AEZ model and DSSAT model is developed and the coupling significantly improves the spatial performance of the AEZ model in simulating the recent dynamics of rice in the Northeast China Plain.

Chapter 3 to 4 focus on the severe groundwater over-exploitation for agricultural irrigation and develop water sustainable cropping system adaptation strategies in the semi-arid North China Plain. Two new cropping systems of early maize winter fallow (EM-F) and winter wheat summer maize relay intercropping (WM-R) are assessed to quantify their advantages in irrigation water saving and higher water productivity. In Chapter 3, a regional adaptation strategy is developed to allocate the two cropping systems according to the sustainable supply capacity of local water resources without compromising the total grain production of the region as a whole. In Chapter 4, the adaptation strategy from Chapter 3, which replaces the double cropping of WM-S by single cropping of EM-F for groundwater recovery in the major wheat cropping areas of Hebei Plain, is further optimized across grid-cells at the county level to dynamically allocate the EM-F and WM-R regimes to each grid-cell, subject to the constraint of local water balance condition and the requirement of minimizing total wheat production loss and then total grain production loss for the Hebei Plain as a whole.

Finally, Chapter 5 summarizes the major findings of Chapters 2 – 4 and points directions for further improvements in cross-scale modelling, and regional adaptation strategy designing for other crops in other regions of China and under future climate projections, and for developing new policy tools to support agricultural adaptations decisions in the future.

Chapter 2: Improving Performance of Agro-ecological Zone (AEZ) Modeling by cross-scale Model Coupling: An Application to Japonica Rice Production in Northeast China

2.1 Introduction

The challenges to food security posed by climate change raise demand for unprecedented efforts and ability to simulate and predict the interactions between crop growth dynamics and the environment and management in general and the responses of crop growth dynamics to the latter in particular (Brown and Funk, 2008; Godfray et al., 2010; Rosgrant and Cline, 2003). While many studies indicate that climate change has exerted negative effects to and may reduce crop productivity in the future (Batts et al., 1997; Ciais et al., 2005; Lobell and Asner, 2003; Morison and Lawlor, 1999; Rasmussen et al., 1998; Tan and Shibasaki, 2003), others show that suitable adaptation strategies and measures can or could compensate the negative influence of climate change and significantly increase crop yield (Dixon et al., 2003; Lobell et al., 2008; Reid et al., 2007; Wang et al. 2012). The adaptation of crop growing ecological system to environmental change is a complex, multi-scale temporal and spatial process. It includes the short-term micro-scale dynamic processes such as the response of the physiologic process of individual crops to micro-environmental changes, the long-term macro-scale progressive processes of crop community's adaptation to regional and global climate changes, and the communication and interaction of these processes across different scales. Stimulated by the above research demand and modeling challenge, many integrated models have been developed to assess the impact of climate change on agriculture. These models can be grouped into two main categories: process-based crop growth dynamic models and agro-ecological productivity models (Tian et al., 2012).

The process-based crop models, such as the Decision Support System for Agro-technology Transfer (DSSAT) model (Jones et al., 2003), simulate the processes occurring within the crop growth cycle after parameters calibration using the multi-year site-level observations. In this research, we will also show that credible parameterization of the eco-physiological characteristics, which are essential for AEZ modeling, can be obtained in specific sites under relatively homogeneous conditions. These models have been wildly applied in evaluating the farm-level response of crop yields to the changes of climate, crop management and varieties. For example, the Agricultural Production System sIMulator (APSIM, Keating et al., 2003) is adopted to simulate the crop growth and grain yield of the wheat-maize double cropping system in response to a planned adaptation strategy to observed climate change – the “Double-Delay” technology, i.e., delay both the sowing time of wheat and the harvesting time of maize – for 1961-2008 (Wang et al. 2012). This farming system model is also applied to analyzing the contribution of fertilization improvement to the yield of wheat and rice in the North China Plain (Wang et al., 2010). DSSAT model is employed to predict regional rice production under different climate change scenarios in the future (Basak, 2012; Xiong et al., 2009; Yao et al., 2007). Oryza2000 model (Bouman and van Laar, 2006) is adopted to study the effect of water control measures on rice production in northern China (Bouman et al., 2007). Agro-C model (Huang et al., 2009) is applied to investigate the contribution of varieties breading, crop management improvements and climate change to the increase of rice yield in China since 1980 (Yu et al., 2012). Nevertheless, it is worth noting that performance of these models going beyond observation sites would be constrained by the availability of sufficiently detailed data to represent the spatial variability (Tubiello and Fischer, 2007). For example, although it has been proved at the observation sites that adaption measures such as shifting sowing and harvest dates (Rosenzweig and Parry, 1994; Wang et al., 2012), adopting high-yield crop varieties and improving plot-specific crop management (Butt et al., 2005; Njie et al., 2006; Ogden and Innes, 2008; Wang et al., 2012) help to reduce the negative impact of climate change, it is practically impossible for researchers to parameterize these site-specific measures for every grid cell of a large area under different climate change scenarios. Owing to these constraints, a direct application of a process-based crop model to a large area without adequately addressing the spatial variability issue of key parameters often produce problematic results.

In contrast, agro-ecological productivity models such as Agro-Ecological Zone (AEZ) model (Fischer et al., 2002a, 2012) employ simple and robust crop models and provide standardized crop-modeling and environmental matching procedure to identify crop-specific limitations of prevailing climate, soil and terrain resources under assumed levels of inputs and management conditions. In the AEZ, the following steps are applied at the grid-cell level to determine potential yield for individual crop and generic production system (called Land Utilization Type or LUT) combinations. First, geo-referenced regional (or national, global) climate, soil and terrain data are combined into a land resources database, assembled on the basis of regional grids, where climatic data comprises precipitation, temperature, wind speed, sunshine hours and relative humidity. In this step, the compilation and analysis of agronomically meaningful climate resources inventories including quantified thermal and moisture regimes in space and time are carried out. Second, defining and compiling all available and plausible LUTs. Attributes specific to each particular LUT include crop information such as crop eco-physiological parameters (harvest index, maximum leaf area index, maximum rate of photosynthesis, etc.), cultivation practices and input requirements, and utilization of main produce, crop residues and by-products. Third, running the crop-modeling and environmental matching procedure to conduct crop/LUT-specific agro-climatic assessment and produce maximum potential and agronomically attainable crop yields for basic land resources units under different agricultural production systems defined by water supply systems and levels of inputs and management circumstances. Fourth, computing yield reductions owing to agro-climatic constraints such as water stress, early or late frosts, pests, diseases, and weeds; and further conducting edaphic assessment to calculate yield reduction owing to soil and terrain limitations.

After the completion of the agro-climate resources inventories assessment and LUT compilation (steps 1 and 2), it is computationally speedy to run the matching procedure across all plausible LUTs in each grid-cell so that the model can automatically select optimum (or desired) crop cultivar and crop calendars (e.g. sowing date) among available choices. This advantage makes AEZ well suited for crop productivity assessment at regional, national and global scales (cf., among others, FAO, 2007; Fischer, 2009; Fischer et al., 2002b, 2005; Fischer and Sun, 2001; Gohari et al. 2013; Masutomi et al. 2009; Tubiello and Fischer, 2007; World Bank, 2011). However, this advantage also implies a disadvantage of lacking a modeling mechanism to update key crop eco-physiological parameters in the LUT database. Because the parameterization of LUT database is largely based on literature review and expert opinion and is exogenous to the AEZ modeling process, it may lag behind real technological progresses in farm fields and may not be representative in such subarctic region as Northeast China, where moderate warming in last 50 years have enabled innovative adaptation efforts for the expansion of rice planting and the adaptation has achieved great success. For example, rice planting area in Heilongjiang Province (the northernmost province in the region) had expanded from 0.22 Mha (million hectares) in the early 1980s to 2.98 Mha in 2010, indicating a northward shift from ~48°N to ~52°N. More impressively, statistical data show that total rice production in this province had increased from 0.7 Mt (million tons) to 18.4 Mt over the same period (National Bureau of Statistics of China, NBSC hereafter, 2009, 2011), implying a yield increase from 3.2 t/ha to 6.7 t/ha. Our initial AEZ model simulation based on existing LUT dataset for rice production in Northeast China does show the inability of the model to capture such progresses. In more detail, the AEZ-v3.0 (2012 version) simulation on the 2000 map of paddy fields, which was produced from visual interpretation of Landsat satellite images by the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Science (Liu et al. 2005), generates an average potential yield of 6.5t/ha for the region, which is lower than the real observed yield of 7.3t/ha in 2000 (NBSC, 2009). In addition, the predicted rice growing area is 22 percent smaller than the area given by the map. This significant gap motivates this research.

Instead of updating crop eco-physiological parameters of the relevant LUTs by running literature review and collecting expert opinion and then verifying the updating by trial and error, this research propose a more systematic way to calibrate key AEZ eco-physiological parameters based on DSSAT model and observed data on farm sites. In more detail, this research intends to establish a smooth coupling procedure between DSSAT and AEZ models so as to enhance the micro foundation of AEZ and improve its performance. The procedure consists of three major steps as follows. First, we calibrate and validate key cultivar parameters within DSSAT model; second, we translate these cultivar parameters into key AEZ eco-physiological parameters and validate them using AEZ model; and third, we run two versions of AEZ model, one with these validated new eco-physiological parameters and the other with original parameters and then compare the two sets of results. We apply this procedure to japonica rice production in Northeast China on paddy fields as given by the 2000 map mentioned above and under the historical climate conditions of 1980-1999. The application shows a significant improvement in spatial performance of the AEZ model with the validated new eco-physiological parameters. The regional average potential yield for the whole period increases from 6.5 t/ha, which is lower than the real observed yield of 7.3 t/ha in 2000, to 9.3 t/ha. The predicted rice planting areas extend significantly and become well coincided with the 2000 map of paddy fields. This application illustrates that the procedure we propose presents a convenient way for AEZ model to update its key genetic parameters based on observed technological progresses in the farm sites.

2.2 Data and methods

2.2.1 Study area and observation sites

The region selected for this study is Northeast China located between 118°50’ -135°05’E in longitude and 38°43’-53°24’N in latitude (Figure 2-1). This northernmost region of China comprises Heilongjiang, Jilin and Liaoning Provinces and has a territory of 787,300 km^2 and a population of 112 million (in 2010), with a continental monsoon climate. In 1980-2000, the number of continuous days with daily average temperature ≥10°C ranged from 120 to 160 days, the effective accumulated temperature sum above 10°C was between 2,000°C and 3,000°C, and the annual sunshine hours were 2,200-3,000. In June-August, daily sunshine hours can reach 14 or more hours. Annual rainfall averages 530-610mm and concentrates mostly in the summer season.

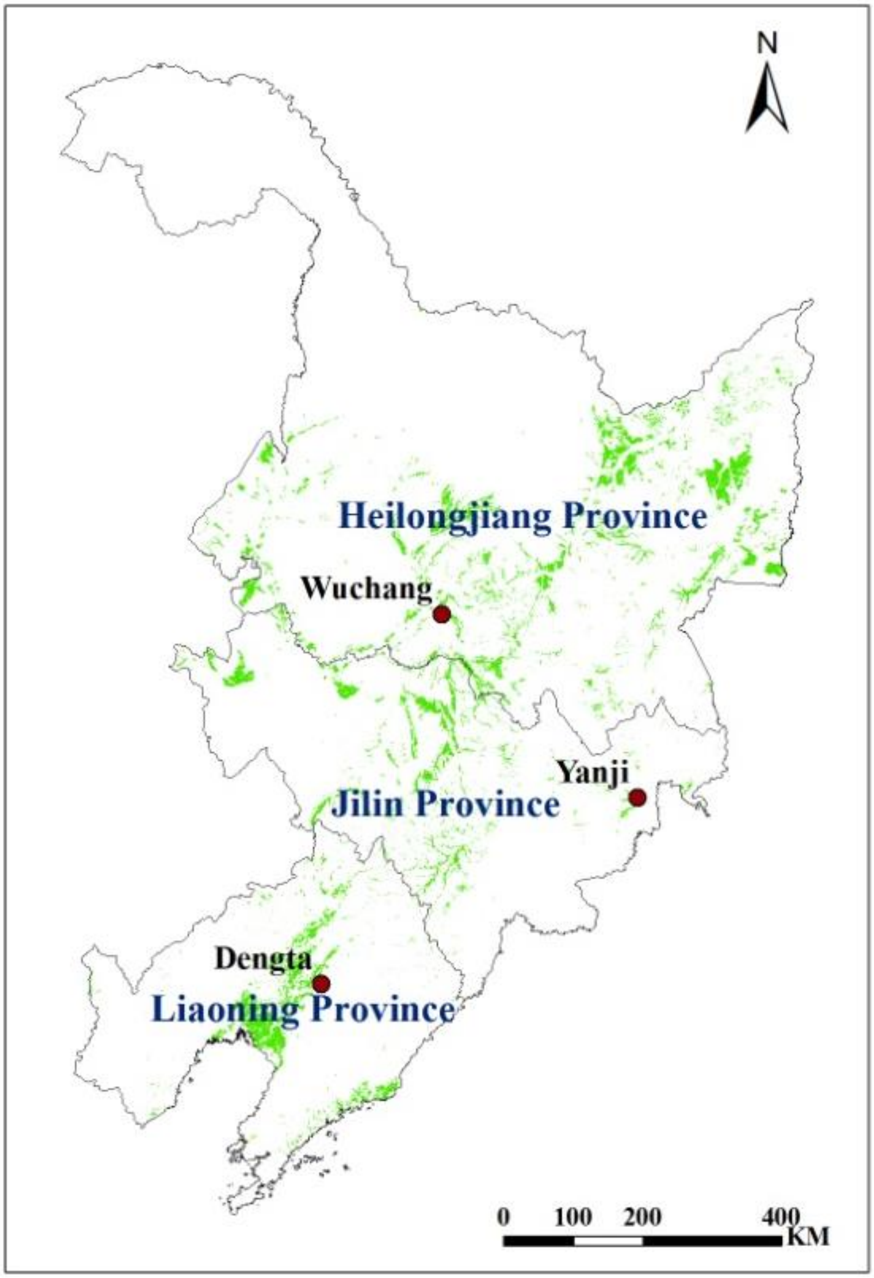


Figure 2-1. The map of paddy fields in Northeast China (2000) and the location of the three selected agro-meteorological observation sites

The most striking agricultural development in the region is arguably its emergence as the rice production base of China since the 1980s. In the early 1950s, the area for rice production amounted to only 250,000 ha and the total rice output was

581,000 tons, accounting for merely 1% of the national total. Even in 1980, the area for rice production was only 848,800 ha and the output 4.22 Mt which accounted for 3% of the national total. Within the 20 years of 1980-2000, paddy area expended by 1.73 Mha, the total output increased by 13.7 Mt, and yield rose by 2.34 t/ha. In the 2000s, the region produced about 10% of the national total rice output (NBSC, 2009, 2011; Ma, 2012). Many factors contribute to such a success, including market and policy incentives to farmers, utilization of emerging regional comparative advantages in rice production, technological and management innovations, and expansion of irrigation infrastructure. From the perspective of ecological science, Gao and Liu (2011) show that a warming of over 2°C in Heilongjiang Province from the 1960s to the 2000s makes it possible for rice planting adaptation measures to emerge and succeed, which in turn leads to the expansion of rice growing areas in the province. They also highlight that the expansion of paddy fields during 1980-2000 coincided closely with the northward shift of the 2°C isoline. The Agro-C model simulation of Yu et al. (2012) with county level statistical data indicates that genetic improvement via variety renewal was the decisive factor of rice yield increase in China during 1980-2009. At the country level, it contributed to 74% of the entire increase, and in the Northeast its contribution share was 67%. The remaining shares can be attributed to management improvement, climate warming, and shift in cropping pattern.

Despite the analytically clear-cut shares across genetic, management, and climate factors in Yu et al. (2012), we recognize that these factors are organically integrated in the real farming practice. In other words, without the facilitations of the moderate climate warming as highlighted by Gao and Liu (2011) and the new adaptive cultivation methods such as the “3-Super” (3-S) as presented in Jin et al. (2005) and Zhang et al. (2005), the gains from genetic improvement would unlikely be materialized. The 3-Super rice cultivation method includes the following three “Supers”: (i) Super early breeding seedling with the application of the greenhouse during the nursery period, (ii) Super sparse planting method, and (iii) Super high yield related rice management technology, such as deep fertilization, irrigation control, crop disease and pest control. These methods facilitate the introduction and enhance the adaptation of new varieties in the fragile and vulnerable subarctic environment of Northeast China and improve the high-yield characteristics of the crop, such as the leaf expanding, tillers growing, grain filling, thus leading to higher rice yield (Sun, 2001). Studies of Cao et al. (2005) and Jin et al. (2005) show that the 3-S cultivation methods could extend the rice growth cycle by about 20 days, increase the effective accumulative temperature by around 300 GDD (°C), and boost the rice yield by nearly 30% in Heilongjiang Province. This research aims to draw updated crop eco-physiological parameters from these genetic and management improvements and then adds the new parameters to the LUT database of AEZ model.

We take detailed meteorological, soil, agronomic and crop cycle information from three agro-meteorological observation stations. They are Wuchang station (45.75°N, 126.77°E) Heilongjiang Province, Yanji (42.88°N, 129.47°E) in Jilin Province and Dengta (41.42°N, 123.32°E) in Liaoning Province. Each station represents a typical agriculture site in the province and keeps the best available records for our research. The average annual temperature during 1961-1990 at

Wuchang, Yanji and Dengta was 4.6 °C, 6.2 °C, and 8.9 °C; and the average annual precipitation was 465.7 mm, 445.6 mm, and 587 mm, respectively.

2.2.2 Data

Daily climate data for 1980-1999 are obtained from the Data Center of the National Meteorological Administration of China. These observations were made at 72 meteorological stations distributed throughout the Northeast region at a wide range of elevations. Few stations are found in the far north of Heilongjiang owing to a low population there, where there is also no rice cultivation. The climate data include minimum and maximum air temperature, daily sunshine hours, precipitation, relative humidity, and wind speed. The dataset also contains the location (longitude and latitude) and elevation of each station. Because both DSSAT and AEZ models need radiation data, we employ the empirical global radiation model to calculate daily radiation levels (Pohlert, 2004). These point-based data are imported to ArcGIS together with the coordinators and then are interpolated into 10 km spatial resolution grid data.

Soil data at the three agro-meteorological observation stations are extracted from the correspondent grid cell in the 1km×1km Harmonized World Soil Database (HWSD, cf. Nachtergaele and Fischer, 2012). This soil database is developed by the Land Use Change and Agriculture Program of International Institute for Applied Systems Analysis (IIASA), the Food and Agriculture Organization of the United Nations (FAO), and other partner organizations. It provides reliable and harmonized soil information at the grid cell level for the world, with a resolution of 1km × 1km for China. The soil is aggregated into topsoil (0-30 cm) and subsoil (30-100 cm).

Information on drainage rate, soil depth, bulk density, organic carbon, mechanic content, soil PH, and cation exchange capacity of the soil and clay fraction etc. can be directly extracted from the database. DSSAT requires additional stratified soil proprieties to bridge the data gap between the HWSD and DSSAT requirement. For this purpose, we work with the soil color from the soil database of World Inventory of Soil Emission Potentials (Batjes, 2009) and the given soil properties from HWSD soil database, and then employ formulas given in the DSSAT literature (Baumer and Rice, 1988; Gijsman et al., 2002; Gijsman et al., 2007; Rawls et al., 1982; Ritchie et al., 1989) to do the required conversion calculations.

The map of paddy fields in Northeast China is extracted from the National Land Cover database (100m × 100m) provided by the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Science. This land cover database was produced from visual interpretation of Landsat satellite images and grouped into ten categories, rice paddy fields is one of the major categories.

Crop phenology and management information for 1980-1999 are collected from the three agro-meteorological observation stations. Their observation records contain the ID, name and location (latitude and longitude) of each station, date of each major phenological stages (sowing, flowering, maturity etc.), yield and yield components (grain weight, grain number per tiller, tiller number per plant etc.), and crop management practices (fertilizing, irrigation etc.).

2.2.3 Framework for cross-scale models upscaling

The major information flows in our general framework for cross-scale models coupling can be grouped into 6 steps as presented in Figure 2-2. We first calibrate the DSSAT model based on the annual records of rice growing calendars (phonological stages) and optimum yield components at the three agro-meteorological stations over 1980-1999. In order to extract cultivar genetic coefficients (details are presented in the subsection 2.4) which are able to sustain maximum attainable yield under ideal management conditions, we assume that the most suitable cultivar is adopted, there is no water and nitrogen limitation and the control of pest and disease is fully effective. In DSSAT modeling terms, this means that automatic irrigation and fertilization applications are set in the DSSAT calibration process to ensure that there is no water or nitrogen stress during the plant growing season.

In step (2), we employ the Generalized Likelihood Uncertainty Estimation (GLUE) Module built in DSSAT (He et al., 2010) to estimate the key cultivar coefficients for the site-specific japonica rice. The main principle of GLUE is to separate the parameter space by generating a large number of parameter values from the prior distribution. Likelihood values are calculated for each parameter set using field observations in the following way: For each sample value of cultivar coefficients, we run DSSAT and then assess the performance of the sample based on its corresponding likelihood value (i.e., by closeness to the key observation values such as flowering day and maximum yield) and thus its probability value in an empirical posterior distribution of the parameters. For each cultivar coefficient, we select the value which is associated with maximum probability. Technical details on the GLUE algorithm are presented in Beven and Binley (1992).

In step (3), the selected values of cultivar coefficients from step (2) are translated into the values of crop eco-physiological parameters which include harvest index, maximum leaf area index, length of growth cycle (LGC, also called length of growth period or LGP), and temperature requirement. In step (4) new LUTs are generated based on the results of step (3) and are added to the LUT database. In step (5) the AEZ model is run with both the original and the newly generated LUTs, under the historic climate condition over 1980-1999, and in each grid-cell of the 2000 rice field map of the Northeast China. A performance comparison is conducted accordingly. In step (6), both DSSAT and AEZ (with both original and new LUTs) are run at the three observation stations with identical climate conditions, soil profile and crop management. The comparison between the DSSAT results and the two sets of AEZ results further evaluates and validates the performance of the newly developed LUTs.

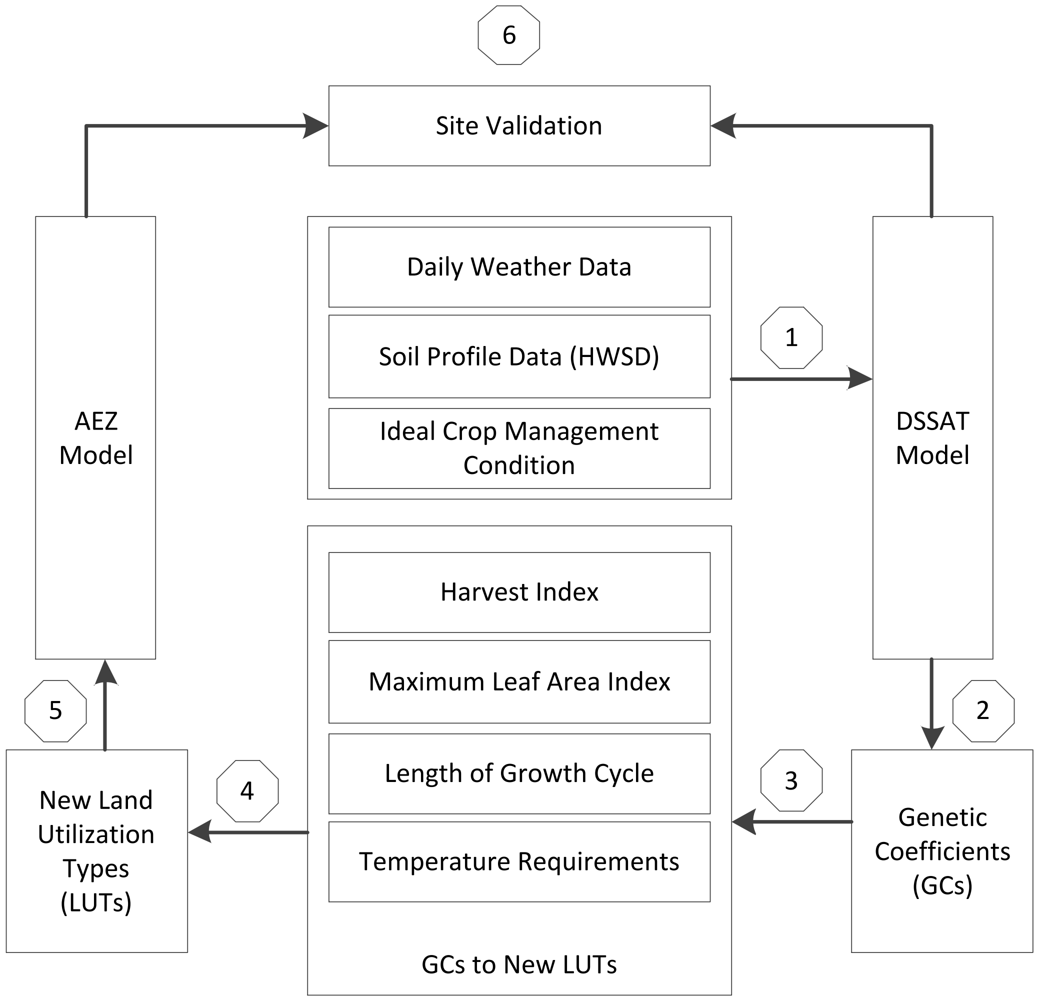


Figure 2-2. Framework for the DSSAT-AEZ coupling

2.2.4 DSSAT calibration and genetic coefficients calculation

Proper parameters estimation would ensure the accuracy of the model prediction (Makowski et al., 2002). Cultivar specific model, such as DSSAT, uses genotype coefficients (GCs) to describe the genotype-by-environment interactions and predict performance of diverse cultivars under different conditions (Penning de Vries et al., 1992), thus enabling the integration of genetic information on physiological traits into crop growth model. In the DSSAT model, each crop has specific parameters to describe the genotypic information of different cultivars of the crop. In the DSSAT's CERES-rice model, 7 parameters are essential for describing the genotypic information of different rice cultivars (Singh et al., 1988). They are juvenile phase coefficient (P1), critical photoperiod (P2O), photoperiodism coefficient (P2R), grain filling duration coefficient (P5) , spikelet number coefficient (G1), single grain weight (G2), tillering coefficient (G3), and temperature tolerance coefficient (G4), as presented in more details in Table 2-1. The values of these coefficients are highly environment dependent and even the same cultivar may have different coefficient values when it is planted in different places. Therefore site-specific values of these 7 cultivar coefficients should be extracted and model should be validated with observations at the site scale before application.

Table 2-1. Cultivar coefficients in the CERES-rice model

Code	Definition	Usual Range of Values
P1	Duration, in degree-days, from emergence to end of juvenile stage	300-900 GDD (°C)
P2O	Longest day length at which the development occurs at a maximum rate	10-14 hours
P2R	Extent to which phasic development leading to panicle initiation is delayed for each hour increase in photoperiod above P2O	5-250 GDD h^{-1}
P5	Time period from beginning of grain filling to physiological maturity with a base temperature of 9°C	300-900 GDD (°C)
G1	Potential spikelet number coefficient as estimated from the number of spikelet per g of main culm dry weight at anthesis	30-100
G2	Single grain weight under ideal growing conditions	0.022-0.029 g
G3	Tillering coefficient (scaled value) relative to IR64 cultivar under ideal conditions	0.5-2.0
G4	Temperature tolerance coefficient	0.7-1.5

Source: Singh et al. (1988)

As mentioned in previous subsection, in order to extract site-specific values of cultivar genetic coefficients which are able to sustain maximum attainable yield under ideal management conditions, the calibration and simulation of the DSSAT model work with phenological stages and optimum yield components observed at each of the three stations. The optimum yield components include the maximum grain number per tiller and the correspondent grain weight, maximum tiller number per plant and the optimum plant density. They are employed to calculate the maximum attainable yield at each station. The newly developed GLUE Module of DSSAT is employed to calibrate and select values for the genetic coefficients at each station. In addition to the probability calculation of GLUE, we also employ the conventional measure of the root mean square error (RMSE), as presented in Eq. (2-1), to directly evaluate the departure between the observed (obs) and the simulated (sim) values.

$$RMSE = \left[\frac{\sum_{i=1}^{n}(sim_i - obs_i)^2}{n}\right]^{1/2} \qquad (2\text{-}1)$$

2.2.5 New Land Utilization Types (LUTs) generation and evaluation

Attributes specific to each particular LUT include crop information such as crop eco-physiological parameters (harvest index, maximum leaf area index, maximum rate of photosynthesis, etc.), cultivation practices and input requirements, and utilization of main produce, crop residues and by-products (Fischer et al., 2002a, 2012). The updating focus of this research is on the crop eco-physiological parameters, including temperature requirement and duration of each phenological stage. In more detail, the key parameters are: Maximum Leaf Area Index (MaxLAI), Harvest Index (HI), growth cycle duration, and specific temperature requirements for japonica rice growth and development.

For the new LUTs, the MaxLAI and HI can be directly extracted from the DSSAT output files and then adopted in the AEZ simulations. However, the definition of the major phenology stages is different between the two models. The DSSAT-Rice model simulates growth in the nursery period and growth after transplanting separately (Salam et al., 2001; Torres et al., 1994) and for the transplanted japonica rice, DSSAT runs simulation from planting to physical maturity (Singh et al., 1988), whereas the AEZ model starts its simulation at the time-point when crop photosynthesis begins (i.e., Emergence) and ends at the time of full maturity (Allen et al., 1998). Low temperature during the nursery stage would have negative influence to the rice development and limit the length of rice growing period in such subarctic region as Northeast China. In order to overcome this constraint, farmers apply measurements such as the greenhouse and plastic film mulching (Gu et al., 2012). DSSAT is advantageous in this regard because it can take into account such rice nursery management practices and conditions. In contrast, the AEZ model is initially driven by agro-climatic resource inventories (“top-down”) and it is very difficult for it to directly simulate the effect of such artificial environment.

The translation of growth cycle between the DSSAT and AEZ model is based on the detailed share distribution of the length of each phenology stage in the total given in the FAO’s Crop Environmental Requirement Database (FAO, 1996). The period from transplanting to emergence is set at five days following the results of DSSAT simulations at the observation stations.

In the AEZ model, temperature profile requirements of japonica rice (Table 2-2) are catered for crop growth cycle duration in different classes (L1-L6) of mean daily temperatures, in 5°C intervals. These are distinguished for days with increasing (L1a-L6a) or decreasing temperature (L1b-L6b) trends. These temperature profiles are matched with rice growth temperature requirements to generate either optimum match, sub-optimum match or not suitable conditions (Fischer et al, 2012). Temperature profile and temperature sum of each phenological stage are calculated at each site with observed daily climate data.

Table 2-2. Definition of the temperature profile classes for japonica wetland rice

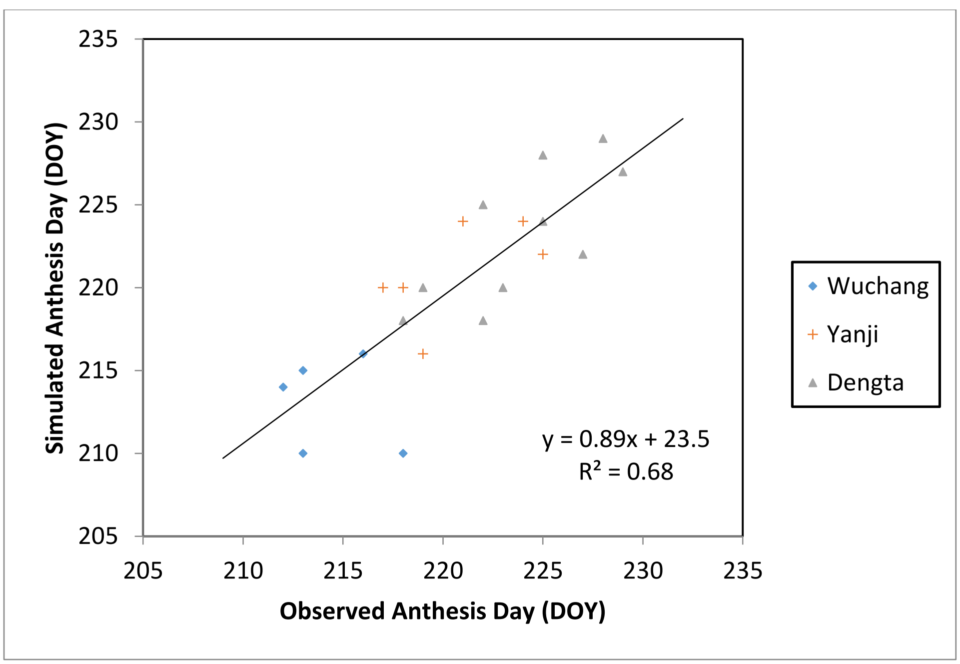
Average Temperature (°C)	Growth Cycle Duration (days)	Temperature Trend	
		Increasing	Decreasing
>30	L1	L1a	L1b
25-30	L2	L2a	L2b
20-25	L3	L3a	L3b
15-20	L4	L4a	L4b
10-15	L5	L5a	L5b
5-10	L6	L6a	L6b

Source: Fischer et al. (2012).

2.3 Results and analysis

2.3.1 From calibrated cultivar coefficients to new LUTs

The values of the site-specific genetic coefficients produced by DSSAT-rice model validation are presented in Table 3. The value variation across three stations is obvious for 7 of the total 8 coefficients except G2. The predicted phonological dates from DSSAT simulations using these coefficient values fit well with the real observations as shown in Figure 2-3. The RMSEs for anthesis day, harvest day and attainable yield are 4.02 days, 2.64 days, and 66.9 kg/ha for the Wuchang site, 2.5 days, 2.9 days and 46.9 kg/ha for the Yanji site, and 2.7 days, 2.2 days and 106.1 kg/ha for the Dengta site, respectively, indicating that the errors as measured by RMSE are less than 2.5% of the real observed values. Considering that the ideal crop management conditions are applied (i.e., no-damages owing to water stress, fertilizer stress, no damages from insects and diseases) in the validation process, values of cultivar coefficients presented in Table 3 can be regarded as sufficiently genetic and therefore can be translated into the values of eco-physiological parameters suitable for AEZ simulation.



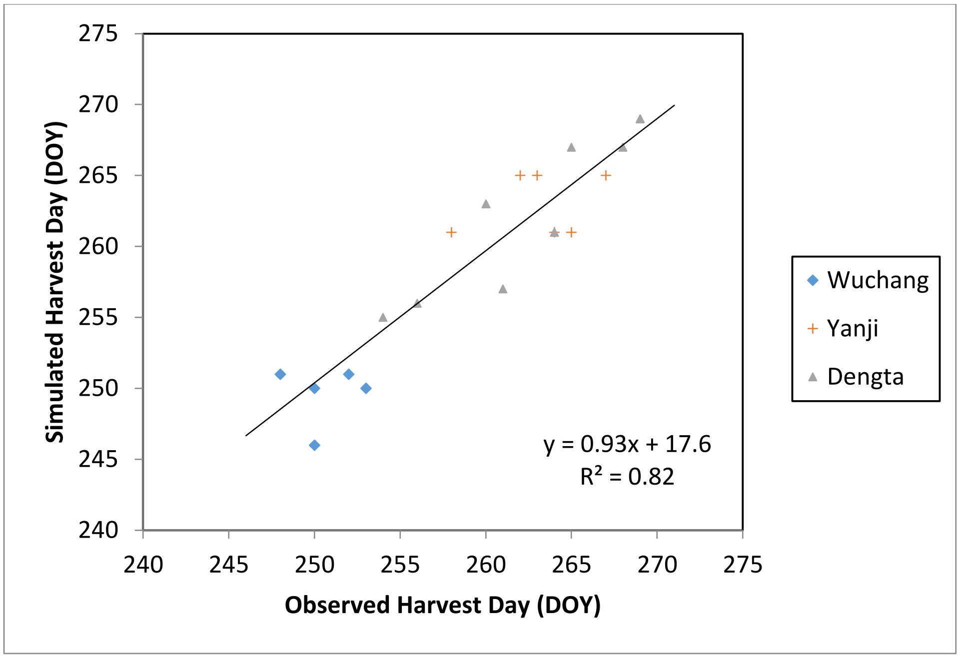


Figure 2-3. Observed and simulated dates of anthesis and maturity days at the three observation stations (unit: day of year or DOY)

Such key eco-physiological parameters as MaxLAI, HI, crop growth cycle which are central for calibrating new LUTs are directly extracted from the output files of the DSSAT simulations using coefficient values of Table 2-3. The temperature profiles are derived from observations and the eco-physiological characteristic outputs of the DSSAT model. Table 4 shows the temperature profile requirements at each stage before and after our modification. To accommodate the greenhouse nursery practice, longer periods are allowed for the stages L4 and L5 (temperature between 10°C to 20°C) so that the natural outdoor environment can accumulate equivalent amount of temperature sums to that accumulated in the indoor environment. Numerically, the multiplying factor before the length of growth cycle ("L" in the Table 2-4) is raised from 0.4 to 0.5 for L5a + L4a, and from 0.25 to 0.35

for L5b + L4b under the optimum condition. A similar increase, although at a less extent, is also applied to the sub-optimum condition, i.e., from 0.4 to 0.45 and 0.25 to 0.3 respectively. Naturally, limitation of the extreme temperature which is not suitable for rice growth (L1 and L6) is not changed.

Table 2-3. Values of site-specific rice genetic coefficients

Observation Stations	Genetic Coefficients							
	P1	P2R	P5	P2O	G1	G2	G3	G4
Wuchang	201.6	32.66	331.6	11.26	70.96	0.025	0.580	0.945
Yanji	221.4	47.16	412.3	13.55	91.02	0.025	0.355	0.983
Dengta	389.7	39.76	394.6	12.71	75.73	0.024	0.875	1.164

Table 2-4. Temperatures profile in the original and new Land Utilization Types (LUTs)

	Optimum condition	Sub-optimum condition
Original LUTs	L5a+L4a < 0.400×L L4b+L5b < 0.250×L L2a+L2b < 0.667×L L4 > 0 (min 5 days) L1 < 0.200×L L6a+L6b = 0	L5a+L4a < 0.400×L L4b+L5b < 0.250×L L2a+L2b < 0.667×L L4 > 0 (min 5 days) L1 < 0.200×L L6 = 0
New LUTs	L5a+L4a < 0.500×L L4b+L5b < 0.350×L l5a+l5b+l4a+l4b < 0.750×L L2a+L2b < 0.667×L L4 > 0 (min 5 days) L1 < 0.200×L L6 < 0.05×L L6b = 0	L5a+L4a < 0.450×L L4b+L5b < 0.300×L l5a+l5b+l4a+l4b < 0.650×L L2a+L2b < 0.667×L L4 > 0 (min 5 days) L1 < 0.200×L L6 < 0.05×L L6b = 0

Note: LGC stands for the length of growth cycle (or growth period).

A summary of the other updated values of LUT parameters are presented in Table 2-5, the maximum LGC is set at 150 days according to the site observations. MaxLAI and HI in the "New LUTs" panel of the table are the average values of DSSAT simulations and are adopted for the corresponding LUTs in line with the LGC. In comparison with the original LUTs for the region, the MaxLAI is increased by 0.5 or 1.0 and the HI by 0.05. Minimum temperature is defined as the threshold for counting the temperature requirement (temperature sum) during the whole crop life cycle. In line with the consideration in the calibration of the temperature profile, we decrease the minimum temperature by 2.5°C so that more low temperature days can be taken into the calculation to allow the natural outdoor environment accumulating temperature sums equivalent to that in the indoor environment.

Table 2-5. Comparison of other LUT parameters

LGC	Original LUTs			New LUTs		
	MaxLAI	HI	Minimum Temperature	MaxLAI	HI	Minimum Temperature
105	5.0	0.40	10°C	5.5	0.45	7.5°C
120	5.0	0.40	10°C	6.0	0.45	7.5°C
135	5.5	0.40	10°C	6.5	0.45	7.5°C
150	6.0	0.40	10°C	7.0	0.45	7.5°C

2.3.2 Improvement of the AEZ model

We run the AEZ model simulation with both the original and new LUTs of japonica rice under the historical climate conditions of 1980-1999 to first check the spatial performance of the new LUT on the 2000 map of paddy fields in the region. In order for the comparison to be carried out in relatively ideal conditions, we deactivate the constraints of pest and disease in the AEZ model and adopt the high input levels under irrigation condition (meaning adequate and sufficient water and nitrogen supply).

The comparison shows that the average potential yield of japonica rice increases from 6.5 t/ha with the old LUTs to 9.3 t/ha with the new LUTs. The latter figure is quite close to that from a field experiment study (Chen et al., 2006). Average increase is more than 2.8 t/ha with the SD of 0.4 t/ha, which indicates a universal increase across virtually every grid-cell on the paddy map. Higher yields mainly present in the central and southern part of the Northeast China Plain. In the northern part, where the temperature is the major constraint for more productive cultivars with longer LGC, yields are significant lower (Figure 2-4).

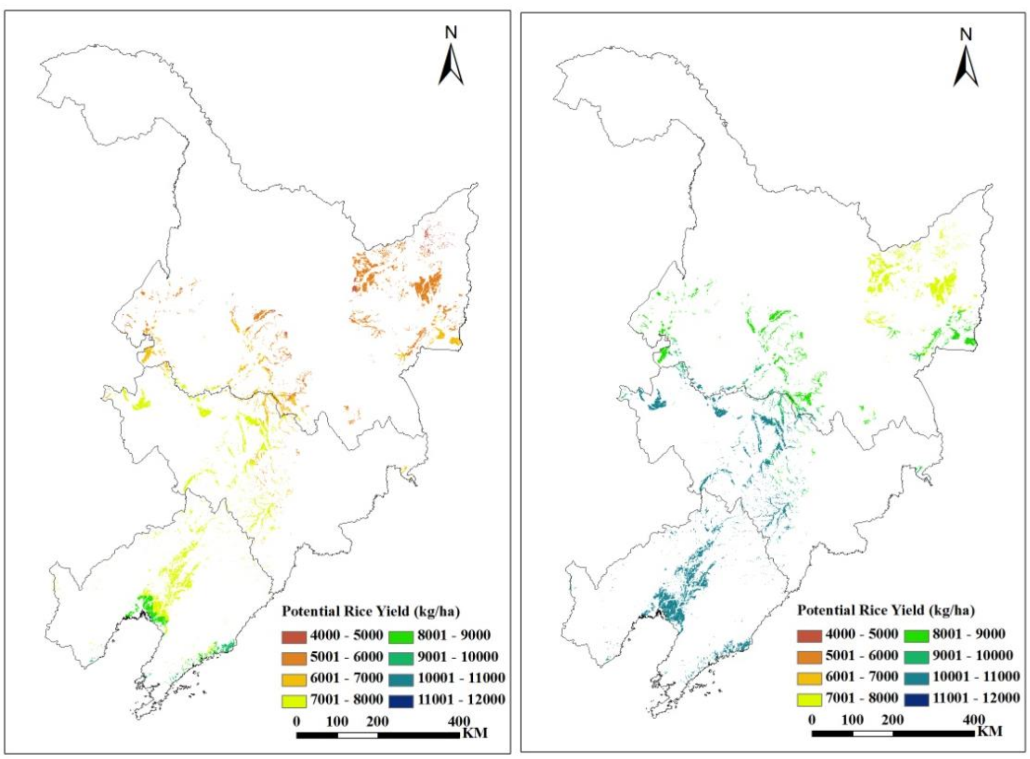


Figure 2-4. Potential yield comparison, the original (left) versus new (right) Land Utilization Types (LUTs)

While AEZ simulation with original LUTs shows that about 22% of the paddy fields on the 2000 map are not suitable for rice production, the suitable areas simulated with the new LUTs take up 99.8% of the paddy fields on the 2000 map. This implies a gap at the scale of more than 570,000 ha between the two simulations. It is also worth noting that longer LGC increases the cumulative heat for crop development and biomass formation and thus leads to increased yield, which is incorporated in the algorithms of both DSSAT and AEZ models.

We also run the above two sets of simulations at the three observation stations and compare the results with the DSSAT simulations. Figure 2-5 presents the comparative results of the three simulations at Wuchang Station in Heilongjiang, which is arguably the most important station in this study given the fact that the poor performance of AEZ with the original LUTs is most severe and widespread in this province. It shows that in contrast to the very low yield produced by the AEZ simulation with original LUT, which is 7.4 t/ha on average, the yields produced by the DSSAT simulation and AEZ simulation with the new LUT are much higher at a level around 9.0 t/ha. Interestingly, the AEZ simulation with the new LUT shows a more stable performance than DSSAT and it gives an average yield of 9.2 t/ha, 23% higher than the average given by the AEZ simulation with original LUT. Similar comparative results are also found at the other two stations and we do not report them here to save space.

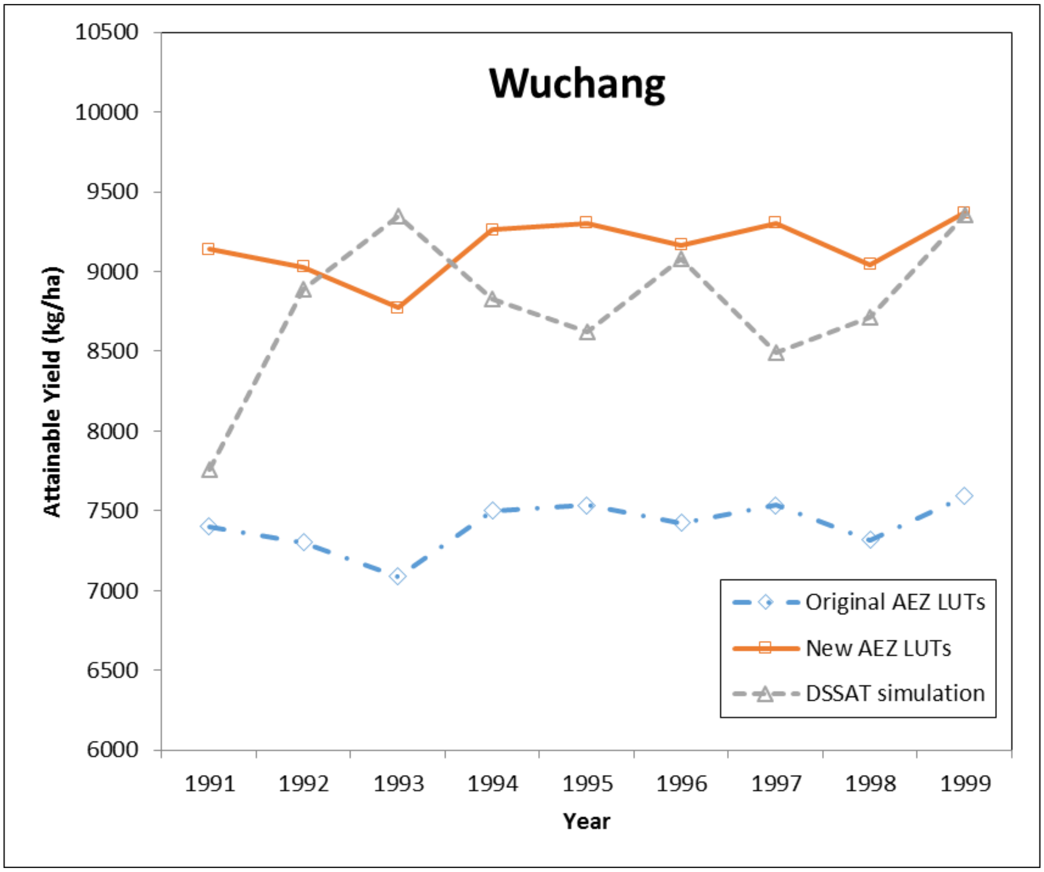


Figure 2-5. Comparison of simulated attainable yields among the AEZ results with original versus new LUT and the DSSAT results at Wuchang Station in Heilongjiang

Owing to the ability of the AEZ model to select the best adaptive cultivar under the given choice sets of all LUTs and agro-climate conditions, the introduction of the new LUTs into the LUT database results in extension of the LGC at the grid-cell level. Figure 2-6 shows the northward shift of rice planting borders from what given under the original LUTs to what under new LUTs. The north border of the LUT with a LGC of 150 days extends northward by about 600 km. This is a very significant shift and implies an extension of LGC by up-to 30 days in the extending areas which cover vast majority territories of Liaoning and Jilin Provinces. The northernmost border of the new LUT with a LGC of 105 days, the shortest LGC in the LUT database, is more or less 50 km further northward in comparison with its original counterpart. This extension is also in agreement with the findings of parallel historical climate change focused studies which show a similar northward shift of border for rice planting in Heilongjiang Province (e.g., Gao and Liu, 2011). This finding indicates that our new LUT with the LGC of 105 days is able to capture the double benefits of the moderate climate warming in the region and the new breeding cultivation technology. On average, the LGC of the japonica rice increases by about 20 days in the Heilongjiang Province, which is quite close to the findings of two field studies on the application of the new rice cultivation technologies in the province (Cao et al., 2005; Jin et al., 2005).

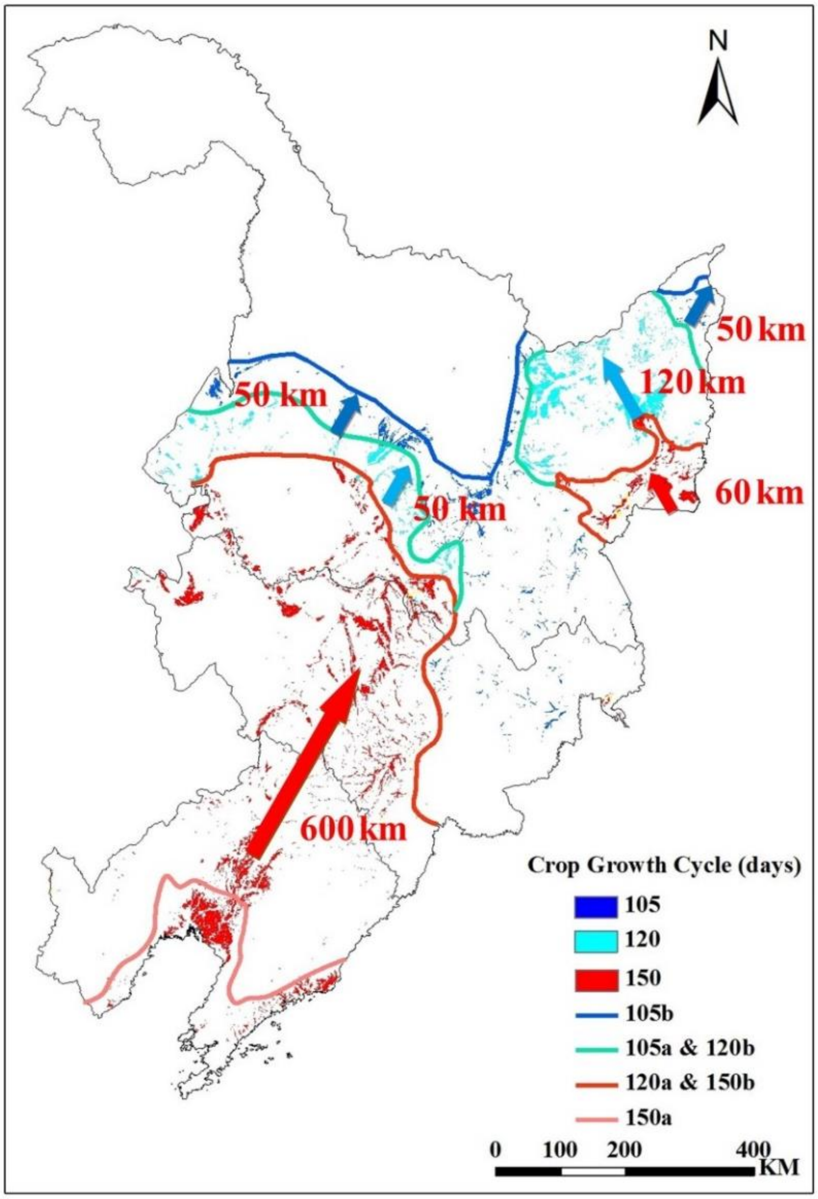


Figure 2-6. Northward shift of rice planting boundary from that with original LUTs (marked as 105a, 120a, 150a) to that with new LUTs (marked as 105b, 120b and 150b)

2.4 Conclusions

This research intends to make a contribution to the model coupling and fusion efforts targeting at exploring the interaction of agro-ecological processes across different scales. It presents a smooth coupling procedure between two popular crop models, the processed based and site specific Decision Support System for Agro-technology Transfer (DSSAT) model and the cropping zone centered Agro-ecological Zone (AEZ) model, with the aim to enhance the micro foundation and improve the performance of the AEZ model. The procedure first calibrates and validates key cultivar parameters using DSSAT, and then translates these cultivar parameters into key AEZ eco-physiological parameters and applies AEZ with the new parameters. An application of this procedure to japonica rice production in Northeast China under the historical climate conditions of 1980-1999 shows a significant improvement in spatial performance of the AEZ model. While the AEZ simulation with original eco-physiological parameters fails to capture the significant development of rice cropping in the region triggered by moderate warming since the 1950s, the same model simulation with the updated eco-physiological parameters captures the development well. In numerical terms, the regional average potential yield estimated by the AEZ with old parameters is merely 6.5 t/ha, which is lower than the real observed yield of 7.3 t/ha in 2000, it reaches 9.3 t/ha in the same model simulation with the updated parameters. Moreover, the suitable areas for rice planting estimated by the AEZ with old parameters cover only 78% of the existing paddy field in 2000, in contrast, the results produced by the same AEZ simulation with the updated parameters cover virtually all existing paddy field of 2000. These findings illustrate that the procedure we propose works well and can serve as a convenient way for AEZ model to update its key genetic parameters based on observed technological progresses in the farm sites.

A potential weakness of this research is that the updating of the key crop eco-physiological parameters relies solely on the DSSAT calibration and simulation. This may lead to robustness concerns with regard to these updated parameters. For example, some studies show that the DSSAT-rice model may overestimate the transplanting shock periods (Torres et al., 1994). This is because the model considers a linear relationship between seedling age (12 to 21 days) at transplanting and the shock period (Salam et al., 2001). In order to overcome potential uncertainty in this regard, it might be necessary to employ multiple process-based crop models, such as ORYZA2000, APSIM, WOFST (Vandiepen et al., 1989), EPIC (Williams et al., 1989; Xiong et al., 2014), to test the robustness of these newly calibrated crop eco-physiological parameters.

Future model coupling and fusion work in the context of DSSAT and AEZ may consider the way for DSSAT and other process-based models to reap benefits from the AEZ. For example, how can we establish a robust up-scaling procedure for the former by borrowing insights from the latter, and in this connection, the best crop rotation regimes produced by the agro-climatic assessment of the AEZ model can provide a sound starting point?

Chapter 3: Mission Impossible? Maintaining regional grain production level and recovering local groundwater table by cropping system adaptation across the North China Plain

3.1 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 requirement 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., 2015b; van Oot et al. 2016).[1] Many

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[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).

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 build-in soil-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 (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.

3.2 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 (Figure 3-1), 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., 2013b). 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 the global data set of monthly irrigated and rainfed crop areas in the year 2000 (MIRCA2000) on the wheat and maize harvest area (Portmann et al., 2010) (Figure 3-2). 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.

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).

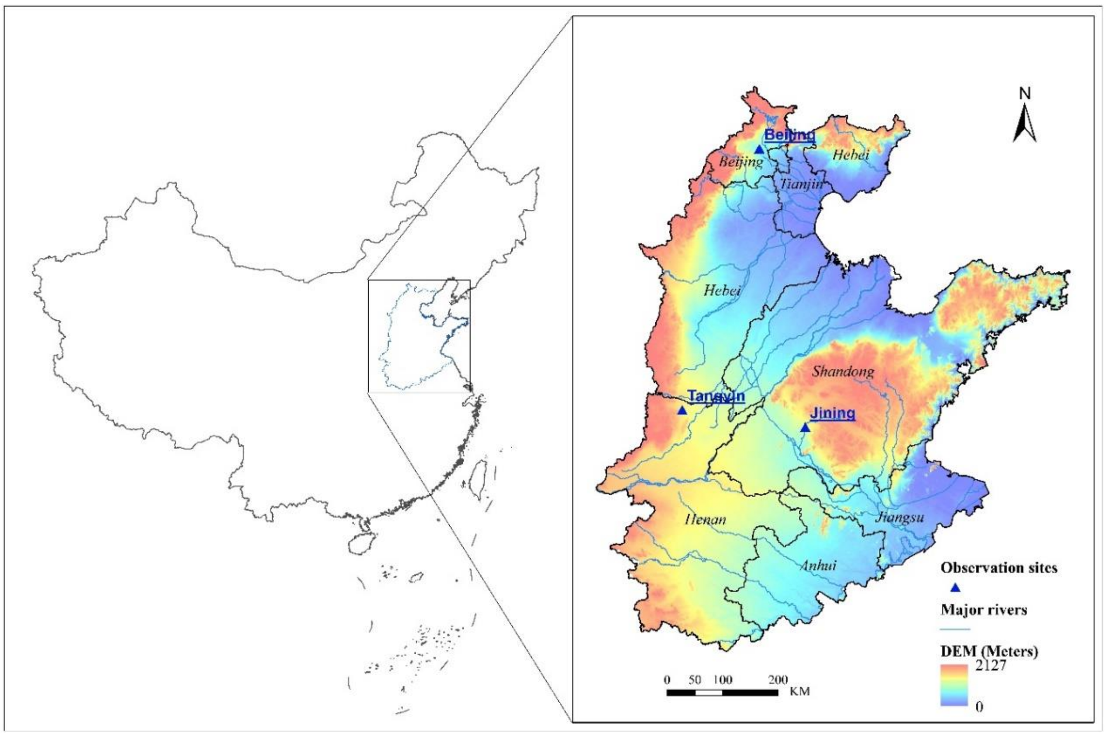

Figure 3-1. The North China Plain and observation sites

3.3 Materials and methods

3.3.1 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 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 1km. 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 (MIRCA2000) (Portmann et al., 2010) (Figure 3-2). 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.

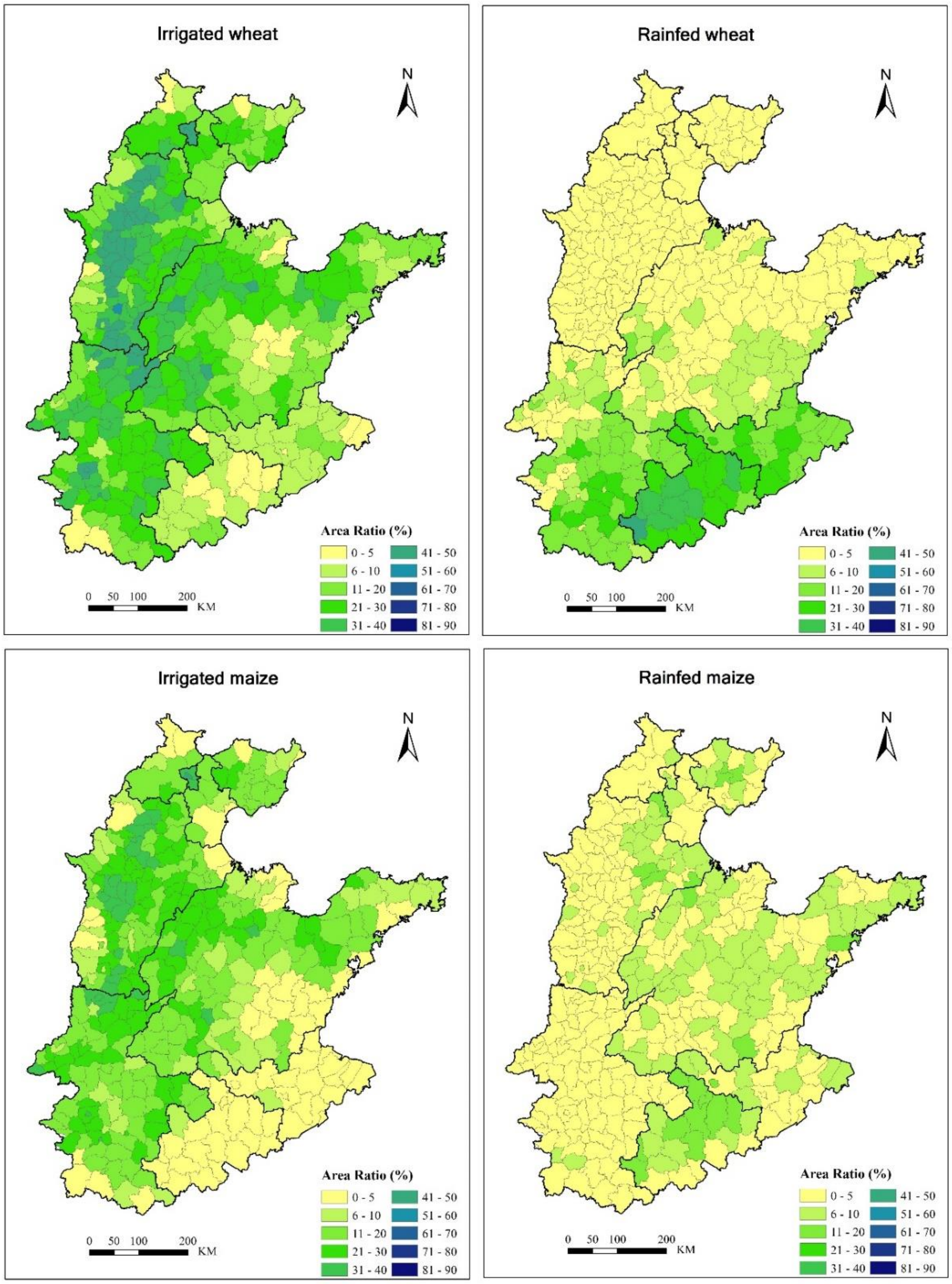

Figure 3-2. Area ratio of irrigated and rainfed wheat and maize to the total cropland at the county level in the NCP in year 2000

3.3.2 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.

3.3.3 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. 3-1 (Yang et al., 2010).

$$IWR = \sum_{i=1}^{2} DR_i \times AR_i \, , \qquad (3\text{-}1)$$

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.

3.3.4 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 3-3 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.

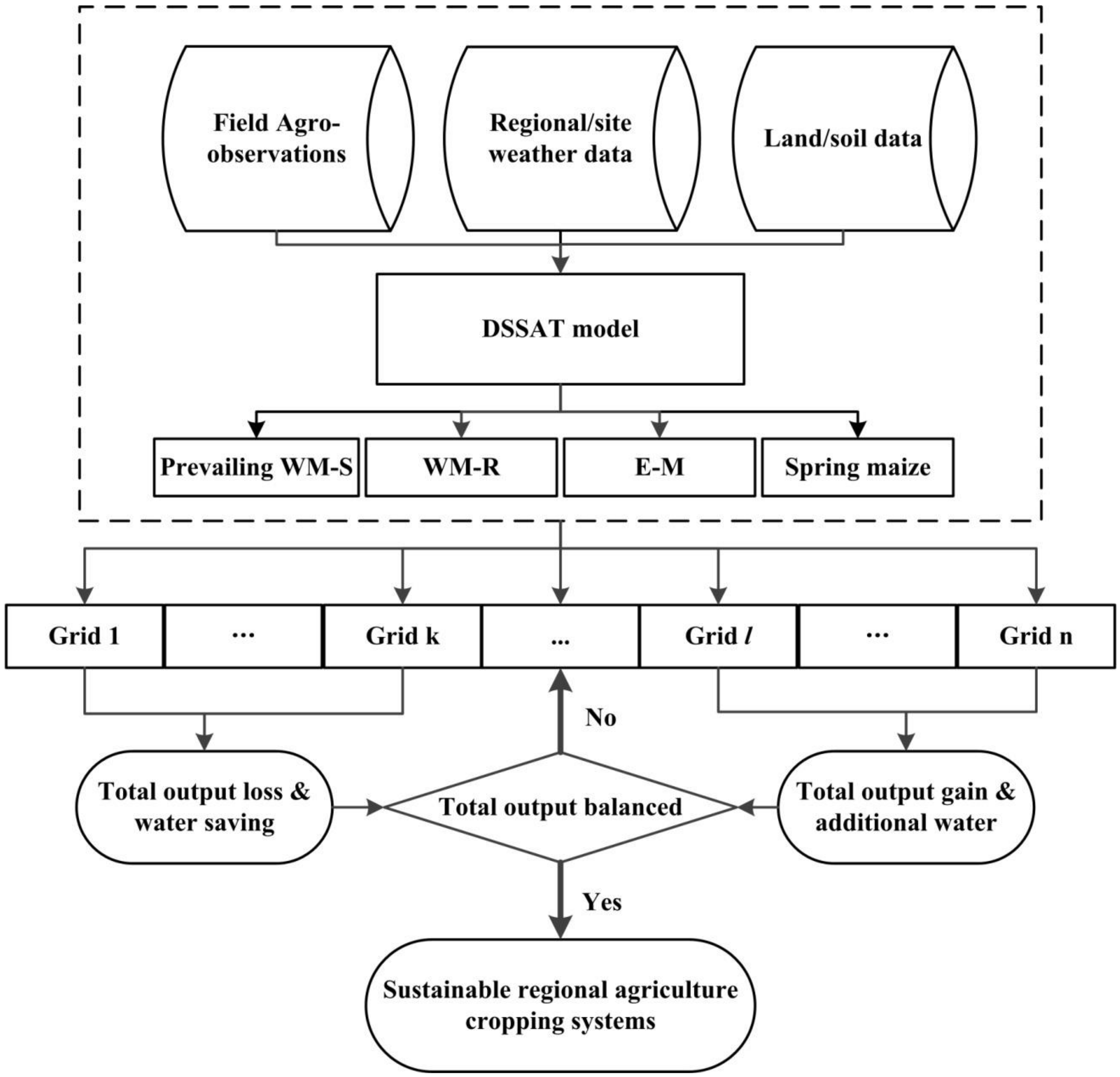

Figure 3-3. Flow chart of the regional cropping systems adaptation strategy

3.3.5 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 field 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. 3-2 is employed (Ali et al., 2007).

$$WUE = \frac{GY}{ET} \tag{3-2}$$

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

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.

3.3.6 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.

3.3.7 DSSAT model calibration and validation

The DSSAT model is developed by the International Benchmark Sites Network for Agro-technology Transfer project, 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 United States (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. 3-3 and mean relative error (MRE) in Eq. 3-4 are employed to evaluate the departure between the observed (Obs) and the simulated (Sim) values.

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

$$MRE = \frac{1}{n}\sum_{j=1}^{n}\frac{Sim_j - Obs_j}{Obs_j} \tag{3-4}$$

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

<u>*3.4 Results*</u>

3.4.1 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 Figures. 3-4 and 3-5. 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 Figure 3-5. 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.

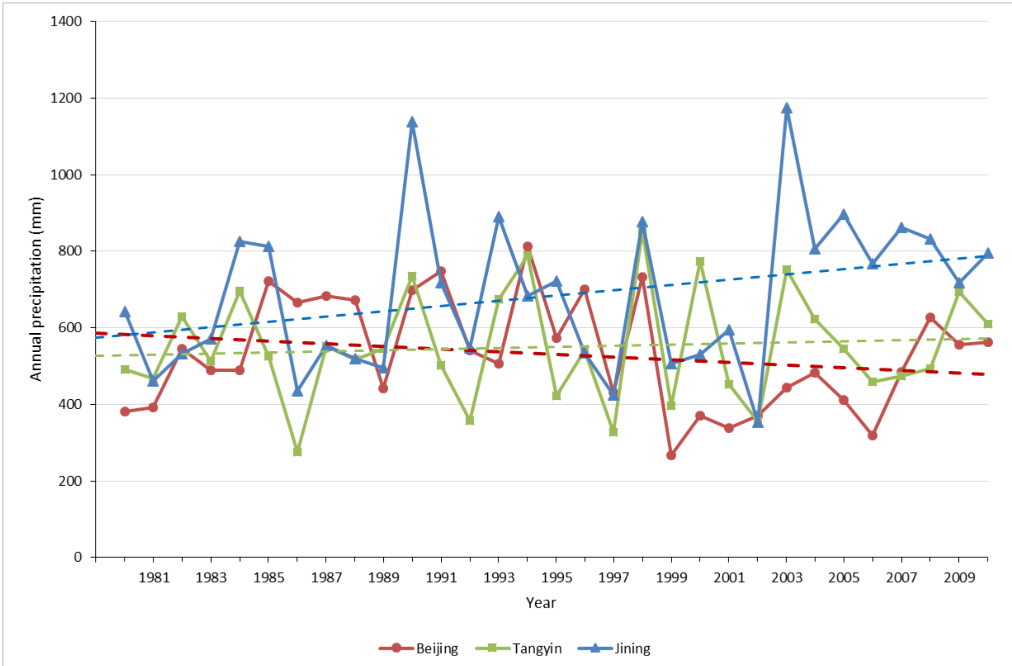

Figure 3-4. Observed annual precipitation at Jining, Tangyin and Beijing sites in 1980-2010

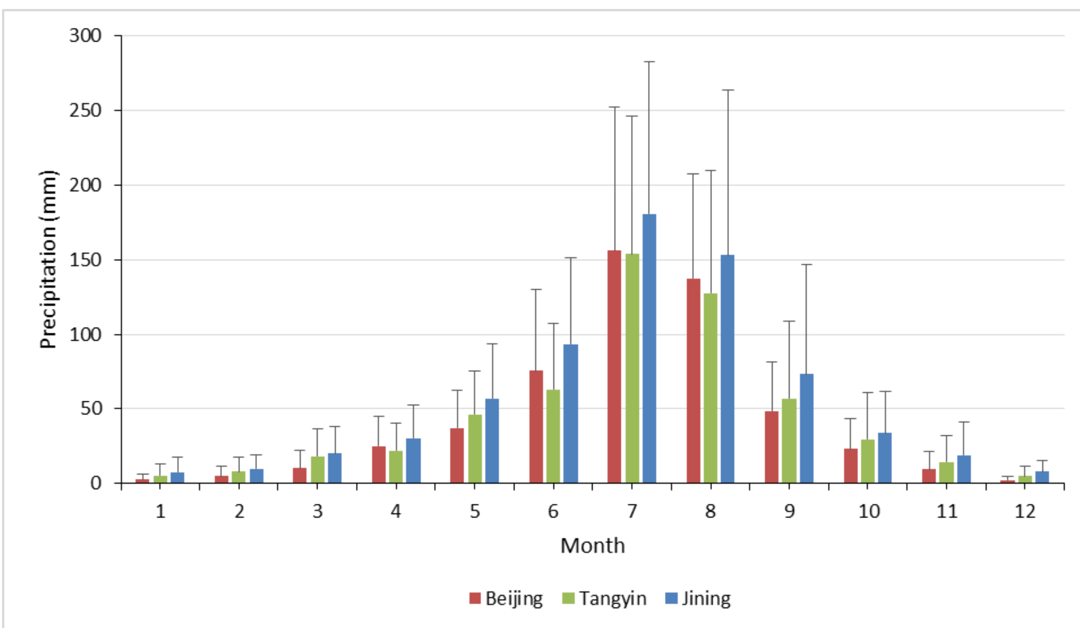

Figure 3-5. Average monthly precipitation at Beijing, Tangyin and Jining sites over 1980-2010

3.4.2 Crop cultivar coefficients and model performance

Tables 3-1 and 3-2 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 3-3 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).

Table 3-1. Cultivar coefficients of maize in sequential 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 3-2. 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 3-3. 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 mean relative error, RMSE is root mean square error, DAP is days after planting.

3.4.3 Comparing the performances of maize at the site

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 3-4 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 happened 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 requirement 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.

Table 3-4. 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).

3.4.4 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 requirement 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 3-5 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 3-6 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%.

Table 3-5. Changes in wheat areas, total grain output, and irrigation water requirement (IWR) under the regional cropping system adaptation strategy

	Winter fallow area		Change in total grain output		Change in IWR	
	10^3 ha	% of existing wheat area	10^3 ton	% of existing total output	10^6 m^3	% of existing IWR
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 requirement by the E-M in comparison with local summer maize leads to the departure between the percentage change of IWR and that of wheat fallow area.

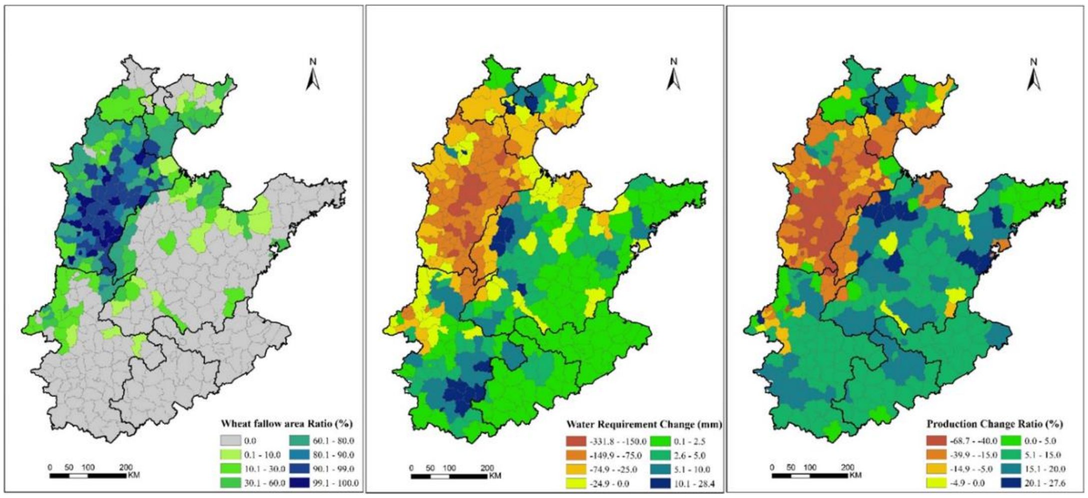

Figure 3-6 Area ratio of winter fallow (Left), change of water requirement (Central) and changes in total grain production (Right) at the county level (2001-2010)

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.

3.5 Conclusions and discussions

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 3.1m 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[2] 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., 2016a). 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 NCP.

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[2]Groundwater contamination from rapid increase of nitrate concentrations and mineralization refer to the groundwater recharge from infiltration of irrigation water, which is typically more saline and contains higher concentrations of nitrate and other contaminants on the cropland (Currell et al., 2012).

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 makes 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-maize 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., 2016b).

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 3-2 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).

Chapter 4: Optimizing regional cropping systems with a dynamic adaptation strategy for water sustainable agriculture in the Hebei Plain

4.1 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 cropping systems consume approximately 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 groundwater is required to irrigate wheat under local farmers' conventional practice (Sun et al., 2011). The large amount of irrigation water demand exceeds the renewable water availability and has led to unsustainable groundwater over-exploitation. As a consequence, groundwater table has dropped from 10m below the land surface in the 1970s to 40m in the early 2010s (Shen et al., 2002; Zhang et al., 2011b), and this drop has directly caused serious environmental degradation and considerable economic losses (Zhang et al., 2009). The scarcity of groundwater resource in the plain is already at an alarming status and the on-going competition from soaring water demand from industries and municipalities puts additional pressure on the limited water resources (Wang et al., 2009b). On the one hand, the irrigation water shortage has threatened wheat production in the region (Li et al., 2015) and thus potentially compromising China's food security. On the other hand, the current practice of groundwater overexploitation will have to come to an end as soon as possible so that groundwater extraction can be drastically reduced to conserve the aquifers (van Oort et al., 2016).

The severe environmental impact and potential grain production risks from groundwater over-exploitation has stimulated a large body of studies dealing with water saving irrigation technologies, less water-intensive agricultural intensification schemes, and the costs-benefits of cropland fallow (Kang et al., 2002; Li et al., 2005; Sun et al., 2011; Yang et al., 2015b; van Oort et al., 2016). Because under current cropping system, such measures as deficit irrigation or reducing irrigation frequency to one per crop growth cycle cannot prevent groundwater table from dropping (Sun et al., 2015), many researchers have tried to construct new water sustainable cropping systems. As wheat growth requires much more irrigation water compared with other cereal crops in the region (Yang et al., 2015b), water sustainable cropping systems with partial/complete wheat fallow are suggested to replace the dominant winter wheat-summer maize sequential cropping (WM-S) in the Hebei Plain. Alternative sequential 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). Strip relay-intercropping of wheat followed by spring maize is also constructed in field experiments in the Hebei Plain (Gao et al., 2009).

The recent field experiments reported in Pei et al. (2015) revealed the great advantages of early maize, which moves the traditional maize sowing date earlier by 10-20 days, in increasing maize production with a higher water productivity compared with summer maize and spring maize (Zhong et al., 2017). Based on the above advantage of early maize, Zhong et al. (2017) promoted a regional-scale cropping system adaptation strategy of replacing the current WM-S with the early maize-winter fallow (EM-F) or the winter wheat-early maize relay intercropping (WM-R) in accordance with the supply constraints of local water resources across grid-cells in North China Plain. They proved the feasibility of this strategy in reconciling the double challenges of maintaining regional grain production and recover groundwater in the North China Plain. However, this reconciliation is a result of compensating the loss of wheat production in the Hebei Plan by production gain from WM-R in Henan and North parts of Jiangsu and Anhui provinces. Although the simple de-intensification from WM-S double cropping to EM-F single cropping in the Hebei Plain as suggested in Zhong et al. (2017) would not result in conflict with existing planting regimes of other crops, large-scale substitution of wheat by maize may lead to great loss to wheat production, thus undermining food security of North China, where wheat has been the number one staple food of local people. Recent important works (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 followed by winter fallow and early maize (WM-FE), at Luancheng Agro-Ecological Experimental Station (114.41°E, 37.53°N). Their simulations using the APSIM model show a promising potential of the WM-FE regime in achieving groundwater neutral with a moderate total grain yield loss of 13%, but a significant wheat yield loss of 49.48% compared with the existing WM-S regime. Nevertheless the groundwater neutral result in their simulations could not be established without 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), and the additional surface water supply of about 41 mm/year from the South-North Water Transfer Project. Moreover, an application of this site-based result to other location is constrained by many factors, and will still lead to a groundwater table drop about 0.2 m/year with a regional total wheat production penalty of 50% in the Hebei Plain (Luo et al., 2018). One important example is the multi-cropping systems of wheat and other crops than maize, which has been a significant presence in the Hebei Plain (Figure 4-2).

Despite the limitations in both Zhong et al. (2017) and Xiao et al. (2017), a combination of their complementary advantages may allow us to develop an allocation procedure of the WM-R and EM-F systems across the Hebei Plain, which is capable of identifying the desired water sustainable cropping systems across different localities in the Hebei Plain. This constitutes the objective of this research. In more details, the procedure proposed by this research allocates the WM-R and EM-F cropping regimes across grid-cells in each county to achieve local water balance without overexploitation of groundwater and to minimize the wheat production loss at the regional level of the Hebei Plain. The procedure also takes care of the existing multi-cropping systems of other crops, vegetables and fruit trees. To facilitate the design and to assess the performance of our procedure, we employ DSSAT 4.6 to simulate the crop growth processes and their associated evapotranspiration levels of the WM-S, WM-R and EM-F regimes under the optimal irrigation schedules presented in Sun et al. (2011). For other crops, fruit trees and vegetables, we employ

AEZ v3.0 to simulate their evapotranspiration levels in each stage of the growth cycle.

Our results confirm that it is feasible to combine the complementary advantages of Zhong et al. (2017) and Xiao et al. (2017) and to meet the double challenges of achieving local water balance without overexploitation of groundwater and minimizing wheat production loss at the regional level of the Hebei Plain. The spatially explicit wheat fallow strategy as demonstrated in this research would be able to provide support to future agricultural policy design aiming at groundwater recovery in the region.

4.2 Study region

The Hebei Plain (Figure 4-1) (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. It includes 84 counties, covers a total area of 61,636 km^2, and has a typical semi-arid monsoon climate with an average annual temperature of 12-13°C and annual precipitation of 450-600mm. Seasonal precipitation varies greatly, about 80% of the precipitation occurs in the summer (June to September), while less than 20% happens in winter and spring. Climate resources in the Hebei Plain are sufficient for sequential cropping systems of two harvests in one year or three harvests in two years, and currently the winter wheat summer maize sequential cropping system dominates in the region. Summer maize is cultivated from mid-June to late September, while winter wheat is sown in the early October and harvested in early June in the following year.

The Hebei Plain can be divided into three zones of the piedmont, central and coastal plain (Figure 4-1). The piedmont plain has relatively richer 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 in the shallow aquifer and better soil conditions made the piedmont plain the most suitable zone for irrigation expansion, and currently the cropland irrigation ratio in this zone is the highest among the three zones. However, the persistent groundwater over-pumping has led to a fast water table drop at an annual rate of 0.3-1.3 meters, with the fastest drop in the Shijiazhuang-Baoding irrigation district of the piedmont plain. By contrast, groundwater resource in most parts of the central and coastal plain is very limited and only stored in the deeper aquifer, while 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 very significantly because surface water flow to the central and coastal plain is often cutoff by the reservoirs built in the upstream, especially during the dry seasons. Limited groundwater availability constrains the cropland irrigation expansion in these regions. On the other hand. the continuous over-pumping of the limited freshwater resources stored in the deep aquifer has caused rapid deep groundwater table drop and triggered considerable seawater intrusion in the coastal regions, with the deepest groundwater table at 100 m below the mean sea level (Foster and Perry, 2010), especially in the Cangzhou irrigation district of the coastal plain.

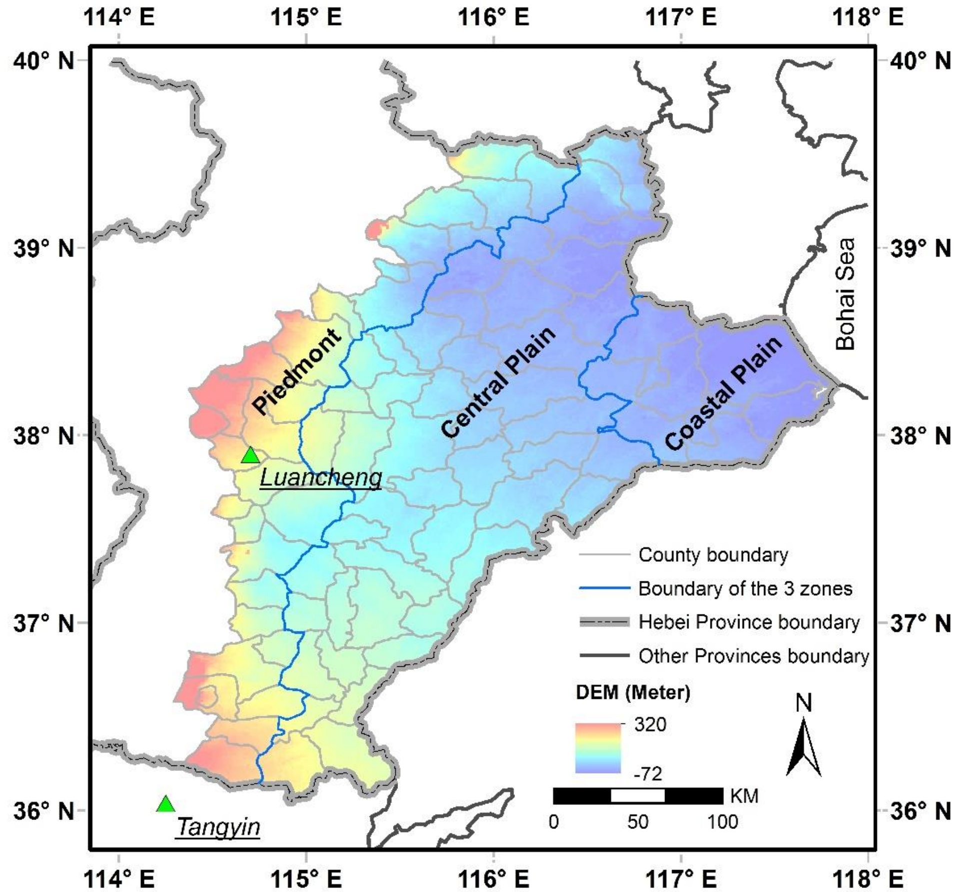

Figure 4-1. The Hebei Plain

4.3 Data and methodology

4.3.1 Data

Input datasets for running the DSSAT and AEZ model include daily weather data, soil profile, land use map, wheat and maize cropping management information, and irrigated and rain-fed areas of all crops and fruit trees growing in the Plain.

Historical daily weather dataset (2000-2010) of the Hebei Plain is taken from the WFDEI meteorological forcing dataset, which applies the observation-based WATCH Forcing Data methodology to ERA-Interim data (WFDEI) (Weedon et al., 2014), with a spatial resolution of 0.5 degree. Meteorological variables of temperature, downward shortwave radiation flux, rainfall rate and snowfall rate are used to generate the weather dataset required by the DSSAT model, which includes daily minimum and maximum temperature, solar radiation and precipitation. In addition, wind speed and relative humidity are required by the AEZ model.

The cropland map of the Hebei Plain in 2000 is 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 m. Cropland is further divided into plain cropland, hilly cropland, mountain cropland and cropland with slope greater than 25 degrees. Only plain cropland is considered suitable for the WM-R in this study, and WM-S on other types of cropland will be partially/completely replaced by EM-F to reach water balance. The soil profile dataset required by the AEZ model is obtained from the Harmonized World Soil Database (HWSD) (Nachtergaele and Batjes, 2012) (1 km resolution), and is also employed as the input for running the DSSAT model. Additional soil properties that are not covered in the HWSD but required by the DSSAT model are retrieved using the method described in Tian et al. (2014).

The crop-specific irrigated and rain-fed harvest areas of wheat, maize and all other crops in the Hebei Plain in 2000 are obtained from the MICRA2000 database (Portmann et al., 2010). It provides the monthly irrigated and rainfed areas for 26 crops in 2000, with a spatial resolution of 5 arc min (about 9.2 km in the Plain). The database is capable of representing multi-cropping systems and keeps consistency by construction with the census-based statistics from the National Bureau of Statistics of China. This dataset has been successfully applied to estimate water consumption change caused by changing area sown to winter wheat in the North China Plain (Wang et al., 2015). Figure 4-2 shows that the area ratios of irrigated wheat, irrigated maize and rainfed maize to the county's total cropland are much higher for wheat and moderately higher for maize in the piedmont than in the central and coastal plains. This pattern is a result of the 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 the DSSAT inputs are resampled into grid cells with a spatial resolution of 1 km.

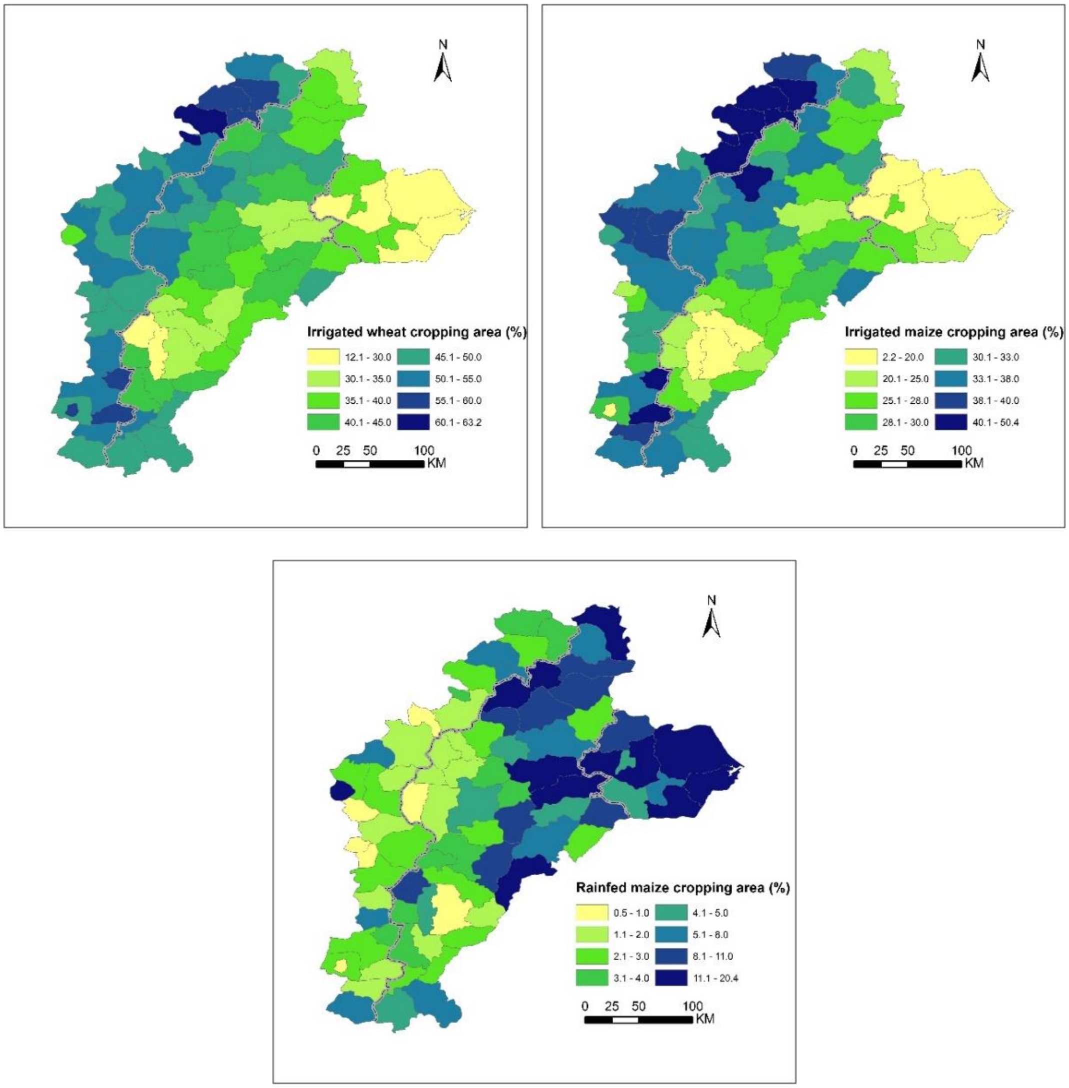

Figure 4-2. The shares of irrigated wheat, irrigated and rainfed maize cropping area in the county's total cropland across the Hebei Plain

4.3.2 DSSAT model

The DSSAT model is developed by the International Benchmark Sites Network for Argo-technology Transfer project (IBSNAT). It simulates in a daily step the growth and development of crops within a uniform plot of cropland under precise or assumed field management conditions. It also simulates soil water, carbon and nitrogen changes 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 has 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 is employed to quantify the amount of irrigation water saving required for stopping groundwater drawdown under the prevalent WM-S regime in Shijiazhuang Irrigation District of the 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), in a way as presented in Eq. 4-1.

$$\Delta S = P + I - ET - R - D \qquad (4\text{-}1)$$

In Eq. 1, ΔS is the net change in soil water content, and P, I, ET, R, and D denote precipitation (water resources), effective irrigation, evapotranspiration, surface runoff, and drainage from the soil profile, respectively. All of them are in unit of length (mm).

To estimate Irrigation Water Requirement (IWR) in the regional scale using the DSSAT model, several critical assumptions have been employed in the previous studies: (1) The surface runoff can be neglected for the regional scale assessment due to the dried off of the surface, high soil infiltration, flat topography and small cropland parcel in the North China Plain (Yang et al., 2015). (2) Because large scale intensive irrigation and the lack of long-term drying trend in the root-zone, soil moisture storage can be considered stable and soil moisture change is negligible in this region (Moiwo et al., 2009; Moiwo et al., 2010). (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 waterbody are not considered in the regional simulation (Chen et al., 2010). Nevertheless, those additional recharge water resources may still benefit the groundwater recovery in our study. Therefore, the local water resource change can be expressed as:

$$D - I = P - ET \qquad (4\text{-}2)$$

In Eq. 4-2, local water resource equals to *P*, and crop water consumption equals to *ET*. The local water balance will be achieved if $P - ET = 0$.

The total *IWR* (IWR_{total}) from the annual harvest area of winter wheat, summer maize and early maize under irrigated condition is calculated using the equation from Yang et al. (2010):

$$IWR_{total} = \sum_{i=1}^{n} IWR_i \times AR_i \qquad (4\text{-}3)$$

Where IWR_i refers to the *IWR* ($P - ET$) of specific crop *i* during the crop growth period, including winter wheat, summer maize and early maize, and *AR* is the current irrigated areas of wheat and maize in each grid cell. *IWR* of all cropping systems (WM-S, WM-R, EM-F) are simulated at daily step under the given crop calendar and irrigation condition.

The DSSAT wheat and maize models have been widely applied in the study region (Figure 4-1). Yang et al. (2006) calibrated and validated the performance of the DSSAT wheat and maize models in 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 demand 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. Please note that among 10 agro-meteorological observation stations in the North China Plain which have valid records of wheat-maize multiple cropping, Tangyin station is the only one with valid records for the WM-R system. Table 4-1 presents the cultivar coefficients of local wheat, summer maize and early maize varieties we employ in our simulations of their water consumption during their growth cycle. For other crops, vegetables and fruit trees planted in the Hebei Plain, we employ the simple soil-water balance module in the AEZ model to simulate their water demand because our simulations do not alter their existing planting locations and areas. The next sub-section will discuss the AEZ model.

Table 4-1. 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).

4.3.3 AEZ model

The AEZ 3.0 model is employed to estimate the ET of other crops. The AEZ model is 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 procedures. Such standardized procedures make the AEZ well suited for crop productivity assessment at the regional level where detailed and spatially explicit inputs are limited (Tubiello and Fischer, 2007; Gohari et al., 2013). The AEZ model has been successfully applied to estimate the actual ET (ET_a) of wheat and maize in the Hebei Plain (Wang et al., 2015). The equation to estimate the ET_a is as follows:

$$ET_a = \begin{cases} ET_0 \times K_c & \rho = 1 \\ P + \rho \times ET_0 \times K_c & \rho < 1 \end{cases} \qquad (4\text{-}4)$$

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 crop coefficients for all the 12 crops (except for wheat, maize and early maize) in this study is 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 (Wb) ≥ the threshold of readily available soil water (Wr), ρ = 1. If Permanent wilting capacity < $Wb < Wr$. If Wb < Permanent wilting capacity, ρ = 0 (IIASA/FAO, 2012).

In this study, the AEZ model is used to estimate the ET_a of all the other crops and fruit trees in the Hebei Plain. Because not all the crops in the MICRA2000 dataset are planted in the Hebei Plain, and there is a mismatch of the crop types between the AEZ model and the MICRA2000 dataset, we group the crops planted in the Hebei Plain into 14 types, including rice, barley, rye, millet, sorghum, soybean, sunflower, potato, sugar cane, sugar beet, groundnut, citrus/fruit tree, cotton, cabbage/vegetables. The ET of fruit trees other than citrus are calculated using the Pan-ET method and the Pan-evaporation coefficient is from Yang et al. (2010).

$$ET_i = \lambda_i \times ET_{pan} \qquad (4\text{-}5)$$

Where ET_i and λ_i refer to the actual ET and the pan-evaporation coefficient for the crop or fruit tree i, respectively, ET_{pan} is the local observation from a 20 cm diameter evaporation pan in the meteorological stations in the Hebei Plain.

4.3.4 Cropping system adaptation strategy

Our cropping system adaptation strategy for keeping the total local agricultural water consumption within the limit of local water resources is established by a loop procedure which replaces the current WM-S with WM-R or EM-F across grid-cells within each county of the Hebei Plain. More details of the WM-S and WM-R cropping systems can be found in the section 3.3.2. For other crops, vegetables and fruit trees, we assume that their locations and planting areas remain the same, so does their ET. The WM-R and EM-F cropping area will be dynamically allocated within the grid-cells occupied by WM-S, aiming to achieve local water balance under the constraint of minimizing losses of wheat production and total grain production in each county. The reason for doing the initial balance loop at the county level is as follows. Our simulation experiments which do the balance loop for the Hebei Plain as a whole lead to a significant loss of wheat production in comparison with the balance loop within each county. The intuition is that while there are no significant lateral water flows across the three sub-plains, at the intermedium scale of a county, it becomes more likely for the groundwater be balanced via lateral underground water flow from the areas with higher groundwater table (groundwater recovery) to the areas with lower groundwater table (groundwater overdraft), as showed in Figure 11 of Kendy et al. (2003). Therefore, the cropping system allocation procedure is apply by county. Major steps of the allocation procedure are depicted in Figure 4-3, which include: (1) At the grid-cell level, we estimate ET of the WM-R, WM-S, EM-F regimes under optimal irrigation schedule using the DSSAT model; and the ET of all other crops, fruit vegetables, and trees are estimated using the AEZ model and the Pan-ET method. (2) Identify the existing planting area of the three cropping systems – WM-S, winter wheat-other crops, and other cropping systems, based on the existing wheat and maize cropping area in each grid cell. We assume that areas occupied by other crops, vegetables and fruit trees remain unchanged, wheat will be put on fallow in the area occupied by wheat-other crops multi-cropping systems for water saving. (3) At the grid-cell level for a given county, calculate the remaining total water resource (WR_{remain}) using the total water supply from precipitation minus the total ET of winter fallow-other crops and other cropping systems than wheat-maize multi-cropping, then sort all the grids in ascending order according to WR_{remain}. (4) Estimate the baseline of WM-R and EM-F allocation under the constraint of no total grain production loss within that county using the algorithm developed by Zhong et al., (2017), then compare the total ET of WM-R and EM-F (ET_{adapt}) and the WR_{remain} from step 3. (5) If the $ET_{adapt} < WR_{remain}$, more water could be used for increase wheat production, then we replace EM-F with WM-R starts from the grid of EM-F with highest WR_{remain}. If the $ET_{adapt} > WR_{remain}$, more water should be saved by wheat fallow, then we substitute WM-R with EM-F starting from the grid of WM-R with lowest $WR_{remain.}$ This further adjustment will stop until the total water resource and demand become balanced within that county. Then continue the steps 3-5 for other counties. (6) Finally, the wheat fallow area and the potential impact of the new cropping systems on the total grain production will be obtained by comparing with corresponding figures in the existing wheat and maize cropping systems in the Hebei Plain.

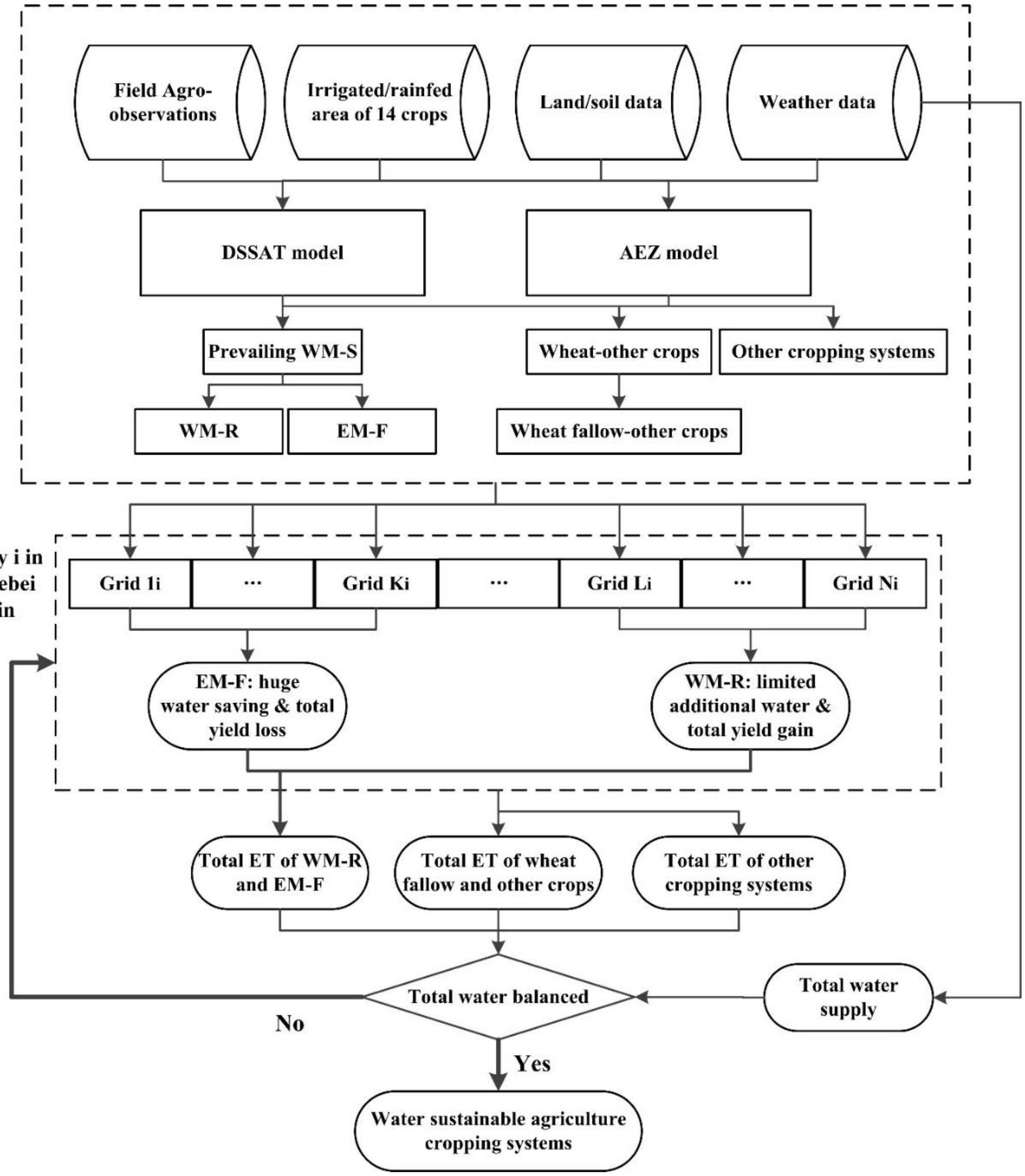

Figure 4-3. Regional cropping systems adaptation strategy: flow chart

4.3.5 Crop management and DSSAT model upscaling

Regional crop production and CWC across the Hebei Plain are 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 are obtained from Figure 2 in Binder et al. (2008), which are based on observations from 14 agro-meteorological stations in the North China Plain. Summer maize is sown right after the harvest of wheat, and wheat is sown 10 days after the harvest of maize for land preparation. Under the WM-R and EM-F, early maize is sown 15 days before the existing wheat harvest date. (Zhong et al., 2017)

Optimal wheat and maize irrigation schedule developed by Sun (2011) is applied to reduce the irrigation water amount, and automatic irrigation is 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 is 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 is applied with the absence of weeds, no pests and diseases, and no nutrient constraint. 100 kg of N fertilizer is 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 here are the attainable yield under optimal crop irrigation and management conditions.

4.4 Results

4.4.1 ET under existing cropping systems

The ET of wheat, summer maize, early maize under optimal irrigation schedule, and ET of other crops and fruit trees under existing regional cropping systems are estimated using the DSSAT model, the AEZ model and the Pan-ET method. Table 4-2 reports the aggregate ET of wheat, maize, and the combination of other crops, vegetables and fruit trees in the three plains and Figure 4-4 depicts the spatial distribution of their ET shares. As shown in Table 4-2, wheat and maize account for 27.9% and 22.61% of the total ET 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 ET. In contrast, the ET shares of wheat and maize in the central and coastal plains are smaller than the ET share of other crops-vegetables-fruit trees combined.

Under the existing cropping system, there is little room for further reducing wheat and maize water consumption in terms of ET once the optimal irrigation schedule is applied as we adopt in this study. The adoption of deficit irrigation will save a small amount of irrigation water but cause yield penalty (Hu et al., 2010) in comparison with the optimal irrigation schedule we adopt. Meanwhile, even under the triple harvest system of WM-FE, over-pumping of groundwater in the piedmont plain would continue to take place if without the consistent large quantity mountain-front recharge (about 150 mm/year) (Xiao et al., 2017). The above discussion indicates that a systematical adoption of more water-efficient cropping systems beyond the site-specific experiments is needed for achieving the local water balance and minimize the losses of total wheat and then grain production in the region.

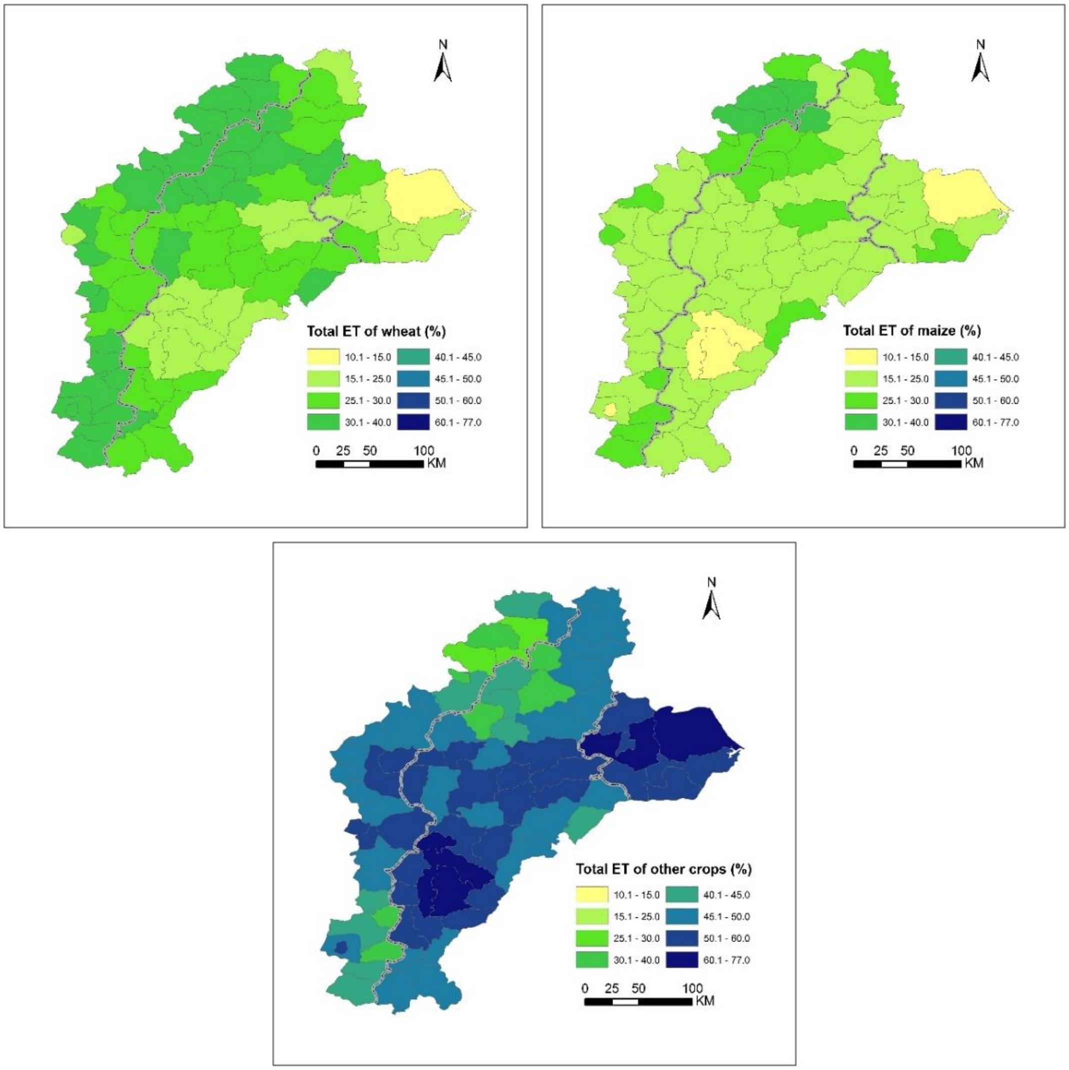

Figure 4-4. ET share of wheat, maize and the combination of all other crops, vegetables, and fruit trees in the total ET at the county level in the Hebei Plain

Table 4-2. ET of wheat, maize and all other crops, vegetables and fruit trees combined in the three plains

Plain	Wheat		Maize		Other	
	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%**

4.4.2 Areas for wheat fallow and WM-R cropping

Table 4-3 presents the aggregate results on areas for winter wheat fallow and for potential WM-R cropping and Figure 4-5 shows the spatial distribution of the area shares for winter wheat fallow compared with existing wheat cropping area and for WM-R compared with existing WM-S cropping area, respectively. Table 4-3 shows that in comparison with the central and coastal plains, the piedmont plain has the highest ratio of wheat fallow area to the existing wheat area (44.78%) because of the higher area-share of wheat in the county’s total cropland area and the heavier IWR of wheat in the piedmont. Some counties in the piedmont plain even have to fallow about 70% of their wheat cropping area to achieve water balance. In contrast, about 36.15% and 32.76% of the wheat cropping area need to be put on fallow in the central plain and coastal plain, especially in the southern part of the Hebei Plain. In terms of total fallow area, the central plain becomes number one because wheat cropping area in the central plain is much bigger than in the piedmont and coastal plains.

Results from Figure 4-5 and Table 4-3 also indicates that WM-R will be the dominant cropping system in the Hebei Plain under our adaptation strategy. 71.5%, 75.66% and 68.05% of the existing WM-S area will be replaced by WM-R in order to minimize the losses of total wheat production and then the total grain production in the region. Figure 4-5 shows that counties in the south Hebei Plain will have a larger portion of existing WM-S cropping area to be replaced by WM-R due to their smaller ratio of wheat fallow area to the existing wheat area. On the contrary, counties with high wheat fallow area ratio located in the middle part of the piedmont plain and the central plain, where a relatively much smaller portion of the existing WM-S cropping area needs to adopt WM-R.

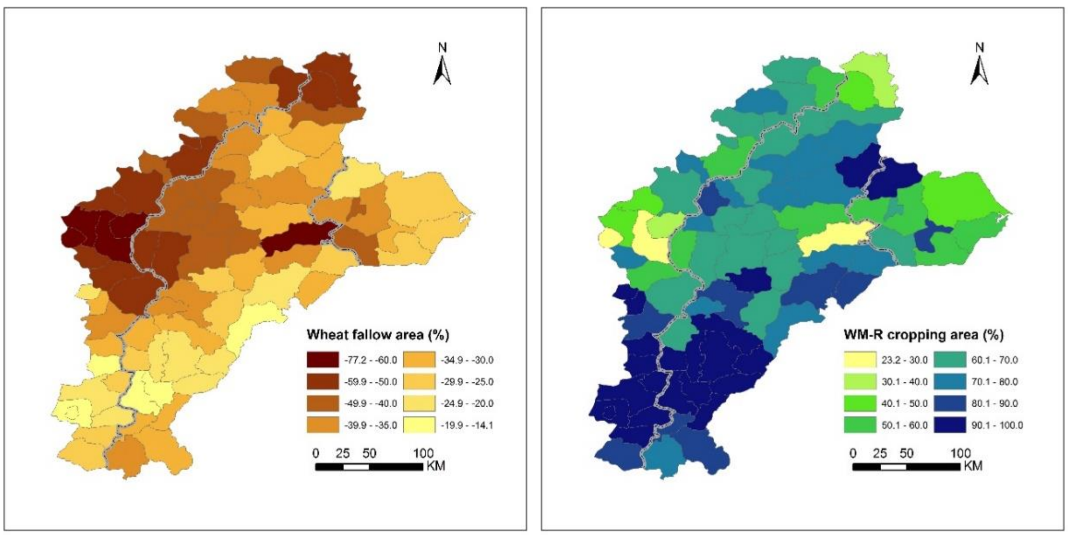

Figure 4-5. The share of wheat fallow area in the existing wheat area (left) and the share of potential WM-R cropping area in the existing WM-S area (right) at the county level in the Hebei Plain

Table 4-3. 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	64.05%
Total	**-736.44**	**-39.22%**	**1141.47**	**73.26%**

4.4.3 Regional grain production and IWR change

Table 4-4 reports 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 44.57%, 36.02% and 32.95% less than that under the existing cropping system, This implies that our wheat fallow strategy may lead to a total wheat production loss of 39.14% in the Hebei Plain, which is smaller than the wheat output loss of about 50% under WM-FE (at Luancheng site in Xiao et al. 2017; and at the regional level without considering water-balance of the whole cropping sector in Luo et al. 2018) and 100% under EM-F. On the other hand, adopting early maize may increase total maize production by about 35.27%, 36.61% and 35.63% in the piedmont, central and coastal plains, respectively, and this means that the total production loss of wheat and maize in the three plains would be reduced to the level of 16.09%, 9.32% and 3.24% respectively. For the Hebei plain as a whole, with the increase of total early maize production by 36%, the total grain production would suffer a moderate loss of 11.49%.

Because almost all the wheat are irrigated in the Hebei Plain, the spatial distribution of the wheat production loss (Figure 4-6) is highly depended on the wheat fallow area ratio (Figure 4-5), and all counties may suffer a wheat production loss to various extent as a result of wheat fallow. Generally speaking, there is a greater increase of maize production in the south Hebei Plain 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 bring more benefit to the maize production in the south. For some counties located in the north piedmont plain, east central plain, and coastal plain, where maize growth is more often under rainfed condition during the summer, the maize production increase there is much smaller than in the rest part of the Hebei Plain.

Changes of the IWR in each county across the Hebei Plain (Figure 4-6) and the total IWR change in the three plains (Table 4-5) are also estimated. The total IWR change of wheat and maize is determined by the total wheat fallow area and the 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 wheat fallow area ratio is the highest in comparison with the rest of the Hebei Plain. Similarly, the IWR increase from replacing summer maize by early maize is also the highest in the same sub-regions because the share of the existing irrigated maize cropping area in the total cropland area (Figure 4-2) is the highest there in comparison with the rest of the Hebei Plain. Aggregated results showed in Table 4-5 indicate that winter fallow may reduce the total wheat IWR by 63.47%, 60.92% and 42.09% in the piedmont, central and coastal plain, respectively, which imply a total IWR saving of 2638.88×10^{6} m^3 for the Hebei Plain as a whole. On the other hand, replacing summer maize with early maize will lead to an IWR increase by 29.89%, 40.71% and 23.14% in the three plains respectively, which imply an increase in the total IWR amount by 316.95×10^{6} m^3 for the Hebei Plain as a whole. Taking together the above IWR saving and increase, the total IWR in the Hebei Plain will decrease by 44.2% (2321.93×10^{6} m^3), which will contribute significantly to the groundwater recovery in this region.

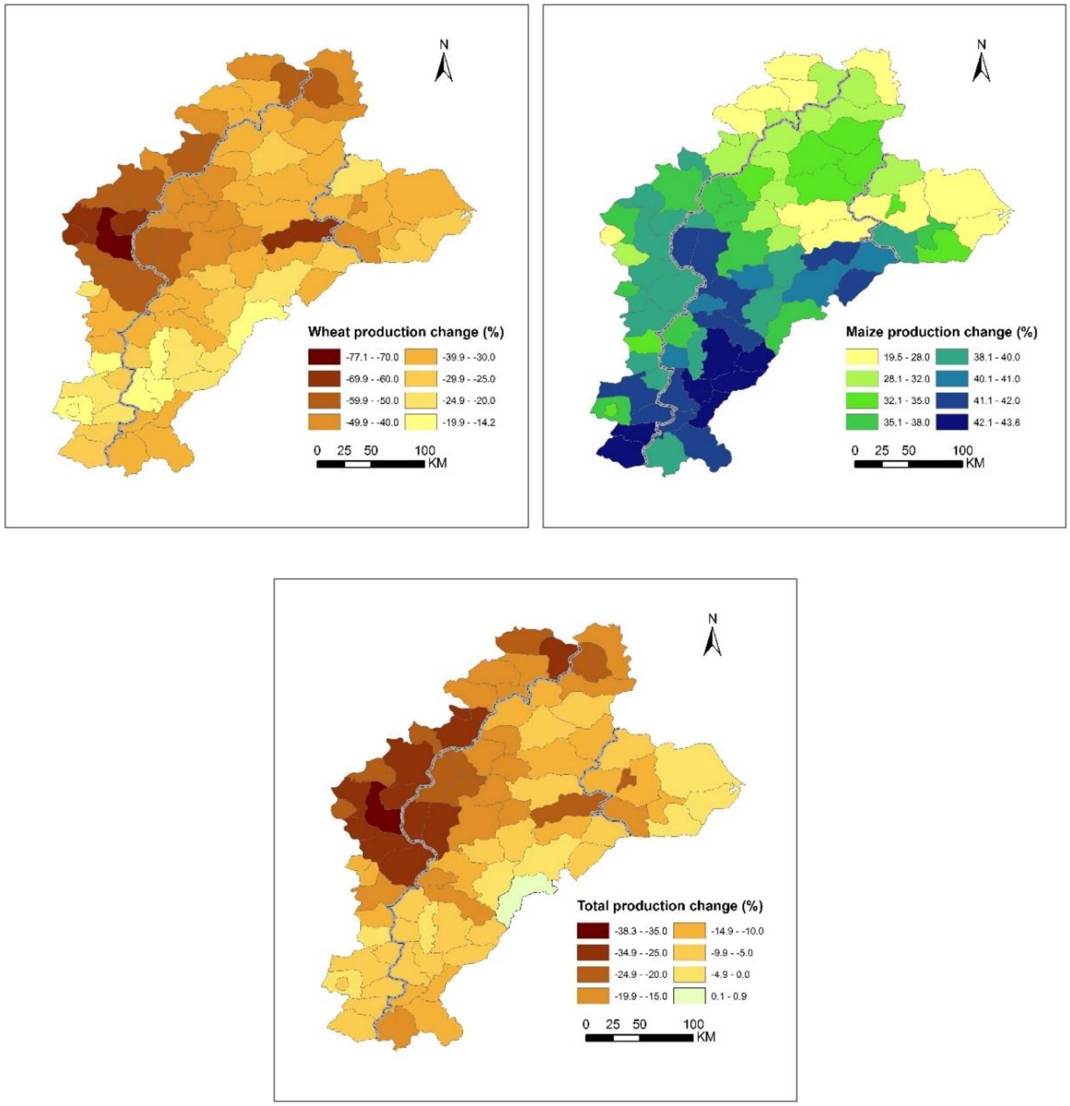

Figure 4-6. Changes in total production of wheat, maize and total grain at the county level in the Hebei Plain

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

Production	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	35.63%	-48.95	-3.24%
Total	**-5610.96**	**-39.14%**	**3005.13**	**36.04%**	**-2605.83**	**-11.49%**

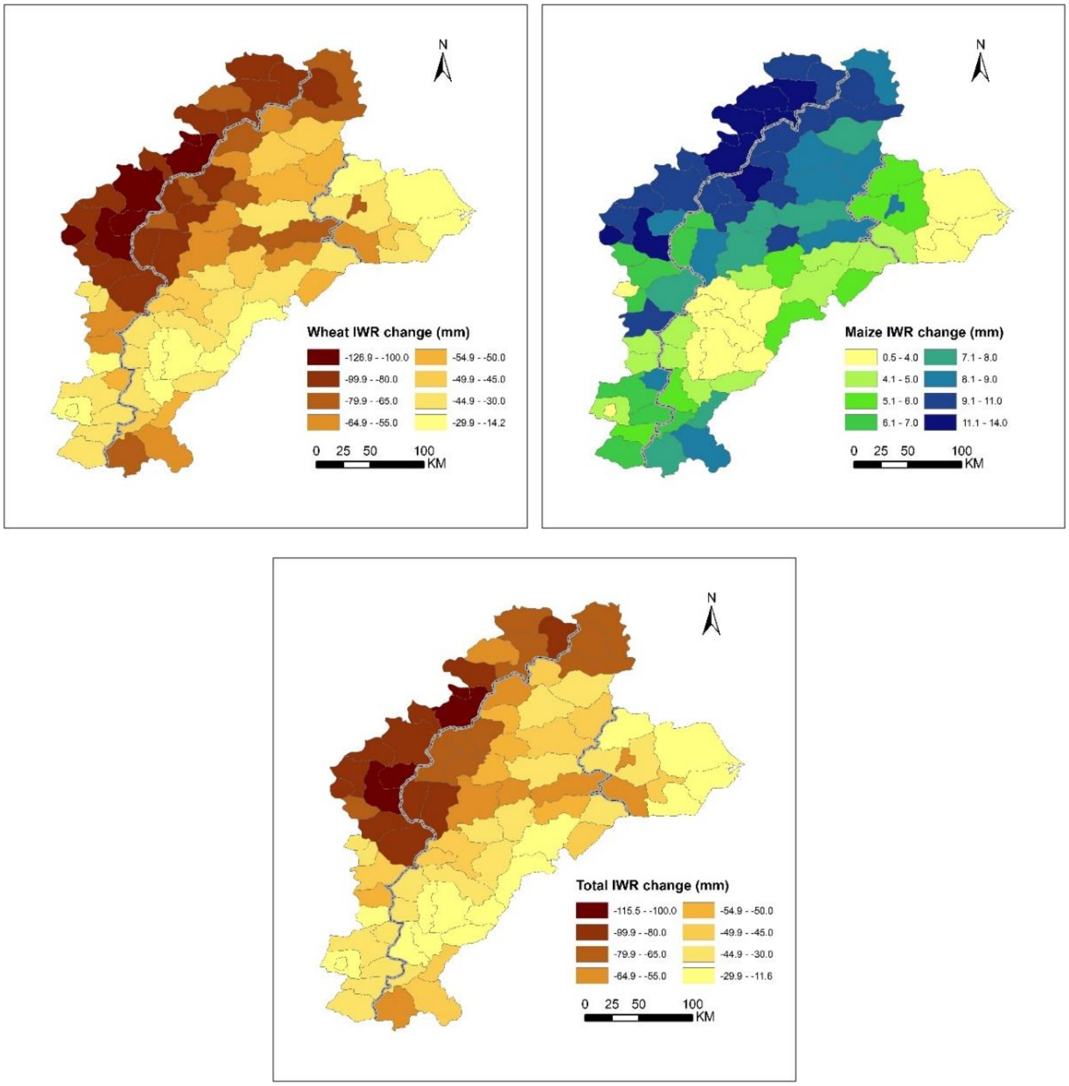

Figure 4-7. Changes in IWR of wheat, maize, and the whole cropping sector at the county level in the Hebei Plain

Table 4-5. Changes in IWR of wheat, maize and the whole cropping sector under the adapted cropping systems

IWR	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	-1019.55	-36.30%	311.79	14.58%	-707.76	-8.00%
Central plain	-1204.22	-28.38%	430.03	12.33%	-774.19	-4.93%
Coastal plain	-129.20	-26.08%	41.29	8.44%	-87.91	-3.53%
Total	**-2352.97**	**-31.18%**	**783.11**	**12.81%**	**-1569.86**	**-5.80%**

4.5 Conclusions and discussions

The on-going water crisis in the semi-arid Hebei Plain driven by rapid urbanization and irrigation-intensive farming has raised great 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 groundwater table. However, they all face the significant cost of wheat production loss, which threats wheat supply to Chinese population in north China, for whom wheat has been the most important staple food. To overcome the limitations of the existing adaptation proposals on wheat production-water saving tradeoffs and to identify sustainable local cropping systems which result in the minimum loss of wheat and then grain production for the region as a whole, a dynamic adaptation strategy is proposed in this research. This strategy takes the advantages of the following two alternative cropping systems: EM-F in water saving and WM-R in increasing grain production, and is subject to the constraints of local water balance and various local conditions which include climate, soil, water resources and existing cropping systems for other crops, vegetables and fruit trees in each county. Results of our simulations using the DSSAT and AEZ models demonstrate that our cropping system adaptation strategy may have a great potential in reducing irrigation water consumption and minimize the penalty of wheat and total grain production losses compared with the alternative cropping system adaptation proposals.

To make the newly proposed dynamic cropping system adaptation strategy more practical to the local farmers, ecological compensation policies for cropland fallow, enforceable regulations for irrigation water use and pricing, 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 efforts should be made to draw the attention of the local farmers to groundwater conservation and more fundamentally to encourage them to participate in winter wheat fallow (Wu and Xie, 2017). Groundwater should be priced in line with its scarcity so as to induce an economic mechanism which facilitates the sustainable use of groundwater for irrigation (Wang et al., 2016a). Ecological compensation policies will greatly promote the winter wheat fallow as most farmers are willing to abandon winter wheat with subsidies from the government. To encourage the adoption of WM-R, 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 WM-R.

In addition to reducing irrigation water demand of wheat and maize, our simulations of total water consumption in terms of ET also indicate that it is important, if not more, to improve the agricultural water use efficiency of other crops, vegetables and fruit trees and increase infrastructure investment for highly water-efficient vegetable production via recycle use of water in green houses. Previous studies have focused on optimizing irrigation water management and water use efficiency of wheat or maize in the piedmont plain. It is worth noting that reducing irrigation water use of other crops, vegetables and fruit trees may have significant effect on groundwater recovery because their total irrigation requirement is close to 50% of the total in the Hebei Plain, as shown by our simulations and by Yang et al. (2010). More studies at both site and regional scales should be constructed to identify detailed water saving measurements and strategy for other crops, vegetables and fruit trees.

Despite the usefulness of both the DSSAT and AEZ models in quantifying the amount of IWR 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 the additional groundwater recharge from ponds and rivers, drainage water from surface water runoff in the central plain, and the underground lateral aquifer flow from the Taihang Mountains mainly in the piedmont. Second, because both the DSSAT and AEZ models can simulate the soil water balance in the root zone during the crop growing cycle only, to assess the impact of irrigation volume change on groundwater variability and to include additional water resources require integration of crop-growth models and physical hydrological models (Nakayama et al., 2006; Hu et al., 2010; Shu et al., 2012) or employ machine learning models (Guzmán et al., 2017). The integration of crop-growth model and hydrological model requires heavy inputs of data for model calibration and up-scaling to the regional scale. However, the presence of numerous dams and wells, which has played critical roles in distributing/controlling water resources in the Hebei Plain, makes it prohibitively costly to collect detailed data across the region to meet the heavy input 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 even though such change only lasts for 15 days at the early stage of maize growth.

Chapter 5: Conclusions

5.1 Summary of this study

Agriculture and food production is critical to the Chinese well beings, social stability, and economic development. Continuous efforts have been made in developing new field adaptation measures to improve land productivity and to guarantee Chinese food security under climate change in the last few decades. Pessimistic inferences of grain production reduction under future climate projections in China call for further innovations on agricultural adaptation to mitigate the negative climate change impact and to capture potential opportunities in increasing grain production and safe-guarding China's food security in the coming decades. To identify the suitable adaptation measures that work well at both the site and regional scales across different agro-ecosystems and to quantify their potential benefits to the grain production and environmental sustainability, we need to understand how the site level adaptation measures interact with the regional level cropping system adaptation strategy.

To answer the above research question, this dissertation focuses on the cross-scale agro-ecosystem interactions between the field agricultural improvement and the large scale cropping system adaptation, and develops coupling framework and procedures to identify feasible cropping system adaptation strategies under observed warmer climate. Three case studies are conducted to demonstrate the applicability of this framework in identifying suitable cropping system adaptation measures for rice, wheat and maize in the Northeast China Plain, North China Plain and Hebei Plain, respectively.

The first case study focuses on the seedling and breeding improvements induced rice growth cycle extension and cropping area northward expansion in the Northeast China Plain under warmer climate. A cross-scale model coupling framework between the DSSAT and AEZ models is developed to improve the spatial performance of the AEZ model in capturing such large scale rice adaptation. In the second case study, the complementary advantages of two cropping systems: the early maize-winter fallow in water saving and wheat-maize relay intercropping in production promotion, are validated via site simulations, compared with the prevalent wheat maize sequential cropping system, and mobilized to allocate water sustainable cropping system at the grid-cell level across North China Plain. The objective of this allocation procedure is to reconcile the conflicts between the groundwater recovery and maintaining the aggregate level of grain production in the water deficit North China Plain under drier climate. In the third case study, the allocation procedure developed in the second case study is further optimized to meet the challenge of recovery local groundwater table and minimize the output losses of wheat and then total grain production in the Hebei Plain.

The original study and the initial results of this dissertation reveal the great potentials and advantages of the adaptations through cropping system allocation across grid-cells of a large region, and provide a comprehensive and reliable procedure to evaluate the benefits-costs of climate change adaptation measures with reference to agricultural production and environmental sustainability, which can function as a decision-making tool to support the localized agricultural adaptation decisions compatible with heterogeneous climate, land, water resources conditions across North China.

5.2 Key findings

The modelling efforts and dynamic adaptation procedures developed in this dissertation research, and their applications in three different cropping regions illustrate the great potential of the procedures in optimizing large scale cropping system adaptation strategies in the context of Northeast and North China Plains. Key findings include the follows.

An illustrative application of the DSSAT-AEZ model coupling framework to japonica rice adaptation in Northeast China is carried under the historical climate conditions of 1980-1999. The updated rice eco-physiological parameters and the best adaptive rice cultivar selected by the AEZ model improves the spatial performance of the AEZ model significantly. The updated AEZ model shows that the adapted rice cropping measures result in an extension of the rice growth length by up to 30 days in the vast majority territories of Liaoning and Jilin Provinces, and by about 20 days in the Heilongjiang Province, which are close to the field experiments in those regions (Gao and Liu, 2011, Cao et al., 2005, Jin et al., 2005). The simulation results of the updated AEZ model also correct the under performance of the original AEZ in estimating potential yield, showing an increase from 6.5 t/ha on average with the original AEZ model (lower than the real observed yield of 7.3 t/ha in 2000) to 9.3 t/ha, which is quite close to the rice yield from Chen's (2006) field experiment study.

The predicted rice planting areas extend significantly and become well coincided with the 2000 map of paddy land generated by remote sensing. Importantly, the procedure presents a convenient way for the AEZ model to update its key genetic parameters based on observed technological progresses in the farm sites.

Application of the cropping system adaptation strategy to North China Plain successfully maintains the regional grain production and allocate the two cropping systems of WM-R and EM-F to meet the requirement local water balance. The DSSAT simulations 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.

The optimal allocation of the WM-R and EM-F systems across grid-cells in the Hebei Plain based on the DSSAT and AEZ simulations can bring great benefits to both grain production and groundwater recovery: Compared with current wheat and summer maize cropping systems, 39.22% of the current wheat cropping area in the

Hebei Plain need to put on fallow in winter to achieve cropland water balance, which would lead to a scale of irrigation water saving at 2638.88×10^6 m^3. Replacing the current wheat-summer maize cropping system with our allocation of WM-R and EM-F systems may bring a 36.04% increase in total maize production and 39.14% decrease in total wheat production, resulting in a reduction in total grain production by 11.49% and a reduction in total agricultural irrigation water consumption by 2321.93 ×10^6 m^3. These findings indicate the potential benefits of our cropping system adaptation procedure in meeting the challenge of recovering local groundwater table with least possible grain production loss in the Hebei Plain.

5.3 Major contributions

This dissertation is a pioneering and systematic study in modelling and identifying the cross-scale agro-ecosystem interactions and potential benefit of the dynamic cropping system adaptation in meeting the double challenge of maintaining environmental sustainability – and guaranteeing food security under climate change conditions. Results from this dissertation underscore the adaptability of the agro-ecosystem from a passive field mitigation to a positive dynamic cropping system evolvement, and to more environmental sustainable agricultural adaptation options with localized new crop varieties, field management, and agro-climate resources.

Inefficient traditional approaches of updating crop bio-physical related information in the AEZ model strongly restricted the ability of the AEZ model in studying dynamic large scale cropping system adaptation. The modelling framework proposed in Chapter 2, aimed at the interconnection between site-base models and regional-scale models, contributes a helpful tool in finding an adaptive solution and direction for cropping system adaptation to incorporate new field-level improvement into regional scale planning. This study provides a reasonable interlinkage solution between these two types of models. The corresponding application in the Northeast China improves the AEZ simulation of rice growing length extension and cropping area northward extension in the last few decades. Similarly, this approach can also be applied to include more new breeding and management technologies of other crops and obtain a more robust assessment of climate change impact on agricultural production under various future climate scenarios in the Northeast China Plain, such as spring maize and soybean, and the rest 23 crop types in the AEZ model.

Recent field experiments in early maize show its advantages in high yield and less water consumption. This dissertation combines the above advantage of early maize with a new optimal irrigation schedule in reducing wheat irrigation water amount to develop a new cropping system adaptation procedure with the aim to – achieve groundwater recovery but without a significant compromise in total grain production in the semi-arid North China Plain. The optimization-based cropping system allocation procedure thus developed in Chapter 3 lead to a large scale solution to reconcile the above two conflicting objectives, which cannot be achieved only based on small scale experiments of alternative cropping systems. This adaptation strategy is designed from the perspective of environmentally sustainable agriculture, and can be applied in an even larger scale of the whole North China because the major crops and cropping system are similar and water deficit is the biggest issue in most regions. More localized adaptation should be designed with the new water saving irrigation techniques and cropping systems, especially the Northwest China.

Previous proposals on water sustainable cropping system adaptations with partial/complete wheat fallow may bring great benefit in groundwater saving, but at the expense of significant reduction in total wheat production in the Hebei Plain, where 11% of China's wheat is produced. A desired water sustainable cropping system adaptation strategy should effectively utilize the supply ability of local water resources, and more importantly, minimize the wheat production loss in the Hebei Plain, in additional to the constraints of diverse local cropping systems. Chapter 4 develops a more carefully calibrated procedure to dynamically allocate cropping system of the WM-R and EM-F regimes across grid-cells in each county to minimize wheat production loss under the constraint of local water balance. This further calibration of the optimization procedure takes care of the existing cropping systems for other crops than wheat and maize and can serve as a more practical policy supporting tool for agricultural planning in the region

5.4 Future directions

This dissertation is an initial step in designing dynamic large scale cropping system adaptation measures via cross-scale agro-ecological model coupling method under the conditions of climate change. It is expected that the results presented in the dissertation can prompt research interests to explore the potential benefits of cross-scale agricultural adaptation efforts in fully and sustainably utilizing the agro-climatic resources for other major crops and in other cropping zones in China, under current climate conditions and future climate projections, respectively. The detailed regional cropping system adaptation designs can also provide scientific support to the policy decisions for the local and national governments.

5.4.1 Modelling improvements

In the view of field scale crop modelling, more efforts are needed to improve our understanding of the phenology, development and evapotranspiration during the co-growing period of wheat and early maize under the relay-intercropping system (Knorzer et al., 2011). Impact of agricultural water consumption change to the groundwater table variability should be further investigated and the investigation needs an integration/coupling between the agro-ecosystem models and the hydrological models. Both the surface and underground water hydrological processes need to be taken into consideration, especially in the piedmont plain of the Hebei Plain where groundwater lateral flow in the shallow aquifer from the Taihang Mountains is an important recharge resource (Sun and Ren, 2014).

In the perspective of regional scale cropping system adaptation modelling, because of the diverse conditions of climate, land, and soil, as well as the difference in local dominate crops and multi-cropping systems across China, a universal application of the large scale adaptation procedures going beyond the case study of this dissertation requires further modelling efforts in efficiently integrating the latest field experiment results at other locations into the coupled modeling framework. An integration between the dynamic multi-cropping system adaptation procedures presented in Chapters 3-4 and the coupling framework developed in Chapter 2 would help future researches to identify the northward extend of multi-cropping systems, which had been observed across China (Yang et al., 2011), and would promote more proactive cropping system adaptation efforts across China, which would lead to a significantly increase in the cropland productivity in the transit zones under future climate projections.

5.4.2 Water, food, land and climate nexus

In addition to the effort to reduce agricultural irrigation water consumption via various water saving measurements and strategies, the trade-induced water saving through water-food nexus analysis is another efficient approach, which brings water embodied in food from water-rich region to water scarce region through food trade. The virtual water or embodied water, which represents the volume of water use in the production of the traded quantity of products (Allan, 1998), offers a new perspective for examining the trade-off of food production and water scarcity. Most existing studies focus on identifying the virtual water transfer and the impact of irrigation area adjustment on groundwater recovery and on food self-sufficiency (Dalin et al., 2014; Dalin et al., 2017; Dang et al., 2015). Different from the widely accepted conclusions of shrinking the wheat cropping area due to its heavy demand for groundwater irrigation, the water-food nexus results in Ren et al. (2018) show that green virtual water accounts for 61% of total virtual water export, and suggests maize cultivation cut could increase the soil water storage and groundwater recharge for wheat cultivation in the next season. Given the top-priority position of wheat production in China’s food security and the development of brackish water irrigation for wheat in the coastal regions of the Hebei Plain, further consideration of wheat-maize cropping system adaptation based on above perspective deserves a priority for future research.

5.4.3 Adaptations in other regions and under future climate projections

To mitigate the negative impact of climate change on crop production, agronomists and local farmers have developed various field measurements in different regions of China to adapt to the local environment change in the last several decades, and these adaptation practices may have changed the local multi-cropping systems. The successful application of the cross-scale agro-ecosystem model-coupling framework in establishing the proper regional cropping system adaptation strategy in the Northeast China Plain and North China Plain indicates its potential in further optimizing multi-cropping systems in other regions of China and in further improving the cropland productivity, especially in the transition zones between two cropping systems (e.g. double cropping system and triple cropping systems) as shown in Yang et al. (2015a).

More importantly, the impacts of future climate change on the total cereal production need to be reevaluated so as to obtain a more reliable estimation. Previous studies mainly focus on the site level measurements under specific crops or cropping systems, and the influence of micro-environment change under projected climate on crop growth process and yield, with the regional cropping system being commonly assumed unchanged. Results showed in this dissertation confirms the great potential of cropping system adaptation triggered by field-level progresses, and the successful application of the cross-scale agro-ecosystem model-coupling framework to the design of the effective regional cropping system adaptation scheme provides a solid support for the future agricultural adaptation policy decisions across China.

Incorporating cropping system adaptation into the assessment of climate change impact on agriculture would partially alter the prevalent negative conclusions.

5.4.4 Agriculture policy implications

Maintaining high food self-sufficiency and guaranteeing food security are the priority of all Chinese agricultural policies in the past, large scale adaptations proposed in this dissertation research will support the policy decisions to further optimize the local cropping systems in the major cropping zones in China. Results in Chapter 2 enhance the conclusion of the rice production increase in the Northeast China Plain. Policies with the infrastructure development support is needed to encourage local farmers to adopt the greenhouse seedling in the early stage of rice growth cycle so as to fully reap the benefit of the warmer climate. Meanwhile, the results also provide detailed spatial distribution of the rice cultivars across the region, which can help local farmers to determine which japonica rice variety is suitable to the local agro-climatic resources conditions.

On the contrary, agricultural de-intensification and groundwater recovery with minimum grain production loss is the major objectives of agricultural adaptation in the North China Plain. Compared with the complicated and highly skillful irrigation water saving technologies, fallowing winter wheat is the most effective way to reduce cropland irrigation demand in the North China Plain. Several groundwater use policies has been made to encourage cutting irrigated cultivation area with wheat fallow, and the Hebei Plain is selected as the pilot region in the “13th Five-year Plan” and the “Notice of Hebei Province People’s Government on the Printing and Distributing a Pilot Program for Comprehensive Treatment of the Overexploitation of

Groundwater in Hebei (2015)” (Wang et al., 2016b; Shao et al., 2017). In fact, more than 87% of the local farmers are willing to accept ecological compensation to fallow winter wheat in Hengshui of the Hebei Plain (Xie et al., 2017). To encourage the local farmers to adopt winter fallow and replace the water-intensive WM-S by spring maize single cropping for groundwater recovery, a subsidy of 280 yuan/mu is suggested to compensate the net income loss from wheat fallow (Wang et al., 2016b). However, the potential significant loss of total wheat production in the major wheat production region of China is the hardest constraint to the vast adoption of winter fallow. The cropping system adaptation strategies proposed in the Chapters 3 and 4 in this dissertation confirm that it is possible to achieve the groundwater recovery with even higher level of regional total grain production. The detailed spatial distribution of winter fallow area and the alternative cropping systems can provide scientific support for the design of agricultural and subsidy policies in the North China Plain, although we know that there is still a long way to go for making the cropping system adaptation measures really practical, accepted, and implemented by the local farmers and local governments.

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